STUDY OF VACCINE SUPPLY CHAIN FOR SUSTAINABLE DEVELOPMENT OF CHILD IMMUNIZATION PROGRAM IN INDIA

Ph.D. THESIS

by

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ROORKEE – 247667 (INDIA)
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Submitted in partial fulfilment of the requirements for the award of the degree

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **"STUDY OF VACCINE SUPPLY CHAIN FOR SUSTAINABLE DEVELOPMENT OF CHILD IMMUNIZATION PROGRAM IN INDIA"** in partial fulfilment of the requirements for the award of the Degree of Doctor of Philosophy and submitted in the Department of Mechanical and Industrial Engineering of the Indian Institute of Technology Roorkee is an authentic record of my own work carried out during a period from December, 2014 to September, 2018 under the supervision of Dr. Dinesh Kumar, Professor, Department of Mechanical and Industrial Engineering, Indian Institute of Technology Roorkee.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other Institute.

(DHEERAJ CHANDRA)

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

Dinesh Kumar
(Supervisor)

The Ph. D. Viva-Voce Examination of Mr. Dheeraj Chandra, Research Scholar, has been held on **………………..**

Chairperson, SRC **Signature of External Examiner**

This is to certify that the student as made all the correction in the thesis.

Signature of Supervisor **Head of the Department**

Dated: …………………

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ABSTRACT

Globalization has created a new opportunity for developing countries and has benefited almost every aspect of human life. It has helped India in many aspects, due to which it has become one of the world's fastest-growing economies. Since the last decade, India has made enormous developments in various sectors such as service, pharmaceuticals, education, software, etc. The pharmaceutical industry that discovers, develops, manufactures and market drugs are considered as one of the key contributors to the growth of India's GDP. The Indian pharmaceuticals market is the third largest in terms of volume and thirteenth largest in terms of value and accounts for 3.1 – 3.6 percent of the global pharmaceutical industry in value terms. It is expected to grow to US$100 billion by 2025. One of the key products of the pharmaceutical industry is the vaccine, which plays an important role in saving human lives. Despite being one the largest supplier of vaccines, India is still struggling to vaccinate its children with lifesaving vaccines. One of the primary causes of low child immunization rate in India is the inefficiencies in the vaccine supply chain (VSC), which hampers the delivery of vaccines to the health centers. Therefore, it is important that the universal immunization program (UIP) India gives proper attention to its VSC so that the opportunity to vaccinate a child is not missed because of the unavailability of vaccines. Thus, the main objective of this work is to study and analyze the supply chain of basic vaccines, required to immunize children in India. The study findings will provide important solutions to help UIP India to measure and improve vaccine supply chain performance (VSCP). Improvement in VSCP can help in delivering vaccines efficiently and effectively to the health centers so that no child remains unimmunized and sustainable child immunization programs are built in India.

To achieve this objective, first, the key issues in the supply chain of basic vaccines have been identified. To do so, a field survey and a thorough literature review were conducted and then using expert's opinions through the Delphi technique, twenty-five key issues have been finalized for the study. By employing interpretive structural modeling (ISM) and fuzzy matrix cross-reference multiplication applied to a classification (FMICMAC) approaches and using senior expert's opinions, critical factors of vaccine supply chain having maximum impact on VSCP improvement have been identified. Next, these twenty-five issues have been categorized into five main domains of issues viz: economy, operational, management, social, and environmental and then using fuzzy analytical process (FANP) methodology, these five main domains, and twenty-five issues have been ranked according to their level of importance. In addition, a sensitivity analysis has been performed to validate the results of the FANP.

After analyzing and identifying the important issues, one of the critical issues i.e. vaccines shortages that are faced by the immunization programs across the globe has been discussed. Using field survey, literature, and expert's opinions, ten causes or criteria for basic vaccine shortages and twelve solutions or alternatives that can help to overcome the shortage problems have been presented. With the help of the analytic hierarchy process (AHP) method, the weights of the criteria's have been computed and then using criteria weights, the final ranking of the alternatives have been obtained using complex proportional assessment of alternatives with grey relations (COPRAS-G) approach. In the end, a simulation has been to validate the results.

Through the study of the VSC issues, it has been found that UIP India is still operating through the conventional vaccine supply chain system to deliver vaccines, which is one of the main reasons for the birth of VSC issues and low efficiency of UIP. Therefore, the focus of the VSC designers should be on moving from the conventional vaccine supply chain system to the direction of the next-generation vaccine supply chain system (NGVSCs) to improve vaccine delivery performance. Hence, a framework that employs an integration of fuzzy analytical hierarchical process (FAHP) with fuzzy multi-objective optimization on the basis of ratio analysis (FMOORA) methodologies to simultaneously propose ten solutions to the identified fifteen barriers have been presented to help decision-makers design NGVSCs. In addition, a sensitivity analysis has been done for measuring the robustness of the ranking of the solutions.

Subsequently, through the framework of NGVSCs, a well-performing vaccine supply chain can be designed. Hence, it is important for the decision-makers to maintain this performance and further improve it for the continuous improvement of the VSC system. In this regard, to help decision-makers measure, monitor, and improve the performance of the supply chain, the key performance indicators (KPIs) of VSC system have been identified using exploratory factor analysis (EFA) in the four dimensions of the balanced scorecard (BSC) approach viz: learning and growth, internal process, customer, and finance. Then using structural equation modeling (SEM), a theoretical framework has been shown that demonstrates how the UIP India can utilize its vaccine supply chain KPIs for the sustainable development of child immunization program. Moreover, Two-Way assessment has been performed to further improve VSCP in order to improve sustainability. The results of the Two-way assessment have been validated with DEMATEL.

To sum up, some suggestion in the conclusion section has been presented that will help UIP India and immunization programs of other developing countries to efficiently and effectively manage the child immunization programs so that no child misses' vaccination dose and sustainable child immunization programs are built.

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LIST OF ABBREVIATIONS

AGFI	Adjusted Goodness of Fit Index
AHP	Analytic Hierarchy Process
AMOS	Analysis of Moment Structures
ANM	Auxiliary Nurse Midwife
ANP	Analytic Network Process
ASV	Average Shared Variance
AVE	Average Variance Extracted
BCG	Bacillus Calmette Guerin
BDRM	Binary Direct Relationship Matrix
BSC	Balanced Scorecard
CFA	Confirmatory Factor Analysis
CFCS	Converting the Fuzzy Data into Crisp Scores
CFI	Comparative fit index
CI	Consistency Index
COPRAS-G	Complex Proportional Assessment of alternatives with Grey relations
CR	Consistency Ratio
CR	Composite Reliability
DALY	Disability-Adjusted Life Years
DEMATEL	Decision Making Trial and Evaluation Laboratory
DPT	Diphtheria, Pertussis and Tetanus Toxoid
EFA	Exploratory factor analysis
EFA	Exploratory Factor Analysis
EPI	Expanded Program on Immunization
eVIN	Electronic Vaccine Intelligence Network
EVM	Effective Vaccine Management
FAHP	Fuzzy Analytic Hierarchy Process
FANP	Fuzzy Analytic Network Process
FDRM	Fuzzy Direct Relationship Matrix
FDRM	Fuzzy Direct Relationship Matrix
FMCDM	Fuzzy Multiple Criteria Decision-Making
FMICMAC	Fuzzy Matrix Cross-Reference Multiplication Applied to a Classification
FMOORA	Fuzzy Multi-Objective Optimization by Ratio Analysis

FRM	Final Reachability Matrix
FSWARA	Fuzzy Step-wise Weight Assessment Ratio Analysis
FTOPSIS	Fuzzy Technique for Order of Preference by Similarity to Ideal Solution
GAVI	Global Alliance for Vaccines and Immunisation
GDP	Gross Domestic Product
GFI	Goodness of Fit Index
GOI	Government of India
GRI	Global Reporting Initiative
ICMR	Indian Council of Medical Research
IFI	Incremental Fit Index
IHC	Immunization Health Center
ILR	Ice-Lined Refrigerators
IPV	Inactivated Poliomyelitis Vaccine
IRM	Initial Reachability Matrix
IRP	Interpretive Ranking Process
ISI	Institute for Scientific Information
ISM	Interpretive Structural Modelling
KMO	Kaiser-Meyer-Olkin
KPI	Key Performance Indicator
MCDM	Multi-Criteria Decision-Making
MICMAC	Matrix Cross-Reference Multiplication Applied to a Classification
MOORA	Multi-Objective Optimization on the Basis of Ratio Analysis
MSV	Maximum Shared Variance
NFI	Normed Fit Index
NGVSCs	Next-Generation Vaccine Supply Chain System
NHRM	National Rural Health Mission
OPV	Oral Polio Vaccine
PATH	Program for Appropriate Technology in Health
PMS	Performance Measurement System
PNFI	Parsimonious Fit
PSC	Pharmaceutical Supply Chain
RFI	Relative Fit Index
RFID	Radio-Frequency Identification
RI	Random Index
RMSEA	Root Mean Square of Approximation

RVV	Rotavirus Vaccine
SBSC	Sustainable Balanced Scorecard
SCM	Supply Chain Management
SCP	Sustainability Practices Criteria
SCPMS	Supply Chain Performance Measurement System
SD	Sustainable Development
SEM	Structural Equation Modelling
SIHC	Sub-Immunization Health Center
SIHC	Sub Immunization Health Center
SKPC	Sustainability Key Practices Criteria
SPSS	Statistical Package for the Social Sciences
SSCM	Sustainable Supply Chain Management
SSIM	Structural Self-Interaction Matrix
TCV	Typhoid Conjugate Vaccine
TFN	Triangular Fuzzy Numbers
TISM	Total Interpretive Structural Modelling
TLI	Tucker-Lewis index
UIP	Universal Immunization Program
UNICEF	United Nations International Children's Emergency Fund
VBA	Visual Basic Applications
VSC	Vaccine Supply Chain
VSCP	Vaccine Supply Chain Performance
VVM	Vaccine Vial Monitors
WCED	World Commission on Environmental and Development
WHO	World Health Organization
3PL	Third Party Logistics

Chapter 1

INTRODUCTION

1.1. Background

India is one of the fastest growing economies in the world. By gross domestic product (GDP), it is the world's sixth-largest economy and third largest by purchasing power. One of the reasons that can be considered for this development is globalization, which provides a net benefit to individual economies around the world. According to the most economist, in today's era, globalization has benefited developing countries in numerous ways such as better healthcare facilities, technological infrastructure developments, improved communication through media, better education, improved economic processes, better and longevity human life, etc. It is true that globalization benefits the country's economy and our daily lives, however, it also has negative effects on environmental damage through the increased waste of harmful substances, air pollution, depletion of ozone layer, etc. Due to such environmental issues, people of all age group are facing the loss of human health and varying degree of vulnerability to various diseases. According to the world health organization (WHO), the change in the environment is the root causes for people to get sick because of several infectious diseases such as malaria, dengue, diarrhea, flu, etc. As children are more susceptible to such infectious diseases, therefore, it is important that they should be properly immunized since their birth. One of the effective ways to immunize children against various diseases is through vaccination at the early age of their birth.

Routine immunization is considered one of the simplest and most cost-effective tools for ensuring child survival. In 1974, the World Health Organization established the Expanded Program on Immunization (EPI) to ensure that all children have access to six basic vaccines. After 40 years of inception of EPI, even today, around 19.5 million infants worldwide are missing out on basic vaccines. According to WHO, vaccination averts 2 to 3 million deaths annually, and an extra 1.5 million lives can be saved if global vaccination coverage improves [1]. In India, for child immunization, the government started a universal immunization program (UIP) in 1985, one of the largest health programs of its kind in the world to cover maximum children for immunization. Today, India is one of the largest suppliers of vaccines to UNICEF and to the globe and is considered as the epicenter for vaccine manufacturing in the world [2]. In spite of being a vaccine manufacturing hub and the continuous operation of UIP for more than 30 years, India is still home to one-third of world unimmunized children. Unfortunately, the UIP has been able to vaccinate only 65% of the children in the first year of their life and the increase in coverage has stabilized in the past 5 years to an average of increase of 1% every year [3].

In recent years, developing countries like India are facing the issue of low child immunization coverage, the primary reason being the outdated and inefficient vaccine supply chain (VSC) [4]. The government wants to provide vaccination to all infants so that none dies due to vaccine-preventable diseases. The goal of ensuring every child is immunized can be achieved by a well-designed, efficient, and effective VSC system. Successful immunization programs can be constructed on an efficient, end-to-end supply chain and logistics systems [5]. The vaccine supply chain, which integrates all personnel, systems, equipment, and activities involved in making sure that vaccines are effectively delivered right from the stage of manufacturing to the people who need them. However, for several reasons, developing countries supply chains are already strained due to the introduction of new vaccines and many several reasons, therefore, the possible inability to distribute new vaccines will position lives at risk [6,7].

Analyzing and identifying the areas of improvement in VSC can help to enhance VSC performance, which will ensure the efficient and effective delivery of vaccines to the health centers. An improved VSC performance can also be helpful to the immunization program in fulfilling its objective of improving child immunization rate and further for the importation of sustainable development strategies, which are necessary for improving the immunization program overall effectiveness. Due to the above discussion and the importance of managing the vaccine supply chain, the main goal of this research is to study and analyze the supply chain of basic vaccines required to immunize children of 0-3 years in India. This study can serve as a guideline for the vaccine supply chain managers and immunization programs policy-makers of developing countries to design better immunization strategies to improve vaccine supply chain performance (VSCP) and to provide a suitable environment for sustainable development of child immunization programs

1.2. Supply chain management

In the current era of the fast-changing market, it is very difficult for any company to compete as a fully individual entity [8]. Customers are becoming more demanding, expecting better-customized products and better customer service than what was in the past. The high competition pressure urges companies to shorten product life cycles, increase product variety, and to adapt to technological changes more quickly than they did in former times. It is important, therefore, that the organization selects a group of attributes that maximize the overall objective of satisfying both corporate and customer requirements and increase profit [9]. Thus, to adapt quickly and efficiently to changes in the market environment in order to satisfy its customers and make a profit, a successful supply chain management is required to be able to produce different products and deliver to market in an acceptable speed and cost [10].

Supply chain management (SCM) is defined as the management of goods and services right from the point of origin until it reaches the final customer. The supply chain integrates various business partners such as suppliers, manufacturers, distributors, and retailers to deliver products and services to the customers in order to fulfill business objectives. Figure 1.1 is a schematic of a supply chain.

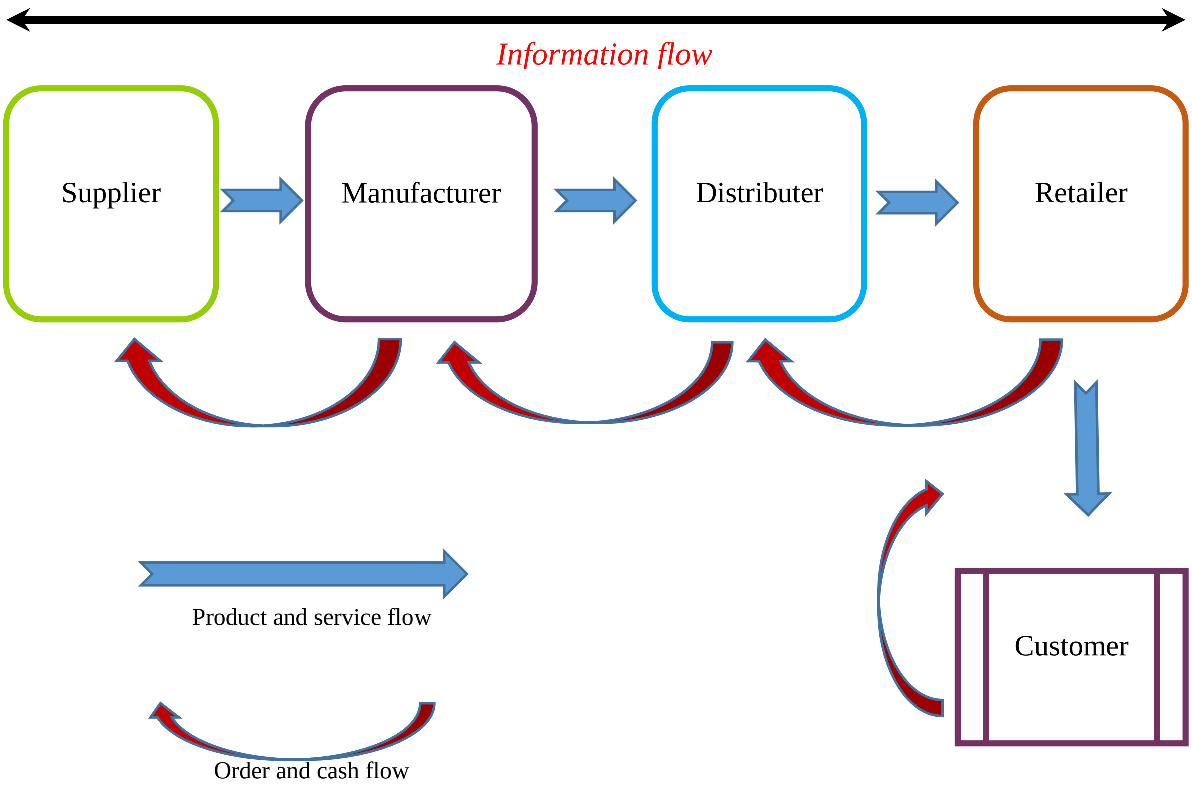


Figure 1.1: A schematic of a supply chain.

Today, SCM plays an important role in various industries such as an automobile, health care, food, textile, chemical, agriculture, etc. Every organization wants that its customers are satisfied along with fulfilling the mission and vision of the organization. That is where SCM plays a crucial role in the industries, organizations and business firms. The present research focusses on the supply chain management of one of the key sector of the healthcare industry i.e. pharmaceuticals and its key component product i.e. vaccines.

1.3. Healthcare industry

The healthcare industry is one of the largest and fastest growing industries globally. In India, the healthcare industry is one of the booming sectors and it is expected to increase from US$ 110 billion in 2016 to US$ 372 billion in 2022. During 2008-20, the market is expected to record a CAGR of 16.5 percent [11].

In the last two decades, the Indian health system has made a tremendous transformation in providing better healthcare facilities, reducing sickness, increase job opportunities, encouragement in foreign direct investment, etc. Until 1980, the government and non-profit organizations ran the healthcare industry in India. Today, it functions with the help of both the public and private sector.

The services and facilities governed by the government of state as well as of central come under the public healthcare system (PHS). The system is helpful in a way as it provides a varied number of services and other facilities at free of cost or at concessional rates to the people of rural areas as well as the to the people of lower income group in urban areas [12,13]. The introduction of the private sector the repute of India's healthcare industry has now been recognized globally. For example, the Serum Institute of India, a manufacturer of vaccines is the world's largest vaccine producer by the number of doses. The market for healthcare functions through six main segments shown in Figure 1.2.

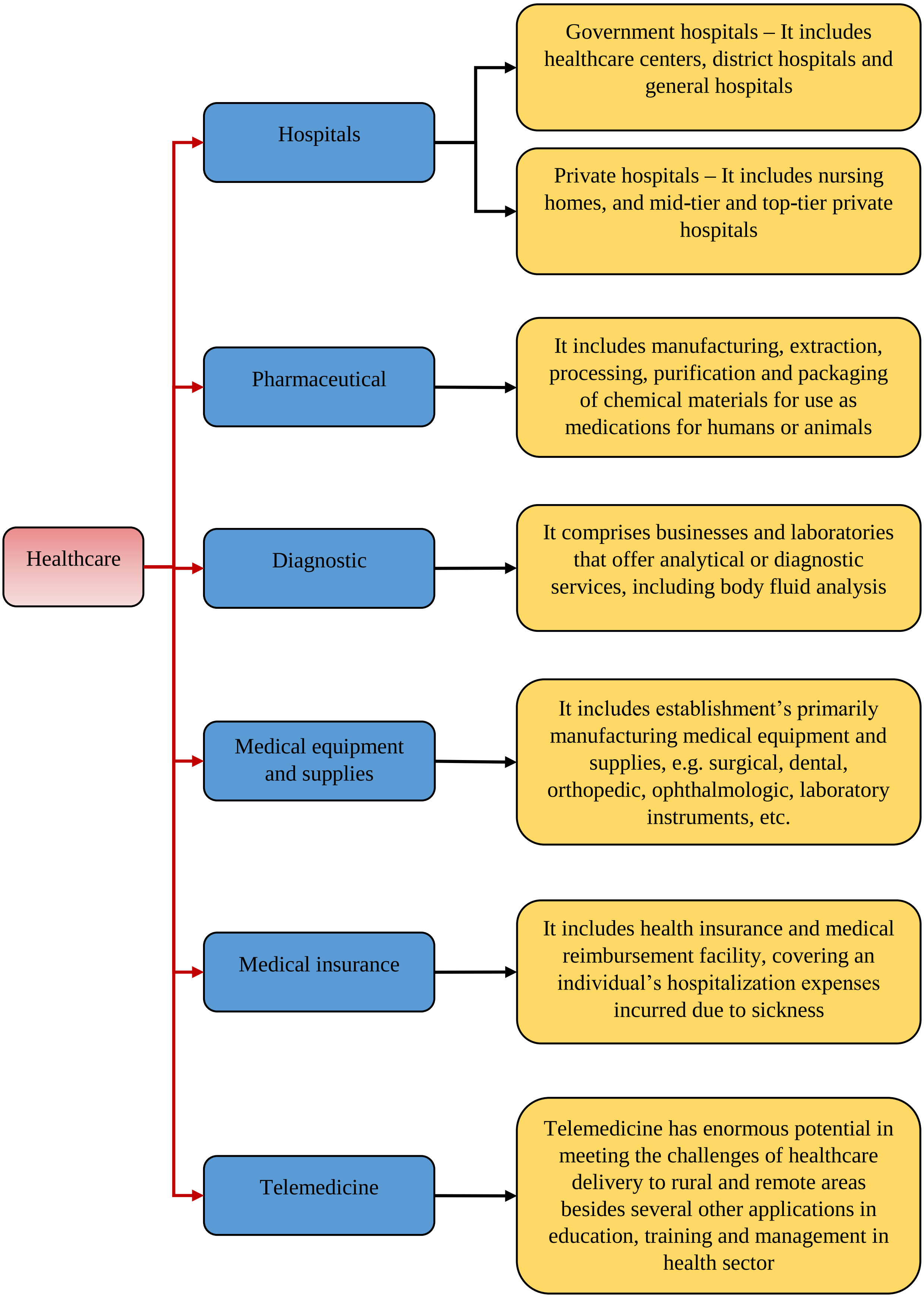


Figure 1.2: Healthcare industry main segments [11].

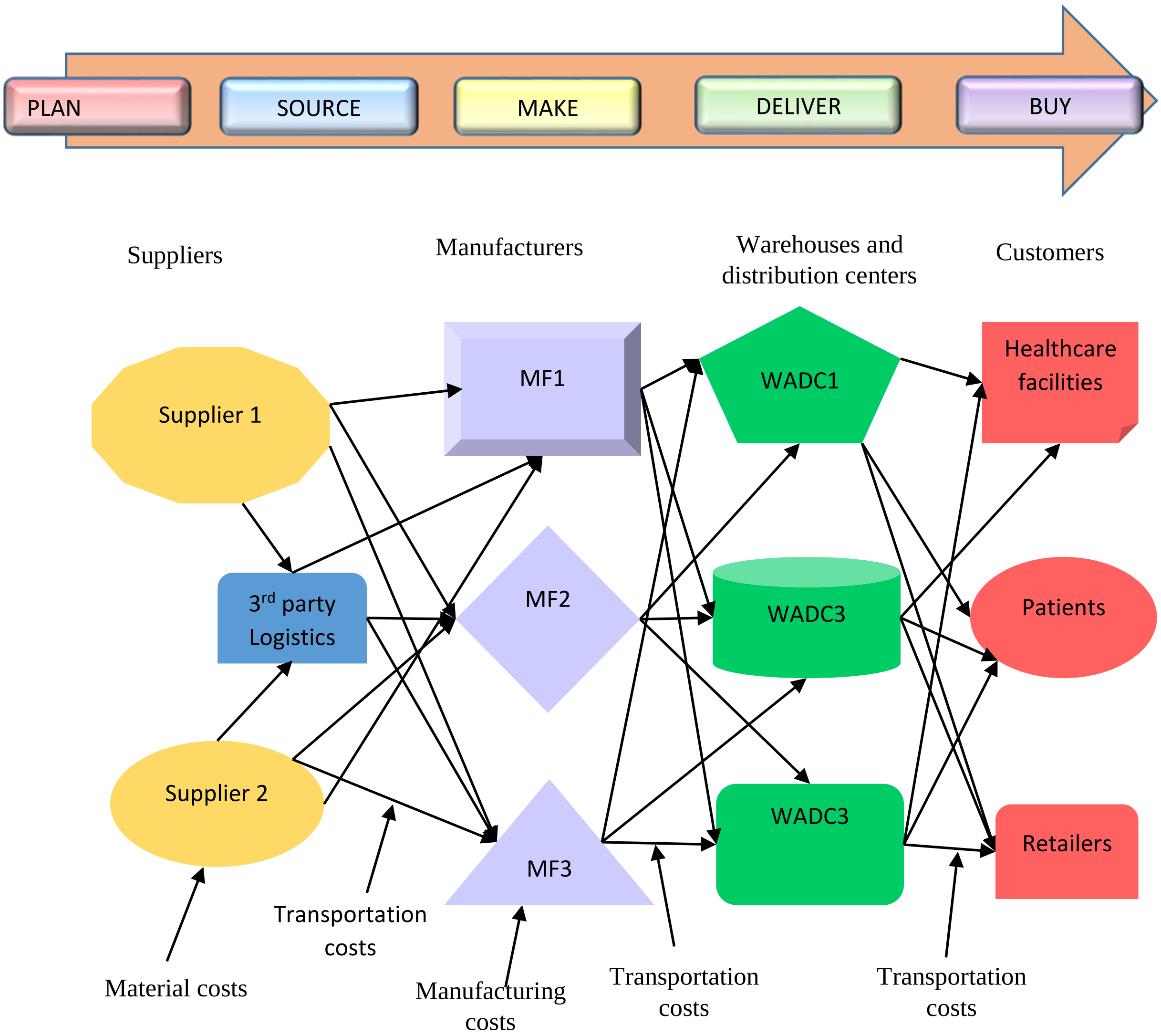
The present work considers a pharmaceutical segment of the healthcare industry for the study and analysis purpose. The pharmaceutical industry assumes a vital part of human well-being and fast access to the medication is one of the key issues that have a significant effect on the government healthcare plans [14]. In the next section, the key aspects of the pharmaceutical sector have been discussed.

1.3.1. Pharmaceutical sector of the healthcare industry

The pharmaceutical sector plays an important role in the economy, society, and public health in almost every country in the world. The sector, as an immense global industry, is responsible for the manufacturing, development, and marketing of medications, hence, the sector plays an important role in human health. The pharmaceutical industry is characterized by a high cost of R&D and innovation complexity in the supply and distribution of pharmaceutical products in both developed and developing countries, and supply-side market power. In the context of India, the Indian pharmaceutical sector is estimated to account for 3.1 – 3.6 percent of the global pharmaceutical industry in value terms and 10 percent in volume terms. It is expected to grow to US$100 billion by 2025. The market is expected to grow to US$ 55 billion by 2020, thereby emerging as the sixth largest pharmaceutical market globally by absolute size. Because of the immense growth of the pharmaceutical industry and lucrative sector, new players are entering the pharma market, hence, complexities in managing and delivering medicines through the pharma supply chain are inevitable. The pharmaceutical supply chain (PSC) is considered one of the most complex supply chains in the present time.

In general, a PSC is a four or sometimes a five-tier supply chain that includes primary manufacturers, secondary manufacturers, main and local distribution centers, and destination zones/demand points (e.g., pharmacies, hospitals, clinics, etc.). The primary manufacturers are responsible for the production of products. Similarly, the secondary manufacturers are responsible for further production procedures with the addition of special technology ranges, packaging and finalizing the goods that are typically in SKU form. If the PSC is compared to a normal manufacturing supply chain, primary producers may be known as suppliers of raw materials, and secondary manufacturers as manufacturing centers. Subsequently, the role of the secondary manufacturers in the production of a final product is less; however, they can also keep the stock of products in the facility for an emergency. Both major and local DCs are responsible for stocking items to fulfill customer demand. Compared to main DCs, local ones are often more dispersed to cover more demand points, and more limited in terms of capacity levels.

Despite coupling with sophisticated technologies and improvements in the quantity and quality of associated products in PSCs, many companies are far from effectively satisfying market demands with respect to arisen concerns [15].



. **Figure 1.3: Pharmaceutical supply chain** [16]**.**

Figure 1.3 shows a four-tier pharmaceutical supply chain starting from the procurement of raw materials from the supplier to the delivery of products and services to the end customers i.e., patients, healthcare facilities, etc. According to leading pharmaceutical companies such as Pfizer, GlaxoSmithKline (GSK), etc., the vaccines are among big pharma's best-selling products and plays an important role in saving human lives. In the present work, consequently, the supply chain of one of the important pharmaceuticals product – the vaccine is discussed.

1.4. Vaccine supply chain

A vaccine is a biological preparation that provides active acquired immunity to a particular disease. A vaccine typically contains an agent that resembles a disease-causing microorganism and is often made from weakened or killed forms of the microbe, its toxins, or one of its surface proteins. The administration of vaccines is called vaccination. The terms vaccine and vaccination are derived from Variolae vaccinae (smallpox of the cow), the term devised by Edward Jenner to denote cowpox. He used it in 1798 in the long title of his inquiry into the Variolae vaccinae known as the Cow Pox, in which he described the protective effect of cowpox against smallpox. In addition, a new field of microbiology and immunology has evolved, called "vaccinology," that comprises not only vaccine development but also the use of vaccines and their effects on public health [17–19].

According to a report "Indian Vaccine Market Report and Forecast 2017-2022", the market of the vaccine in India reached a value of around INR 59 Billion in 2016, with a CAGR of nearly 18% during 2009-2016. Indian vaccine industry with best manufacturing facilities has earned India the recognition of having the largest global capacity for WHO prequalified vaccine manufacturing. The vaccine marketplace has very distinctive features, which increase the complexity of procurement and supply of vaccines to the destination. It is made up of individual markets for specific vaccines or vaccine varieties, every with their specificities, in particular on the giving aspect [20]. Hence, managing the immunization programs and its vaccine supply chain is not an easy task for the policy-makers, decision-makers, health workers and all other people involved in the child immunization program in India.

The journey of a vaccine is very complex starting from the R&D and regulatory approval until the distribution of the vaccine. A vaccine typically travels through various stages before being ready for shipments. Supplying vaccines efficiently and effectively to the health centers require safe, temperature controlled and optimized vaccine supply chains. The role of the vaccine supply chain is to ensure better storage and handling of vaccines, proper stock management, careful temperature control in the cold chain; and maintenance of logistics management information system. The purpose is to assure the continuous accessibility of quality vaccines from the manufacturing until the delivery so that opportunities to vaccinate are not missed because of the vaccine stock-outs [5].

1.4.1. Vaccine procurement and delivery mechanism

To provide vaccines to the public, various players are involved in the supply chain e.g. government immunization programs, government hospitals, clinics, private organizations, etc. In this study, the focus is on the vaccination of children through government immunization programs and government hospitals. A generic map of vaccine supply chain procurement and delivery mechanism in India is shown in Figure 1.4. The central drugs and standards control organization (CDSCO), which is a national regulatory authority (NRA) is responsible for the vaccine regulatory system in India. The drugs controller general of India heads CDSCO. It approves vaccines introduced in the country, grants consent to conduct the clinical trials, registers and controlling the quality of imported vaccines. The vaccine supply chain in India and many developing countries takes almost takes a similar form starting from the procurement stage. All UIP vaccines are procured at the central level for distribution to various regions. The procurement of vaccines in the Government of India is done under the broad overarching general financing rules (GFR). The vaccines are purchased using annual rate contracts (as per GFR) and the supply orders are issued.

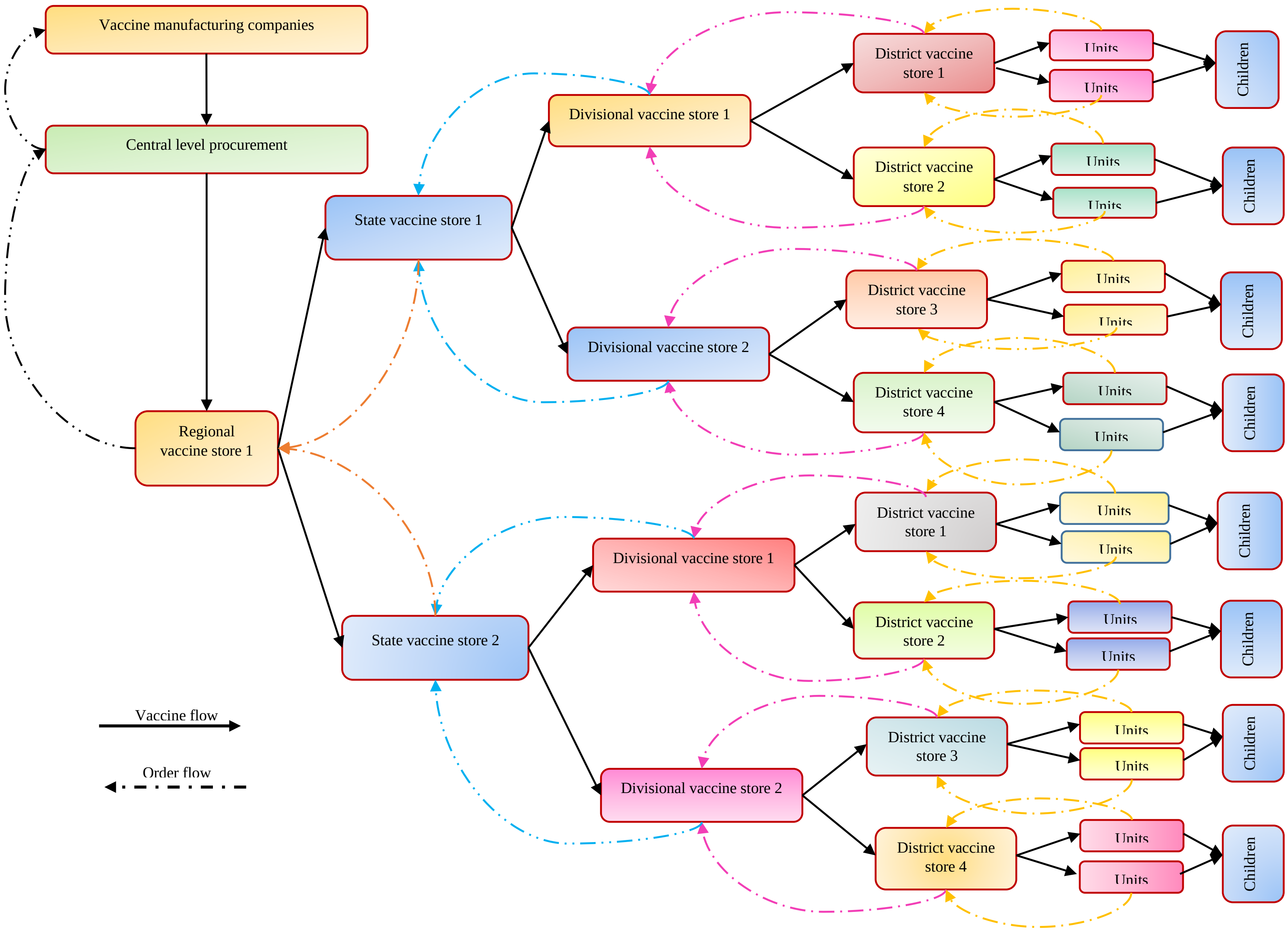


Figure 1.4: Vaccine supply chain generic map in India.

Parallel contracts are awarded for most vaccines because no single domestic manufacturer has enough available production capacity to cover the entire annual requirement [21]. The vaccines to various states in India is supplied by regional vaccine store that purchases vaccines from the central level. From the state vaccine store, the vaccines move to various divisional stores, which covers district vaccine store or immunization health centers (IHCs). The IHC supplies vaccines to each town/units/sub-immunization health center (SIHCs) of its district. Finally, at each SIHC the health workers vaccinate children, or the health workers like Anganwadi workers or auxiliary nurse midwife move to each house to vaccinate children.

1.5. Supply chain performance measurement system

Supply chain performance measurement systems (SCPMS) are significant in light of the fact that they are the main managerial tools for accomplishing efficient and effective supply chain management. With appropriate performance management system inserted in a supply chain, supply chain procedure execution, control, decision-making, correspondence, and improvement can be comprehended [23]. The majority of the organizations have understood the significance of financial and nonfinancial related performance measures; in any case, they have neglected to infer them in a balanced framework. Kaplan and Norton [24] expressed that few researchers have focused on financial performance measures and others have concentrated on non-financial and operational measures. But, it is required to create and examine the balancing framework having financial and non-financial related estimates at the same time so as to envision the real picture of firm execution [25].

According to Park et al. [26], the measurement of healthcare system performance usually concentrates on technical concerns and the delivery process. They pointed out that patient satisfaction is one of the significant factors for service quality assurance. For example, in case of vaccination of infants and children, the patients i.e. parents of children are satisfied with the immunization programs service are more likely to be positive about their situation and therefore be more compliant and cooperative as well as more engaged in the child vaccination treatment. Similarly, Van et al. [27] suggest that performance information is essential for the regulatory role of the government to monitor the overall quality of the healthcare system. Specifically, monitoring can assure a level playing field to guide market competition among health plans and among healthcare organizations. The authors in highlighting the benefits of performance measures of healthcare system pointed out that health system performance can be used at several levels that reflect differing interactions between participants in the healthcare system. Clinicians and health workers may use quality measures to assess individual interactions with patients and for quality improvement within their organizations. Comparisons of the performance of healthcare providers can inform health insurers as they implement performance-based contracting, and public reporting can support patients and consumers in choosing health plans and providers. Taken together, performance measures enable the government to monitor the quality of the health care system as a whole. In healthcare service industry mostly for the non-profit organizations, the measurement system is dependent on the mission, vision, and goal of the organization, and less emphasis is given to the financial measures [28].

Hence, while designing the effective SCPMS for vaccine supply chain, it is important that the key performance indicators (KPIs) of the supply chain should be designed according to the mission and vision of the organization. An incorrectly designed SCPMS can have a negative impact to the organization in terms of economic, social and environmental, therefore, proper and careful attention is required by the decision-makers while building an effective SCPMS for the healthcare organization.

1.6. Sustainable development

In today's competitive environment, where the companies are focusing more to reduce product cost and services, are giving less importance to the environmental and social factors. Hence, it is important that the organization should pay attention to not only in the financial improvement, but the economic development should be balanced with environmental safety and social care. According to Hsu et al. [22], sustainability has become a vital responsibility for the firms to continue to exist within the modern-day society because of the threats created by using conventional manufacturing practices, and policies imposed with the aid of stakeholders. Therefore, the idea of sustainable development (SD) has progressively obtained attention. Sustainable production implies the creation of products that make use of minimal assets, has minimized negative influences on the environment and are safe for society at a reasonable cost. Thus, organizations should alternate the conventional operating model. When thinking about the organization's strategic direction, they should additionally include the situation of sustainable improvement in the strategic analysis.

The sustainability development concept includes social, economic, and environmental development [23]. According to WHO, "Human beings are at the center of concerns for sustainable development. They are entitled to a healthy and productive life in harmony with nature". The goals of sustainable development can't be completed while there's a high occurrence of debilitating ailments, and public health can't be maintained without ecologically sustainable development. They also point out that the globalization of trade, travel, and tradition is in all likelihood to have both high quality and negative effects on health. Increased trade in products and services dangerous to health and the environment, journey and mass migration of human beings represent additional global threats to health. Today, many of the key determinants of health and disease as well as the solutions lie outside the direct control of the health sector, in sectors concerned with the environment, water, and sanitation, agriculture, education, employment, urban and rural livelihoods, trade, tourism, energy, and housing. Addressing the underlying determinants of health is key to ensuring sustainable development and sustained health improvements in the long term [24].

In the case of vaccinology, if vaccine supply chains are performing well then the vaccines can be delivered efficiently and effectively and the health issues that can arise due to a child not being vaccinated can be minimized. Therefore, when the immunization programs think of their objectives of improving child immunization rate and SD of child immunization programs, they must consider their vaccine supply chain performance improvement so that vaccine delivery performance can be improved. Hsu et al. [22] point out that organizations need to experiment with how performance factors can be used to create managerial momentum, not only in the direction of greater competitiveness but also greater sustainability. Organizations should effectively utilize their limited resources and prioritize their performance factors in terms of the balanced scorecard (BSC) approach in elaborating their sustainable development. Hence, in this study, we have considered the sustainability development of child immunization program in India, and further, suggested various frameworks for improving VSC performance for the SD of the child immunization program.

1.7. Child immunization program

As per WHO guidelines, it is important that all the children of 0-5 years be properly vaccinated to protect them from any deadly diseases. To achieve this objective, GOI started to UIP in 1985. The UIP became an important part of child survival and safe motherhood program in 1992 and presently is one of the main areas under the National Rural Health Mission (NHRM) since 2005. The child immunization program consists of vaccines for 12 life-threatening diseases: tuberculosis, diphtheria, pertussis (whooping cough), tetanus, poliomyelitis, measles, Hepatitis B, Diarrhea, Japanese Encephalitis, rubella, Pneumonia (Haemophilus Influenza Type B) and Pneumococcal diseases (Pneumococcal Pneumonia and Meningitis). Hepatitis B and Pneumococcal diseases were added to the UIP in 2007 and 2017 respectively.

The basic vaccines under the UIP India include vaccines of BCG (Bacillus Calmette Guerin), DPT (Diphtheria, Pertussis and Tetanus Toxoid), OPV (Oral Polio Vaccine), Hepatitis B, and Measles. Further, a combination of five vaccines in one (Diphtheria, Pertussis and Tetanus Toxoid), Hepatitis B and Haemophilus influenza type b is also included in the immunization scheduled. Recently, India added four new vaccines; Inactivated Poliomyelitis Vaccine (IPV) for polio, rotavirus vaccine (RVV), a vaccine against rubella (Measles-Rubella vaccine), and Japanese encephalitis vaccine in its immunization program. Presently, the UIP provides free vaccines for life-threatening diseases, to 26 million children annually. According to the NHRM, the addition of new vaccines will play a vital role in reducing child mortality and morbidity in the country [25–27]. Because of such large-scale operation of UIP and the addition of new vaccines in the immunization schedule, the complexities in the vaccine supply chain are inevitable. Therefore, it is important that the UIP India should pay more attention to the vaccine supply chain so that the vaccines reach to all the needy children at the proper time and no child dies because of non-availability of vaccines.

1.8. Research motivation

Children are the future pillars of any nation and they should be well protected since their birth. The best way to protect children is by immunizing them against various diseases through vaccination. In spite of best efforts to immunize the child today, millions of children go unimmunized each year because of delivery issues, including anything from transportation disruptions and ineffective cold chain equipment, high procurement lead time and improper forecasting to poor stock management. Shockingly, these issues have been reported for a substantial number of children who miss out on their prescribed vaccination schedules and add to the deaths of millions of children each year from vaccine-preventable diseases, by far most in developing countries. The condition of child immunization coverage has not met satisfactorily for many years in India and other countries. For example:

- Worldwide, 12.9 million infants, nearly 1 in 10, did not receive any vaccinations in 2016, according to the most recent WHO and UNICEF immunization estimates.
- In 2016, an estimated 19.5 million infants worldwide were not reached with routine immunization services such as a DTP3 vaccine. Around 60% of these children live in 10 countries: Angola, Brazil, the Democratic Republic of the Congo, Ethiopia, India, Indonesia, Iraq, Nigeria, Pakistan, and South Africa.
- Around 134 200 deaths from measles were recorded in 2015 (15 deaths every hour).
- Twenty-seven million children are born in India every year. According to the primary immunization schedule, the child should be fully vaccinated by the time he/she is 12 months old. An analysis of the data shows that the proportion of children of age 12-23 months receiving full immunization coverage is about 65 percent.
- Approximately 1.83 million children in India die before their fifth birthday. It is the low-income families who lose the most children to disease.

- According to a study, India records 0.5 million child deaths annually due to vaccine-preventable diseases.
- Despite high childhood mortality rates due to vaccine-preventable diseases, 30 percent of Indian children miss the benefits of full immunization every year. That is, an estimated 8.9 million children across the country that either get only a few vaccines or no vaccines at all.
- It is observed that one out of every 3 children in India does not receive all vaccines that are available under the UIP (Universal Immunization Program). Five percent of children in urban areas and 8 percent in rural areas are unimmunized.

Currently 60% of all GAVI, UNICEF, and WHO procured vaccines are manufactured in India, still, a number of children remain unimmunized in the country due to inefficiencies in the vaccine supply chain. Although the Government of India has started new missions and implemented new technologies for improving child immunization coverage, for a country like India with such large population and varied demographic patterns still much effort is required to deliver vaccines efficiently and effectively to the health centers. In addition, there is no substantial amount of literature available and research done on vaccine supply chains in India and other developing countries, which address the key issues and challenges of vaccine supply chains and further, any performance measurement systems (PMS) on child immunization program. Hence, based on the above discussion, this research is an attempt to improve vaccine supply chain performance, so that the results of this work can be beneficial to the immunization programs of India and also to other developing countries for the sustainable development of child immunization program.

1.9. Research objectives

Based upon the complexity in the vaccine supply chain system in India and various developing countries, the present work has the following objectives:

1. To identify the key issues in the supply chain of basic vaccines required for the child immunization in India and other developing countries.
2. To establish interrelationships among the issues and classify the issues based on their driving power and dependence to help decision-makers differentiate between independent and dependent issues and their mutual relationships.
3. To prioritize the issues and its domain based on their relative importance in the vaccine supply chain to help decision-makers drive their efforts and resources on mitigating/eliminating the most important issues.

4. To figure out the critical issues which have maximum influence on vaccine supply chain performance.
5. To identify the major causes of vaccine shortages and solutions to overcome shortages.
6. To prioritize the causes and solutions to help policy-makers to reduce or eliminate the impact of shortages on the immunization programs performance.
7. To identify key barriers and solutions in the design of NGVSC in India.
8. To prioritize key solutions to assist decision-makers to mitigate/remove key barriers to designing next-generation vaccine supply chain system (NGVSCs) in India.
9. To identifying and classifying KPIs of VSC in terms of the balanced scorecard (BSC).
10. To develop a linkage between the KPIs and sustainable development of child immunization program in India.
11. To identify critical performance indicators that have maximum effect on improving VSCP to improve sustainability.

1.10. Research methodology

The research methodologies used in the present work are:

1. *Delphi approach:* Delphi approach has been used to identify the key issues of vaccine supply chain based on the expert's opinions.
2. *Interpretive Structural Modelling (ISM):* The ISM has been used to model and analyze various issues in the supply chain of basic vaccines. The developed model may be helpful for managers in taking decision-making and framing policies to improve their SCP.
3. *Fuzzy* Matrix Cross-Reference Multiplication Applied to a Classification (*FMICMAC):* The fuzzy MICMAC analysis has been carried out to classify the identified issues into the four important regions i.e. autonomous, dependent, linkage, and dependent and also for developing an improved model based on their driving power and dependence. The results of the analysis will help the decision-makers to focus on the critical issues of the vaccine supply chain.
4. *Fuzzy Analytic Network Process (FANP):* FANP has been used to prioritize or rank the issues based on their weights. The determination of the priorities and ranking of the issues can hold great value for immunization programs that wish to prioritize their efforts and assets to eliminate the most vital issues and challenges for the successful implementation of immunization programs.
5. *Analytic Hierarchy Process (AHP):* AHP has been used as an effective tool for decision-makers in case of multi-criteria decision-making (MCDM) problems. By converting linguistic variables into crisp numbers, a pairwise comparison matrix between the

vaccines shortage reasons as various criteria to be evaluated is developed, which helps to calculate weights and aid the decision-makers to make the best decision.

6. *Complex Proportional Assessment of alternatives with Grey relations (COPRAS-G):* COPRAS-G approach has been applied to select the best solution to overcome vaccine shortage issues. This method selects the best alternative considering both the ideal and the ideal-worst solutions in order to improve decision-making.
7. *Fuzzy Analytic Hierarchy Process (FAHP):* Chang's extent's analysis based FAHP has been applied for determining the weight of issues that act as barriers to designing next-generation vaccine supply chain system in India.
8. *Fuzzy Multi-Objective Optimization by Ratio Analysis (FMOORA):* An integrated FAHP-FMOORA has been applied to select the best alternative or solution to design next-generation vaccine supply chain system in India. The integrated model takes care of the vaccine supply chain issues through emphasizing on appropriate alternative and provides aid to the managers in the decision-making process.
9. *Exploratory factor analysis (EFA):* Using EFA, the KPIs of VSC and sustainability practices criteria (SPC) have been identified.
10. *Structural Equation Modelling (SEM):* SEM has been used to develop a framework to show a relationship between the KPIs of vaccine supply chain and sustainable development of child immunization program.
11. *Two-way assessment:* Two-way assessment has been used to measure the effect of each KPIs in performance improvement of the vaccine supply chain.

1.11. Research Framework

To achieve the research objectives, a framework is designed and is shown in Figure 1.5. The work starts with the exhaustive literature review on the topic with key areas: vaccine procurement issues and challenges, vaccine storage and shortage issues and challenges, vaccine supply chain issues and challenges, issues, and challenges in child immunization program in India and globally, and the sustainability development. From the study & analysis of the literature, the potential areas of research have been identified. Finally, through the applications of various tools & techniques, efforts have been made to achieve the framed objectives.

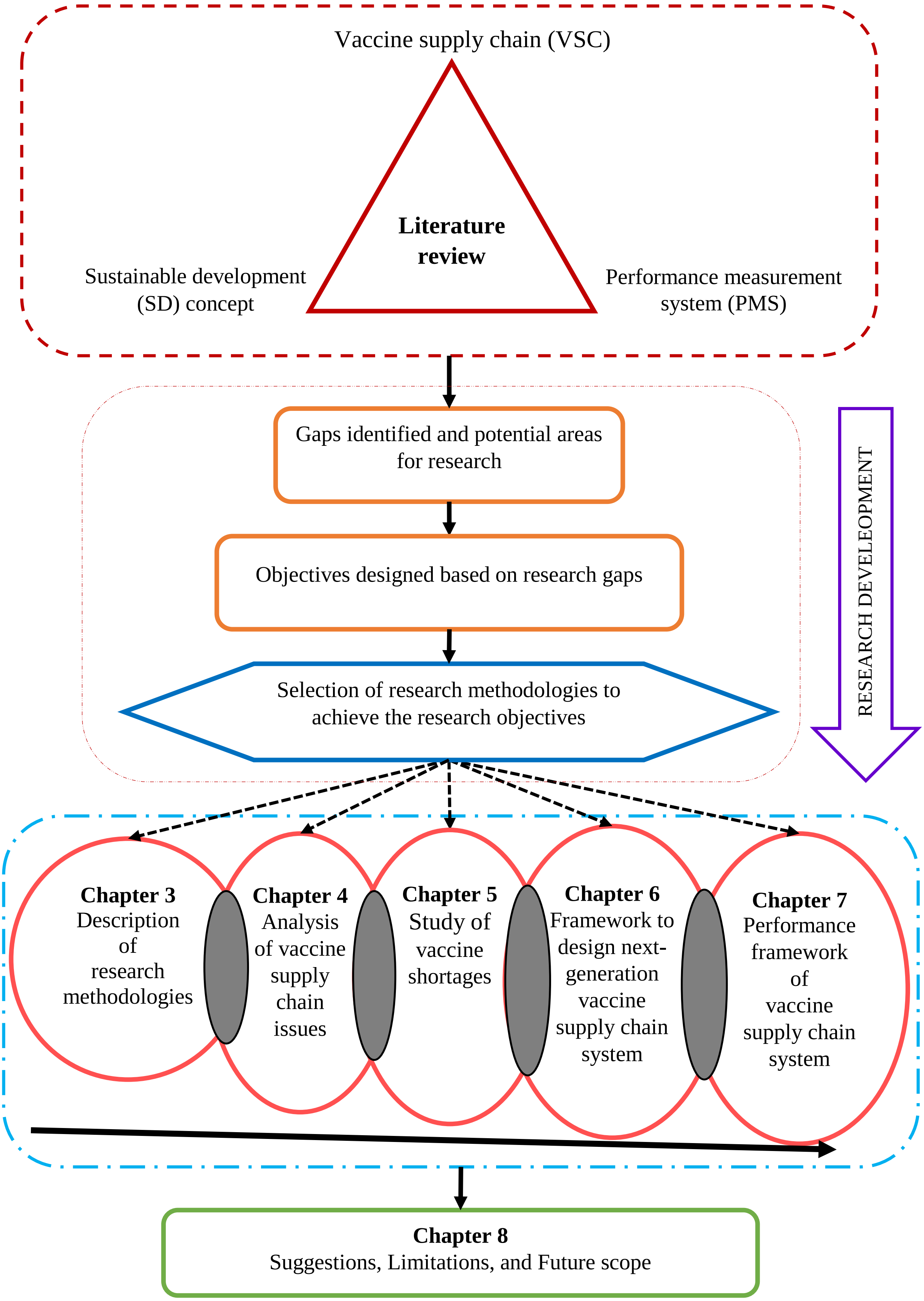


Figure 1.5: Research framework

1.12. Organization of Thesis

The present research work is organized in eight chapters and is visualized in Figure 1.5. A brief overview of all chapters is as below:

Chapter 1

This chapter begins with a brief introduction to the background of research, SCM, healthcare industry, a pharmaceutical sector of healthcare, vaccine supply chain, performance measurement system, sustainability development concept, and child immunization program. Apart from this, the motivation of the present research, research objectives, research methodologies, framework of the research, organization of the thesis, and finally the conclusion has also been discussed in Chapter 1.

Chapter 2

This chapter comprises a thorough literature review in the relevant area of the research. The literature review covers the aspects related to VSC, PMS, and Sustainability development concept, etc. The chapter also presents literature on the methodologies used in the present research Through the literature review, gaps in contemporary research in this area have been identified. In the end, literature review work is summarized with a brief conclusion.

Chapter 3

Chapter 3 presents detailed description of research methodologies encompassing Delphi technique, interpretive structural modelling (ISM), fuzzy matrix cross-reference multiplication applied to a classification (FMICMAC), fuzzy analytic network process (FANP), analytic hierarchy process (AHP), complex proportional assessment of alternatives with grey relations (COPRAS-G), fuzzy analytic hierarchy process (FAHP), fuzzy multi-objective optimization by ratio analysis (FMOORA), exploratory factor analysis (EFA), structural equation modelling (SEM), and Two-way assessment.

Chapter 4

This chapter presents identification and analysis of key issues of the vaccine supply chain using interpretive structural modeling (ISM) and fuzzy matrix cross-reference multiplication applied to a classification (FMICMAC) method. Further, the key issues have been divided into five main domains and prioritized and analyzed using fuzzy analytic network process (FANP).

Chapter 5

The chapter discusses one of the important issues of the vaccine supply chain i.e. vaccine shortages. Further, a framework that uses analytic hierarchy process (AHP) and complex proportional assessment of alternatives with grey relations (COPRAS-G) have been presented to prioritize the important solutions in order to overcome vaccine shortages problems in India and other countries.

Chapter 6

Chapter 5 comprises the framework to design a next-generation vaccine supply chain system in India. Using integrated fuzzy analytic hierarchy process (FAHP) and fuzzy multi-objective optimization by ratio analysis (FMOORA) method, the key issues that hinder the design of next-generation vaccine supply chain system and the solutions to help designers build next-generation vaccine supply chain have been analyzed and discussed.

Chapter 7

Chapter 7 presents a novel framework that suggests how universal immunization program (UIP) India can utilize key performance indicators (KPIs) of its vaccine supply chain for the sustainability development (SD) of the child immunization program in India. The KPIs have been discussed in the four dimensions of the balanced scorecard (BSC) approach, whereas, the analysis of the framework has been performed using EFA, SEM, and Two-way assessment.

Chapter 8

Finally, this chapter highlights the summary of the work addressed in the study. Further, triangulation, major suggestions, significant contributions, key findings and managerial implications of the work have been discussed. Conclusion along with the limitations and scope for future work has also been highlighted in the last.

1.13. Conclusion

In this chapter, an overview of the research has been presented. Further, research motivation, research objectives, research methodologies, and research framework have also been presented. At last, various chapters that discuss the work to be done to achieve the research objectives have been presented.

Chapter 2

LITERATURE REVIEW

2.1. Introduction

Efficient and effective supply chains are required to deliver vaccines to children who need them. However, in developing countries such as India, the vaccine supply chains are not given proper attention, which causes a delay in the delivery of basic vaccines. There are many factors that contribute to the improper functioning of the vaccine supply chain such as inaccurate forecasting, vaccine shortages, insufficient and outdated cold chain equipment's, poor infrastructure, lack of health workers, etc. To help decision-makers design a well-functioning vaccine supply chain, it is essential that each should know the magnitude of these issues so that effective decision may be taken with optimum utilization of available resources. Further, the decision-makers should be aware of the importance of measuring the performance of the organization, in order to assist in identifying the most accurate and efficient method of operation for reducing the supply chain and other operational costs. Continuous improvement in the vaccine supply chain will help the immunization programs run by the GOI to fulfill its objective of increasing child immunization coverage and hence, for the sustainable development of child immunization program. The present work highlights some of the key aspects to measure and improve VSC performance and for the sustainable development of child immunization program in India and other developing countries. The detailed discussion related to the major aspects of the present work has been discussed in this chapter.

2.2. Review of literature on vaccine and vaccinology research

First, it is vital to know whether the vaccine supply chain has been given importance or not by the researchers, academicians, industries, government bodies, etc., in the field of vaccine and vaccinology research. To know the answer and achieve this objective, a science mapping analysis is done in the field of vaccine and vaccinology using the VOSviewer software. VOSviewer is a software tool for analyzing bibliometric networks, creating maps based on network data and for visualizing and exploring these maps. These maps are constructed through the networks of scientific publications, scientific journals, researchers, research organizations, countries, keywords, or terms. Based on this network, VOSviewer identifies a number of clusters. The most important output of the software is the attribute 'occurrence', which indicates the number of documents in which a keyword occurs. Further, it creates a co-occurrence network of the terms obtained from the titles, abstract and keywords. Two terms are said to co-occur if they both occur on the same line [28,29].

For using VOSviewer, important keyword 'vaccine' is performed on the electronic database 'Web of Science'. Web of Science (previously known as Web of Knowledge) is an online subscription-based scientific citation indexing service originally produced by the Institute for Scientific Information (ISI), now maintained by Clarivate Analytics that provides a comprehensive citation search. It gives access to multiple databases that reference cross-disciplinary research, which allows for in-depth exploration of specialized sub-fields within an academic or scientific discipline. Hence, based on the keyword search, 5000 most relevant papers published in peer review journals between 1990-2018 were extracted.

Figure 2.1 shows the co-occurrence network of the terms used in vaccine literature and the clusters identified (each color represents one cluster). From the VOSviewer analysis, terms related to vaccine and vaccinology are extracted from the title and abstract fields of the paper and then classified into three main clusters. Three clusters represents the most popular keywords used for the research in vaccine and vaccinology between 1990-2018 (2018 articles till March) The most popular keywords in each cluster are listed in Table 2.1.

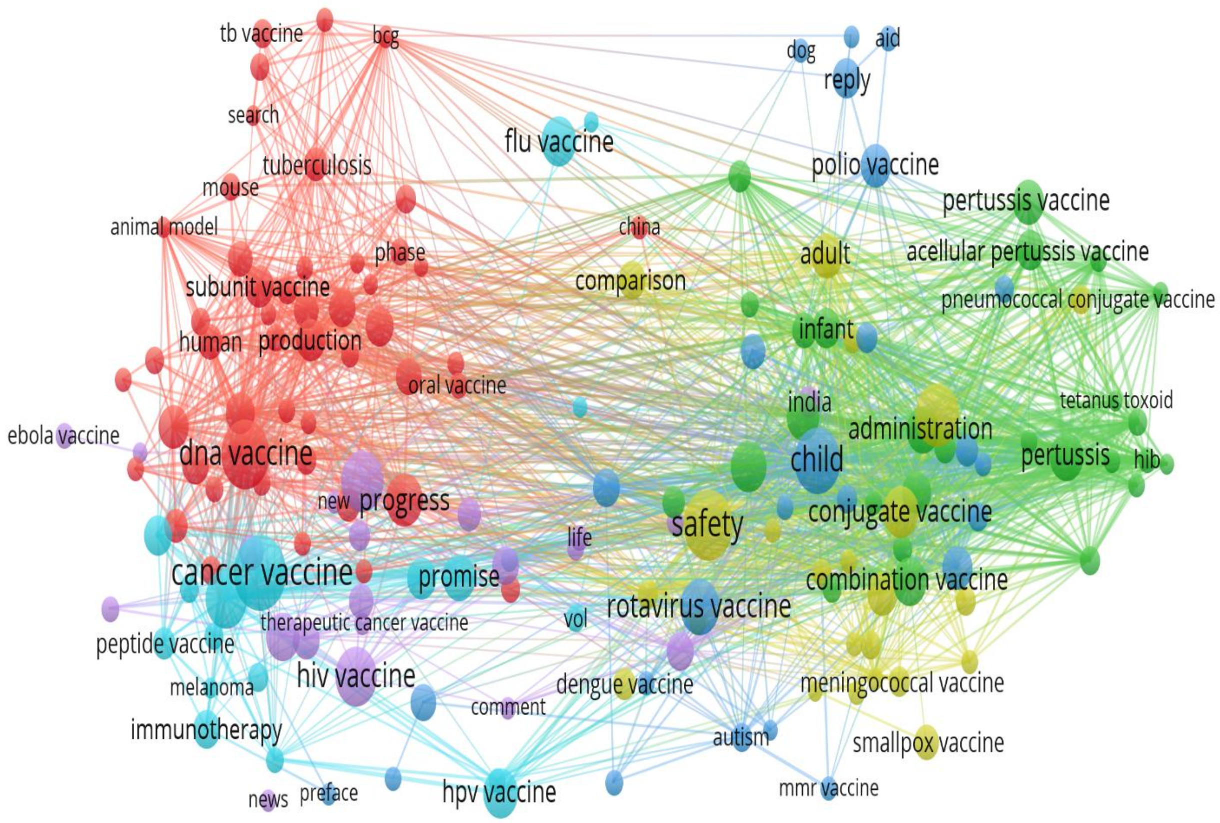


Figure 2.1: Bibliographic mapping of vaccine and vaccinology research.

Table 2.1: Top fifteen popular keywords in five clusters of vaccine and vaccinology research with their occurrences.

Terms	Occurrences
cancer vaccine	127
safety	113
dna vaccine	106
child	98
pneumococcal vaccine	88
malaria vaccine	83
cancer	81
hiv vaccine	80
rotavirus vaccine	71
progress	62
conjugate vaccine	60
hepatitis vaccine	60
flu vaccine	57
hpv vaccine	55
aids vaccine	54

Table 2.2: Top fifteen popular keywords in each cluster of vaccine and vaccinology research.

Cluster 1 (red)	Cluster 2 (green)	Cluster 3 (blue)	Cluster 4 (Yellow)	Cluster 5 (Violet)	Cluster 6 (Cyan)
dna vaccine	hepatitis b vaccine	child	safety	hiv vaccine	cancer vaccine
human	pertussis	rotavirus vaccine	pneumococcal vaccine	aids vaccine	cancer
production	pertussis vaccine	polio vaccine	adult	malaria vaccine	flu vaccine
vaccine production	administration	reply	conjugate vaccine	malaria	hpv vaccine
subunit vaccine	combination vaccine	dog	comparison	hope	promise
tuberculosis	acellular pertussis vaccine	aid	smallpox vaccine	success	immunotherapy
sample	dose	vaccines	hepatitis	perspective	therapeutic vaccine
malaria vaccine	infant	measles vaccine	meningococcal vaccine	vaccine design	peptide vaccine
progress	question	measles	dengue vaccine	cholera vaccine	treatment
vector	age	reply	pneumonia	new approach	melanoma vaccine

From the analysis, it can be seen that among the most popular keywords in the field of vaccine and vaccinology research, the vaccine supply chain has not attracted the researchers, and the area needs more research. In the next section, research on the vaccine supply chain has been discussed.

2.3. Review of literature on vaccine supply chain (VSC) research

Vaccine supply chain plays an important role in delivering vaccines efficiently and effectively to the health centers. In this section, the important literature published in the field of vaccine supply chain research has been presented. Firstly, in order to identify the relevant journals and important literature published in the field of VSC, Science Mapping Analysis Tool (SciMAT, v-1.1.0.4) is used. SciMAT is an open source (GPLv3) software developed to perform a science mapping analysis under a longitudinal framework. To start the analysis, the keyword 'vaccine supply chain' is searched on the database 'Web of Science'. Based on the search, 225 papers are extracted, published between 1993-2018 (2018 articles until March). From Figure 2.2, it can be seen that the number of articles reporting to the vaccine supply chain has been significantly increasing, especially during the last five years (2014-2018). The top fifteen journals having maximum articles related to vaccine supply, and seven main keywords of the research have been also identified from the software, shown in Figure 2.3. & 2.4. The screenshot of the SciMAT software used for the literature review is shown in Figure 2.5.

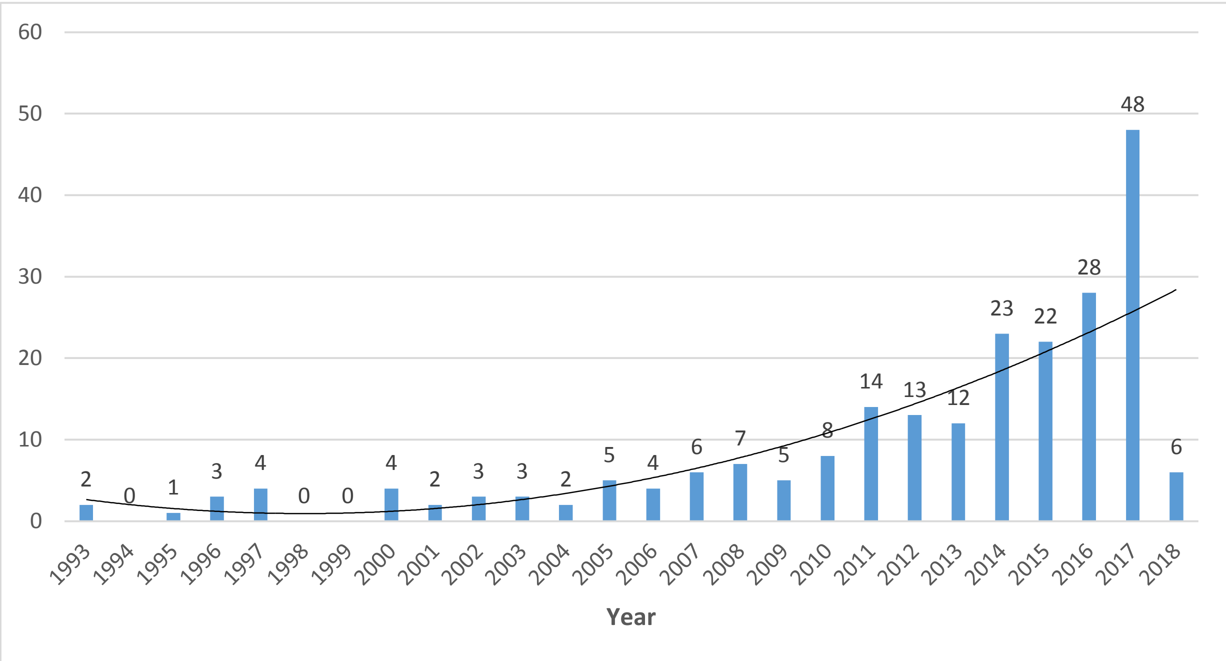


Figure 2.2: Publication of vaccine supply chain per year (225 papers: 1993-2018).

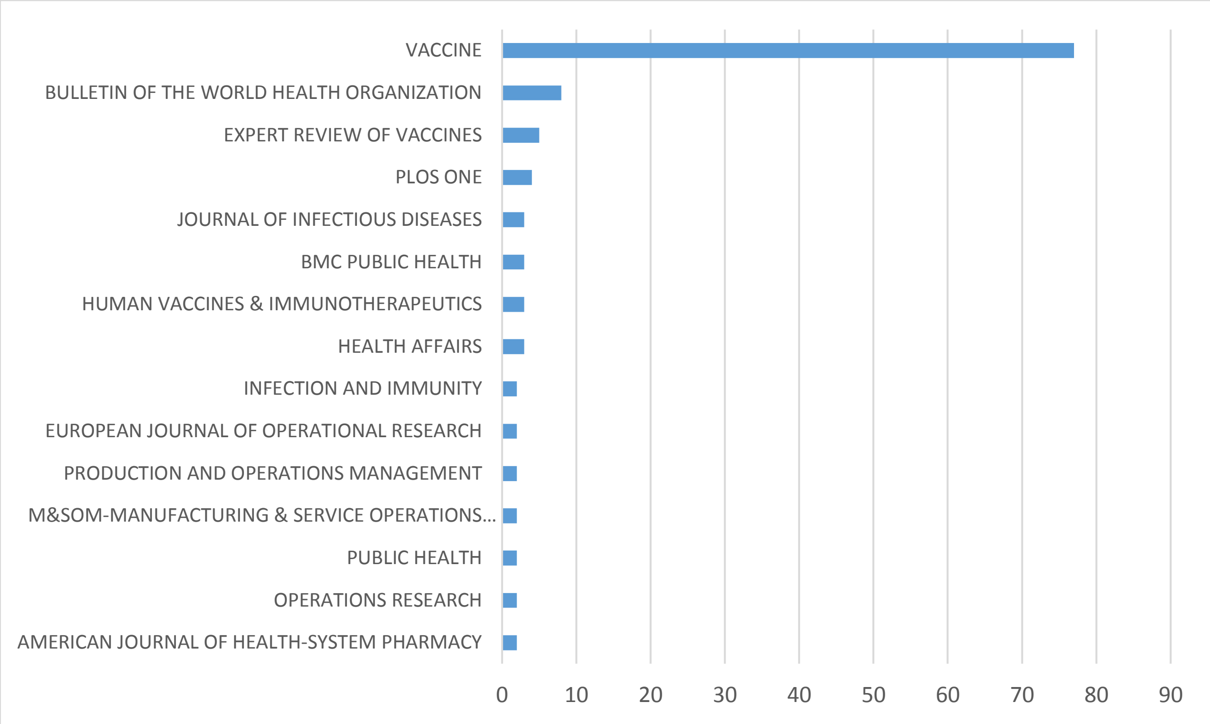


Figure 2.3: Distribution of publications based on the top fifteen journals (225 papers: 1993-2018).

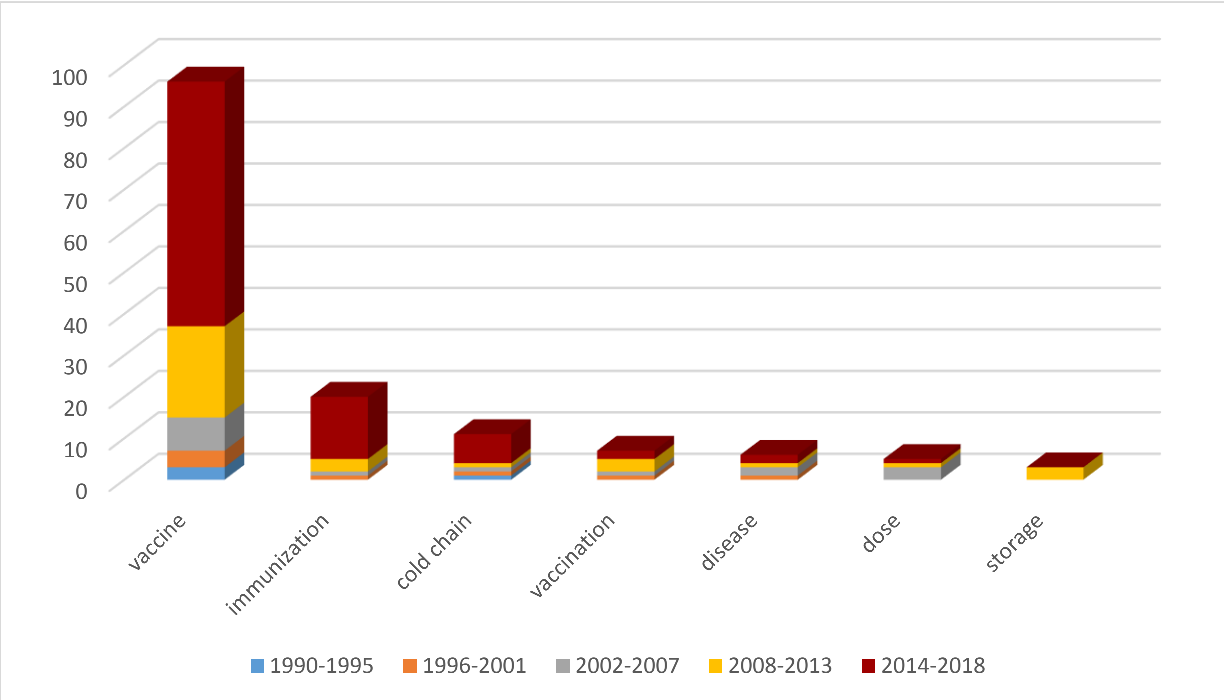


Figure 2.4: The seven main keywords/field of the VSC research (225 papers: 1993-2018).

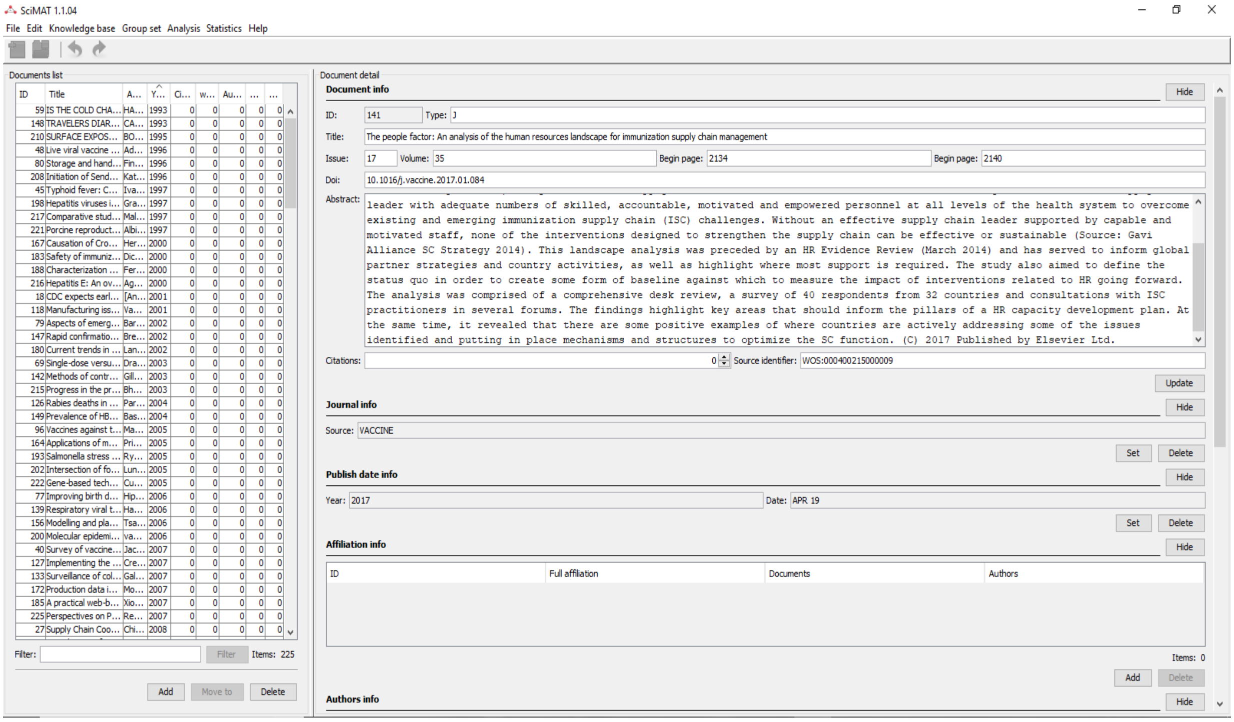


Figure 2.5: Screenshot of SciMAT software.

Next, to know the important keywords published in the field of the vaccine supply chain, the bibliometric analysis is done using the VOSViewer software. To conduct bibliometric analysis using VOSviewer' the same 225 papers extracted from 'Web of Science' are used. Figure 2.6 shows the co-occurrence network of the terms used in vaccine supply chain literature and the three recognized clusters (each color represents one cluster). The three clusters represents the most popular keywords used in the research in vaccine supply chain between 1990-2018. Table 2.3 presents the combined fifteen popular keywords in all the three clusters with their occurrences, and the most popular keywords in each cluster are listed in Table 2.4.

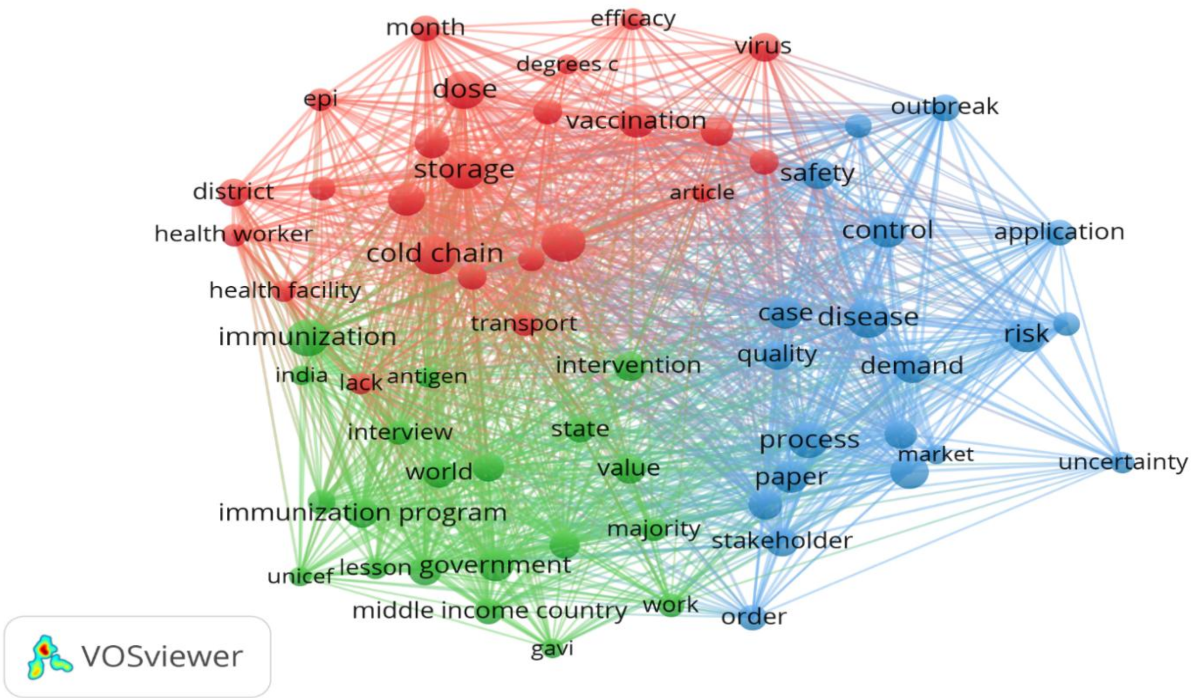


Figure 2.6: Bibliographic mapping of vaccine supply chain research.

Table 2.3: Top fifteen popular keywords in three clusters of VSC research with their occurrences.

Terms	Occurrences
cold chain	43
disease	40
storage	37
dose	36
product	30
benefit	30
risk	29
manufacturer	29
demand	27
vaccination	27
availability	27
control	26
case	26
safety	25
cold chain	43

Table 2.4: Top fifteen popular keywords in each cluster of VSC research.

Cluster 1 (red)	Cluster 2 (green)	Cluster 3 (blue)
cold chain	immunization	disease
storage	immunization program	process
dose	government	risk
availability	intervention	control
vaccination	world	demand
child	value	product
district	world health organization	case
effect	access	paper
stage	state	safety
health worker	interview	quality
virus	lesson	stakeholder
article	unicef	outbreak
efficacy	middle-income country	application
epi	gavi	order
health facility	antigen	uncertainty

After performing science mapping analysis on VSC, important papers related to vaccine supply chain and child immunization program, and popular keywords in VSC research have been identified. In addition, the same keyword is also searched on the search engine 'Google' in order to identify important articles, journals, or websites that may have been ignored during the analysis. Based on the search, important websites such as WHO, UNICEF, PATH, GAVI and libraries such as PubMed, PubMed Central, etc. are also identified. Finally, from the analysis results, it has been found that in the context of the vaccine supply chain of India and other developing countries; vaccine demand, vaccine wastages, storage, cold chain, risk, disease health workers, etc. have been some of the main keywords/fields for discussion by various researchers. Table 2.5 discusses some of the important contributions of the researchers in the field of the vaccine supply chain.

Table 2.5: Review of selected papers on VSC research.

Author/s	Journal name	Publisher	Contribution
Tan et al. [30]	Vaccine	Elsevier	• Identified issues in the vaccine delivery process from the stage of the cold chain until the child is vaccinated.
Nath et al. [31]	International Journal of Community Medicine	Indian Association of Preventive & Social Medicine	• Evaluated the universal immunization program challenges in Coverage of Migrant Children in Haridwar, Uttarakhand, India. Results showed that there was low immunization coverage among migrants within adequate supervision, poor cold chain maintenance, and improper tracking of dropouts.
Mvundura et al. [32]	Vaccine	Elsevier	• This paper estimated the supply chain and immunization service delivery costs and cost per dose in selected districts in Kenya and Tanzania.
Zaffran et al. [33]	Vaccine	Elsevier	• Suggested the importance of vaccine supply chain and logistics systems in vaccine delivery process.
Kartoglu and Milstien [34]	Expert Review of Vaccines	Taylor & Francis	• Suggested tools and approaches to ensure the quality of vaccines throughout the cold chain for the supply chain of developing countries.
Dube et al. [35]	Expert Review of Vaccines	Taylor & Francis	• Identified the determinants of vaccine hesitancy.
Laxminarayan and Ganguly [36]	Health Affairs	Project HOPE - The People-to-People Health Foundation, Inc.	• The study identified various reasons for low immunization in India such as finance, vaccine procurement shortage of human resource, manufacturing companies, reporting, and surveillance. etc.

Author/s	Journal name	Publisher	Contribution
Agrawal and Kumari [37]	Indian Journal of Community Health	Indian Association of Preventive & Social Medicine	• Conducted a study for the immunization status of children and its decline with age in a hospital-based study of 1000 children at a teaching hospital in western Uttar Pradesh. The results showed the need for improving the immunization coverage, particularly for the older children for reducing the burden of vaccine-preventable diseases.
Agrawal and Kumari [38]	Pediatric Infectious Disease	Elsevier	• Conducted a study for immunization status of children and the influence of social factors in a hospital-based study in western Uttar Pradesh. The results showed that the factors, which had a significant impact on immunization status were the gender of the child, family's income, and parental education.
Kaufmann et al. [7]	Health Affairs	Project HOPE - The People-to-People Health Foundation, Inc.	• The literature examined vaccine supply chains in developing countries, based on the collective efforts and the views of experts. The important findings were the key challenges related to the delivery of vaccines right from the point of production to the people who need them. Challenges identified were such as demand forecasting, financing, and procurement processes, storage and transportation, human resources, maintenance etc.
Murhekar et al. [39]	Bulletin of the World Health Organization	World Health Organization	• WHO suggests that vaccine should be maintained between 0 degree and 8 degrees Celsius. The studied was performed in 10 states of India to estimate the proportion of time the vaccines in the cold-chain system in India are exposed to temperatures of < 0 or > 8 °C. The results indicated that the cold chain system in India was not performing satisfactorily.

Author/s	Journal name	Publisher	Contribution
Lahariya et al. [40]	Indian Journal of Public Health	Indian Public Health Association, India.	• The assessment was planned and conducted to ascertain the reasons for low reported coverage of Hepatitis B (Hep B) vaccine in comparison to similarly timed diphtheria, pertussis, and tetanus (DPT) vaccine. • Coverage with three doses of Hep B vaccine was lower than similarly timed three doses of DPT vaccine. Poor stock management ("stock outs or nil stocks" at various levels), incomplete recording and reporting, perceived costly vaccine & related fear of wastage of vaccine in 10 dose vial, and incomplete knowledge amongst health functionaries about vaccination schedule were the main reasons cited for reported lower coverage. • The additional reasons for low Hep B birth dose coverage were lack of knowledge amongst health workers about birth dose administration, no mechanism for recording birth dose, and insufficient training etc.
Huang et al. [41]	Vaccine	Elsevier	• Performed a costing analysis of vaccine supply redesign in Comé District of Benin.
Le Gargasson et al. [42]	Vaccine	Elsevier	• Estimated the costs of routine immunization in Ghana.
Mueller et al. [43]	Vaccine	Elsevier	• Studied the impact of demand forecasting system into a low-income country's vaccine supply chain.
Shreyash et al. [44]	National Journal of Community Medicine	National Association of Community Medicine	• This study was conducted to assess the amount of vaccine wastage; its correlation with the type of vaccine and place of vaccination; with the route of administration and wastage and with beneficiaries per session and wastage factor (WF) • The results reveal that the wastage factor was high for BCG, OPV, DPT vaccines.

Author/s	Journal name	Publisher	Contribution
Privett and Gonsalvez. [45]	Operations Research for Healthcare	Elsevier	• Identified top 10 global health pharmaceutical supply chain challenges: i. Lack of coordination ii. Inventory management iii. Absent demand information iv. Human resource dependency v. Order management vi. Shortage avoidance vii. Expiration viii. warehouse management, ix. Temperature control x. Shipment visibility
P et al. [46]	Journal of Pediatric Sciences	Bilal YILDIZ	• Conducted a study in 2012 in the urban city of India and found that in primary care settings, vial size is statistically considerably related to vaccine wastage.
Chiu and Kuo [47]	International Journal of Electronic Healthcare	Inderscience	• Presented a demand forecasting model to support the decision-making of Taiwan national vaccine purchase using ARIMA and Neural Network Models.
Mogasale et al. [48]	Human Vaccines & Immunotherapeutics	Taylor & Francis	• Developed a method of forecasting vaccine introduction and estimating vaccine demand in the future for Typhoid Conjugate Vaccine (TCV) in low and middle-income countries.
Gupta et al. [49]	Vaccine	Elsevier	• This paper reviews the development of the Indian vaccine industry, policy support for it and its status. It also highlights opportunities and challenges for the introduction of new and underutilized vaccines.

Author/s	Journal name	Publisher	Contribution
Lydon et al. [50]	Vaccine	Elsevier	• Studied the reasons for stock-outs in 194 WHO members states and found that 18% of the vaccine stock-outs at country level was due to poor forecasting and inventory management.
Chen et al. [51]	Annals of Operations Research	Springer	• Developed a computational model for passive cold devices designs and suggests that passive cold devices and their optimal design would be the most cost-effective equipment for immunization officials in developing countries and manufacturers
Kaplan et al. [52]	Human Resources for Health	BioMed Central	• Evaluated the condition of health-workers in 20 low and middle-income countries.
Datar et al. [53]	Indian Journal of Medical Research	Indian Council of Medical Research, India	• The study carried out to examine the role of health infrastructure and community health workers in expanding immunization coverage in rural India. • The sample consisted of 43,416 children aged 2-35 months residing in rural India from the National Family Health Surveys conducted in 1993 and 1998. • Results showed that the availability of health infrastructure had only a modest effect on immunization coverage. Larger and better-equipped facilities had bigger effects on immunization coverage. The presence of community health workers in the village was not associated with increased immunization coverage.
Sarley et al. [54]	Vaccine	Elsevier	• Discussed how the transformation of Nigeria vaccine supply chain helped in reducing important issues such as vaccine stock-outs, cost of vaccine delivery services, low immunization coverage, etc.

Author/s	Journal name	Publisher	Contribution
Jayaraman et al. [55]	IISE Transactions on Healthcare Systems Engineering	Taylor & Francis	• Designed a decision support tool for healthcare providers to evaluate their performance and also measured the impact of adopting supply chain standards by healthcare workers
Xinghao and Gregory S. [56]	IISE Transactions on Healthcare Systems Engineering	Taylor & Francis	• Developed an influenza vaccination supply chain model consisting of a vaccine manufacturer, a health authority and the population.
Chiu et al. [57]	Proceedings - 4th International Conference on Natural Computation, ICNC 2008	IEEE	• The study presents a computer-based forecast model for building a decision support system for forecasting the annual vaccine demand of a specific vaccine. • The result generated from the system may be taken by the governmental immunization authority to make a better decision for budgeting and purchasing the annual requirement of specific vaccines.
MacDonald et al. [58]	Vaccine	Elsevier	• The paper discussed the reason for vaccine hesitancy.
Dube et al. [59]	Human Vaccines & Immunotherapeutics	Taylor & Francis	• The study highlighted various factors for vaccine hesitancy such as emotional, cultural, social, spiritual and political factors as much as cognitive factors, were the main factors for low vaccine coverage.
Eskola et al. [60]	Vaccine	Elsevier	• Highlighted important factors related to vaccine hesitancy: **i.** Understanding of vaccine hesitancy should be increased and disseminated **ii.** Sharing best practices and implementing new tools to deal with vaccine hesitancy **iii.** Encourage and support research on vaccine hesitancy etc.

Author/s	Journal name	Publisher	Contribution
Sabot et al. [61]	Impact and Innovation Series	National Bureau of Asian Research (NBR)	• Large-scale investments and a wider portfolio of vaccines have highlighted the need to achieve higher efficiency in vaccine supply chains. • High rates of vaccine wastage were tolerable in the past when vaccines cost a few cents per dose, but wastage will be a major drain on resources once vaccines that are as much as 50 times more expensive are introduced.
Samant et al. [62]	Rural and Remote Health	Deakin University	• This study was conducted to evaluate the relationship between the adequacy of cold chain infrastructure and the proper use of Vaccine Vial Monitor in a rural district of India. • Forty-six health centers in a rural district were included in the evaluation of the cold chain equipment and the Vaccine Vial Monitors. • Cold chain equipment and vaccine vials within each health center were evaluated for adherence to WHO cold chain maintenance protocols and the Vaccine Vial Monitor stage, respectively. Among the 46 health centers, Vaccine Vial Monitor stage I was found at 58% of the health centers, 33% of the health centers reported stage II and 9% reported a stage III, indicating weaknesses in the cold chain mechanism.
Amarasinghe and Mahoney [63]	Human Vaccines	Taylor & Francis	• Estimated the potential demand and supply of dengue vaccine in Brazil. The results show that improper forecasting and planning can lead to the extra burden of supply of vaccines for the immunization programs.

Author/s	Journal name	Publisher	Contribution
Dasaklis et al. [64]	International Journal of Systems Science: Operations & Logistics	Taylor & Francis	• Studied the logistical requirements for implementing a regional mass vaccination campaign for controlling the smallpox outbreak. For predicting the course of the epidemic, a deterministic mathematical model is used, and a linear programming model is developed for framing the emergency supply chain problem that addresses the optimal vaccine stockpile distribution to several affected destination populations.
Duintjer et al. [65]	Vaccine	Elsevier	• Developed a mathematical model for determining the optimal management of vaccine stockpile
Shrivastava et al. [66]	Indian Journal of Medical Research	Indian Council of Medical Research, India	• Stabilized live attenuated oral polio vaccine (OPV) is used to immunize children up to the age of five years to prevent poliomyelitis. It is strongly advised that the cold-chain should be maintained until the vaccine is administered. • It is assumed, that vaccine vial monitors (VVMs) are reliable at all temperatures. This study was undertaken to see if VVMs were reliable when exposed to high temperatures as can occur in field conditions in India. • Vaccine vials with VVMs were incubated (10 vials for each temperature) in an incubator at different temperatures at 37, 41, 45 and 49.5°C. Time-lapse photographs of the VVMs on vials were taken hourly to look for their discard-point. • At 37 and 41°C, the VVMs worked well. At 45°C, vaccine potency is known to drop to the discard level within 14 h whereas the VVM discard point was reached at 16 h. At 49.5°C, the VVMs reached discard point at 9 h when these should have reached it at 3 h.

Author/s	Journal name	Publisher	Contribution
Hovav and Tsadikovich [67]	Operations Research for Health Care	Elsevier	• Developed a network flow model for inventory management and distribution of influenza vaccines through a supply chain.
Mofrad et al. [68]	IIE Transactions	Taylor & Francis	• Formulates a Markov decision process model that addresses the issue of open-vial wastage.
Lemmens et al. [69]	Chemical Engineering Research and Design	Elsevier	• Reviews the literature on model-based supply chain design to find the applicability of these models to the key issues for vaccine supply chain design.
Popova and Ibarra de Palacios [70]	Current Medical Research and Opinion	Taylor & Francis	• Discusses some of the barriers to vaccine access in developing countries.
Riewpaiboon et al. [71]	Public Health	Elsevier	• Studied the economic analysis of conventional vaccine and logistics systems to the Vendor Managed Inventory (VMI) in Thailand.
Mukherjee et al. [72]	Journal of Health, Population and Nutrition	BioMed Central	• A study to assess the wastage factor of oral polio vaccine (OPV) in the pulse polio immunization program of the GOI was undertaken by the Indian Council of Medical Research (ICMR) at approximately 31,000 immunization booths all over the country. • The study was conducted through the network of 31 Human Reproduction Research Centers and other ICMR institutes. • Wastage at the point of administration of OPV was estimated to be 14.5% with a wastage factor of 1.17. • Minimum wastage (6.3%) at Kanchipuram and maximum wastage (22.1%) at Kanpur were observed. • Further, the wastage of unopened vials and vials during use was also observed following color changes on the vaccine vial monitor (VVM), indicating poor cold-chain maintenance at the immunization site.

Author/s	Journal name	Publisher	Contribution
Kartoglu et al. [73]	Vaccine	Elsevier	• Suggested measures of improving temperature monitoring in the vaccine cold chain at the periphery using a 30-day electronic refrigerator temperature logger.
Chiodini [74]	Nursing Standard	Royal College of Nursing	• Discussed the role of proper storage and handling of vaccines in immunization supply chains.
Favin et al. [75]	International Health	Oxford University Press	• Pointed out in their study that the geographical locations are the key barriers reasons for low vaccination rate and the introduction of a new vaccine in developing countries
Varma and Kusuma [76]	Indian Journal of Public Health	Indian Public Health Association, India.	• This paper aims to report and compare the immunization coverage of various vaccines among tribal and rural children in a distinct socio-economic environment in India. • By employing both qualitative and quantitative data collection techniques. Data collected included the immunization coverage and the associated socio-demographic factors. • The coverage of various vaccines was higher among the tribal than among the rural population. Of the eligible children aged above 9 months, 63.3% of tribal children and only 14.5% of rural children were fully vaccinated. The coverage of vaccination against measles and vitamin-A supplementation were very low among rural children (19.6% and 15.2%, respectively) when compared to tribal children (69.2% and 64.2%, respectively). • The qualitative data indicated that the community was not satisfied with regard to vaccination services, particularly in the rural area.

Author/s	Journal name	Publisher	Contribution
Babu et al. [77]	International Journal of Medicine and Public Health	Phcog.Net	• The study was aimed at evaluating immunization coverage in Bellary district against Tuberculosis, Poliomyelitis, Diphtheria, Pertussis, and Measles. • The study found poor state and district level supervision as the predominant reason for the poor immunization coverage against vaccine-preventable diseases. • Other reasons include an ineffective plan for social mobilization and the inability of local Governments to improve routine immunization services in the high-risk areas.
Bhatia et al. [78]	Indian Journal of Pediatrics	Springer	• A rapid assessment technique was used on National Immunization Day to assess the immunization status among children in the age group of 12-23 months covering urban, rural and slum areas in UT, Chandigarh. • The study covered 796 children in the proportion to their distribution in urban, rural and slum areas. • Evaluation recorded fully immunized children as 72.23%, partially immunized as 22.99%, and unimmunized as 4.64%. Only 58.66% of children in urban slums were fully immunized. No sex-wise difference was noticed in the study. • The coverage for DPT3/OPV3 and measles in slum children were comparatively much lower than in urban and rural children.
Mallik et al. [79]	African Health Sciences	Makerere University Medical School (Uganda)	• Conducted a study in Kolkata, India to check the cold chain maintenance status, which is a crucial activity to retain the potency of vaccines and found out that the results were unsatisfactory.

Author/s	Journal name	Publisher	Contribution
Assija et al. [80]	Indian Pediatrics	Indian Academy of Pediatrics	• The present study assessed the coverage and quality of immunization services for children aged 12-23 months and mothers who delivered a baby in the last one year in rural areas of Chandigarh. Two hundred ten children and 210 mothers were enrolled. The results show that 69% of children were fully immunized, 15% were partially immunized and 16% were unimmunized. Among mothers, 79% were fully immunized, 11% partially immunized and 10% were unimmunized. • The immunization coverage was found to be unsatisfactory. • Evaluation of the quality of the immunization services at the sub-centers revealed poor planning, work organization, record keeping, and communication. • Planning was found to be deficient among health workers when the investigator observed immunization services.
Chen et al. [81]	IIE Transactions	Taylor & Francis	• Developed a mathematical model for WHO-EPI vaccine distribution networks in developing countries.

2.4. Review of literature on performance measurement system (PMS) research

In this dynamically changing business environment, the adoption of appropriate performance management and measurement framework has been realized as one of the major challenges [82]. A performance measurement system (PMS) is required to measure the company or organization development in attaining the goals and objectives. PMS can be in financial and non-financial measures [83]. According to Okwo and Marire [84], the concept of measuring overall performance is not only to perceive the current performance of the enterprise, but it also permits the enterprise to perform well in the future. The performance measures and metrics are essential for the efficient and effective management of supply chain and logistics operations. According to Kaplan, "No measures, no improvements", therefore, it is essential to measure the right thing, at the right time and in at the right manner in a supply chain so that timely actions can be taken for better decision-making. Identifying which PMS will be suitable for your organization and the true performance indicators is a crucial decision for managers because this may result in undervalued or overvalued performance results or incorrectly named key performance indicators.

Therefore, a performance measurement system that creates and manages key performance indicators (KPIs) needs to be management's eyes to the process and system. It needs to stimulate the most appropriate behavior. Successful performance measures incorporate a naturally balanced organizational set of measurements which provides an unbiased process performance evaluation that results in the 3 Rs of commercial enterprise; i.e., all of us does the right things while doing them right at the right time [85]. The various researcher has proposed benefits have PMS described below:

In recent years, researchers have proposed new performance measures according to the change in the market and customer requirements. Gunasekaran and Kobu [86] in their review paper identified seven performance measurement framework, which is based on different criteria. The seven categories of performance measurement in the logistics and supply chain system are shown in Table 2.6.

Table 2.6: Seven categories of performance measurement in logistics and SC system.

Criteria	Details
Balanced scorecard perspective	Learning and growth, internal process, customers, Finance
Components of performance measures	Resource utilization, Time, Output, Flexibility,
Location of measures in supply chain links	Planning and product design, Supplier, Production, Delivery, Customer
Decision-making levels	Strategic, Tactical, Operational
Nature of measures	Financial, Non-financial
Measurement base	Quantitative, Non-quantitative
Tradition vs. modern measures	Function-based, Value-based

Okongwu et al. [87] designed a performance pyramid (see Figure 2.7) and observed that these seven performance metrics create quality and delivery performance measures that give rise to the customer's satisfaction, which in turn contributes to the high market and financial position, therefore, achieving the firm's strategic goals can be achieved in relation to the efficiency and effectiveness.

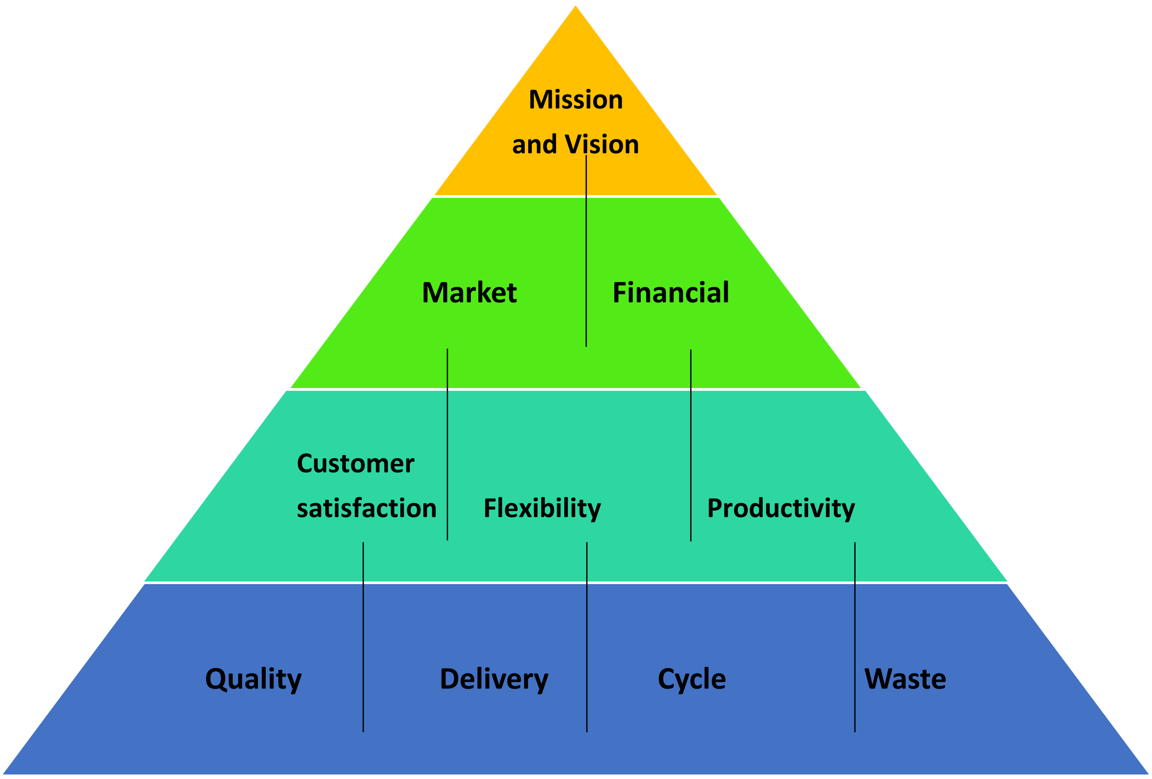


Figure 2.7: Performance pyramid.

The performance pyramid shows that attributes quality, delivery, cycle, and waste as placed in bottom level are more important or drivers of the performance of any organization. Therefore, they should be considered while improving the performance of the organization.

After discussing the significance of PMS, next, important research published in the field of PMS needs to be extracted. To do so, similar steps for plotting SciMAT and VOSviewer results are used as discussed in the previous section. The results of the SciMAT analysis are shown in Figure 2.8 & 2.9.

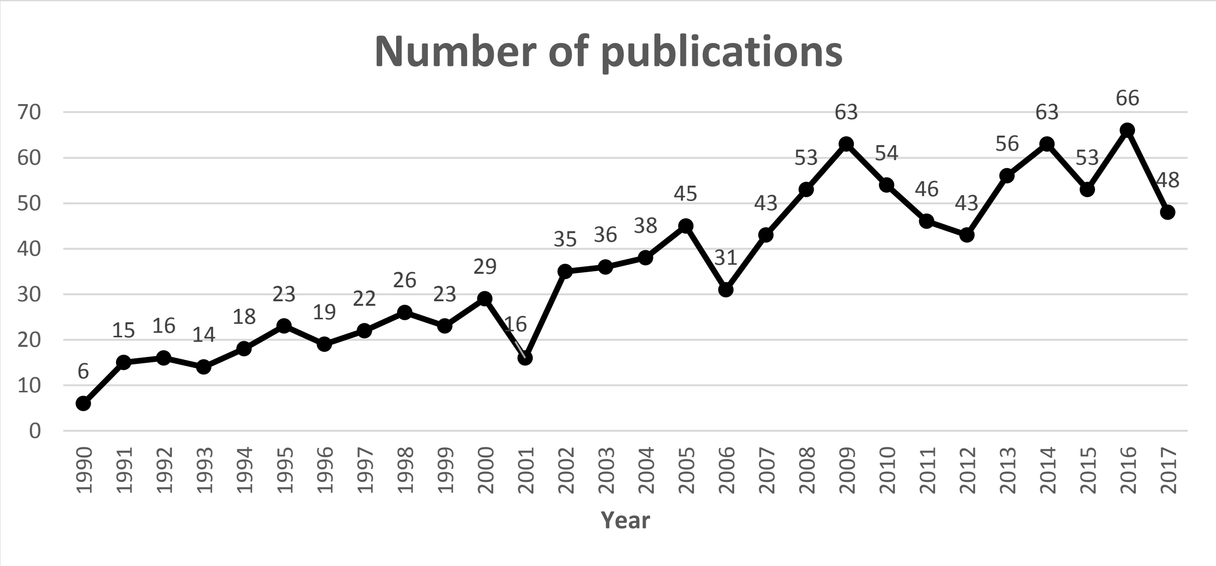


Figure 2.8: Publication of PMS research per year (1000 papers: 1990-2017).

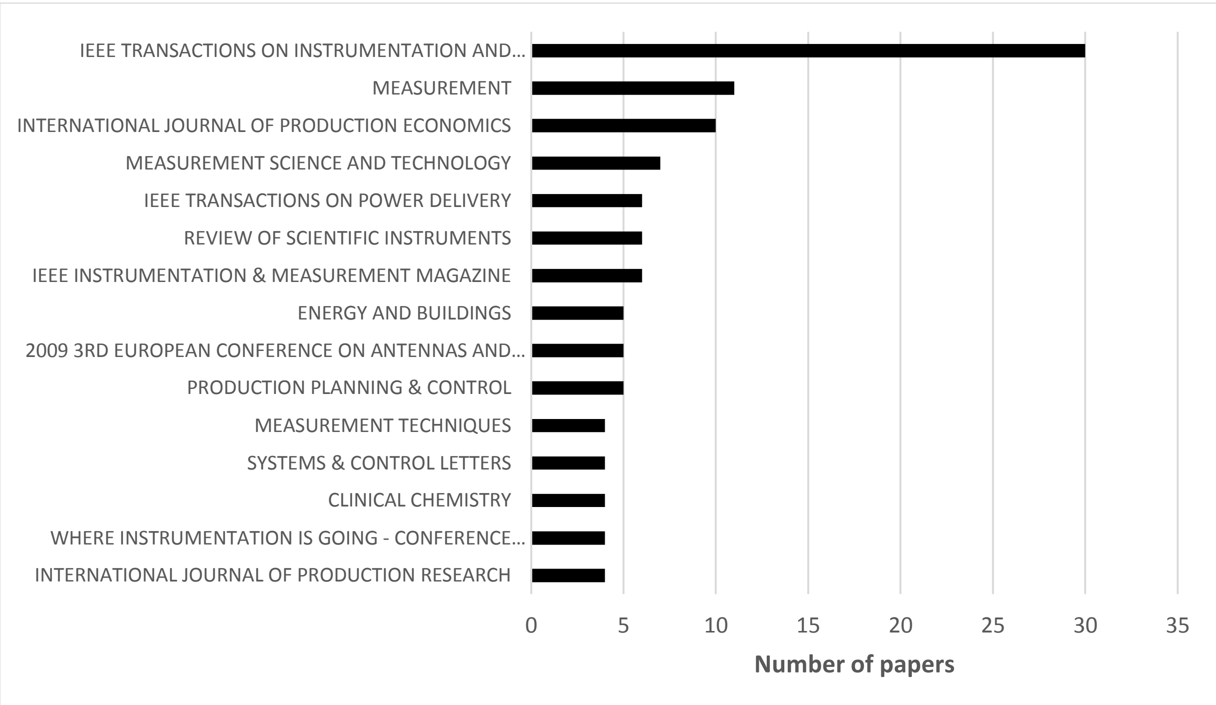


Figure 2.9: Distribution of PMS publications based on the top fifteen journals (1000 papers: 1990-2017).

Results of bibliographic mapping with the most popular keywords in PMS research are shown in Figure 2.10 and Table 2.7.

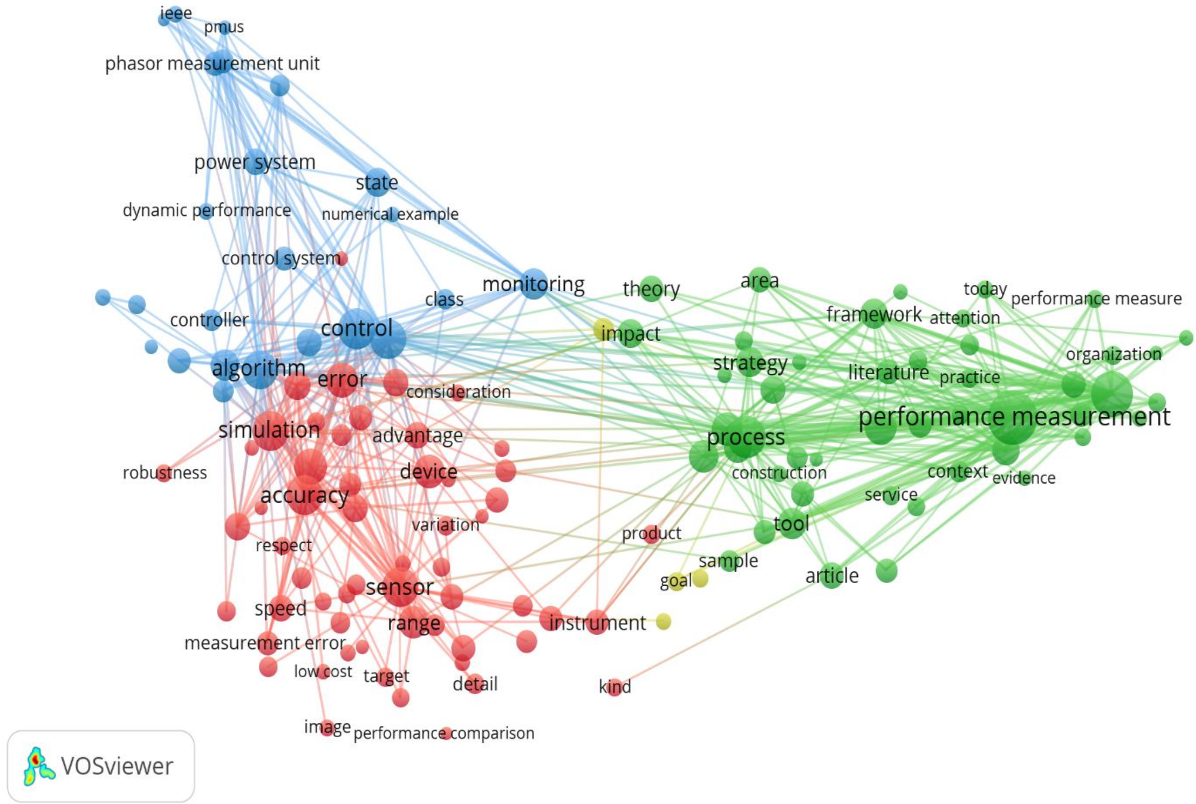


Figure 2.10: Bibliographic mapping of PMS research.

Table 2.7: Top fifteen popular keywords in PMS research.

Terms	Occurrences
performance measurement	151
performance measurement system	107
process	95
control	85
sensor	84
condition	84
accuracy	83
simulation	81
algorithm	77
signal	67
error	65
research	62
methodology	61
device	59
range	54

Remark: Results of the bibliographic mapping reveal that four clusters are identified and in the list of most popular keywords, the keywords 'supply chain with occurrence 17', 'BSC with occurrence 14' are less popular because of low occurrence, whereas, important keywords of this research such as 'vaccine', vaccine supply chain', 'healthcare', 'immunization' are missing among the popular keywords.

2.4.1. Review of literature on balanced scorecard (BSC) research

In this study, balanced scorecard approach as a performance measurement system has been used because of its worldwide acceptability as an important tool to measure the effectiveness of the organization activity against the strategic plans of a company. The balanced scorecard (BSC) is a performance measurement system (PMS) developed by Kaplan and Norton in 1992 [88]. It is a strategic planning tool that is used broadly in business and enterprise, government, and non-profit organizations worldwide to align commercial business activities to the mission, vision, and strategies of the organization, enhance inner and external communications and monitor organization performance towards strategic goals. The BSC provides a framework that helps planners identify what they should do and measure, and thus enables executives to actually execute their strategies [89].

Successful implementation of BSC in any non-profit and government operating healthcare organization will give the same positive results as in any private organization [90]. In a healthcare organization, the BSC is the current "meal for today", with specialists advocating this "incredible treatment" [91]. Kaplan and Norton point out that an organization should identify the best set of indicators that reflect their strategy. Indicators or key performance indicators (KPIs) in the business environment are mostly quantitative information, which explains the systems and processes of a company. KPIs act as a set of measures focusing on those aspects of organizational performance, which can be crucial for the success of the organization [92,93]. Lord Kelvin defined KPIs as "When you can measure what you are talking about and measure it in numbers, you realize something about it, however, if you cannot measure it in numbers, your expertise is of a meager and unsatisfactory kind"[94]. For the profit organizations who have to earn profits through their actions and are concerned about their own interests, financial KPIs are their most important set of criteria. For a non-profit organization, however, Kaplan and Norton recommend that customers can be placed – not the financial- at the top for achieving the organization's mission [95].

According to Gurd & Gao [95], the healthcare organizations have had to meet some unique challenges to meet the BSC to their environment. Identifying performance measures in terms of BSC in a healthcare supply chain as that of vaccines are very problematic compared to the supply chain of other products. The issue is mainly because each personal and public healthcare business should cope with an unstable environment due to severe forces, which encompass modern technology devices, demographic component, scarcity of skilled health workers, less financial support from the authorities, and change in lifestyles [96,97]. Since 1994, when the first study was published on BSC in healthcare, many researchers have successfully applied BSC in non-profit and healthcare organization.

In order to identify relevant journals and keywords on PMS research, similar steps for plotting SciMAT and VOSviewer results are used and the results of the SciMAT analysis are shown in Figure 2.11 & 2.12.

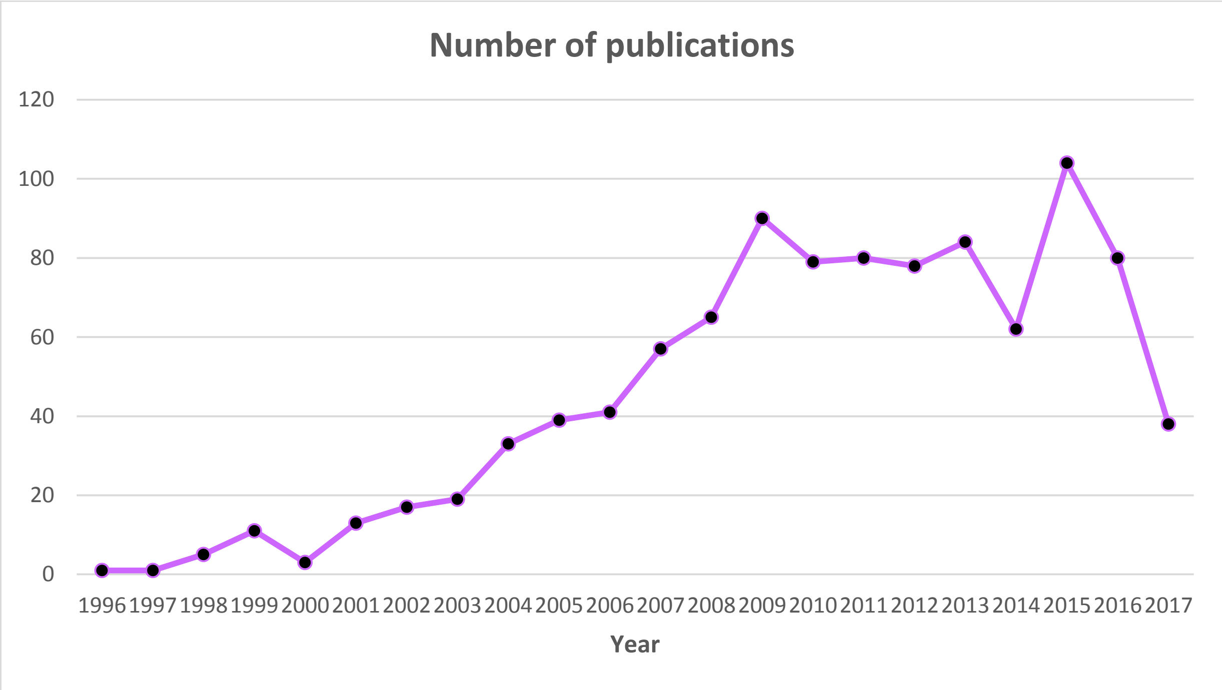


Figure 2.11: Publication of BSC research per year (1000 papers: 1996-2017).

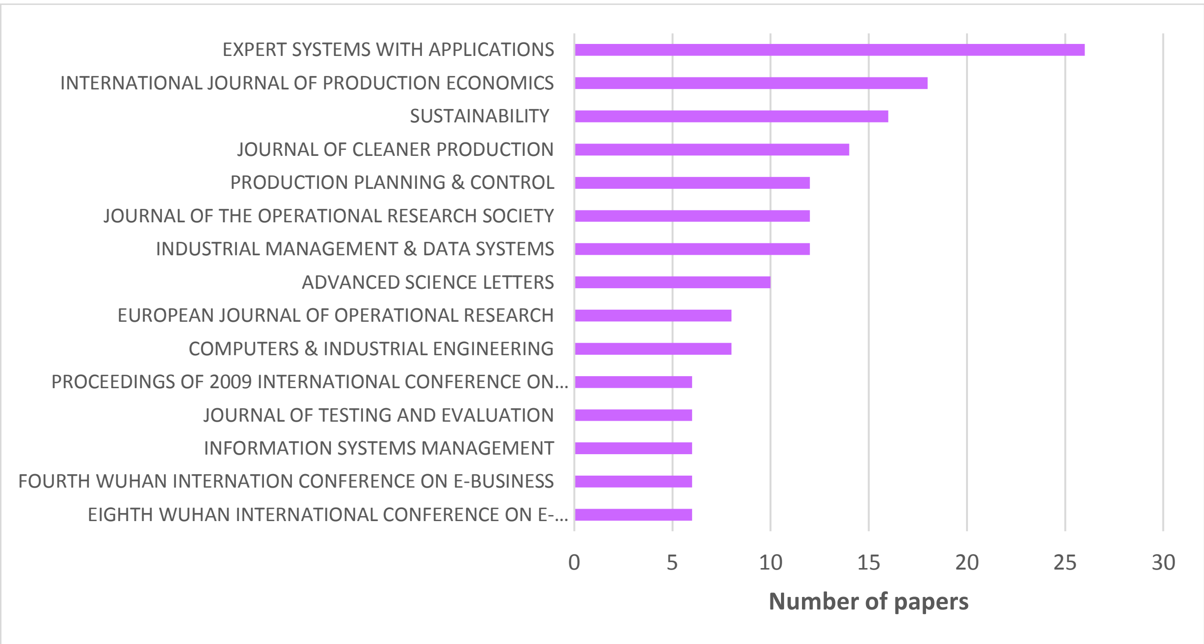


Figure 2.12: Distribution of BSC publications based on the top fifteen journals (1000 papers: 1990-2017).

Results of bibliographic mapping with the most popular keywords in BSC research are shown in Figure 2.13 and Table 2.8, while, the review of the selected papers related to BSC research is discussed in Table 2.9.

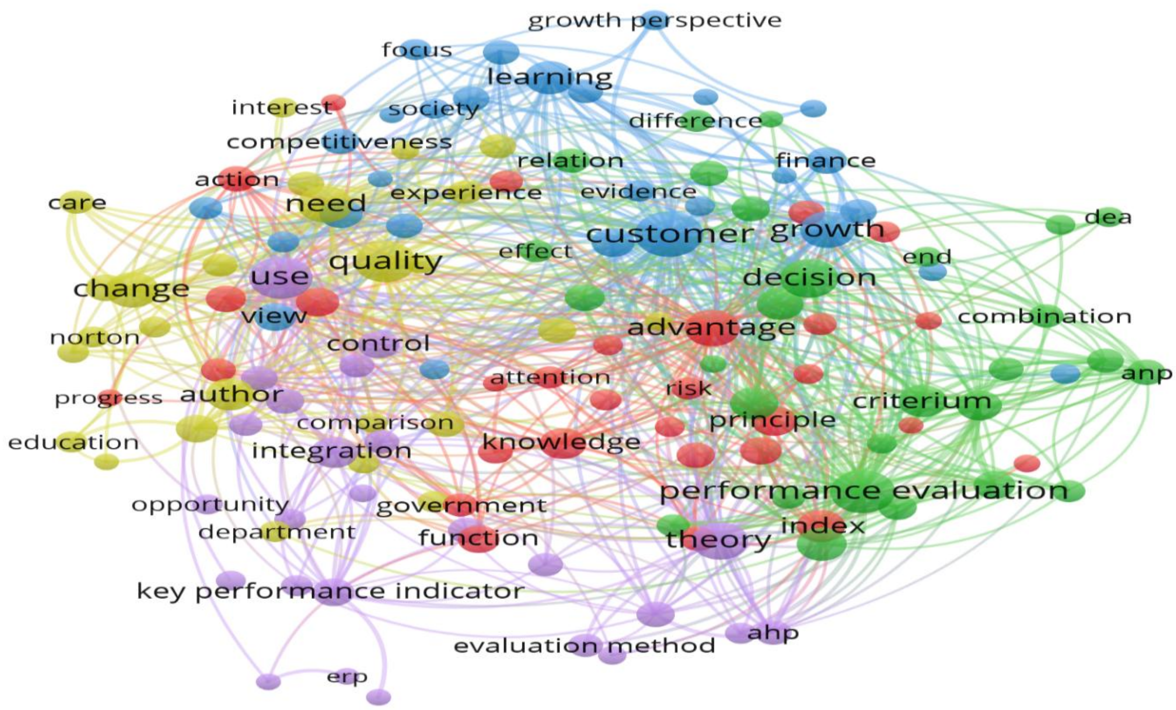


Figure 2.13: Bibliographic mapping of BSC research.

Table 2.8: Top fifteen popular keywords in BSC research.

Terms	Occurrences
customer	74
performance evaluation	67
use	65
quality	59
decision	55
theory	50
growth	49
need	49
advantage	48
change	46
dimension	40
learning	39
criterium	38
index	37
decision making	37

Remark: Results of the bibliographic mapping reveal that five clusters are identified and in the list of most popular keywords, the keywords 'supply chain with occurrence 28', 'key performance indicator with occurrence 27', 'sustainability with occurrence 24', 'hospital with occurrence 22', and 'government with occurrence 20', are less popular because of low occurrence, whereas, important keywords of this research such as 'vaccine', vaccine supply chain', 'healthcare', 'immunization' are missing among the popular keywords.

Table 2.9: Review of selected papers on BSC research.

Author/s	Journal name	Publisher	Contribution
Baker and H.Pink [98]	Healthcare Management Forum	SAGE	For measuring Canadian hospital performance
Greiling [99]	International Journal of Productivity and Performance Management	Emerald	In German non-profit organizations.
Tsai et al. [100]	International Journal of Gerontology	Elsevier	Reducing Fall Incidents and Injuries Among Elderly Cancer Patients in a Medical Center in Taiwan.
Yuksel and Dagdeviren [101]	Expert Systems with Applications	Elsevier	To determine the performance level of a business based on its vision and strategies.
Voelker et al., [102]	Hospital Topics	Taylor & Francis	For measuring healthcare organization performance.
Lee et al., [103]	Information and Management	Elsevier	Used a balanced scorecard for the evaluation of software-as-a-service.
Othman et al. [104]	Journal of Asia-Pacific Business	Taylor & Francis	Used bsc in a Malaysian company.
Wu et al.. [105]	The Service Industries Journal	Taylor & Francis	Government performance evaluation using a balanced scorecard with a fuzzy linguistic scale
Hunt et al. [106]	Journal of Education for Business	Taylor & Francis	To enhance undergraduate education in a first-year business course: A pilot study.
Hasan et al. [107]	Journal of Air Transport Management	Elsevier	Balanced scorecard based performance measurement of European airlines using a hybrid multi-criteria decision-making approach under the fuzzy environment.
N et al. [108]	Journal of Healthcare Management	American College of Healthcare Executives	Developed guidelines for healthcare provider organizations to capture the benefits of the Balanced Scorecard performance management system.

Author/s	Journal name	Publisher	Contribution
Balkovskaya and Filneva [109]	International Journal of Business Excellence	Inderscience	Used the balanced scorecard in bank strategic management.
Gama [110]	International Journal of Business Performance Management	Inderscience	In marketing performance assessment.
Gurd and Gao [95]	International Journal of Productivity and Performance Management	Emerald	Presented BSC as a prominent innovation in the strategic performance measurement system for a healthcare organization.

2.5. Review of literature on sustainable development and assessment research

Organizational sustainability lies in the center of the overall sustainable development of the countries and the world because it was institutional and organizational growth which brought huge wealth and prosperity over the last 200 years [111]. The sustainability concept became formally accepted in 1987 when the world commission on environmental and development (WCED) posted the Brundtland Report titled "Our Common Future". In this document, the Commission defined sustainable development as "the overall goal of sustainable development is the long-term stability of the economy and environment; that is only manageable through the integration and acknowledgment of economic, environmental, and social issues throughout the decision-making process" [112]. To achieve sustainability, it is important that organizations focus not only on the economic values but also on the environmental and social aspects [113]. There is strong evidence that developing and promoting socially and environmentally responsible business practices are likely to help companies increase their earnings because sustainable practices positively affect customers' perceptions and actions [114]. Generally, sustainability evaluations are made on the grounds of the triple bottom line dimensions – economic, social and environmental, which are discussed below:

- **Economic dimension:** it is usually regarded as a 'generic dimension' that captures an organizations element that has to be addressed to remain competitive in the marketplace on the long-run [115]. It includes profit and value; investments; developments; crisis management etc.

- **Social dimension:** encompasses notions of equity, empowerment, accessibility, participation, sharing, cultural identity, and institutional stability. It seeks to keep the environment through economic growth and the alleviation of poverty [116]. This dimension consists of labor practices, work environment; salary and remuneration, suppliers and partners, etc.

- **Environmental dimension:** involves ecosystem integrity, carrying capability and biodiversity. It requires that natural capital is maintained as a supply of economic inputs and as a sink for wastes. Resources must be harvested no quicker than they may be regenerated. Wastes must be emitted no quicker than they can be assimilated by means of the environment [116]. The dimension includes factors such as material; energy; gas emissions; land; waste; water, etc.

In recent times, sustainable supply chain management (SSCM) has become a topic of interest for academics and practitioners. Sustainable supply chain concerns the "management of material, information and capital flows as well as cooperation among companies along the supply chain while taking goals from all three dimensions of sustainable development, i.e., economic, environmental and social, into account which are derived from customer and stakeholder requirements" [117]. Today, many Indian industries are also integrating their supply chain with sustainability practices. In this regard, Kausar [118] also points out that in most of the Indian industries, sustainability has grown into supply chain management with a clear explanation because of less available resource, greenhouse gas emissions, degradation of natural resources and consumers' awareness about labor issues. It is expected that in future almost every Indian company and organization should incorporate the sustainability practices into them so that it benefits the organization, environment, and the society for the long term.

To identify relevant journals and important keywords in sustainable development research, 1000 papers are extracted from 'Web of Science' and used for analysis in SciMAT and VOSviewer software. The results of the SciMAT analysis are shown in Figure 2.14 & 2.15.

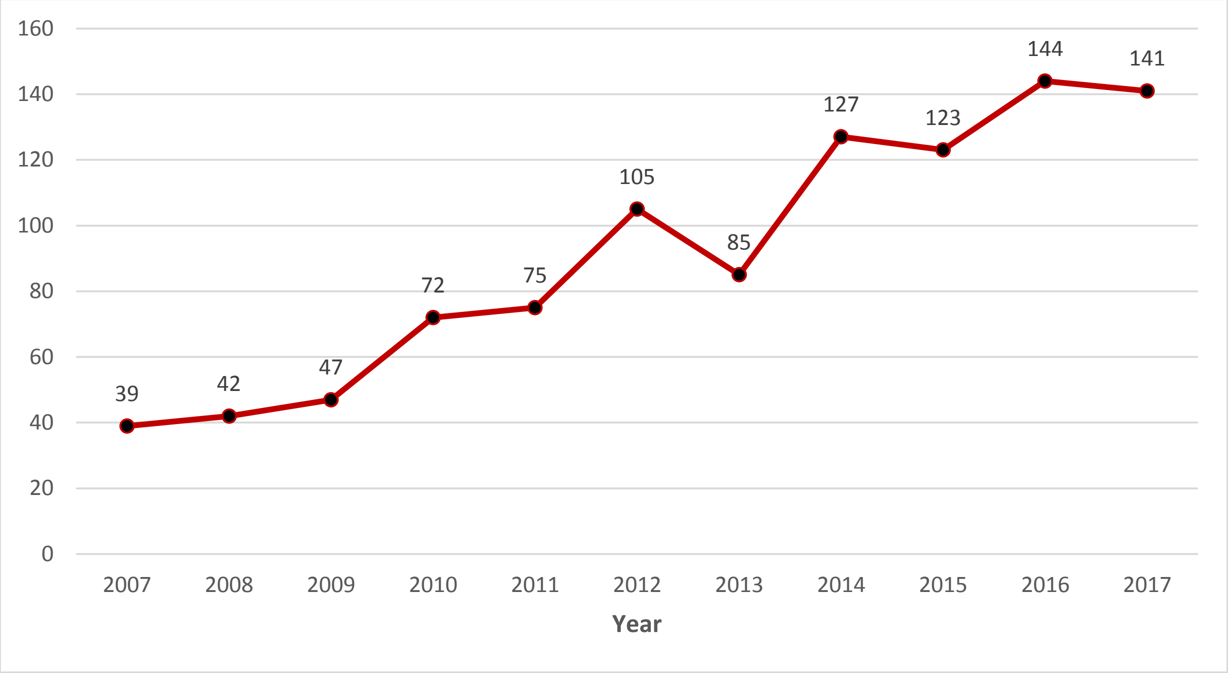


Figure 2.14: Publication of sustainable development research per year (1000 papers: 2007-2017).

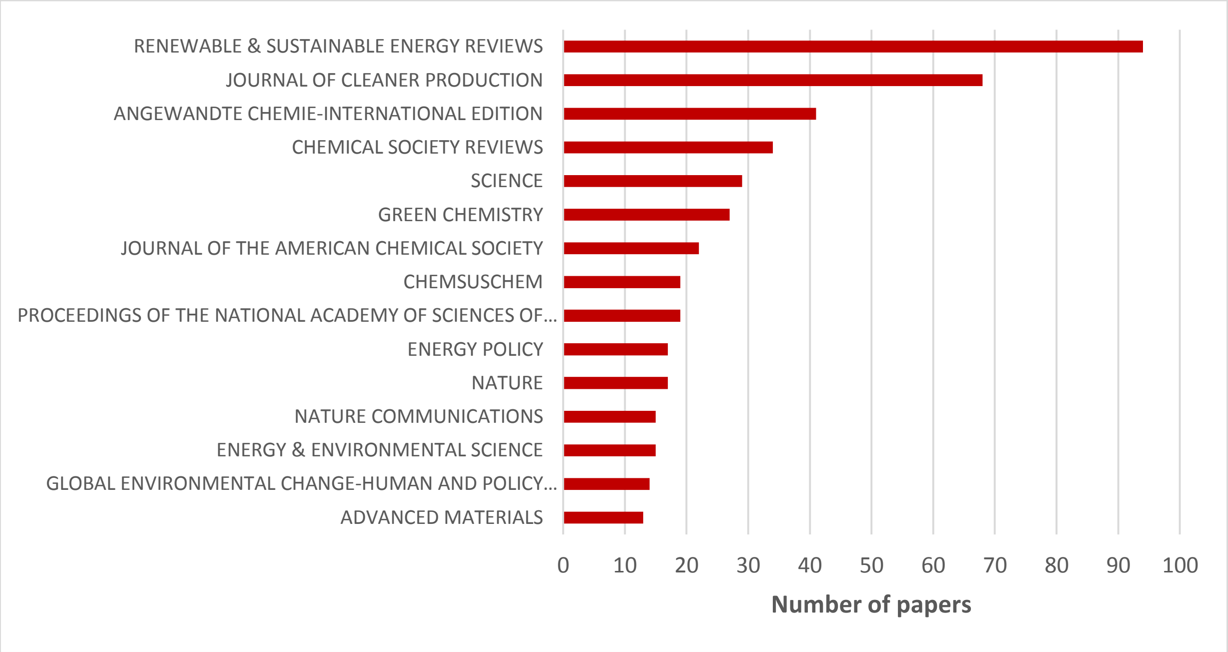


Figure 2.15: Distribution of sustainability development publications based on the top fifteen journals (1000 papers: 2007-2017).

Further, the result of the VOSviewer for bibliographic mapping is shown in Figure 2.16; four clusters have been identified and the popular keywords of all the clusters are shown in Table 2.10. Table 2.11 discusses the review of the selected papers related to sustainable development research.

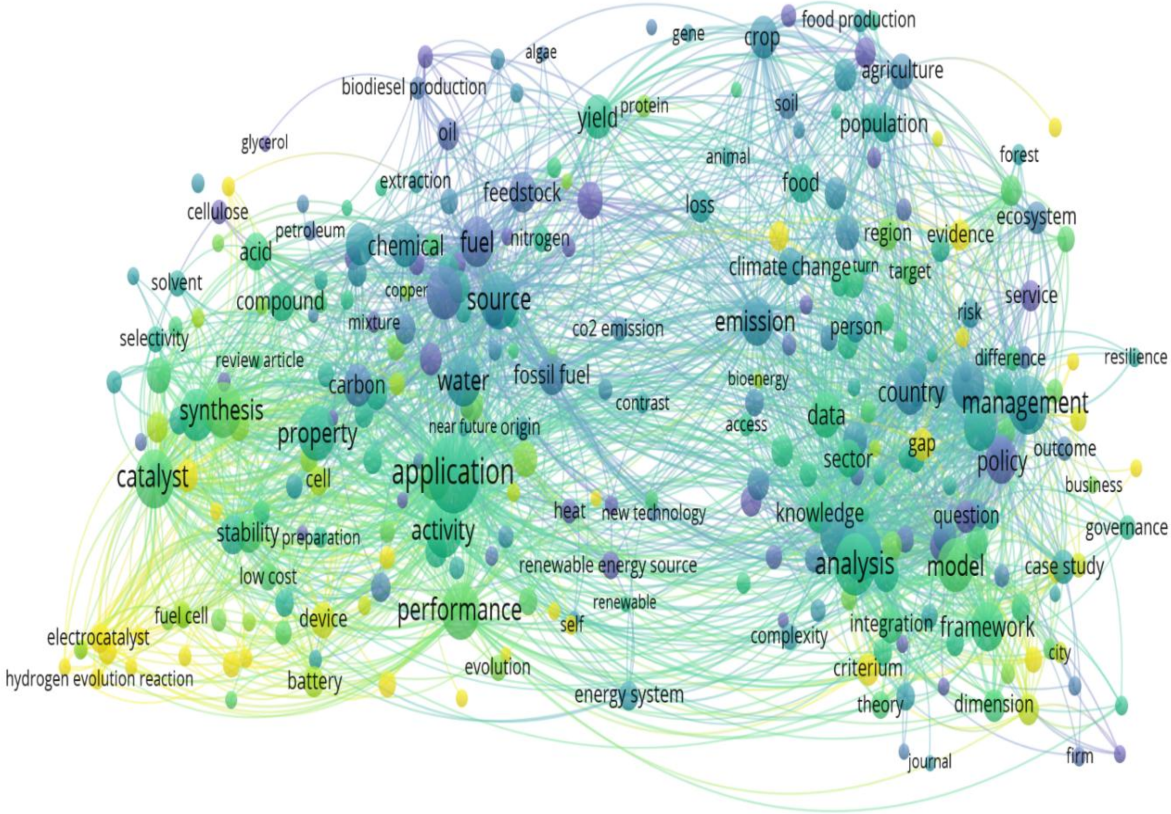


Figure 2.16: Bibliographic mapping of sustainable development research

Table 2.10: Top fifteen popular keywords in sustainable development research.

Terms	Occurrences
application	227
analysis	145
sustainability	133
management	131
catalyst	125
performance	123
source	121
activity	114
property	112
synthesis	112
sustainable development	109
biomass	106
model	105
reaction	102
water	101

Remark: Results of the bibliographic mapping reveal that four clusters are identified and in the list of most popular keywords, the keywords 'supply chain with occurrence 36', 'SSCM with occurrence 16', and 'sustainable supply chain with occurrence 13' are less popular because of low occurrence, whereas, important keywords of this research such as 'vaccine', vaccine supply chain', 'healthcare', 'immunization' are missing among the popular keywords.

Table 2.11: Review of selected papers on sustainable development research.

Author/s	Journal name	Publisher	Contribution
Dubey et al. [117]	Journal of Cleaner Production	Elsevier	Identified the antecedents and drivers for the adoption of SSCM.
Glover et al. [119]	International Journal of Production Research	Taylor & Francis	To identify the relationship between continuous improvement and rapid improvement sustainability.
Cavicchi [120]	Journal of Intellectual Capital	Emerald	The papers discuss the role of intellectual capital in promoting the sustainable development program of the Emilia-Romagna Health Service.
Cantore et al. [121]	International Journal of Sustainable Development & World Ecology	Taylor & Francis	This paper proposes an analytical toolkit to measure the sustainability of industrialization across countries.
Galal and Moneim [122]	Procedia CIRP	Elsevier	This work presents a supply chain assessment model integrating the three dimensions of sustainability i.e. economic, social and environmental.
Carter and Rogers [123]	International Journal of Physical Distribution & Logistics Management	Emerald	This work demonstrates the relationships among environmental, social, and economic performance within a supply chain management context.
Ahmed et al. [124]	International Journal of Environment and Sustainable Development	Inderscience	Developed a framework for sustainable wastewater management for underdeveloped communities.
Jacqueline Mutumi and Simatele [125]	International Journal of Sustainable Development	Inderscience	The study identified the relationships between profitability, the green economy and environmental sustainability in South Africa.
Glover et al. [126]	International Journal of Production Economics	Elsevier	Critical success factors for the sustainability of Kaizen event human resource outcomes.
Schneider et al. [127]	Benchmarking: An International Journal	Emerald	To benchmark the evolution of reported sustainability activity in the pharmaceutical sector, which has been recognized as a leading sector in industrial sustainability.

2.5.1. Review of literature on prospects of balanced scorecard towards sustainability

Another important aspect of the present research is the combination of sustainability improvement and balanced scorecards. Considering the extensible benefit of the balanced scorecards, now, many researchers have included the issue of sustainable development in the balanced scorecard as a measure of an organization [22].

To identify literature and keywords on possibilities of BSC towards sustainability, 109 papers are extracted published between the period 1990-2017 through 'Web of Science' using the advanced search option (Balanced scorecard AND Sustainability). Then, similar steps for plotting SciMAT and VOSviewer results have been used. The results of the SciMAT analysis are shown in Figure 2.17 & 2.18.

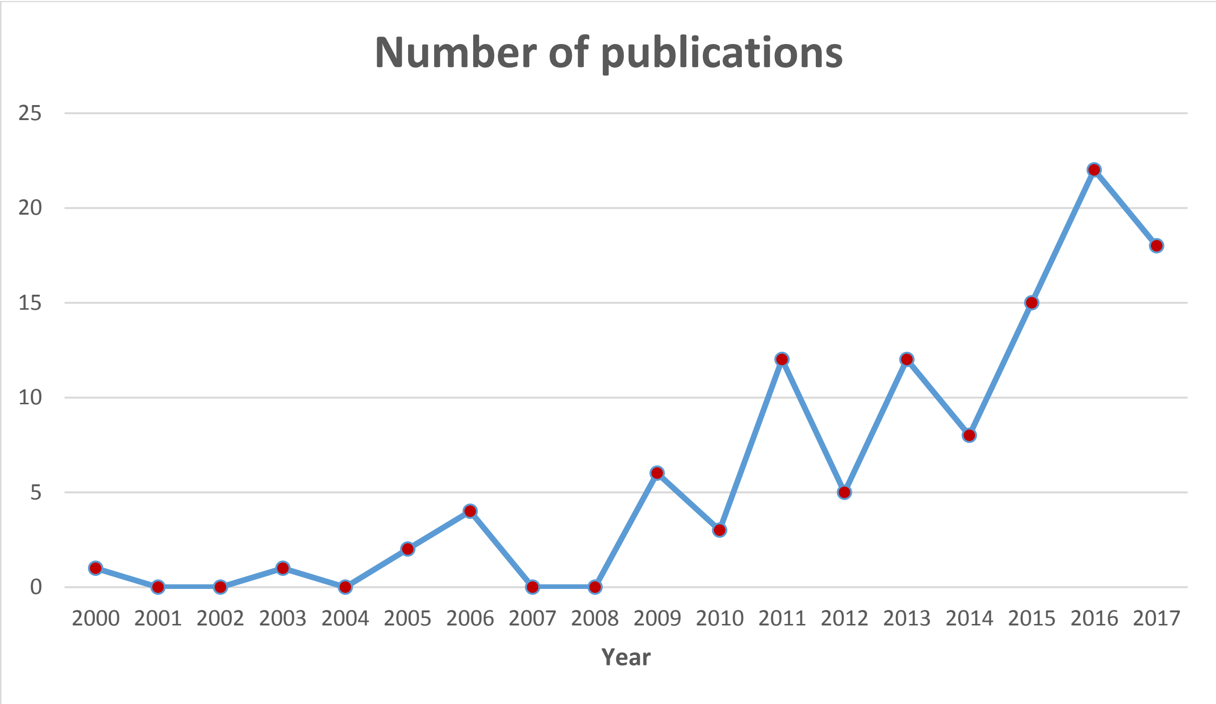


Figure 2.17: Publication of BSC towards sustainability research (109 papers: 2000-2017).

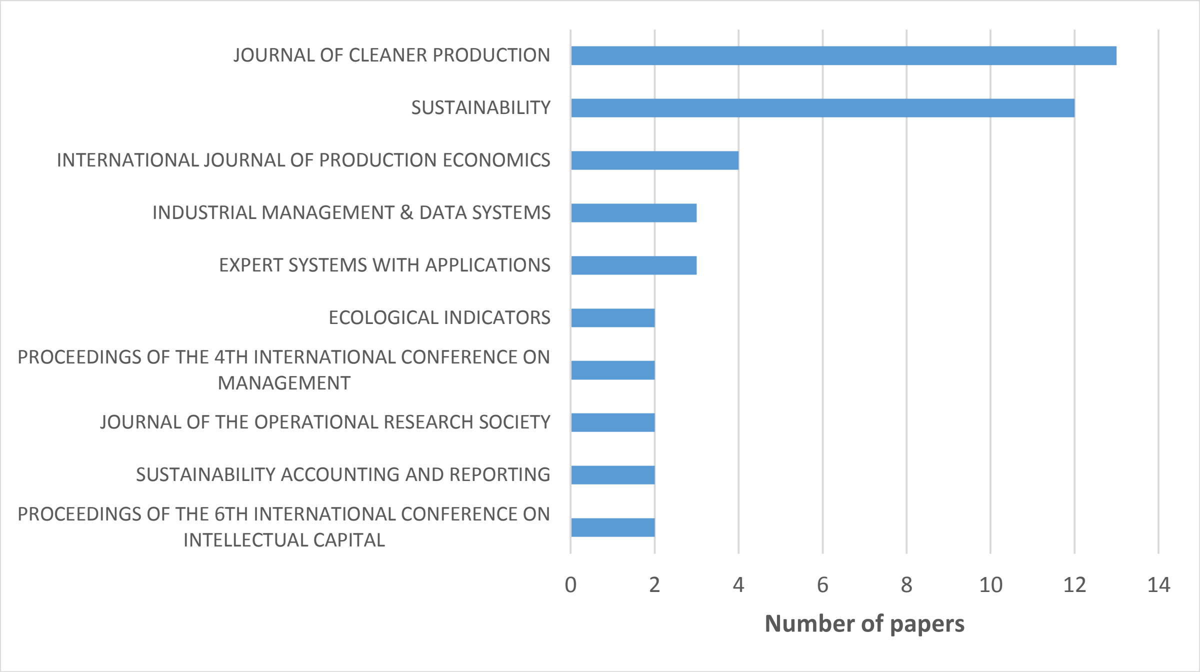


Figure 2.18: Distribution of BSC towards sustainability publications based on top ten journals (109 papers: (2000-2017).

Results of bibliographic mapping with the most popular keywords are shown in Figure 2.19 and Table 2.12, while the review of the selected papers is discussed in Table 2.13.

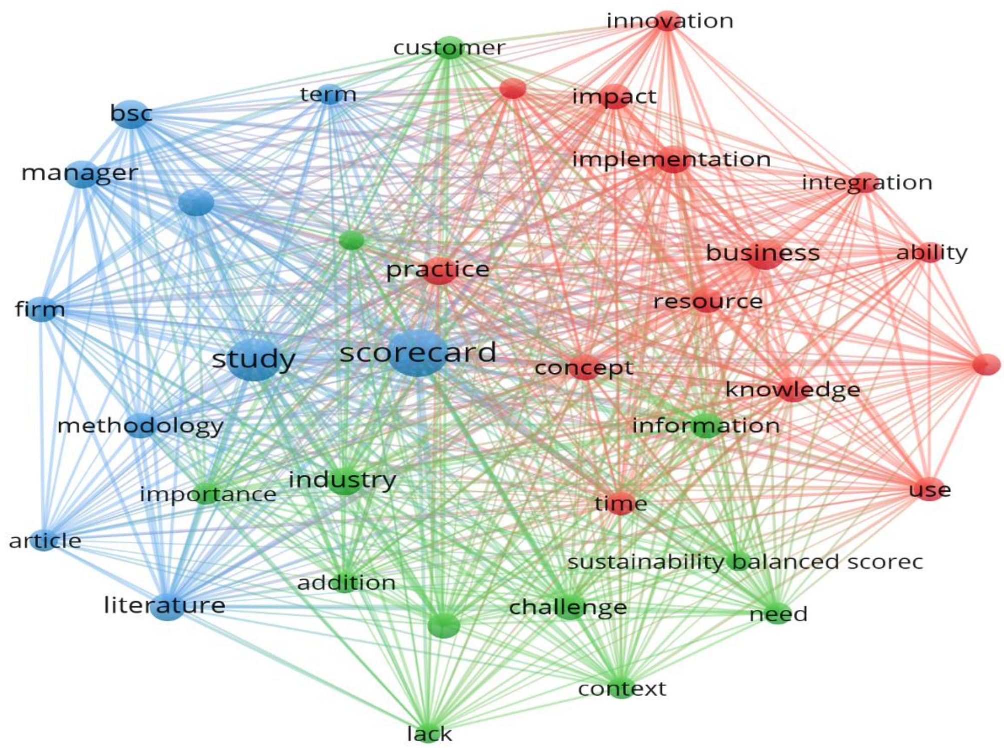


Figure 2.19: Bibliographic mapping of BSC towards sustainability research.

Table 2.12: Top fifteen popular keywords in BSC towards sustainable development research.

Terms	Occurrences
scorecard	63
study	53
business	26
bsc	24
manager	23
literature	23
industry	23
practice	23
relationship	22
implementation	22
firm	19
knowledge	19
challenge	19
impact	19
methodology	19

Remark: Results of the bibliographic mapping reveal that three clusters are identified and in the list of most popular keywords, the keywords 'supply chain with occurrence 11', 'sustainable development with occurrence 11', and 'sustainability balanced scorecard with occurrence 11', are less popular because of low occurrence, whereas, important keywords of this research such as 'vaccine', vaccine supply chain', 'healthcare', 'immunization' are missing among the popular keywords.

Table 2.13: Review of selected papers on BSC towards sustainable development research.

Author/s	Journal name	Publisher	Contribution
Hsu et al. [22]	Journal of Cleaner Production	Elsevier	Used balanced scorecard for sustainable development of small and medium enterprises.
Epstein and Wisner [128]	Environmental Quality Management	Wiley	Used the balanced scorecard to help EH&S managers to implement sustainability
Figge et al. [129]	Business Strategy and the Environment	Wiley	Combined environmental and social factors into the four views of the balanced scorecard.
Dias Sardinha [130]	Environmental Quality Management	Wiley	For developing sustainability balanced scorecards for environmental services units of three large Portuguese companies.
Kalender and Vayvay [131]	Procedia - Social and Behavioral Sciences	Elsevier	Used the integrated BSC and sustainability to form the fifth pillar of BSC as sustainability.

Author/s	Journal name	Publisher	Contribution
Tsai et al. [132]	Journal of Operational Research Society	Springer	Used the SBSC as a multi-standards framework to assess socially accountable investment, which included decision making trial and evaluation laboratory (DEMATEL), analytical network process (ANP) and zero-one intention programming methods to pick out the first-class funding for socially responsible investment aggregate.
Nikolaou and Tsalis [133]	Ecological Indicators	Elsevier	Developed the SBSC scoring framework to measure business sustainability the use of the Global Reporting Initiative (GRI) metrics and implemented it to a case employer in Greece.
Hansen and Schaltegger [134]	Journal of Business Ethics	Springer	This study contributes to the development of the emerging SBSC literature and practice and, to the research on corporate sustainability performance measurement and management.
Moller and Schaltegger [135]	Journal of Industrial Ecology	Wiley	Extended the balanced scorecard to sustainable development and called this improved scorecard as a sustainably balanced scorecard.
Journeault [136]	Journal of Environmental Management	Elsevier	Suggested that SBSC is one of the effective tools of sustainable development techniques. The study also proposed an integrated scorecard, a specific SBSC that included the performance of the three pillars of sustainability into four perspectives of BSC, particularly, environmental, social and financial performance, stakeholder management, internal processes, and abilities and skills.
Hsu et al. [137]	Journal of Cleaner Production,	Elsevier	Constructed the SBSC and used the fuzzy Delphi method and ANP to determine the maximum critical metrics for the sustainability performance of the semiconductor industry in Taiwan.
Tsalis et al. [138]	Journal of Integrative Environmental Sciences	Taylor & Francis	Developed a framework development to evaluate the needs of small and medium enterprises in order to adopt a sustainability-balanced scorecard.

2.6. Review of methodologies adopted in the research work

In this section, a review of the various methodologies used in the work is discussed.

2.6.1. Delphi technique

Various researchers have used the Delphi technique for selection of important factors. The Delphi method a structured communication technique or method, originally developed as a systematic, interactive forecasting method which relies on a panel of experts The experts answer questionnaires in two or more rounds. After each round, a facilitator or change agent provides an anonymized summary of the experts' forecasts from the previous round as well as the reasons they provided for their judgments. Thus, experts are encouraged to revise their earlier answers in light of the replies of other members of their panel.

To identify relevant journals and keywords on Delphi research, similar steps for plotting SciMAT and VOSviewer are and the results of the SciMAT analysis are shown in Figure 2.20 & 2.21.

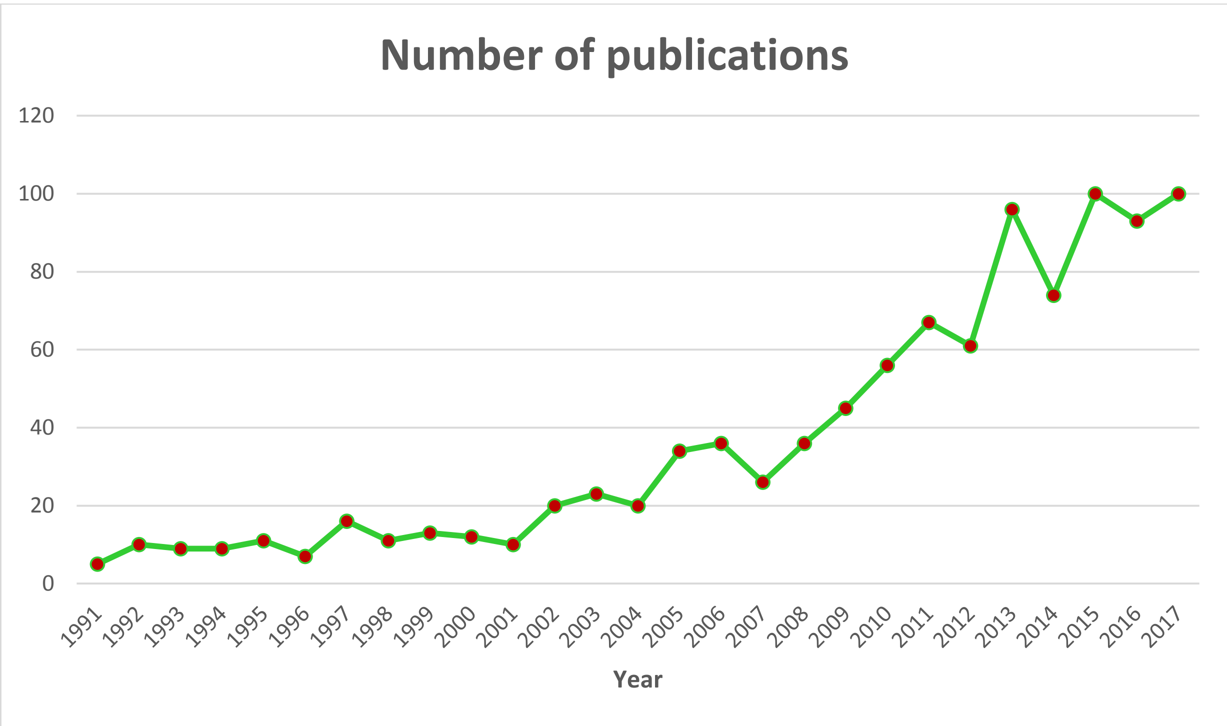


Figure 2.20: Publication of Delphi technique research per year (1000 papers: 1991-2017).

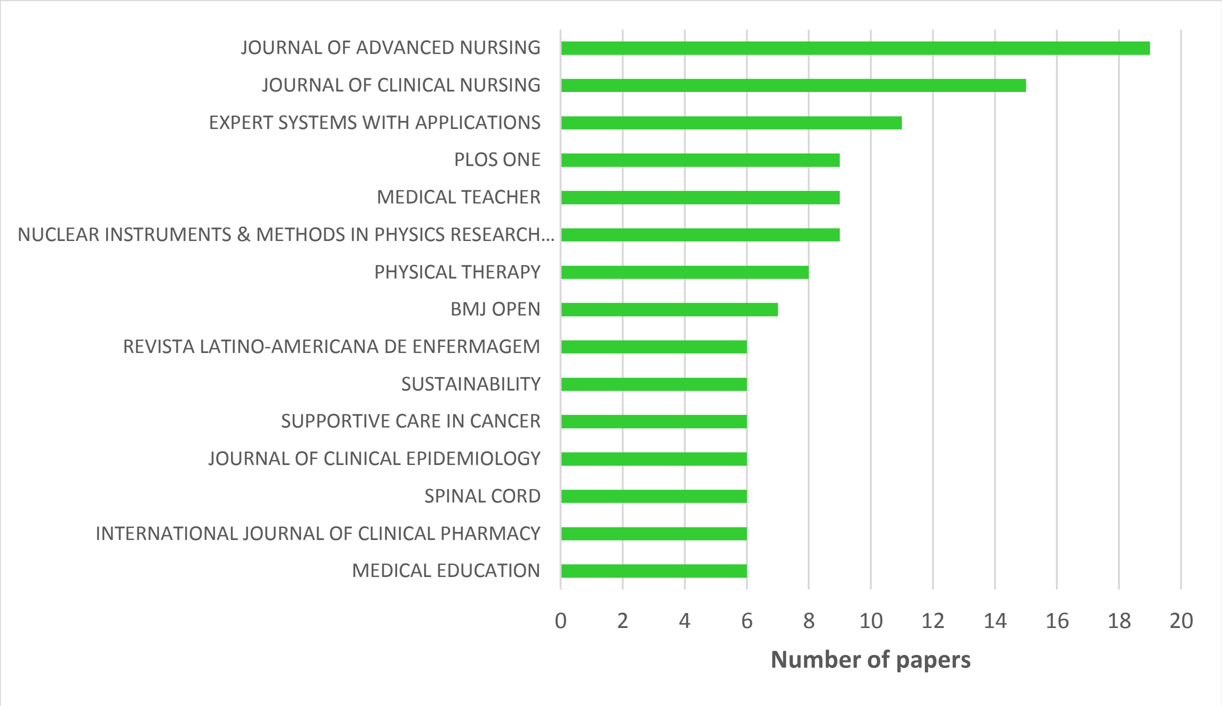


Figure 2.21: Distribution of Delphi technique publications based on the top fifteen journals (1000 papers: 1991-2017).

Results of bibliographic mapping with the most popular keywords in Delphi technique research are shown in Figure 2.22 and Table 2.14.

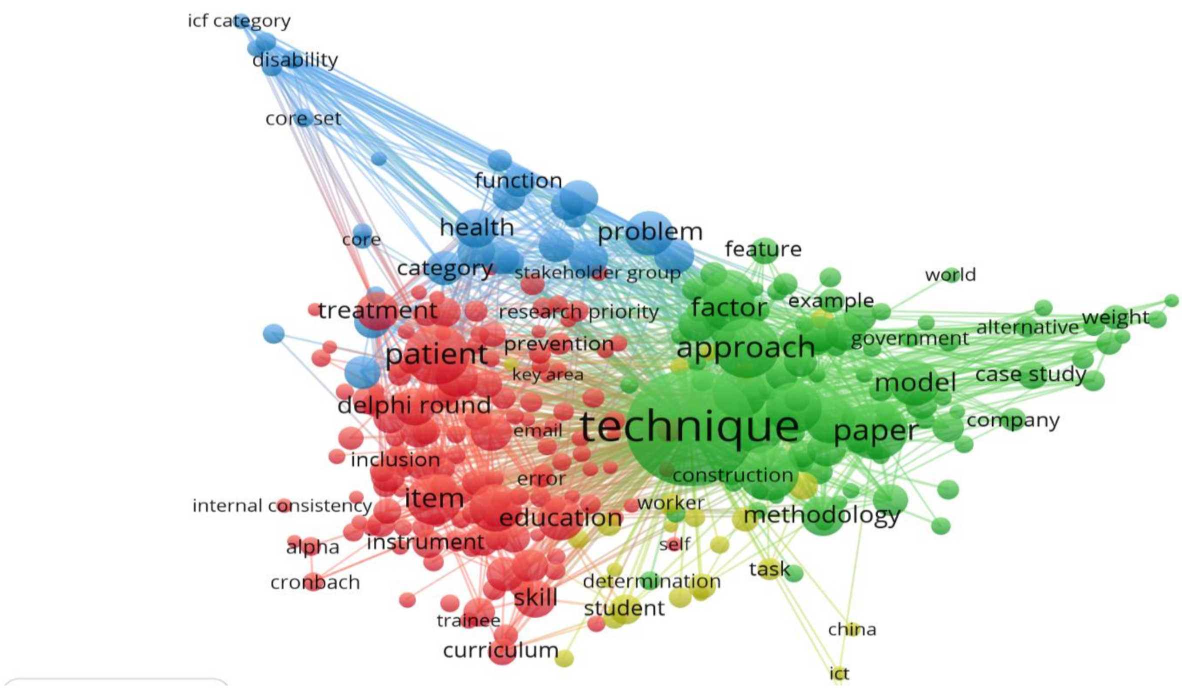


Figure 2.22: Bibliographic mapping of Delphi technique research.

Table 2.14: Top fifteen popular keywords in the Delphi technique research.

Terms	Occurrences
technique	753
approach	199
patient	196
paper	187
analysis	171
system	145
item	144
criterium	139
delphi	129
factor	128
application	125
review	124
model	115
order	115
problem	108

Remark: Results of the bibliographic mapping reveal that four clusters are identified and in the list of most popular keywords, the keywords 'health with occurrence 83', 'hospital with occurrence 53', 'health professionally with occurrence 23', and 'government with occurrence 19', are less popular because of low occurrence, whereas, important keywords of this research such as 'vaccine', vaccine supply chain', 'healthcare', 'immunization' are missing among the popular keywords.

Further, the review of the selected papers related to Delphi technique research is discussed in Table 2.15.

Table 2.15: Review of selected papers on Delphi technique research.

Author/s	Journal name	Publisher	Contribution
Zitz and Matopoulos [139]	International Journal of Logistics Systems and Management	Inderscience	For the developments and prospects of freight railway transport in Northern Germany.
Walker et al. [140]	Midwifery	Elsevier	To establish a consensus on standards of competence for professionals attending upright breech births.
Morgan et al. [141]	Journal of Affective Disorders	Elsevier	To identify the strategies which are helpful for mild anxiety.
Villiers and Kent [142]	Medical Teacher	Taylor & Francis	For identifying the recommendations regarding educations and training of medical practitioner's in South Africa.

Author/s	Journal name	Publisher	Contribution
Almeland et al. [143]	Journal of Plastic Surgery and Hand Surgery	Taylor & Francis	To establish a Scandinavian core undergraduate curriculum of competences in plastic surgery, using scientific methods.
N. et al. [144]	Contemporary Issues and Development in the Global Halal Industry	Springer	For the formation of Shariah-Compliant Gold Instrument.
Stanley and Akintola [145]	International Journal of Health Care Quality Assurance	Emerald	To identify, refine and rate the critical success factors and performance measures in maintenance-associated infections.
Soon et al. [146]	Expert Systems with Applications	Elsevier	For developing and validating a farm food safety risk assessment tool by experts
Raut [147]	International Journal of Logistics Systems and Management	Inderscience	For identification, synthesis, and prioritization of key performance factors and sub-factors for supplier selection problem.

2.6.2. Interpretive structural modeling (ISM)

ISM is an interactive computer-assisted learning process into a set of heterogeneous directly related elements are structured into a comprehensive systematic model. ISM also gives the basic ideas to develop a map of the compound associations between the numerous elements concerned in multifaceted circumstances

2.6.3. Fuzzy MICMAC (FMICMAC)

Fuzzy MICMAC is used in conjunction with the ISM method because ISM not reveals the indirect relationship between the factors or elements. The fuzzy MICMAC analysis identifies the driving power and dependence of the factors and based on that power it divides factor into four important dimensions.

To identify relevant journals on ISM&FMICMAC, the important keyword ‘ISM AND FMICMAC’ is performed on ‘Web of Science’ using the advanced search option, and based on the search, 391 papers until 2017 period are extracted. The results of the SciMAT analysis are shown in Figure 2.23 and 2.24.

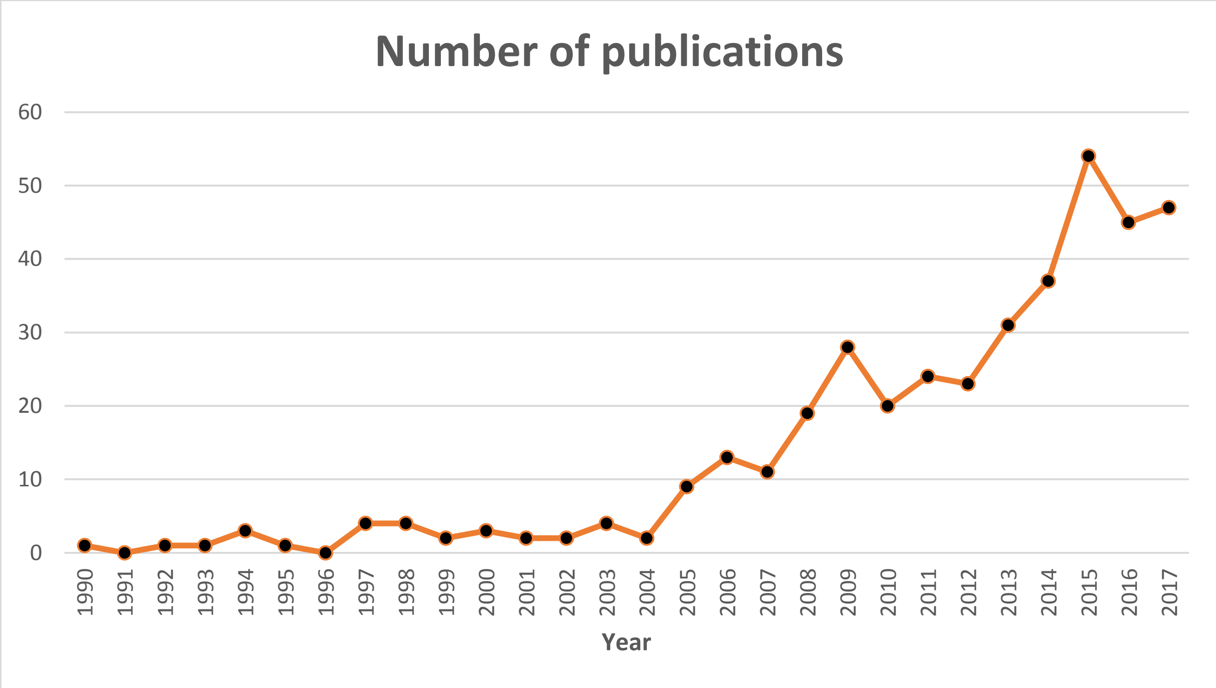


Figure 2.23: Publication of ISM&FMICMAC research per year (1000 papers: 1990-2017).

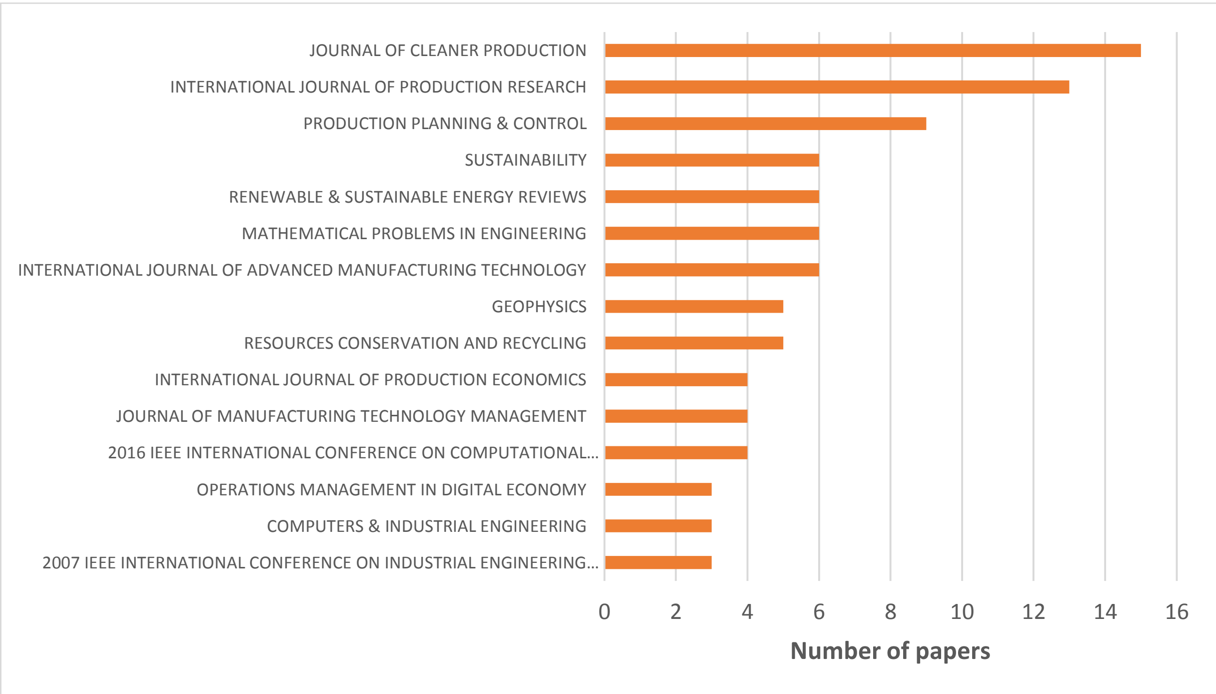


Figure 2.24: Distribution of ISM&FMICMAC publications based on the top fifteen journals (1000 papers: 1990-2017).

Results of bibliographic mapping with the most popular keywords in ISM&FMICMAC research are shown in Figure 2.25 and Table 2.16.

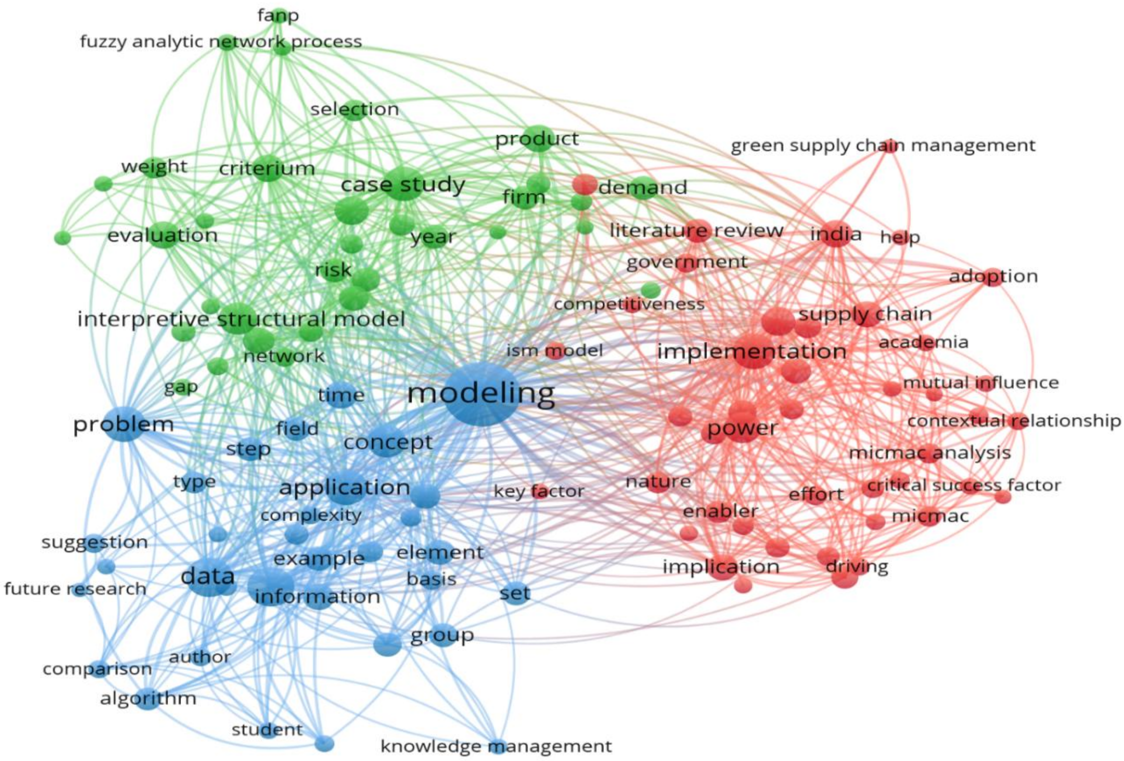


Figure 2.25: Bibliographic mapping of ISM&FMICMAC research.

Table 2.16: Top fifteen popular keywords in ISM&FMICMAC research.

Terms	Occurrences
modeling	206
data	76
structure	75
implementation	65
problem	62
application	62
case study	58
interpretive structural model	50
concept	50
power	47
decision	42
barrier	40
criterium	38
product	38
evaluation	37

Remark: Results of the bibliographic mapping reveal that three clusters are identified and in the list of most popular keywords, the keywords 'supply chain with occurrence 35', 'sustainability with occurrence 22', 'and 'government with occurrence 19', are less popular because of low occurrence, whereas, important keywords of this research such as 'vaccine', vaccine supply chain', 'healthcare', 'immunization' are missing among the popular keywords.

Table 2.17 presents a review of the selected papers related to ISM&FMICMAC.

Table 2.17: Review of selected papers on ISM&FMICMAC research.

Author/s	Journal name	Publisher	Contribution
Jain and Raj [148]	International Journal of Systems Assurance Engineering and Management	Springer	For modeling and analysis of flexible manufacturing system factors.
Kumar et al. [149]	Journal of Business & Industrial Marketing	Emerald	For modeling of supplier selection process enablers.
Jain et al. [150]	International Journal of Productivity and Quality Management	Inderscience	To identify key success factors behind the total productive maintenance implementation in Indian small and medium enterprises.
Khan and Haleem [151]	International Journal of Intelligent Enterprise	Inderscience	An integrated approach using ISM and FMICMAC is proposed for modeling of enablers of the smart organization.
Sindhu et al. [152]	Renewable and Sustainable Energy Reviews	Elsevier	Identification and analysis of barriers in the implementation of solar energy in the Indian rural sector.
Dube and Gawande [153]	International Journal of Logistics Systems and Management	Inderscience	A framework using ISM and FMICMAC is presented for the analysis of green supply chain management enablers.
Jia et al. [154]	Resources Policy	Elsevier	For analysis of SSCM practices.
Bhosale and Kant [155]	International Journal of Production Research	Taylor & Francis	An integrated ISM and FMICMAC is used for modeling the supply chain knowledge enablers.

Author/s	Journal name	Publisher	Contribution
Haleem et al. [156]	Production Planning & Control	Taylor & Francis	To analyze the key factors behind the successful implementation of world-class manufacturing practices using ISM and Interpretive Ranking Process (IRP).
Venkatesh et al. [157]	Journal of Retailing and Consumer Services	Elsevier	For analysis of supply chain risks in Indian apparel retail chains.
Kumar and Kumar [158]	International Journal of Logistics Systems and Management	Inderscience	Used ISM for modeling hospital inventory management

2.6.4. Fuzzy ANP

Fuzzy analytic network process (FANP) is a multi-criteria decision-making technique that is used to rank the criteria or alternatives by using expert's opinions in the form of linguistic scales. These linguistic scales are further converted into numerical values and then the final weights of the factors are calculated to rank or prioritize the factors.

Using same search criteria on 'Web of Science', 485 papers are extracted on FANP research, and the results of the SciMAT analysis are shown in Figure 2.26 & 2.27.

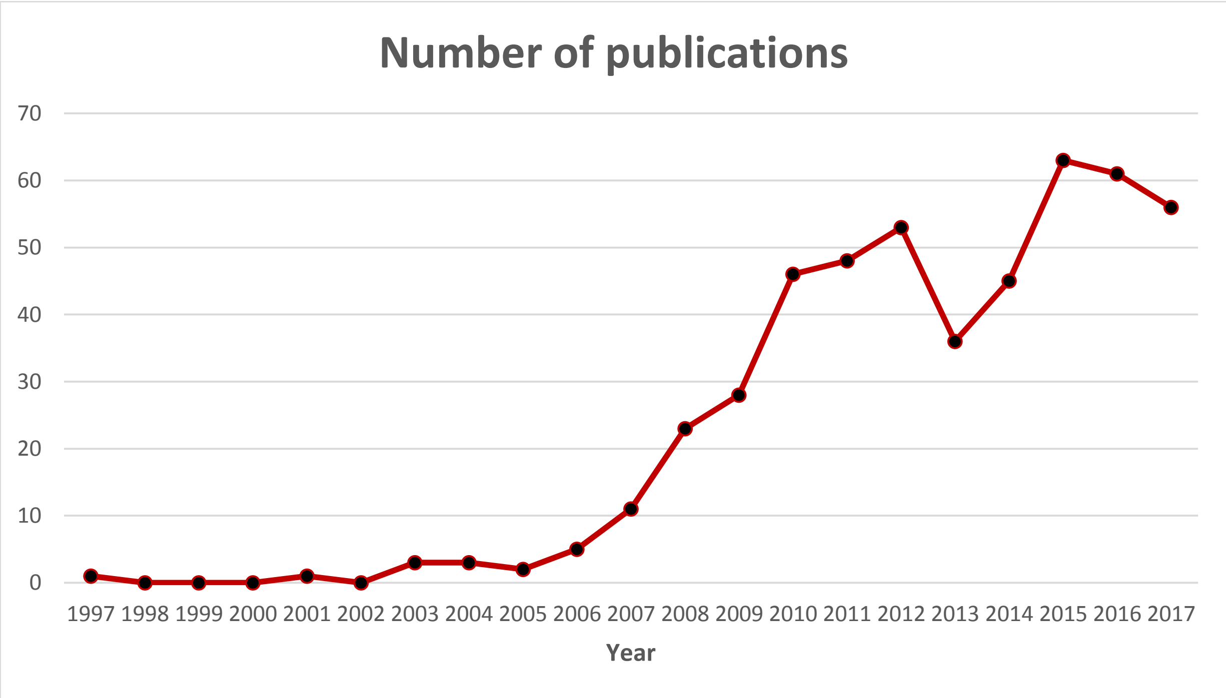


Figure 2.26: Publication of fuzzy ANP research per year (485 papers: 1997-2017).

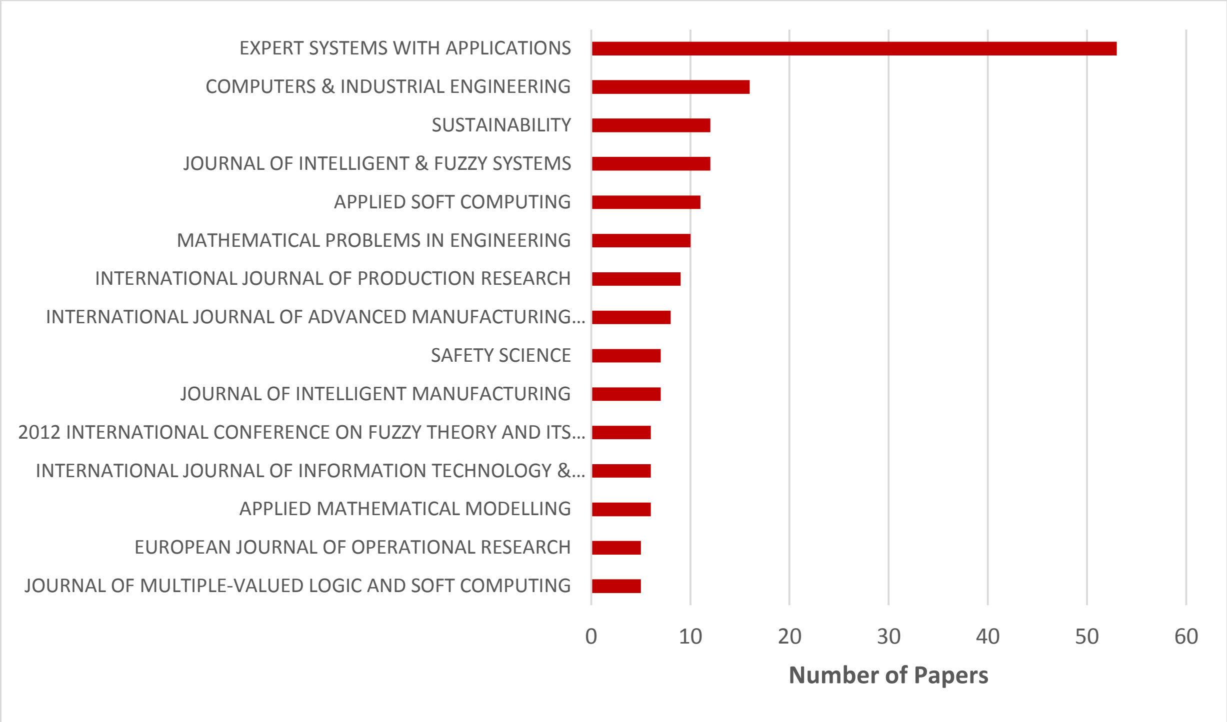


Figure 2.27: Distribution of fuzzy ANP publications based on the top fifteen journals (485 papers: 1997-2017).

Results of bibliographic mapping with the most popular keywords in FANP research are shown in Figure 2.28 and Table 2.18, while the review of the important literature has been presented in Table 2.19.

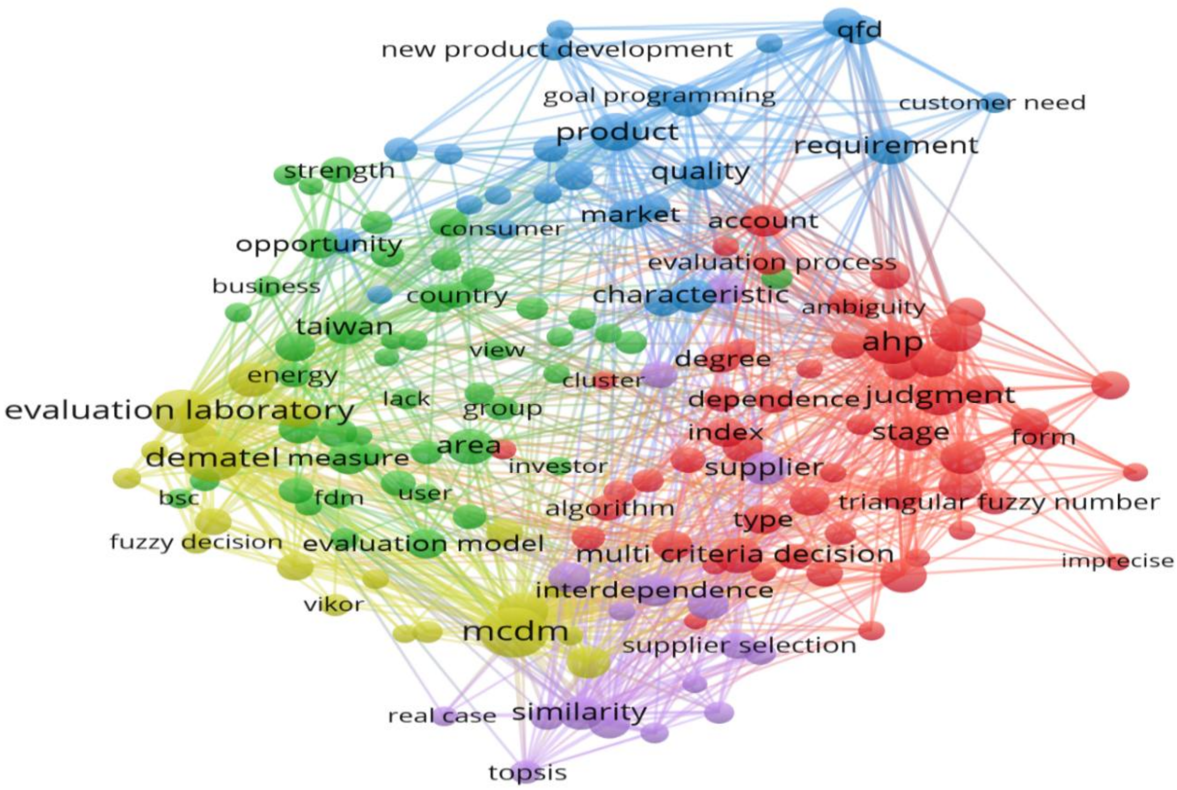


Figure 2.28: Bibliographic mapping of fuzzy ANP research.

Table 2.18: Top fifteen popular keywords in FANP research.

Terms	Occurrences
mcdm	80
dematel	65
evaluation laboratory	61
ahp	59
judgment	48
product	46
matrix	46
multi-criteria decision making	42
area	41
requirement	40
multi-criteria decision	40
decision-making trial	38
preferences	38
vagueness	38
quality	37

Remark: Results of the bibliographic mapping reveal that five clusters are identified and in the list of most popular keywords, the keywords 'supply chain with occurrence 27', 'supply chain management with occurrence 23', 'government with occurrence 20', 'sustainability with occurrence 12', and 'sustainable development with occurrence 12', are less popular because of low occurrence, whereas, important keywords of this research such as 'vaccine', vaccine supply chain', 'healthcare', 'immunization' are missing among the popular keywords.

Table 2.19: Review of selected papers on FANP research.

Author/s	Journal name	Publisher	Contribution
Vinodh et al. [159]	Expert Systems with Applications	Elsevier	Fuzzy ANP has been used for supplier selection in a manufacturing organization.
Buyukozkan and Cifci [160]	Production Planning & Control	Taylor & Francis	For the evaluation of green supply chain management practices.
Mungle et al. [161]	Applications of Multi-Criteria and Game Theory Approaches	Springer	Developed a multi-objective optimization approach to product-planning in quality function deployment incorporated with fuzzy-ANP.

Author/s	Journal name	Publisher	Contribution
Valmohammadi and Dashti [162]	Information & Management	Elsevier	Integrated ISM & FANP has been used for identification and prioritization of barriers for e-commerce implementation.
Govindan et al. [163]	Journal of Cleaner Production	Elsevier	FANP has been used for barrier evaluation in Indian automotive industry.
Kang et al. [164]	Journal of Intelligent Manufacturing	Springer	A fuzzy model has been proposed that can be used by IC packaging companies for its supplier selection.
Ayag [165]	International Journal of Business and Systems Research	Inderscience	To evaluate computer simulation packages.
Uygun et al. [166]			An integrated model using FANP has been presented for evaluation and selection of outsourcing providers for a telecommunication company.
Bhattacharya et al. [167]	Production Planning & Control	Taylor & Francis	Green supply chain performance measurement using a fuzzy ANP-based balanced scorecard.

2.6.5. Analytic hierarchy process (AHP)

Analytic network process (AHP) is another multi-criteria decision-making technique that is used to rank or weight the criteria by using expert's opinions.

In AHP research, 1000 articles are extracted and the results of the SciMAT analysis are shown in Figure 2.29 and 2.30.

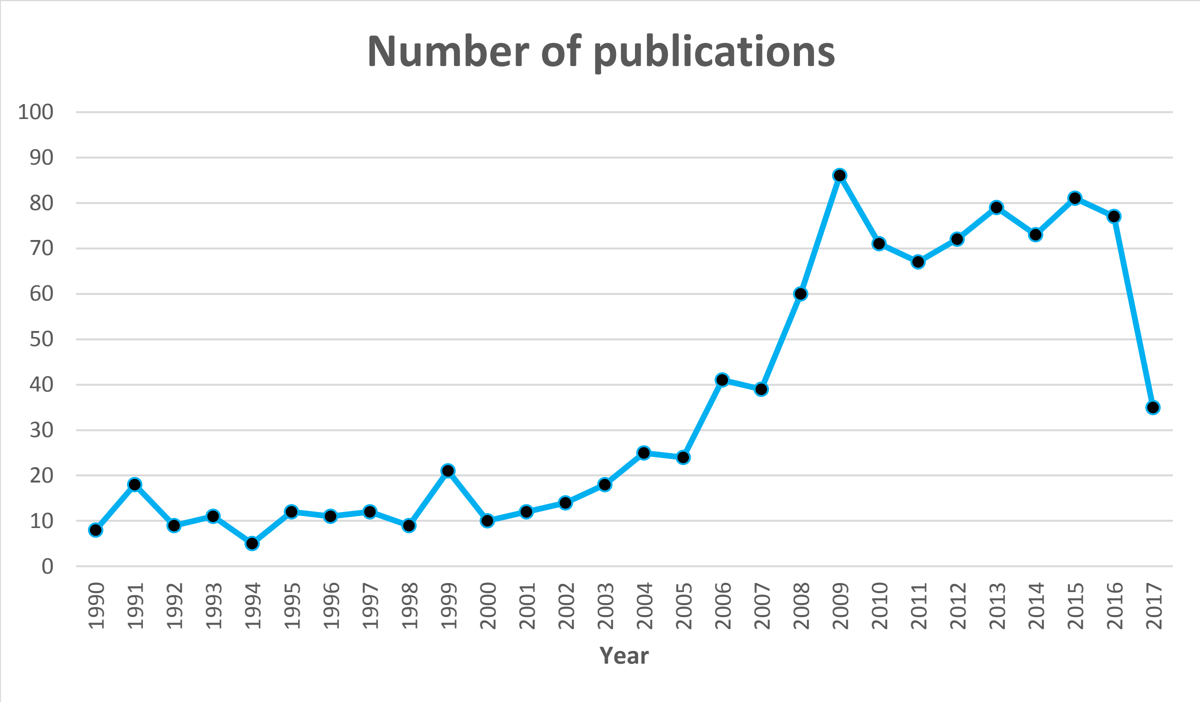


Figure 2.29: Publication of AHP research per year (1000 papers: 1990-2017).

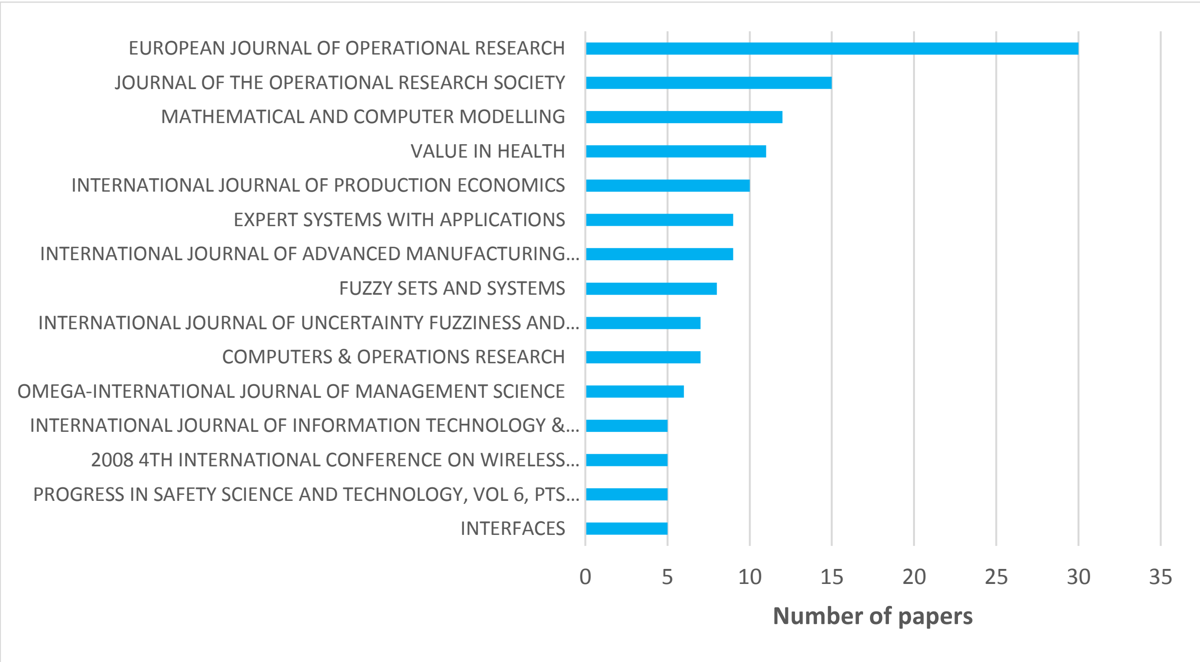


Figure 2.30: Distribution of AHP publications based on the top fifteen journals (1000 papers: 1990-2017).

Results of VOSviewer for bibliographic mapping with the most popular keywords in AHP research are shown in Figure 2.31 and Table 2.20.

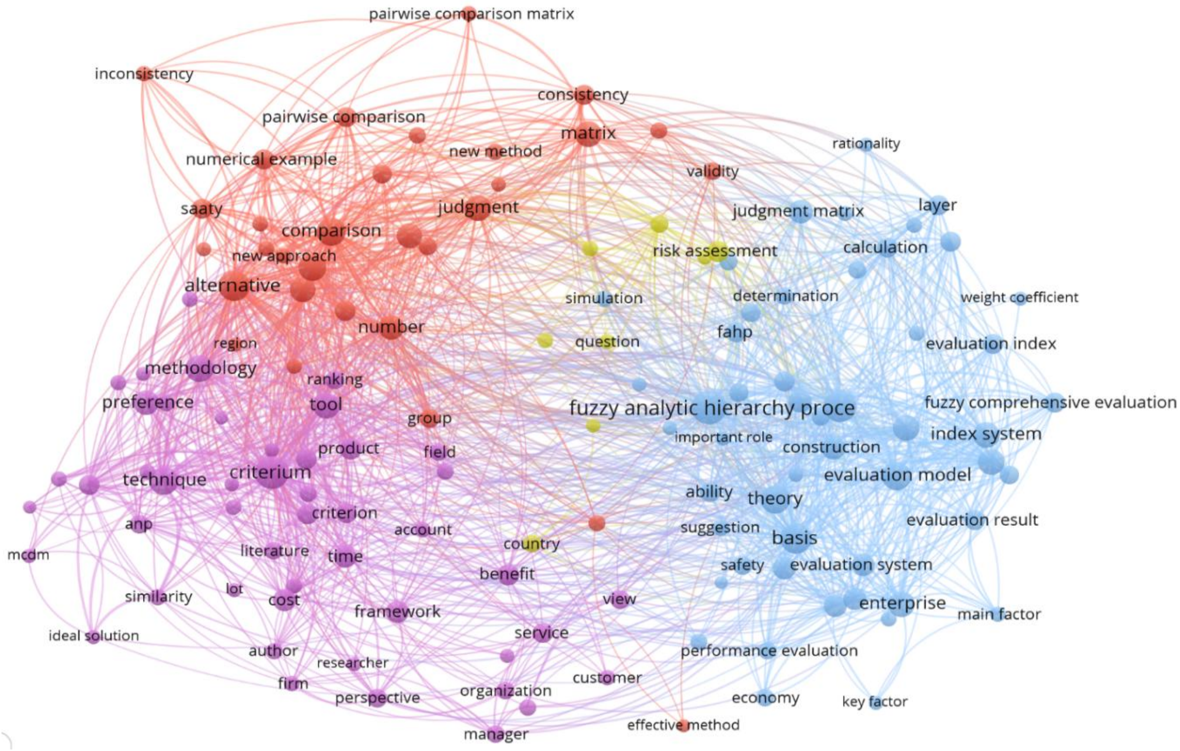


Figure 2.31: Bibliographic mapping of AHP research.

Table 2.20: Top fifteen popular keywords in AHP research.

Terms	Occurrences
fuzzy analytic hierarchy process	120
criterium	117
index	106
alternative	91
basis	90
technique	75
evaluation model	72
theory	72
comparison	72
methodology	67
decision maker	67
evaluation index system	63
index system	62
evaluation method	62
matrix	60

Remark: Results of the bibliographic mapping reveal that four clusters are identified and in the list of the most popular keywords, all important keywords of this research such as 'vaccine', vaccine supply chain', 'immunization', 'performance' etc. are missing.

The review of the selected papers related to AHP research is discussed in Table 2.21.

Table 2.21: Review of selected papers on AHP research.

Author/s	Journal name	Publisher	Contribution
Kumru and Kumru [168]	Journal of Advanced Transportation	Wiley	Proposed a framework for selecting the mode of transport for a logistics company.
Singh and Kulkarni [169]	International Journal of Industrial Engineering & Technology	Trans Stellar	The present paper has explored to identify the critical equipment's of a coal-based power plant and rank them accordingly using AHP.
Bhatti et al. [170]	International Journal of Business Performance and Supply Chain Modelling	Inderscience	Used an integrated AHP and Data Envelopment Analysis model for the selection of third-party service providers by global lead logistics providers.
Azam et al. [171]	International Journal of Reliability and Safety	Inderscience	For the reliability allocation for control and monitoring subsystem.
Morgan [172]	Marine Policy	Elsevier	Used AHP for the investigation of constraints upon fisheries diversification.
Singh et al. [173]	International Journal of Procurement Management	Inderscience	An AHP based model for prioritization of flexibility enablers in steel making.
Luthra et al. [174]	International Journal of Production Economics	Elsevier	To evaluate barriers to adopting sustainable consumption and production initiatives in a supply chain
Daim et al. [175]	Journal of Manufacturing Technology Management	Emerald	To present a decision model for selecting a third-party logistics (3PL), provider
Singh et al. [176]	Journal of Modelling in Management	Emerald	For third-party service provider selection in lead logistics provider environments
Sreekumar and Mahapatra [177]	African Journal of Business Management	Academic Journals	A fuzzy multi-criteria decision-making approach for supplier selection in supply chain management

2.6.6. Complex proportional assessment of alternatives with grey relations (COPRAS-G)

Decision analysis is concerned with the situation when a decision-maker has to choose among several alternatives considering a particular set of evaluation criteria. For this reason, the COPRAS-G method can be applied.

In order to extract articles, two keywords 'COPRAS and COPRAS-G' are performed on Web of Science, and based on the search, 111 papers are extracted covering a time-period of 2006-2017. The similar steps for plotting SciMAT and VOSviewer results are used. The results of the SciMAT analysis are shown in Figure 2.32 & 2.33.

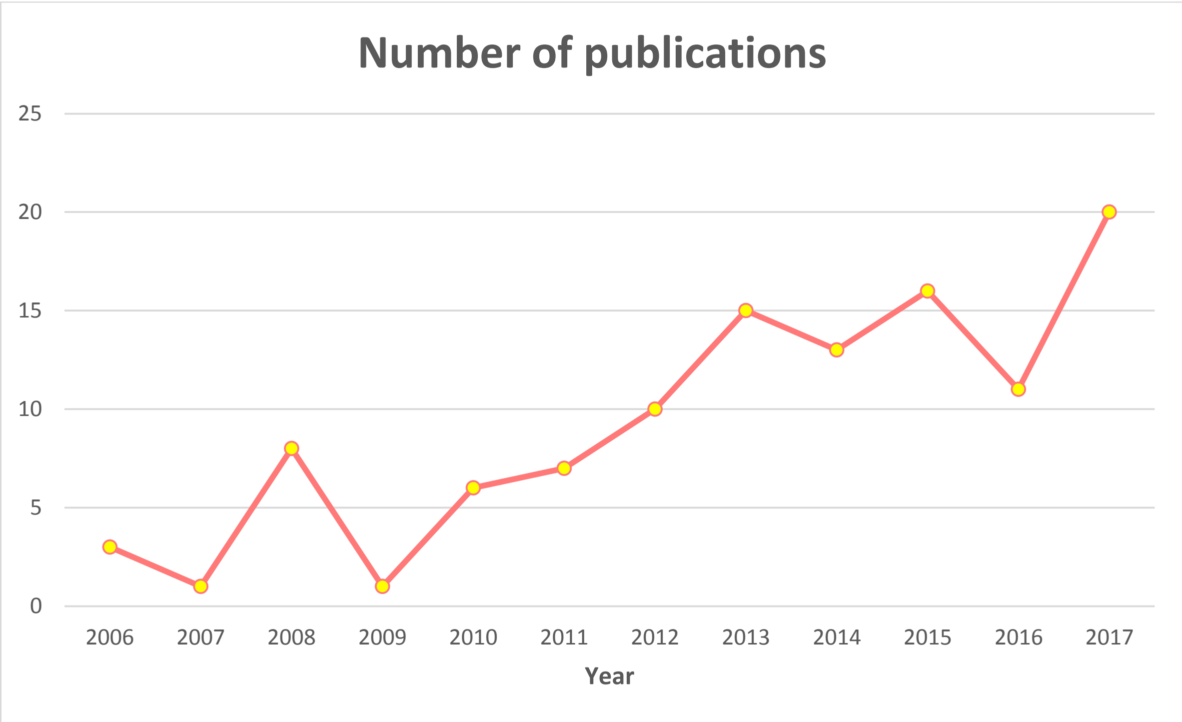


Figure 2.32: Publication of COPRAS and COPRAS-G research per year (111 papers: 2006-2017).

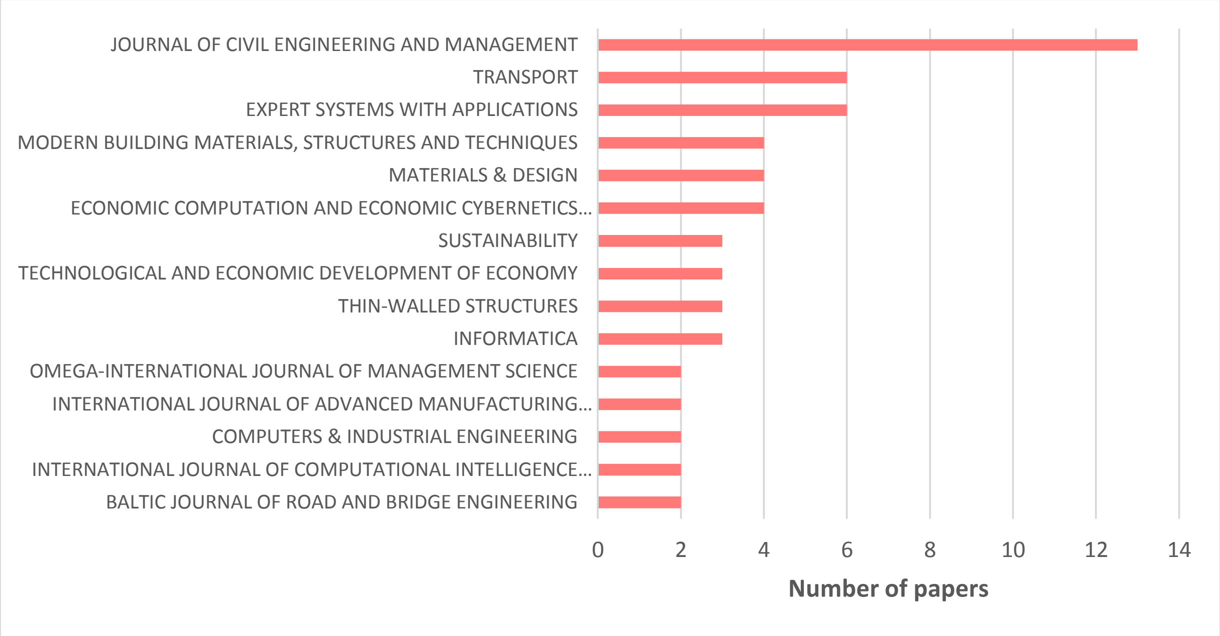


Figure 2.33: Distribution of COPRAS and COPRAS-G publications based on the top fifteen journals (111 papers: 2006-2017).

Results of bibliographic mapping with the most popular keywords in COPRAS and COPRAS-G research are shown in Figure 2.34 and Table 2.22.

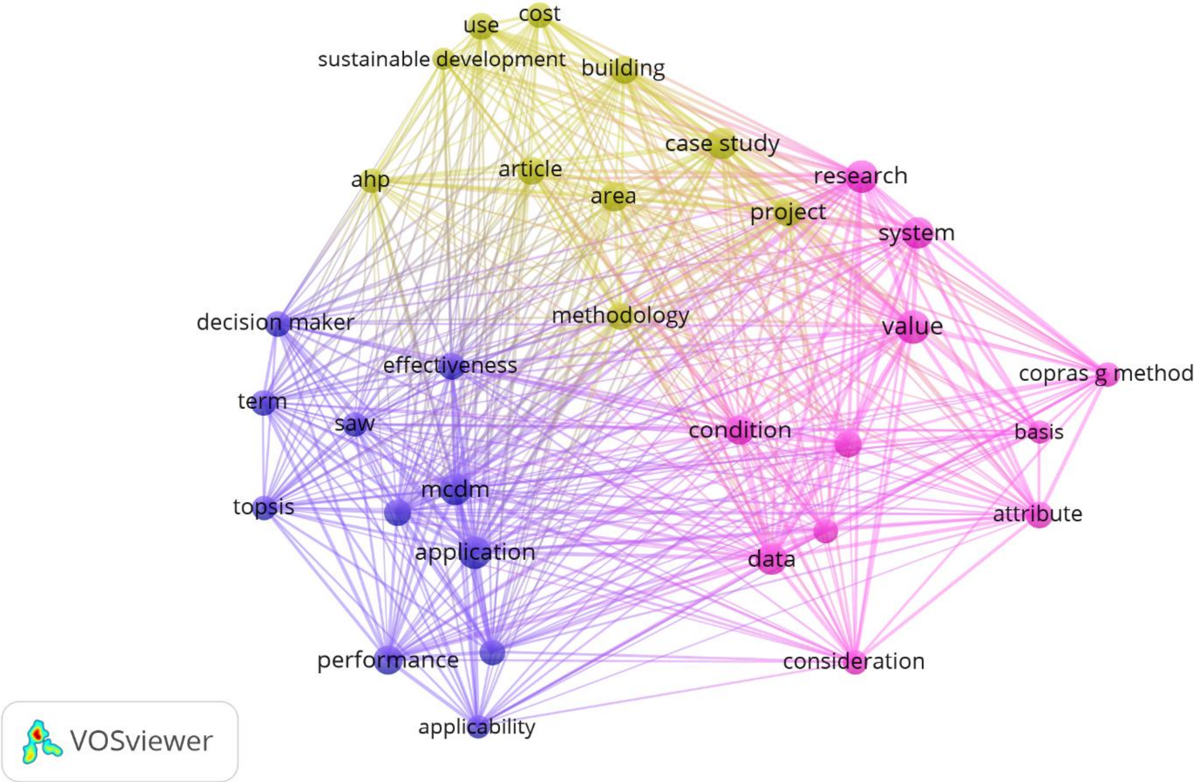


Figure 2.34: Bibliographic mapping of COPRAS and COPRAS-G research.

Table 2.22: Top fifteen popular keywords in COPRAS and COPRAS-G research.

Terms	Occurrences
value	29
application	27
research	27
system	25
mcdm	25
data	25
case study	23
performance	20
condition	20
project	20
area	19
article	18
building	17
attribute	16
mcdm method	16

***Remark:** Results of the bibliographic mapping reveal that three clusters are identified, and in the list of the most popular keywords, all important keywords of this research such as 'vaccine', vaccine supply chain', 'immunization', 'performance' etc. are missing, except' sustainable development with occurrence of 10.*

Table 2.23 discusses the review of the selected papers related to COPRAS-G research.

Table 2.23: Review of selected papers on COPRAS and COPRAS-G research.

Author/s	Journal name	Publisher	Contribution
Tavana et al. [178]	Expert Systems with Applications	Elsevier	A novel hybrid method is proposed for social media platform selection.
Ghorabaee et al. [179]	The International Journal of Advanced Manufacturing Technology	Springer	Multiple criteria group decision-making for supplier selection
Ecer [180]	Technological and Economic Development of Economy	Taylor & Francis	For banking websites quality evaluation.
Liou et al. [181]	International Journal of Production Research	Taylor & Francis	For improving and selecting suppliers in green supply chain management.

Author/s	Journal name	Publisher	Contribution
Zolfani et al. [182]	Technological and Economic Development of Economy	Taylor & Francis	A hybrid model using AHP and COPRAS-G is used for selecting a company supplier in Iran.
Chatterjee and Chakraborty [183]	International Journal of Materials and Structural Integrity	Inderscience	For the material selection problem.
Adhikary et al. [184]	International Journal of Quality & Reliability Management	Emerald	For multi-criteria failure mode, effects and criticality analysis in coal-fired thermal power plants.

2.6.7. Fuzzy analytic hierarchy process (FAHP)

Fuzzy analytic hierarchy process (FAHP) is an extension of the AHP method, where the concept of the fuzzy set theory is applied to improve the results for better decision-making.

Further, similar steps for plotting SciMAT and VOSviewer results are used with 1000 papers extracted from 'Web of Science'. The results of the SciMAT analysis are shown in Figure 2.35 & 2.36.

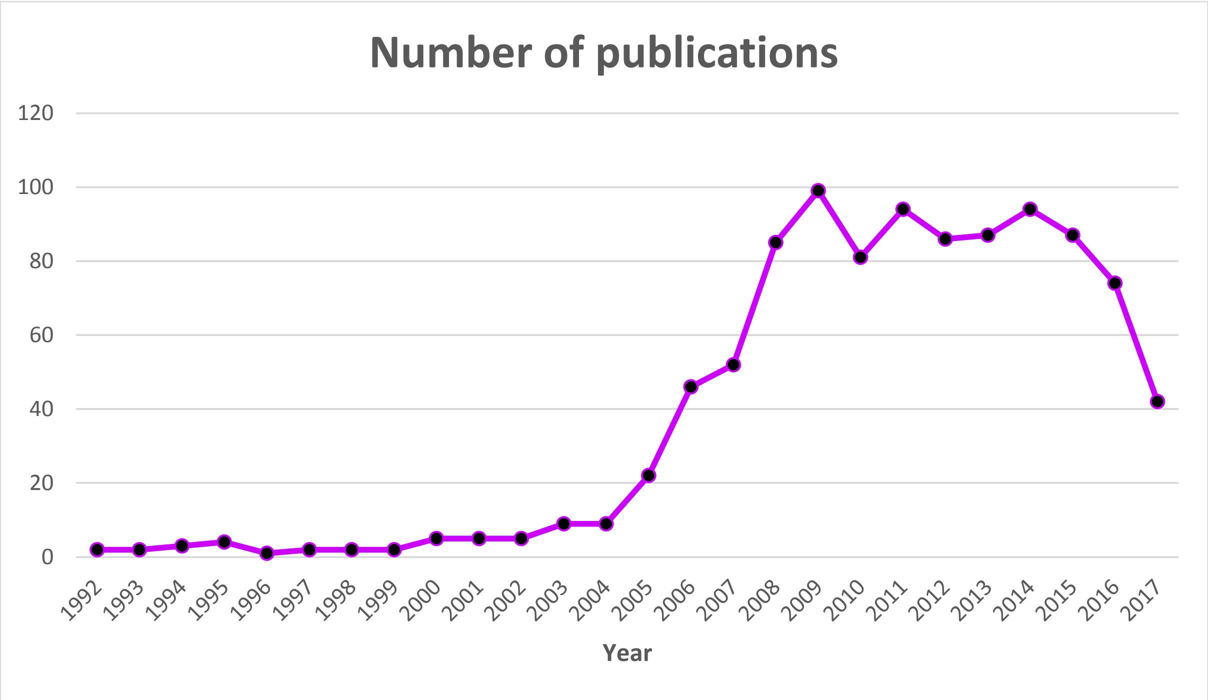


Figure 2.35: Publication of FAHP research per year (1000 papers: 1992-2017).

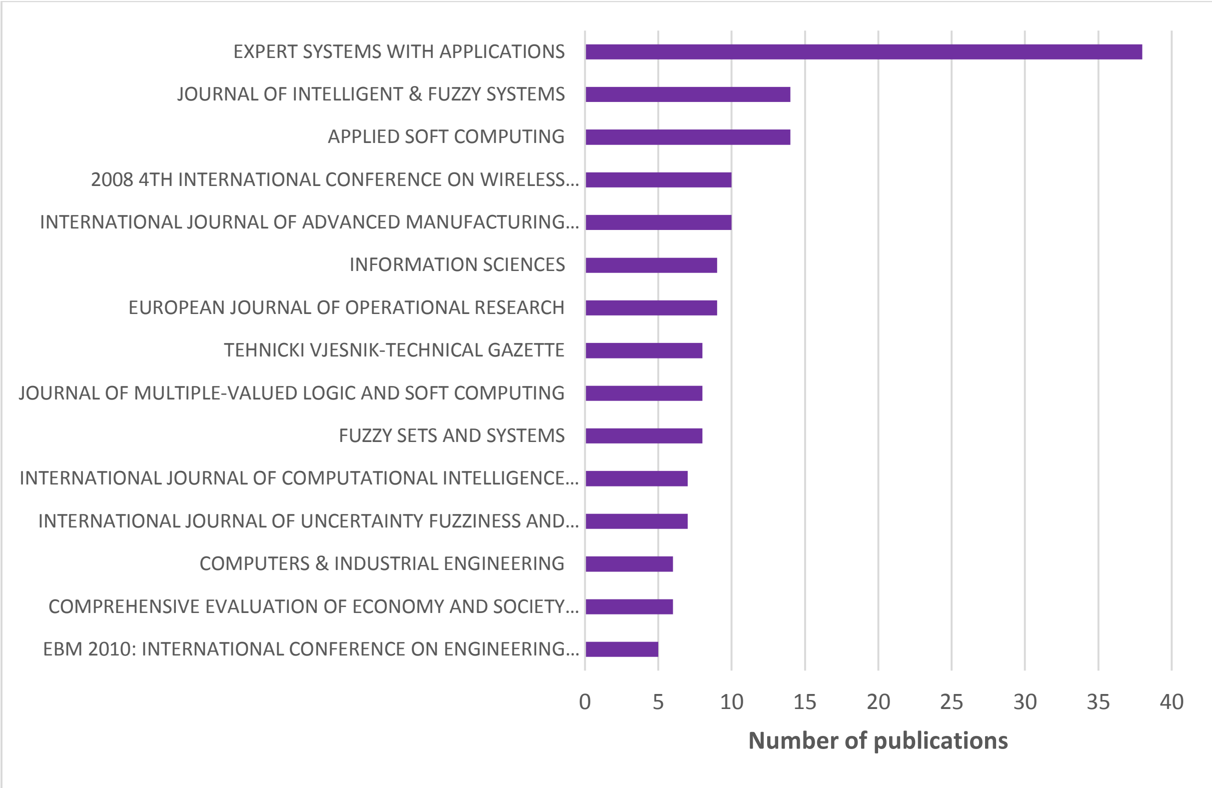


Figure 2.36: Distribution of FAHP publications based on the top fifteen journals (1000 papers: 1992-2017).

Results of bibliographic mapping with the most popular keywords in FAHP research are shown in Figure 2.37 and Table 2.24.

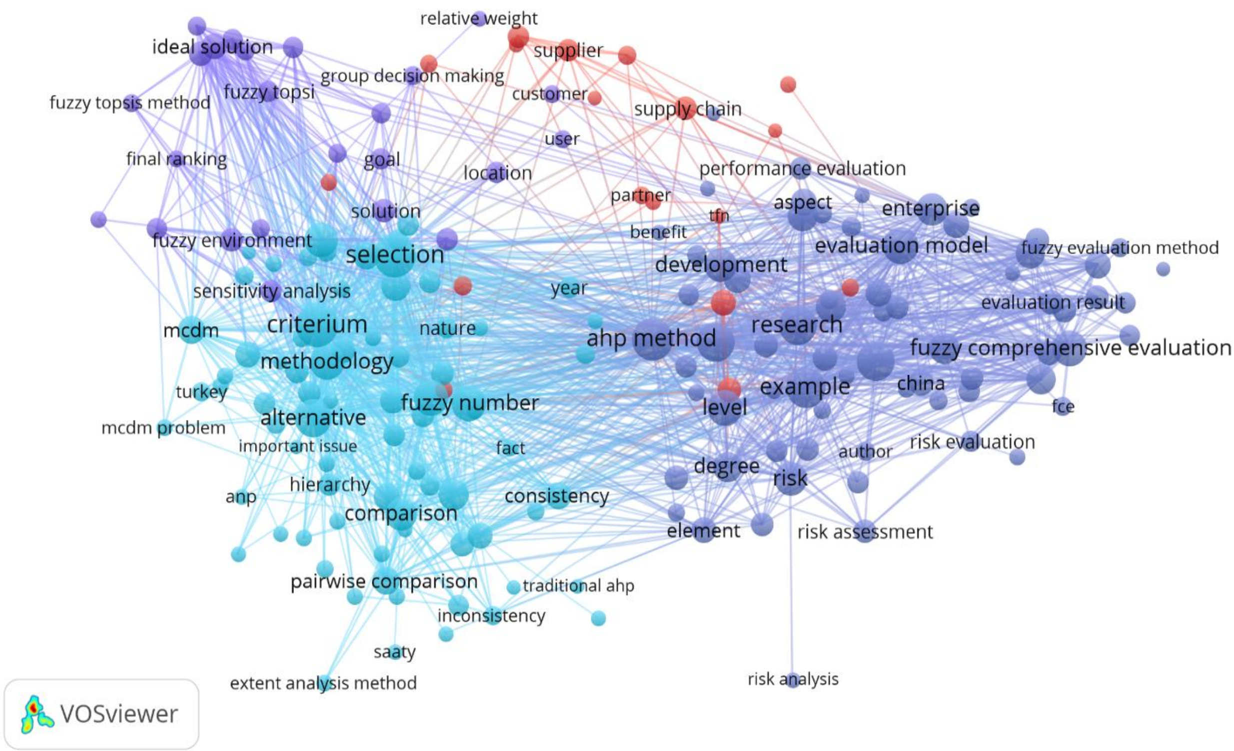


Figure 2.37: Bibliographic mapping of FAHP research.

Table 2.24: Top fifteen popular keywords in FAHP research.

Terms	Occurrences
criterium	186
selection	181
ahp method	174
example	150
research	144
theory	144
index	137
alternative	129
evaluation model	114
level	113
fuzzy comprehensive evaluation	112
fuzzy number	111
decision maker	109
methodology	108
technique	102

Remark: Results of the bibliographic mapping reveal that four clusters are identified and in the list of most popular keywords, the keywords 'supply chain with occurrence 37', 'supply chain management with occurrence 22', 'sustainable development with occurrence 11', are less popular because of low occurrence, whereas, important keywords of this research such as 'vaccine', vaccine supply chain', 'healthcare', 'immunization' are missing among the most popular keywords.

The review of the selected papers related to FAHP research is discussed in Table 2.25.

Table 2.25: Review of selected papers on FAHP research.

Author/s	Journal name	Publisher	Contribution
Nieto-Morote et al. [185]	International Journal of Energy Research	Wiley	For a selection of trigeneration systems that are suitable for small-scale operations.
Zhang et al. [186]	Computer-Aided Civil and Infrastructure Engineering	Wiley	Applied fuzzy AHP synthetic evaluation models for the health monitoring of shield tunnels.
Chan et al. [187]	International Journal of Production Research	Taylor & Francis	Global supplier selection using the fuzzy-AHP approach.
Boutkhoum et al. [188]	International Journal of System Assurance Engineering and Management	Springer	A decision-making approach is presented based on FAHP and FTOPSIS methodology for selecting the appropriate cloud solution to manage big data projects.

Author/s	Journal name	Publisher	Contribution
Bhatti et al. [189]	Enterprise Information Systems and Implementing IT Infrastructures: Challenges and Issues	IGI Global	For 3PL Selection in lead logistics provider Scenarios
Khodaei et al. [190]	Advanced Materials Research	Trans Tech	For recycler Selection using fuzzy AHP by Considering Sustainability
Arsovski et al. [191]	Mathematical Problems in Engineering	Hindawi	For the selection of the best location for parking lots using fuzzy AHP and Hurwitz methods.
Shukla and Agarwal [192]	Production & Manufacturing Research	Taylor & Francis	Used an integrated approach of FAHP and FTOPSIS (Fuzzy Technique for Order of Preference by Similarity to Ideal Solution) in modeling supply chain coordination
Besikci et al.,[193]	Ocean Engineering	Elsevier	Application of fuzzy-AHP to ship operational energy efficiency measures.
Shukla et al. [194]	Production & Manufacturing Research	Taylor & Francis	Developed an integrated approach of FAHP and FTOPSIS in the modeling of supply chain coordination.
Patil and Kant [195]	Expert Systems with Applications	Elsevier	Presented a framework using hybrid FAHP & FTOPSIS for ranking the solutions of knowledge management adoption in the supply chain to overcome its barriers.

2.6.8. Fuzzy Multi-Objective Optimization by Ratio Analysis (FMOORA)

The fuzzy MOORA, which is an MCDM method was developed by Brauers and Zavadskas in 2006 for the analysis of complex alternatives [196].

Similar steps are used for science mapping analysis and the results of the SciMAT analysis using 1000 papers are shown in Figure 2.38 & 2.39.

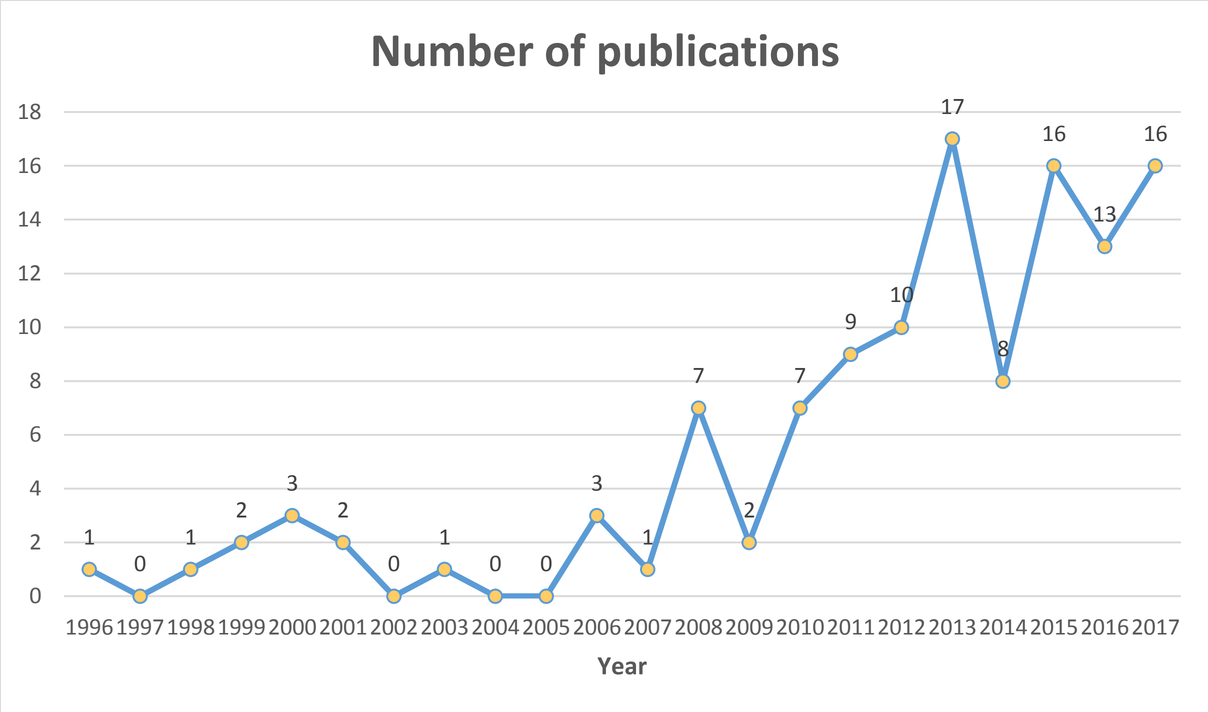


Figure 2.38: Publication of FMOORA research per year (1000 papers: 1996-2017).

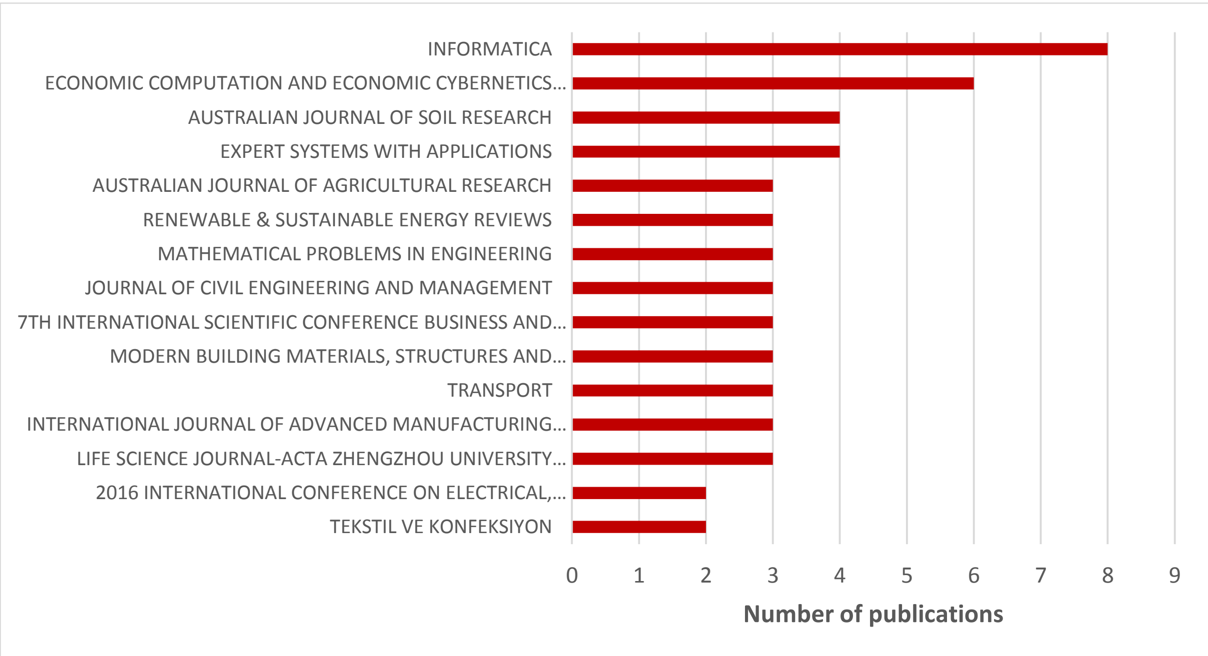


Figure 2.39: Distribution of FMOORA publications based on the top fifteen journals (1000 papers: 1990-2017).

Results of bibliographic mapping with the most popular keywords in FMOORA research are shown in Figure 2.40 and Table 2.26.

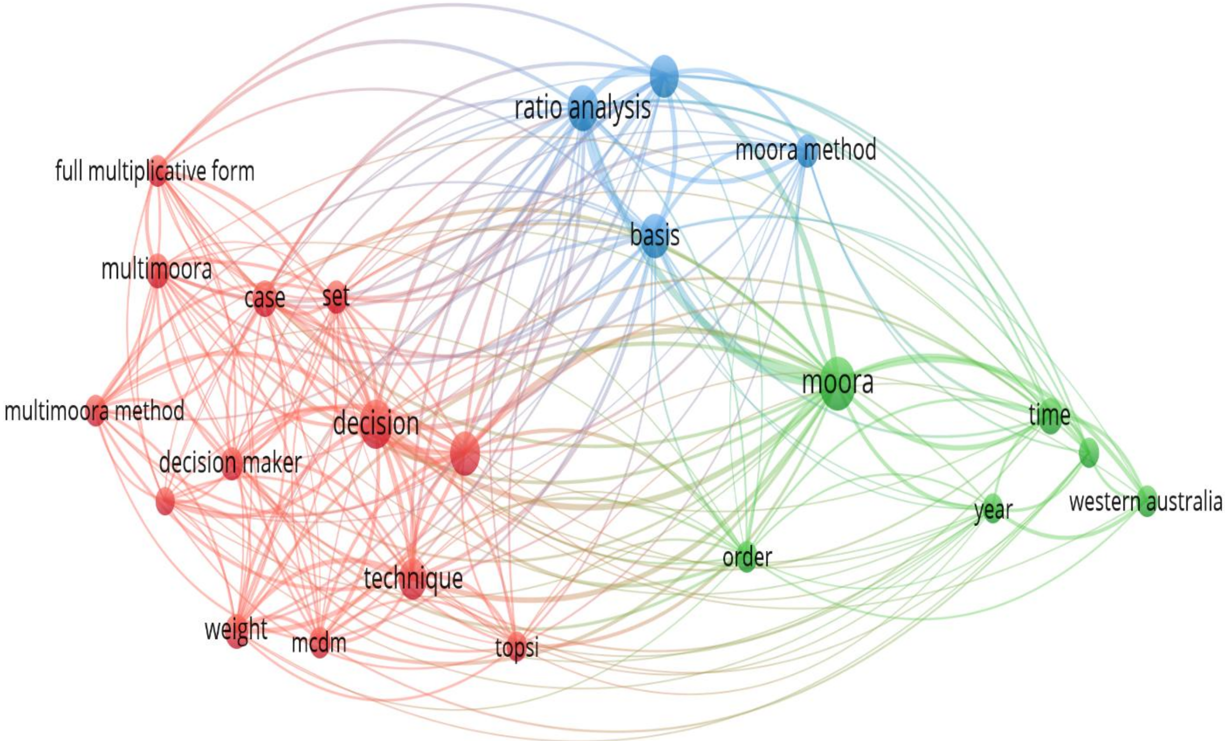


Figure 2.40: Bibliographic mapping of FMOORA research.

Table 2.26: Top fifteen popular keywords in FMOORA research.

Terms	Occurrences
moora	59
ratio	44
decision analysis	37
criterium	35
basis	34
multi objective optimization	32
technique	28
time	20
case	20
multimoora	18
weight	18
decision maker	17
moora method	16
set	16
multimoora method	15

Remark:* *Results of the bibliographic mapping reveal that three clusters are identified and in the list of the most popular keywords, all the important keywords used in this research such as 'vaccine', vaccine supply chain', 'immunization', 'performance' etc. are missing.

Table 2.27 presents, the review of the selected papers on FMOORA research.

Table 2.27: Review of selected papers on FMOORA research.

Author/s	**Journal name**	**Publisher**	**Contribution**
Akkaya et al. [197]	Expert Systems With Applications	Elsevier	An integrated fuzzy AHP and fuzzy MOORA framework are presented to solve the problem of industrial engineering sector choosing.
Matawale et al. [198]	Benchmarking: An International Journal	Emerald	For the problem of supplier selection.
Karande and Chakraborty [199]	Decision Science Letters	Growing Science	For the correct choice of an enterprise resource planning system.
Archana and Sujatha [200]	International Journal of Computer Applications	Foundation of Computer Science	Applied fuzzy MOORA and gray relational analysis method for a wireless network problem.
Sreekumar and Mahapatra [177]	Grey Systems: Theory and Application	Emerald	Robot selection based on the grey-MULTIMOORA approach
Mavi et al. [201]	The International Journal of Advanced Manufacturing Technology	Springer	Used an integrated fuzzy step-wise weight assessment ratio analysis (FSWARA) and FMOORA for the sustainable third-party reverse logistics provider selection within the plastic industry.
Can and Delice [202]	Soft Computing	Springer	A task-based fuzzy integrated MCDM approach for shopping mall selection considering universal design criteria.
Sahu et al. [203]	Grey Systems: Theory and Application	Emerald	Supply chain performance benchmarking using grey-MOORA approach: An empirical research

2.6.9. Exploratory factor analysis (EFA)

In multivariate statistics, exploratory factor analysis (EFA) is a statistical method used to uncover the underlying structure of a relatively large set of variables. EFA is a technique within factor analysis whose overarching goal is to identify the underlying relationships between measured variables. It is commonly used by researchers when developing a scale (a scale is a collection of questions used to measure a particular research topic) and serves to identify a set of latent constructs underlying a battery of measured variables.

To perform a literature review on EFA, 1000 papers between time-period 1990-2017 are extracted from 'Web of Science', and the results are plotted using SciMAT and VOSviewer. The results of the SciMAT analysis are shown in Figure 2.41 & 2.42.

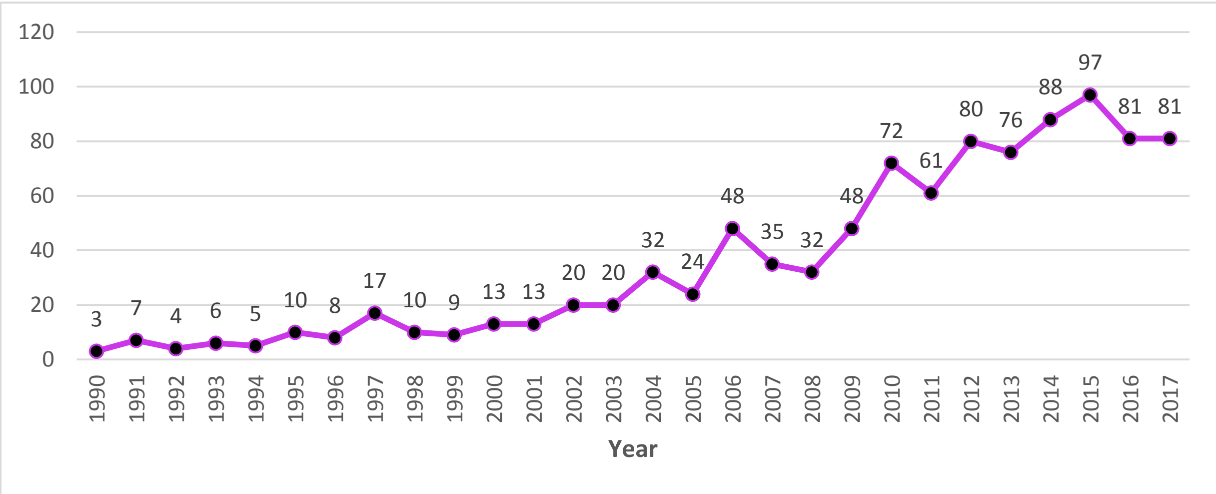


Figure 2.41: Publication of EFA research per year (1000 papers: 1990-2017).

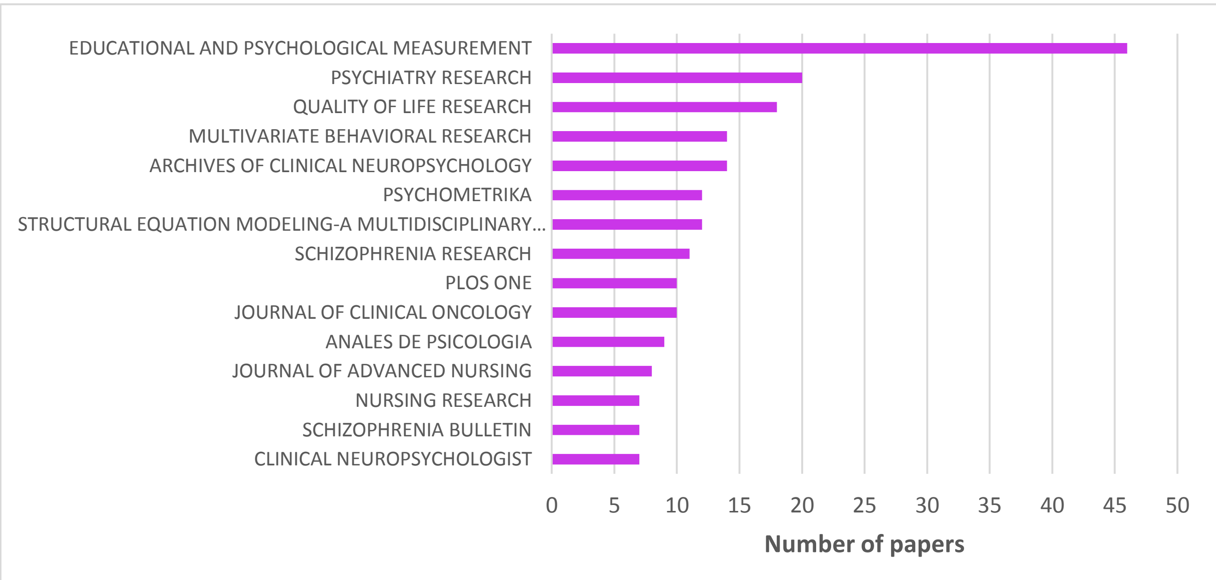


Figure 2.42: Distribution of EFA publications based on the top fifteen journals (1000 papers: 1990-2017).

Results of bibliographic mapping with the most popular keywords in EFA research are shown in Figure 2.43 and Table 2.28.

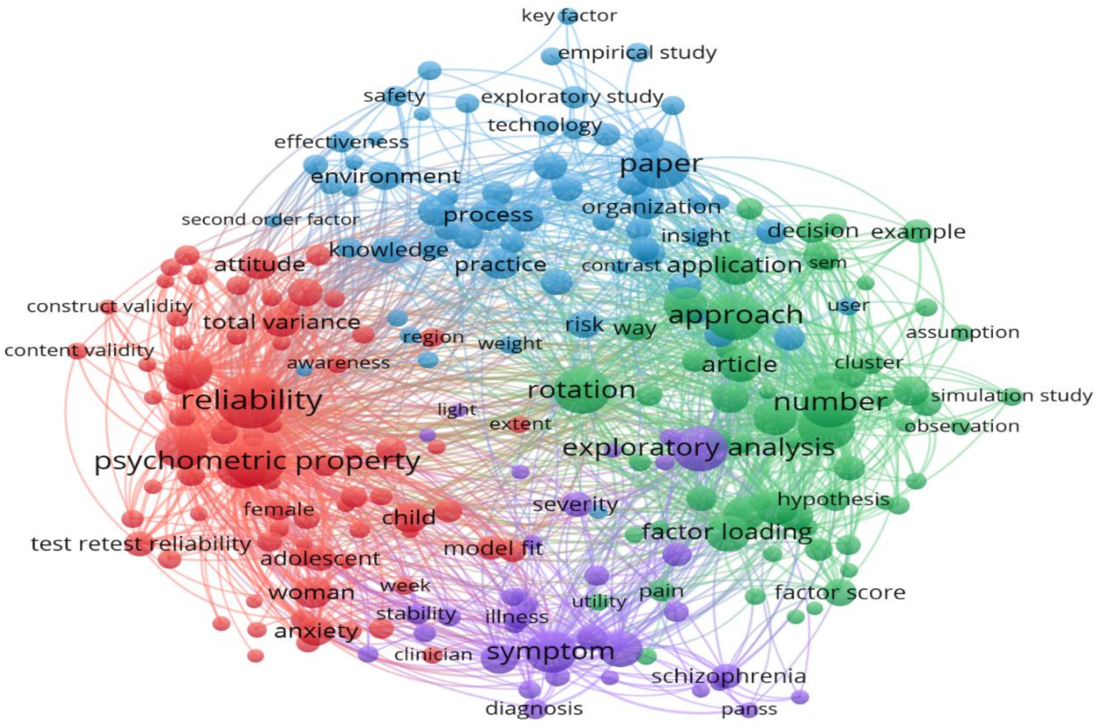


Figure 2.43: Bibliographic mapping of EFA research.

Table 2.28: Top fifteen popular keywords in EFA research.

Terms	Occurrences
reliability	153
psychometric property	116
paper	114
number	113
approach	110
variable	108
rotation	104
exploratory analysis	101
internal consistency	93
symptom	87
alpha	81
cronbach	78
factor loading	66
disorder	64
application	63

Remark: Results of the bibliographic mapping reveal that four clusters are identified and in the list of the most popular keywords, all the important keywords used in this research such as 'vaccine', vaccine supply chain', 'immunization', 'performance' etc. are missing

The review of the selected papers related to EFA research is discussed in Table 2.29.

Table 2.29: Review of selected papers on EFA research.

Author/s	Journal name	Publisher	Contribution
Ballard et al. [204]	Journal of Affective Disorders	Elsevier	For commonly used depression rating scales.
Kim et al. [205]	Environmental Modelling and Software	Elsevier	For the assessment of water quality variation of a monitoring network
Walton and Kim [206]	Journal of Social Service Research	Taylor & Francis	For validating a Behavioral Health Instrument for Adults.
Tejpal et al. [207]	Industrial Engineering and Engineering Management	IEEE Explore	Factor analysis of rational trust among supply chain partners in Indian industries.
Barendse et al. [208]	Structural Equation Modeling: A Multidisciplinary Journal	Taylor & Francis	To Determine the Dimensionality of Discrete Responses
Dhone and Kamble [209]	International Journal of Logistics Systems and Management	Inderscience	Scale development for supply chain operational performance model in the Indian automobile industry.
Tejpal et al. [210]	Proceedings of the International Conference on Research and Innovations in Mechanical Engineering	Springer	Factor analysis of sourcing flexibility among supply chain partners in Indian industries.
Wiktorowicz [211]	International Journal of Social Economics	Emerald	Proposed the method of measurement of competencies using EFA and the evaluation of the relationship between competencies and economic activity of mature people.

2.6.10. Structural equation modeling (SEM)

Structural equation modeling (SEM) includes a diverse set of mathematical models, computer algorithms, and statistical methods that fit networks of constructs to data. SEM includes confirmatory factor analysis, path analysis, partial least squares path modeling, and latent growth modeling. The concept should not be confused with the related concept of structural models in econometrics, nor with structural models in economics. Structural equation models are often used to assess unobservable 'latent' constructs.

To perform a science mapping on SEM, 1000 papers between time-period 1990-2017 are extracted, and the results of the SciMAT analysis are shown in Figure 2.44 & 2.45.

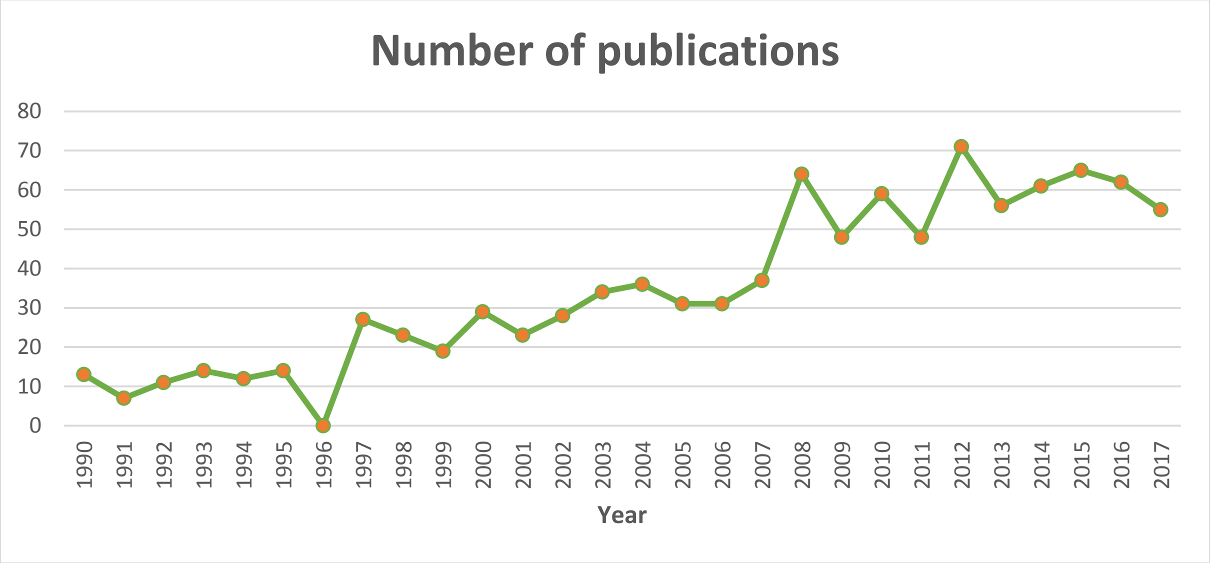


Figure 2.44: Publication of SEM research per year (1000 papers: 1990-2017).

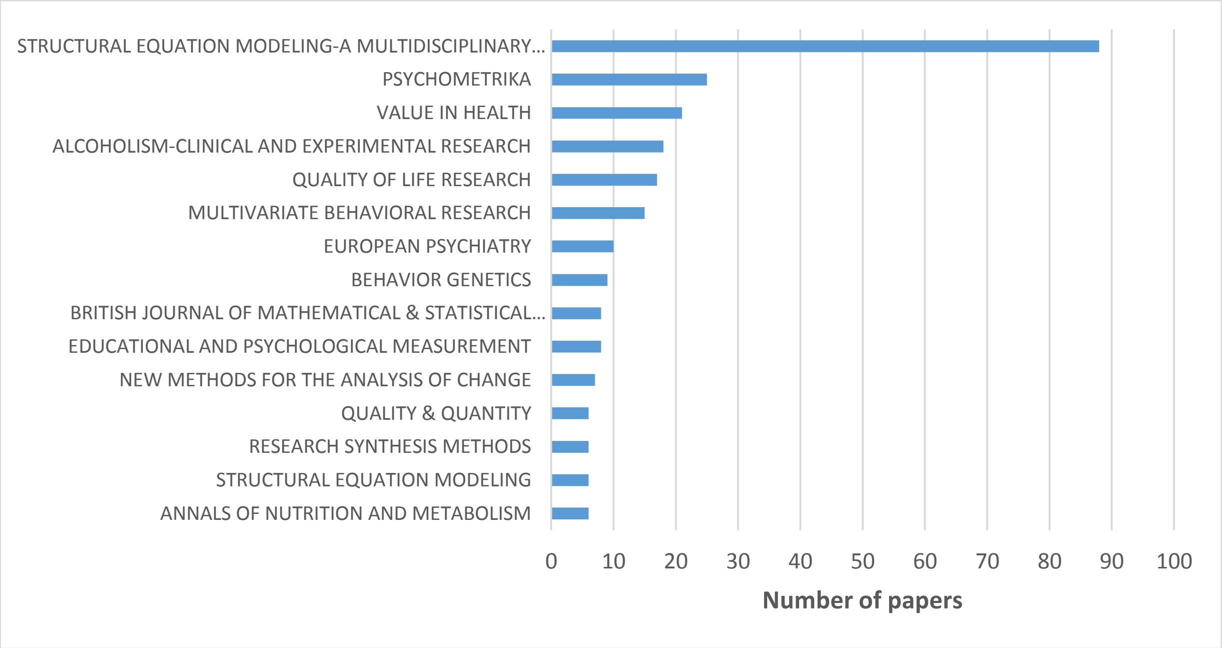


Figure 2.45: Distribution of SEM publications based on the top fifteen journals (1000 papers: 1990-2017).

Results of bibliographic mapping with the most popular keywords in BSC research are shown in Figure 2.46 and Table 2.30.

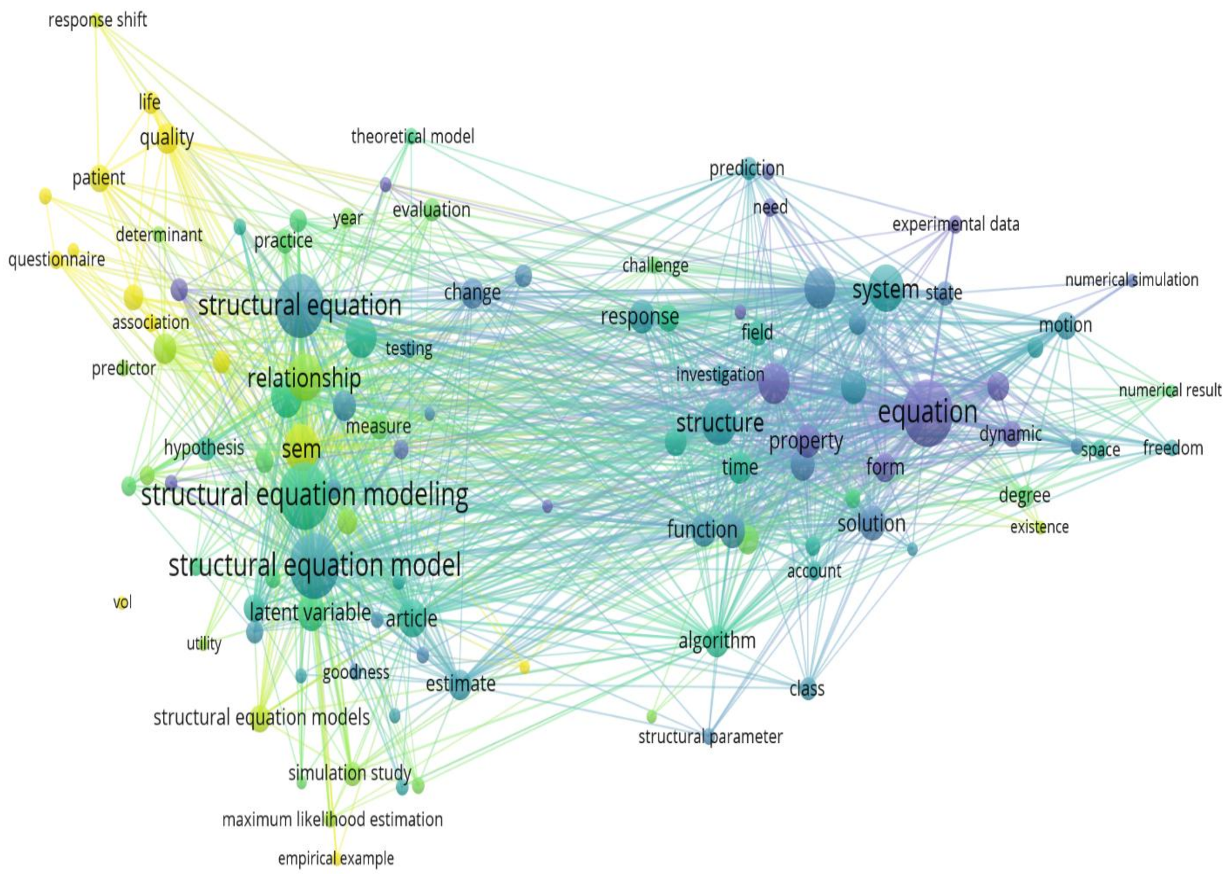


Figure 2.46: Bibliographic mapping of SEM research.

Table 2.30: Top fifteen popular keywords in SEM research.

Terms	Occurrences
equation	227
structural equation modeling	225
structural equation model	217
structural equation	201
system	115
sem	113
structure	113
relationship	112
research	89
factor	89
problem	86
modelling	84
article	76
latent variable	69
solution	64

Remark: Results of the bibliographic mapping reveal that three clusters are identified and in the list of the most popular keywords, all the important keywords used in this research such as 'vaccine', vaccine supply chain', 'immunization', 'performance' etc. are missing.

Table 2.31 discusses the selected papers related to BSC research.

Table 2.31: Review of selected papers on SEM research.

Author/s	Journal name	Publisher	Contribution
Rahman et al. [212]	International Emergency Nursing	Elsevier	Modeling and analysis of psychosocial factors, musculoskeletal disorders and work-related fatigue amongst nurses in Brunei using a structural equation model approach.
Rezai et al. [213]	Journal of Food Products Marketing	Taylor & Francis	For consumer purchase intention toward synthetic functional foods.
Jenatabadi and Ismail [214]	Journal of Air Transport Management	Elsevier	Application of structural equation modeling for estimating airline performance.
Mitchell et al. [215]	Journal of Hospital Infection	Elsevier	To the model number of days from infection to discharge in patients with healthcare-associated urinary tract infections.
Farooq et al. [216]	Journal of Advances in Management Research	Emerald	Application in scale development and the problems faced by researchers in developing the scale using SEM.
Singh et al. [217]	International Journal of Productivity and Quality Management	Inderscience	Applied structural equation modeling in technology innovation model for Indian micro, small & medium enterprises.

2.6.11. Two-way assessment

Two-way assessment methodology that uses the analytic hierarchy process (AHP) as one of the inputs is useful in measuring the overall impact or effectiveness of the attributes, which defines a system or process.

As very limited research has been done in using Two-way assessment for measuring the impact of attributes in any system, therefore, it is not feasible to conduct science mapping analysis on Two-way assessment research. The review of some of the work done in Two-way assessment is shown in Table 2.32.

Table 2.32: Review of selected papers on Two-way assessment research.

Author/s	Journal name	Publisher	Contribution
Mittal et al. [218]	International Journal of Systems Assurance Engineering and Management	Springer	For assessment of barriers to Lean–Green Manufacturing System in India.
Gupta et al. [219]	Information and Software Technology	Elsevier	Two-way assessment is applied for modeling and measuring attributes influencing DevOps implementation in an Indian enterprise.
Gupta et al. [220]	International Journal of Systems Assurance Engineering and Management	Springer	Modeling and measuring code smell in enterprise applications using total interpretive structural modeling (TISM) and two-way assessment.
Tiemessen et al. [221]	Journal of Sound and Vibration	Elsevier	To assess the whole body vibration exposure in an exposed population and to assess other physical work demands in two ways.
Kapur et al. [222]	Proceedings - 2014 3rd International Conference on Reliability, Infocom Technologies and Optimization: Trends and Future Directions, ICRITO 2014	IEEE	For measuring software testing efficiency.

2.7. Gaps identified from the literature review

After performing a thorough literature analysis, research gaps in five broad areas are identified, which are discussed below:

2.7.1. Gaps identified in vaccine and vaccinology research

From the science mapping analysis results, cluster and popular keywords in vaccine and vaccinology research have been identified. By comparing popular keywords presented in Table 2.2, it can be observed that the keyword 'vaccine supply chain' is missing from the popular keywords. This gap may arise because researchers and various countries immunization programs have not given emphasis to the vaccine supply chain. Therefore, further research and consideration of the vaccine supply chain in the field of vaccine and vaccinology research is required.

2.7.2. Gaps identified in vaccine supply chain research

The vaccine supply chain is essential for the success of the child immunization program of any nation. Therefore, it is important that the issues coming in the vaccine supply chain should be removed/eliminated for improving the child immunization programs performance. The review of the existing literature reveals that there was no earlier study, which identifies and analyses the issues in the supply chain of basic vaccines from the stage of procurement until delivery. Though some authors do consider issues and challenges, for example, Kaufmann et al. [7] highlighted issues in the vaccine supply chain of developing countries, Lydon et al. [50] studied vaccine stock-out reasons in 194 countries, Popova and Ibarra [70] discussed some of the barriers to vaccine access in developing countries., Praveena et al. [223] studied vaccine wastage in a district of India, but they are limited to either a single or few issues, without being analyzed by any qualitative or quantitative techniques.

In addition, the science mapping analysis results shown in Table 2.4 indicate that the keyword ‘issue’ is missing from the list of popular keywords, which means that either no research or limited research has been done in the area of vaccine supply chain issues. Also, no such study is available that suggests, using an analysis, how the issues can be corrected to help vaccine supply chain designers to improve vaccine delivery performance.

To fill this gap, hence with the aid of the proposed research framework, the present study identifies and priorities the key issues in the supply chain of basic vaccines of India and other developing countries. Some of the research highlights are such as:

- Identification of issues from field survey and a thorough literature review.
- The finalization and validation of the key issues from the experts through personal interactions and questionnaire response.
- Various frameworks to prioritize and analyze the issues.
- Suggestions to mitigate issues and improve supply chain performance.
- Discussion of the results with the experts and the existing literature.

2.7.3. Gaps identified in performance measurement system research

Performance measurement system (PMS) is required by any organization, whether it is profitable or non-profitable, for measuring and improving the organization's performance. The science mapping analysis results for PMS in Table 2.7 point out that BSC is less popular among the researchers as PMS. Although, some researchers have used a balanced scorecard (BSC) as one of the performance measurement system (PMS) in the context of healthcare organizations, but it has been mostly used for measuring hospitals performance and there is no such study that uses PMS such as BSC for measuring the vaccine supply chain performance of India or other developing/developed countries.

In addition, by looking at the results of science mapping analysis of BSC research in Table 2.8, keywords such as healthcare, immunization, vaccine supply chain are missing from the list of popular keywords that implies that researchers have given less importance to these areas. Shukri and Ramli [83] point out that the majority of work done in BSC in the healthcare sector used case study as their research method and those studies focused on the application and utilization of BSC in healthcare. Another study by Zelman et al. [224], which does a comprehensive review on BSC in healthcare concluded that BSC has been used by researchers in healthcare organizations mainly in the field of hospital systems, hospitals, psychiatric centers, and national health care organizations. Also, by observing the science mapping analysis results of VSC in Table 2.4, the focus of the researchers in the field of vaccine supply chain was mainly in the fields such as cold chain, immunization, disease, storage, dose, etc., but vaccine supply performance measurement has not attracted the researchers and the area needs more research.

To fill this gap, this study highlights key performance indicators (KPIs) of vaccine supply chain from field survey and literature in the four dimension of the balanced scorecard (BSC) as one of the important PMS, in order to help vaccine supply chain decision-makers measure and improve VSCP. Some of the research highlights are such as:

- Identification of KPIs of VSC from field survey and a thorough literature review.
- The finalization and validation of the KPIs from the experts through personal interactions and questionnaire response.
- Various frameworks to analyze the KPIs.
- Discussion of the results with the experts and the existing literature.

2.7.4. Gaps identified in sustainable development research

Any organization moving towards sustainability is not only beneficial to the organization for its economic development but also to society and the environment in various aspects. Therefore, the concept of sustainable development has received greater attention nowadays. The literature review related to sustainable development reveal that many researchers have applied sustainability concept in various profit and non-profit organizations, for example, Cantore et al. [121] to measure the sustainability of industrialization across countries, Ahmed et al. [124] for sustainable wastewater management for underdeveloped communities, Gopal and Thakkar [225] for sustainable supply chain management (SSCM) practices in Indian automobile industry, Govindan [226] for sustainable consumption and production with a focus on the food supply chain, but the topic of sustainability has been neglected by researcher's in the context of immunization programs.

The same results can be also observed through science mapping results in Table 2.10, which indicates that although keywords 'supply chain, 'sustainable supply chain', 'sustainable supply chain management' were considered by the researchers, but they were having very less occurrence number, and keywords 'vaccine', 'healthcare', immunization' etc. are missing from the popular keywords. Therefore, in this study, a set of sustainability practices criteria's (SPC) have been presented along with a framework to achieve sustainability in immunization programs to help UIP India and other developing countries for the sustainable development of child immunization programs. Some of the research highlights are as follows:

- Identification of sustainable practices criteria (SPCs) for VSC from field survey and literature review.
- Finalizing of sustainable key practices criteria SKPCs using well-established methodology.
- A framework to establish a relation between KPIs and SKPCs.
- Discussion of the results with the existing literature.

2.7.5. Gaps identified in research methodologies

Qualitative and quantitative methods or approaches are required at various stages of problem-solving by the decision-makers to arrive at a conclusion and for decision-making. For this reason, various methodologies in the field of Industrial engineering such as ISM, AHP, FANP, SEM, etc. have been developed by the researchers to help decision-makers solve various problems. By looking at the literature of various well-established methodologies, it is observed that these techniques have been applied to various sectors such as automobile, banking, supplier selection, green supply chain management, etc., but no study is available that uses these techniques in the context of vaccine supply chain problems or sustainable development of immunization program. The science mapping analysis results also indicate that the methodologies used in this research are among the less popular keywords in the area of the healthcare sector. Hence, in this research, these approaches have been selected and applied for the analysis purpose.

2.8. Conclusion

This chapter discussed the literature related to the present research work in three broad areas: vaccine supply chain (VSC), performance measurement system (PMS), and sustainable development (SD) concept. Further, the literature of various methodologies adopted in the research has also been discussed. From the literature review, various gaps are reported, which provide basis and direction to open the area of present work and to propose a research framework. The proposed research framework shown in Figure 1.5 has been applied to solve the problem of vaccine supply chain aimed at improving its performance for the sustainable development of the child immunization program. In Chapter 3, the brief description of various methodologies to achieve the research objectives has been discussed.

Chapter 3

DESCRIPTION OF RESEARCH METHODOLOGIES

3.1. Introduction

To achieve the objectives of the work, various methodologies were identified from the literature and are described in this chapter. Using these tools and techniques, various frameworks have been designed to help attain the objectives of each chapter.

The applications of the following qualitative and quantitative techniques have been used in the research work:

1. Delphi technique
2. ISM
3. Fuzzy MICMAC
4. Fuzzy ANP
5. AHP
6. COPRAS-G
7. Fuzzy AHP
8. Fuzzy MOORA
9. EFA
10. SEM
11. Two-way assessment

3.2. Motivation for research methodologies

In any study, the appropriate selection of methodologies plays an important role as it helps the researchers to reach the best solution possible for the identified problem. By doing so, the identified solutions can assist the decision-makers to move in the right direction to improve the system performance. Therefore, the researchers while selecting the research methodologies for their study should give rigorous effort as it affects the quality of decision-making. In this study, the research methodologies have been identified and selected, first, based on the detailed and systematic literature review and second, on their ability to solve qualitative and quantitative problems efficiently and effectively. Many researchers have already used the methodologies selected in this research, and their applications have demonstrated their ability to improve the decision-making process. For instance, studies published in ISM have shown that it is one of the powerful qualitative technique, which can be used by the decision-makers to help improve system performance. The results obtained from various ISM studies as already been used by many organizations and the outcome have shown positive results. Delphi technique has been long used by the researchers to obtain a consensus on any problem when various experts are involved in decision-making. As fuzzy set theory can deal with subjectivity and vagueness in decision-making problems, therefore, in numerous studies, fuzzy logic has been integrated with various traditional techniques like AHP, MICMAC, MOORA, etc., to arrive at better decision-making. In solving multi-criteria problems, FANP is one the effective tools for decision-makers. The FANP considers the interrelationships among the criteria's and its feedback approach replaces hierarchies with networks, therefore, it has shown better results in prioritizing/ranking factors as compared to FAHP or other techniques.

While solving various MCDM methods, it has often been observed that some weights should be given to the criteria's so that these weights can serve as an input to rank sub criteria's/alternatives. In this condition, often researchers assume arbitrary weights, which, may lead to wrong results. Therefore, in such situations, instead of putting arbitrary weights, taking expert's opinions and finding weights with AHP/FAHP method can be helpful in getting more realistic weights of the criteria; hence better decision-making results. Henceforth, in this study, often AHP has been integrated with various MCDM techniques like AHP-COPRAS-G, FAHP-FMOORA, AHP & Two-way assessment to obtain weights of the criteria's using expert's opinions. Similarly in MCDM, FMOORA method is very simple, requires minimum mathematical calculations and the results of various studies have shown that MOORA method is stronger in many aspects than the traditional MCDM methods [197]. Likewise, COPRAS-G helps the decision-makers to make more decisions that are accurate. COPRAS-G is accepted for efficiently managing the problems of uncertainty, subjectivity and imprecise information [227,228]. In the case of exploratory research, factor analysis is the appropriate method to deal with a large amount of data, as it a data reduction technique and enables the design of measured variables. Correspondingly, structural equation modeling (SEM) is a very effective tool to show the relationships between the dependent and the independent variables using statistical data and qualitative assumptions. Two-way assessment, based on utility theory and AHP, is a very useful method that uses the expert opinion and converts the data of qualitative judgments into quantitative data specialists.

The bibliographic mapping results in Chapter 2 shows that the selected methodologies of the present research have not been used in the field of the vaccine supply chain. In addition, because the selected methodologies are appropriate to achieve the objectives of the present study and their application has shown benefits and positive results in other studies, therefore, the above-discussed methods have been finalized for the analysis purpose in the present research.

3.3. Description of the methodologies

In this section, the detailed description of the methodologies used in the research work has been discussed. The description of the methodologies is as follows:

3.3.1. Delphi technique

The Delphi approach was originally conceived as a manner to achieve the opinion of experts without necessarily bringing them collectively face to face [147]. It is a well-structured manner of accumulating information and gaining consensus among experts on various factors or issues under consideration. The technique involves a way of "structuring communications between a group of people who can provide valued contributions in an effort to solve a complex problem" [229].

The Delphi technique, due to its flexibility, is exceptionally appropriate to the exploration of issues that contain a mixture of scientific evidence and social values. Furthermore, the method attempts to add to the validity and reliability of those subjective opinions via establishing the evaluations to the critique of the professionals involved, through repetitive feedback rounds. This repetitive nature of the technique is based on the belief that this consensus based on the discussion of various experts is more reliable than the individual ideas [230]. The following steps or rounds are required to use the Delphi process as a data collection technique [231]:

Round 1: The Delphi techniques usually starts with an open-ended questionnaire. The open-ended questionnaire serves as the foundation for asking particular information about the topic for which Delphi is being used. After receiving the responses, investigators need to convert the collected information into a well-structured questionnaire. This questionnaire is used as the survey tool for the second round of data collection.

Round 2: In the second round, each Delphi panelist gets the second set of questionnaire and is asked to study the items summarized by means of the investigators based on the information furnished from the first round. Accordingly, the Delphi panelists may be required to rate or "rank-order" items to establish preliminary priorities among items. As an end result of the second round, regions of disagreement and agreement are recognized.

Round 3: In the third round, each Delphi panelist receives a questionnaire that consists of the items and their score summarized by the investigators within the preceding round. Further, the panelist is asked to revise his/her judgments or "to specify the motives for remaining outside the consensus". This round offers Delphi panelists a possibility to make additional clarifications of both the information and their judgments of the relative importance of the items. However, compared to the previous round, only a slight increase in the degree of consensus may be expected.

Round 4: In the fourth and mostly the final round, the list of remaining items, their ratings, marginal reviews, and items accomplishing consensus are dispensed to the panelists. This round provides a final opportunity for members to revise their judgments. It must be remembered that the variety of Delphi iterations depends largely on the degree of consensus sought by the investigators and can range from three to five.

3.3.2. Interpretive structural modeling (ISM)

Interpretive structural modeling (ISM) is a well-appreciated modeling technique, which was developed by Warfield in 1974. It is used to identify the relationship between specific items, which define any issue or problem [232]. The ISM model helps in transforming any unclear picture, problem, or complex articulated mental models of systems into well-defined models, which can be easy, understood [233]. ISM helps in arranging elements of the system into a hierarchical relation. Using the ISM approach any structural model can be created for the factors associated with a system based on their relationships [234]. The flowchart of the ISM method is shown in Figure 3.1.

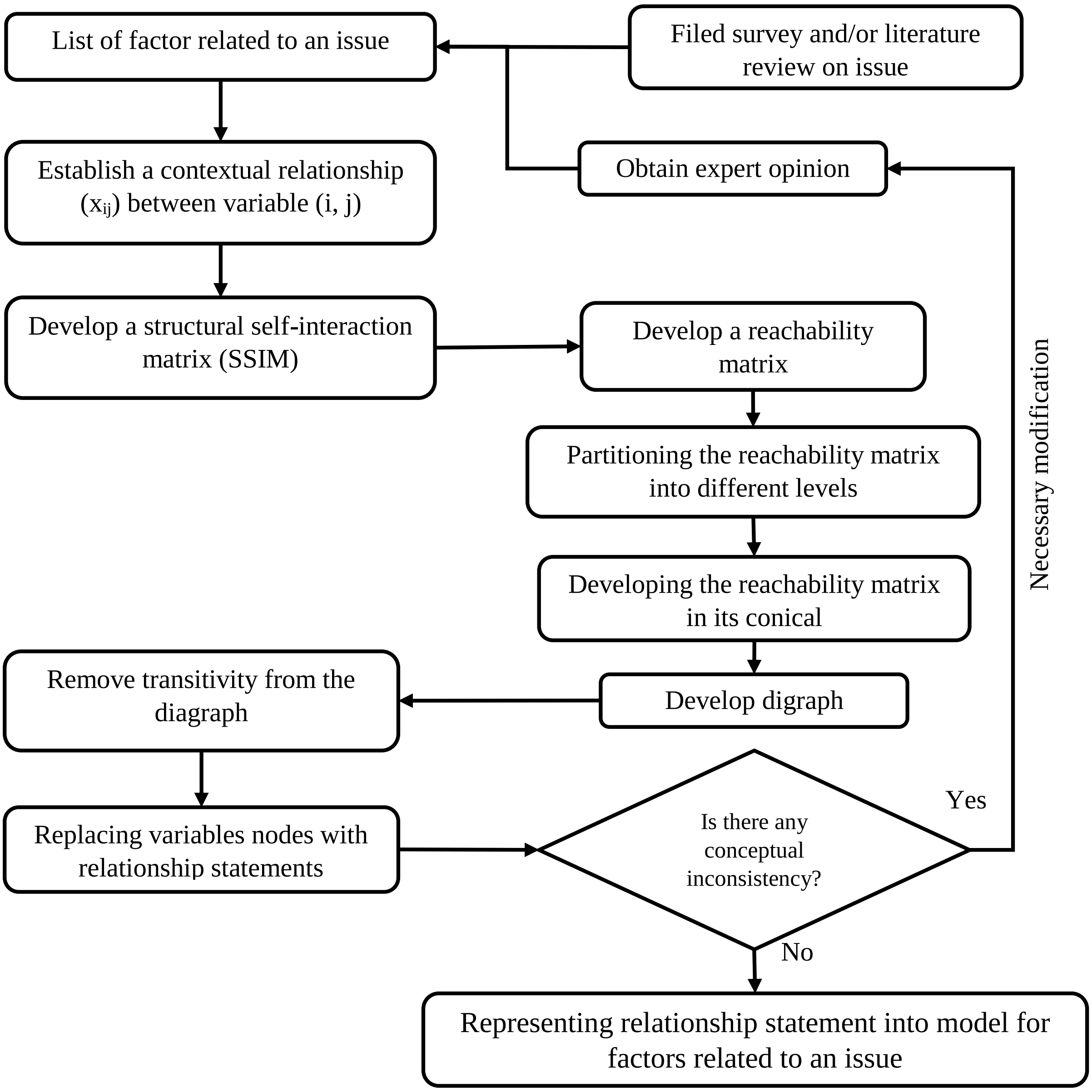


Figure 3.1: Flowchart of ISM methodology [232]**.**

3.3.3. Analytic hierarchy process (AHP)

Analytic hierarchy process (AHP) is a multi-criteria decision-making methodology developed by L. Saaty in 1977 for organizing and analyzing complex decision-making problems. It converts the problem assumed into a hierarchical structure, which includes numerous definite levels, inclusive of goal, criteria, and sub-criteria. There are numerous additional techniques, like ANP, PROMETHEE, ELECTRE, and TOPSIS that have been provided to solve the multi-criterion decision-making problems. However, AHP is suggested as a better methodology in contrast to others because of its wide applicability and simplicity in use [174].

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. 3.1-3.2, the aggregated final judgment matrix of all k experts can be obtained.

$$a_{ij}^{*} = \sqrt[k]{a_{ij}^{*1} \times a_{ij}^{*2} ......a_{ij}^{*k}} \quad (3.1)$$

$$A_{ij}^{*} = [a_{ij}^{*}] \quad (3.2)$$

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:

$$C.R. = CI / RI \quad (3.3)$$

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:

$$C.I = (\lambda_{\max} - n) / (n-1) \quad (3.4)$$

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

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. 3.5.

$$w_i = \frac{\left(\sum_{j=1}^{n} a_{ij}^{*}\right)}{n} \qquad i = 1,\ 2,\ \ldots.,\ n;\ n\ =\ number\ of\ factors \tag{3.5}$$

3.3.4. Fuzzy methodologies

Fuzzy logic depends on the idea of utilizing words instead of numbers for processing since words, in general, are considered less precise than numbers. Computing has customarily included computations that use exact numerical values, while human thinking, for the most part, uses words. Fuzzy logic tries to estimate human thinking by utilizing linguistic variables. Linguistic variables are words that are used to portray a parameter [235]. Since linguistic variables are inalienably unclear and vague parameters are treated as imprecise as opposed to precise values, hence, this fact can be addressed by fuzzy set theory, the procedure that is more prevailing and results are more reliable [236]. The core of fuzzy logic is the theory of a fuzzy set.

The fuzzy set theory, which, captures the uncertainty associated with both input and output attributes and imprecise knowledge about the relationship between input-output variables, provides a fundamental basis to map the approximate relationship between fuzzy variables [237]. Lotfi A. Zadeh and Dieter Klaua in 1965 introduced fuzzy set theory in dealing with uncertainty resulting from human language, human judgment, assessments, and decisions [238]. One benefit of the fuzzy set theory as pointed out by Pradeep and Praveen [239] is that the theory provides a natural way of dealing with problems in which the source of imprecision is the absence of sharply defined criteria. Hence, the fuzzy sets were used for the first time in the analysis of decision-making problems by Bellman and Zadeh in 1970 [240]. Fuzzy set theory, an extension of the crisp set theory, uses linguistic phrases to symbolize the decision maker's choices.

In fuzzy multiple criteria decision-making (FMCDM) that uses fuzzy set theory, the scores and weights of the attributes anticipated on ambiguity, inaccuracy, and subjectivity are expressed in linguistic phrases and then transformed to fuzzy numbers [241]. In practice, triangular fuzzy numbers (TFN) are commonly used for review of decision-makers preference as it captures the vagueness of the linguistic assessments and thereby contributes to the smooth usage and computational simplicity [242]. A TFN is defined as (p, q, r), where $p \leq q \leq r$. The parameters p, q, and r denote the smallest possible value, the most promising value, and the largest possible value that describe a fuzzy event. Few relevant definitions of the fuzzy set theory used in the present work are discussed below [195,241].

Definition 1 *(fuzzy set)*. A fuzzy set Ã is a subset of the universe of discourse X, which is a set of ordered pairs and is characterized by a membership function $u_{\tilde{A}}(x)$ representing a mapping $u_{\tilde{A}} : x \rightarrow [0,1]$. The function value of $u_{\tilde{A}}(x)$ for the fuzzy set Ã is called the membership value of x in Ã, which represents the degree of truth that x is an element of the fuzzy set Ã. It is assumed that $u_{\tilde{A}} : x \in [0,1]$ where $u_{\tilde{A}}(x) = 1$ reveals that x belongs to Ã, while $u_{\tilde{A}}(x) = 0$ indicates that x does not belong to the fuzzy set Ã.

Therefore, $\tilde{A} = \{(x, u_{\tilde{A}}(x))\}, \qquad x \in X$

where $u_{\tilde{A}}(x)$ is the membership function and $X = \{x\}$ represents a collection of elements x.

Definition 2 *(fuzzy number)*. A triangular fuzzy number can be expressed as a triplet (p, q, r); the membership function of the fuzzy number $u_{\tilde{A}}(x)$ is illustrated in Figure 3.2 and defined as:

$$u_{\tilde{A}}(x) = \begin{cases} 0 & x < p, \\ \dfrac{x-p}{q-p} & p \le x \le q, \\ \dfrac{r-x}{r-q} & q \le x \le r, \\ 0 & x > r, \end{cases}$$

Due to their conceptual and computational simplicity, TFN is more generally used in decision-making [243].

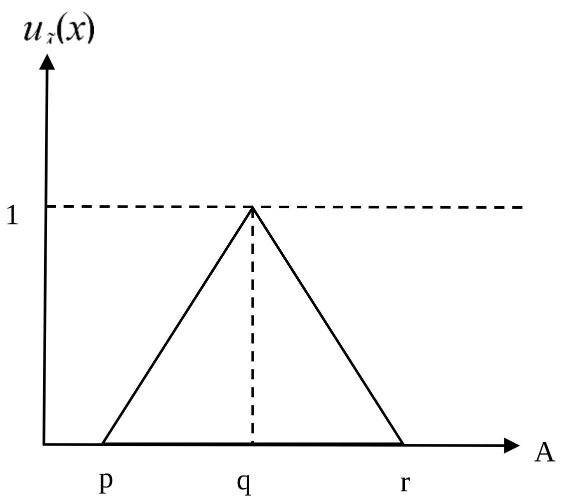


Figure 3.2: A membership function of triangular fuzzy number.

In this study, various fuzzy methodologies have been used for analysis purpose. The objective of using fuzzy logic is because, in India and other developing countries due to the lack of financial support for vaccination programs, often the decisions of procurement, forecasting, cold chain etc. are taken by the knowledge of decision-makers instead of any analytical tools or techniques. The knowledge of decision-makers is constructed on linguistics tags such as experience rather than mathematical data. Often words have higher significance in the real world of VSC decision-makers than data. For example, decision-makers may take judgments with words like 'do not order BCG vaccine in very large quantity as they have a very high vaccine wastage rate' instead of numerical data as if 'BCG has wastages rate of 40%, 50%, etc., in different states of India so place the order accordingly'. Because many times the real world problems are based on words and words comprises the premise to solve problems, decisions or draw assumptions consequently, using fuzzy theory in such situations can be found valuable. The discussions of different fuzzy methods used in this research are given below.

3.3.4.1. Fuzzy MICMAC

To analyze the inter-relationships and to study their role and behavior, Duperrin and Godet introduced MICMAC method. MICMAC (matrix cross-reference multiplication applied to a classification) is used for the analysis of hidden and indirect relationships between the elements of the system which is obtained by the ISM methodology [244]. ISM only captures the direct relationship between the elements, thus MICMAC analysis can further improve the results obtained through ISM. The method enables the study of the diffusion of impacts through reaction paths and loops for developing a hierarchy of the indicators. The matrix multiplication properties are used for the MICMAC analysis. If element i directly affects element k and if k directly affects element j, then any change affecting indicator i can have repercussions on indicator j. An indirect connection is present between i and j. A number of indirect relationships of i→j type, which are present in the structural matrix, cannot be taken into account in a direct relationship approach. When the matrix is squared, second-order relationships are revealed, such as i→j. Likewise, when the matrix is multiplied, 3, 4, or n times, the number of influencing paths (for influence loops) of the 3rd, 4^{th} order interconnecting the elements can be found. Every time this process is repeated, a new hierarchy of elements can be obtained. Their classification is based on the number of indirect actions (influences) they have on other elements. When power is raised to a certain level, the hierarchy starts repeating in the next stage of the multiplication (both in the column as well as in the row of the hierarchy) and such a stage is called a stable stage and such matrix is called stabilized indirect matrix.

To increase the sensitivity of the result fuzzy set theory is applied to the conventional MICMAC. Whereas MICMAC considers the only binary type of relationships i.e. 0 or 1, in fuzzy-MICMAC an additional input of the possibility of interaction between the elements is introduced. Even though fuzzy-MICMAC is more sensitive than ordinary MICMAC analysis, the former continues to be useful in cases where enormous resources would be required to decide the possibility of interaction. In FMICMAC analysis direct relationship matrix deduced from digraph (basic input to MICMAC) is enriched by incorporating in it the possibility of interactions using fuzzy numbers. It is then called a fuzzy direct relationship matrix (FDRM). Because input to FMICMAC analysis is a fuzzy matrix, therefore; instead of using Boolean multiplication of matrices to stabilize the ranks, fuzzy matrix multiplication is used. Fuzzy matrix multiplication is basically a generalization of Boolean matrix multiplication. According to the fuzzy sets theory when two fuzzy matrices are being multiplied the product matrix will also be a fuzzy matrix.

Multiplication follows the given rule:

$$AB = \max \{\min a_{ij}, b_{ij}\} \tag{3.6}$$

Where, $A = [a_{ij}]$ and $B = [b_{ij}]$ are two fuzzy matrices.

3.3.4.2. Fuzzy AHP

The Analytic Hierarchy Process (AHP) is one of the most extensively used multi-criteria decision-making method that was originally developed by Saaty in 1980. However, this technique has few limitations such as: (1) The AHP method is used crisp decision-making problems only (2) The AHP method create and deal with the very unbalanced scale of judgment. (3) It is regularly criticized due to its inability to assign exact numerical values to the comparison judgments and being ineffective when applied to vague problems. (4) Ranking obtained from AHP approach is rather imprecise. (5) The subjective judgment, selection, and preference of decision-makers have a great effect on the AHP results. Since the traditional AHP cannot offer direction about the highly ambiguous world, Chang combined the fuzzy concept with the AHP approach to handle fuzzy comparison matrices and developed Chang's extend evaluation method for calculating exact weights [193,195,245].

The steps of fuzzy AHP proposed by Chang's are described below [193,197,245].

Step 1: Let $X = \{x_1, x_2, \ldots\ldots, x_n\}$ be the criteria set and $U = \{u_1, u_2, \ldots\ldots, u_n\}$ be the targets set. Now, degree analysis (g_i) is applied to every target set by concerning every criterion. M degree analysis values related to the targets are expressed in triangular fuzzy numbers $M_{gi}^1, M_{gi}^2, M_{gi}^3$

were, $i=1,2,..,n$ and $j=1,2,...,n.$ So, M_{gi}^{j} shows triangular fuzzy number related to j target according to i criteria.

Step 2: Fuzzy synthetic degree value related to i the criterion is stated as;

$$S_i = \sum_{j=1}^{m} M_{gi}^{j} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} \right]^{-1} \tag{3.7}$$

In order to obtain $\sum_{j=1}^{m} M_{gi}^{j}$ the fuzzy addition operation of m extent analysis values is performed such as $\sum_{j=1}^{m} M_{gi}^{j} = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j \right)$

In Eq. 3.7, the inverse vector $\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} \right]^{-1}$ is calculated as below

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} \right]^{-1} = \left(\frac{1}{\sum_{i=1}^{m} u_i}, \frac{1}{\sum_{i=1}^{m} m_i}, \frac{1}{\sum_{i=1}^{m} l_i} \right)$$

Step 3: The fuzzy synthetic degree will result in triangular fuzzy numbers $M_i = (l_i, m_i, u_i), i=1,2,..,n.$ For any two triangular fuzzy numbers $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$, the numbers M_1 and M_2 should be compared calculating both $V(M_2 \geq M_1)$ and $V(M_1 \geq M_2)$.

The degree of possibility of $V(M_2 \geq M_1)$ is given as:

$$V(M_2 \geq M_1) = \begin{cases} 1, & m_2 \geq m_1 \\ 0, & l_1 \geq u_2 \\ \dfrac{(l_1 - u_2)}{(m_2 - u_2) - (m_1 - l_1)}, & otherwise \end{cases} \tag{3.8}$$

Since, M_1 and M_2 are convex fuzzy numbers, therefore, the degree possibility of a convex fuzzy number to be greater than k convex fuzzy numbers $M_i (i=1,2,..,n)$ can be defined by

$$V(M \geq M_1, M_2, ..., M_k)$$
$$= \min V(M \geq M_i), \quad i=1,2,..,n \tag{3.9}$$

Step 4: Assume that, $d'(A_i) = \min V(S_i \geq S_j),\ k=1,2,.....,n\ and\ k \neq i$

Then, the weight vector is calculated indicated as:

$$W' = \left(d'(A_1), d'(A_2), \ldots\ldots\ldots, d'(A_n)\right)^T . \qquad (3.10)$$

Where, $A_i \ (i = 1, 2, .., n)$ are n elements.

Step 5: After normalizing, we obtain the normalize weight vectors W

$$W = \left(d(A_1), d(A_2), \ldots\ldots\ldots, d(A_n)\right)^T$$

Where W is a nonfuzzy number

Elements of W the vector are calculated as:

$$d(A_i) = d'(A_i) \Big/ \left[d'(A_1) + d'(A_2) + \ldots\ldots d'(A_n)\right] \quad i = 1, 2, \ldots, n \qquad (3.11)$$

3.3.4.3. Fuzzy ANP

In multi-criteria decision-making problems, one of the important tools for decision-makers is the analytic network process (ANP) developed by Saaty in 1996 [246]. It is a comprehensive decision-making technique that converts the opinions of experts on any subject into weights. Although the ANP is an extension of the analytic hierarchy process (AHP), the main difference lies in considering the interdependencies between the clusters. Figure 3.3 shows the difference between the hierarchy and the network. AHP is a hierarchical structure and ANP is a network structure. The ANP allows for complex interrelationships among decision levels and attributes. The ANP feedback approach replaces hierarchies with networks, so the network that considers the interdependencies of the clusters results in more accurate findings. It is a generalized model, so it does not consider any assumptions in decision-making application [163]. To improve the accuracy of the results of the ANP, the fuzzy logic is integrated with ANP. The FANP deals with inconsistent and uncertain human judgments to reduce the potential biases in the results. According to [247], fuzzy integration in decision-making processes improves the precision of the results.

One significant disadvantage/complexity that arises with the usage of the ANP technique is that when the number of factors/criteria and respective interrelationships increases, the effort required by the decision-makers and analysts also increases [248]. To avoid such complexities, therefore, fuzzy ANP can be linked with other qualitative decision-making methods such as ISM or Decision-Making Trial and Evaluation Laboratory (DEMATEL), which easily find interrelationships between elements. According to Yu and Hu [249], the integration of ISM with ANP helps researchers to get more specific feedback within different dimensions of the problem and with fewer questionnaires. Because of these benefits, this study has used an integrated ISM-

FANP approach for exploring the dominant issues in the vaccine supply chain of developing countries.

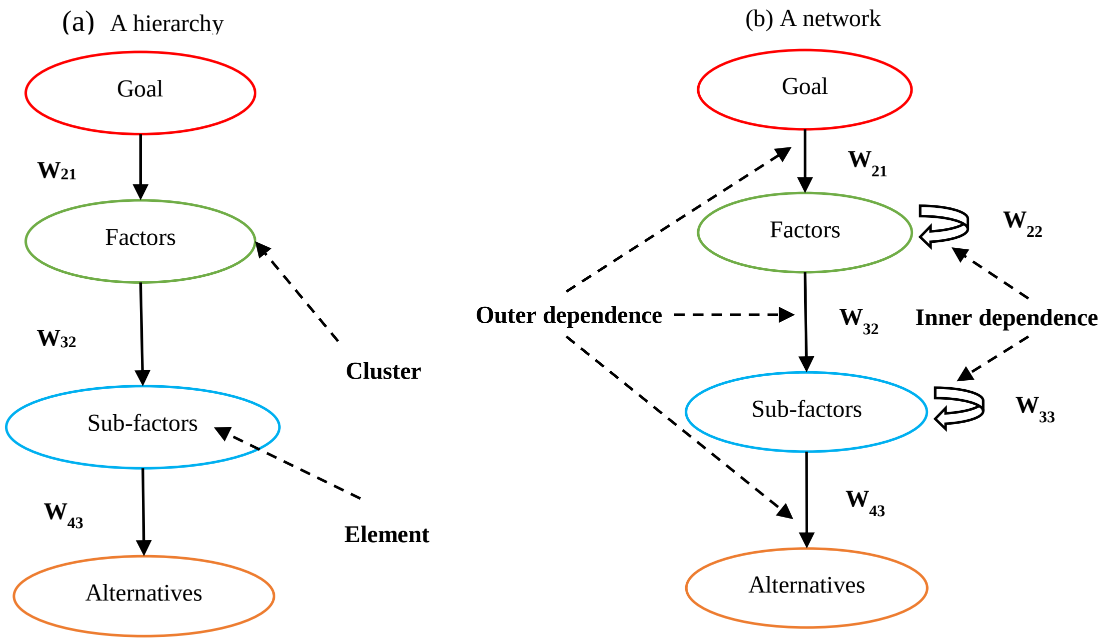


Figure 3.3: Structure of (a) a hierarchy and (b) a network

The FANP approach comprises the following steps [162,163,246,250–252]:

Step 1: Identify inner and outer dependencies among the clusters and the elements.

Step 2: Based on the interdependencies identified from the previous step, construct a pairwise comparison matrix for the inner and outer dependencies.

Step 3: Perform a consistency check for the pairwise comparison matrix to move to the next step. The consistency ratio for each matrix is calculated in the same way as for AHP.

Step 4: After the consistency check, the next step is defuzzification, which involves transforming fuzzy numbers into crisp numbers.

Step 5: Next, the geometric mean is calculated using Eq. 3.12-3.13, to compute the final integrated crisp values of all k experts.

$$a_{ij}^{*} = \sqrt[k]{a_{ij}^{*1} \times a_{ij}^{*2} ......a_{ij}^{*k}} \quad (3.12)$$

$$A_{ij}^{*} = [a_{ij}^{*}] \quad (3.13)$$

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

Step 6: In the next step, the final inner and outer dependence weights are calculated using the geometric mean method shown in Eq. 3.14.

$$w_{ij} = \frac{\left(\prod_{j=1}^{n} a_{ij}^{*}\right)^{1/n}}{\sum\left(\prod_{j=1}^{n} a_{ij}^{*}\right)^{1/n}} \qquad \text{i, j = 1, 2…, n} \tag{3.14}$$

Step 7: Create a supermatrix W. The supermatrix is a partitioned matrix where each submatrix is composed of a set of quantified relations between the elements from the same or different clusters. The general form of a supermatrix in a four-level hierarchy is shown in Eq. 3.15.

$$\begin{array}{r} \\ Goal(G) \\ Criteria(C) \\ Sub-Criteria(SC) \\ Alternatives(A) \end{array} \begin{array}{c} \begin{array}{cccc} G & C & SC & A \end{array} \\ \begin{bmatrix} 0 & 0 & 0 & 0 \\ W_{21} & W_{22} & 0 & 0 \\ 0 & W_{32} & W_{33} & 0 \\ 0 & 0 & W_{43} & I \end{bmatrix} \end{array} \tag{3.15}$$

Where vector W_{21} represents the influence of the goal on the factors, the vector W_{22} and vector W_{33} represents the mutual influence among factors and sub-factors, the vector W_{32} represents the influence of the factors on each sub-factors, vector W_{43} represents the influence of the sub-factors on each alternative and I is the identity matrix. The initial supermatrix formed is the unweighted supermatrix. As it may not fit the columns stochastic rule, therefore, the columns whose weight do not sum up to 1 will be normalized to form a weighted supermatrix.

Step 8: In the final step, to obtain the limited supermatrix, the weighted matrix is raised to a power of 2p+1, where p is sufficiently large numbers until it reaches convergence. In a converging matrix, all column values will be the same.

3.3.4.4. Fuzzy MOORA

Multi-objective optimization, also known as multi-criteria or multi-attribute optimization, is the method of simultaneously optimizing two or more conflicting elements, criteria or attributes. In a decision-making problem, the values of such objectives are measured for every decision alternative, and this presents the basis for assessment of choices and consequently allows the selection of the best alternative. Such techniques, hence, seem to be a suitable tool for ranking or selecting the best alternative from a set of available alternatives [199,253]. The fuzzy MOORA, which is an extension of MOORA is an MCDM technique that was developed by

Brauers and Zavadskas for the analysis of complex alternatives using fuzzy theory concept [196]. The FMOORA method is very simple, requires minimum mathematical calculations and the results of various studies have shown that MOORA method is stronger in many aspects than the traditional MCDM methods [197].

In the evaluation process of FMOORA method, the subsequent steps will be taken into consideration [196,197].

Step 1: Decision matrix is formed using triangular fuzzy numbers.

$$\tilde{A} = \begin{bmatrix} \left[a_{11}^{l}, a_{11}^{m}, a_{11}^{u}\right] & \left[a_{12}^{l}, a_{12}^{m}, a_{12}^{u}\right] & \cdots & \left[a_{1n}^{l}, a_{1n}^{m}, a_{1n}^{u}\right] \\ \vdots & \vdots & & \vdots \\ \vdots & \vdots & & \vdots \\ \left[a_{m1}^{l}, a_{m1}^{m}, a_{m1}^{u}\right] & \left[a_{m2}^{l}, a_{m2}^{m}, a_{m2}^{u}\right] & \cdots & \left[a_{mn}^{l}, a_{mn}^{m}, a_{mn}^{u}\right] \end{bmatrix} \qquad (3.16)$$

In Eq. 3.16, m refers to the number of alternatives; n provides information about the criteria. On the other side, a_{mn} , a_{mm} represents the value that the option takes in n criteria.

Step 2: Normalization of the fuzzy matrix is performed and this normalization technique is accomplished by means of the use of vector normalization.

$$\tilde{A}_{ij}^{*} = (a_{ij}^{l*}, a_{ij}^{m*}, a_{ij}^{u*}) \quad and\ \forall_{ij}:$$

$$a_{ij}^{l*} = a_{ij}^{l} \Big/ \sqrt{\sum_{i=1}^{m}\left[(a_{ij}^{l})^{2} + (a_{ij}^{m})^{2} + (a_{ij}^{u})^{2}\right]} \qquad (3.17)$$

$$a_{ij}^{m*} = a_{ij}^{m} \Big/ \sqrt{\sum_{i=1}^{m}\left[(a_{ij}^{l})^{2} + (a_{ij}^{m})^{2} + (a_{ij}^{u})^{2}\right]} \qquad (3.18)$$

$$a_{ij}^{u*} = a_{ij}^{u} \Big/ \sqrt{\sum_{i=1}^{m}\left[(a_{ij}^{l})^{2} + (a_{ij}^{m})^{2} + (a_{ij}^{u})^{2}\right]} \qquad (3.19)$$

Step 3: Weighted normalized fuzzy decision matrix is formed by using normalize weight vectors W calculated in fuzzy AHP

$$\tilde{n}_{ij} = (n_{ij}^{l*}, n_{ij}^{m*}, n_{ij}^{u*});$$

$$n_{ij}^{l} = w_j a_{ij}^{l*} \quad (3.20)$$

$$n_{ij}^{m} = w_j a_{ij}^{m*} \quad (3.21)$$

$$n_{ij}^{u} = w_j a_{ij}^{u*} \quad (3.22)$$

Step 4: In this step, normalized performance values are calculated through subtracting the useless criteria from the total of useful criteria.

$$\tilde{y}_i = \sum_{j=1}^{g} \tilde{n}_{ij} - \sum_{j=g+1}^{n} \tilde{n}_{ij} \quad (3.23)$$

Here,

$\sum_{j=1}^{g} \tilde{n}_{ij}$, is the benefit criteria for $1,...,g$

$\sum_{j=g+1}^{g} \tilde{n}_{ij}$, is the cost criteria for $g+1,...n$

Step 5: Since normalized overall performance values are also fuzzy numbers, those values must be transformed into performance values that are not fuzzy (Best Non-fuzzy overall performance/BNP). In this study, the subsequent equality has been used so that it will calculate BNP values

$$\tilde{y}_i = \left(y_i^l, y_i^m, y_i^u\right)$$

$$BNP_i\left(y_i\right) = \frac{\left(y_i^u - y_i^l\right) + \left(y_i^m - y_i^l\right)}{3} + y_i^l \quad (3.24)$$

3.3.5. COPRAS-G

Zavadeski recommended the COPRAS-G method (Complex Proportional Assessment of alternatives with Grey relations) for evaluating several alternatives by considering multiple evaluation criteria. It uses the applications of grey theory in which the criteria values are expressed at intervals to acquire the incomplete information in the decision-makers judgments. The grey relational grade model could be very effective at coping with discrete data. A grey number is a fundamental concept in theory of grey systems, used to resolve the unsure information, which may be modeled as the white, black and grey structures. In specific, the white system is a system wherein the internal information is actually absolutely known, whereas the black system is a system in which no statistics and characteristics or properties may be attained.

Hence, a grey system is described as a system with uncertain information between the white and black systems. Thus, the decision-makers judgments, which accommodate an uncertain stage of information, may be defined through the grey system over the classification of white, black and grey numbers [180,254,255].

The COPRAS-G is completely logical and useful mathematically for processing incomplete data about the system and is supposed to upsurge the performance and enhance the accuracy stage of the process within the decision-making system. 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 illustrates the degree to which one alternative is considered as higher as or worse than the set of existing alternatives. Other MCDM techniques do no longer have such features and that is the cause why COPRAS-G succeeded in the decision--making the process. COPRAS-G helps the decision-makers to make more decisions that are accurate. COPRAS-G is accepted for efficiently managing the problems of uncertainty, subjectivity and imprecise information [227,228].

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 for MCDM process.

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

$$X = \begin{bmatrix} [x_{11}, u_{11}] & [x_{12}, u_{12}] & \cdots & [x_{1n}, u_{1n}] \\ \vdots & \vdots & & \vdots \\ \vdots & \vdots & & \vdots \\ [x_{m1}, u_{m1}] & [x_{m2}, u_{m2}] & \cdots & [x_{mn}, u_{mn}] \end{bmatrix} \quad i = 1,\ldots,m; \ j = 1,\ldots,n \tag{3.25}$$

where m and n are the number of alternatives and criteria's respectively and $[x_{ij}, u_{ij}]$ is the interval value of the ith alternative with respect to the jth 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 Eq. 3.26-3.27.

$$\left[\bar{x}_{ij}\right]_{m\times n} = \frac{2x_{ij}}{\left[\sum_{i=1}^{m} x_{ij} + \sum_{i=1}^{m} u_{ij}\right]} \tag{3.26}$$

$$\left[\bar{u}_{ij}\right]_{m\times n} = \frac{2u_{ij}}{\left[\sum_{i=1}^{m} x_{ij} + \sum_{i=1}^{m} u_{ij}\right]} \tag{3.27}$$

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

$$\bar{X} = \begin{bmatrix} [\bar{x}_{11},\bar{u}_{11}] & [\bar{x}_{12},\bar{u}_{12}] & \cdots & [\bar{x}_{1n},\bar{u}_{1n}] \\ \vdots & \vdots & & \vdots \\ \vdots & \vdots & & \vdots \\ [\bar{x}_{m1},\bar{u}_{m1}] & [\bar{x}_{m2},\bar{u}_{m2}] & \cdots & [\bar{x}_{mn},\bar{u}_{mn}] \end{bmatrix} \tag{3.28}$$

Step 3: Construct a weighted normalized decision support matrix $\hat{x}$ by using Eq. 3.29-3.30.

$$\hat{x}_{ij} = \bar{x}_{ij} \times q_j \tag{3.29}$$

$$\hat{u}_{ij} = \bar{u}_{ij} \times q_j \tag{3.30}$$

where i = 1,2,.,m; j = 1,2,…,n and q_j is the weight of the jth criteria.

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

$$\hat{X} = \begin{bmatrix} [\hat{x}_{11},\hat{u}_{11}] & [\hat{x}_{12},\hat{u}_{12}] & \cdots & [\hat{x}_{1n},\hat{u}_{1n}] \\ \vdots & \vdots & & \vdots \\ \vdots & \vdots & & \vdots \\ [\hat{x}_{m1},\hat{u}_{m1}] & [\hat{x}_{m2},\hat{u}_{m2}] & \cdots & [\hat{x}_{mn},\hat{u}_{mn}] \end{bmatrix} \tag{3.31}$$

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).

$$P_i = \frac{1}{2}\sum_{j=1}^{k}\left(\hat{x}_{ij} + \hat{u}_{ij}\right) \tag{3.32}$$

$$R_i = \frac{1}{2}\sum_{j=k+1}^{m-k}\left(\hat{x}_{ij} + \hat{u}_{ij}\right) \tag{3.33}$$

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:

$$R_{\min} = \min R_i \ (i = 1, 2, ..., m) \tag{3.34}$$

Calculate the relative significance or weights of each alternative Q_i:

$$Q_i = P_i + \frac{R_{\min} \sum_{i=1}^{m} R_i}{R_i \sum_{i=1}^{m} \left(R_{\min} / R_i \right)} = P_i + \frac{\sum_{i=1}^{m} R_i}{R_i \sum_{i=1}^{m} \left(1 / R_i \right)} \tag{3.35}$$

Step 6: Determine the maximum weight of the alternative:

$$Q_{\max} = \max Q_i \ (i = 1, 2, ..., m) \tag{3.36}$$

Step 7: Calculate the utility degree of each alternative

$$U_i = \left(\frac{Q_i}{Q_{\max}} \right) \times 100\% \tag{3.37}$$

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.

3.3.6. Exploratory factor analysis

Exploratory factor analysis **(**EFA) is a multivariate analysis approach whose goal is to identify the underlying relationships among measured variables. One assumption in the EFA is that the variance in the observed variables is due to the presence of one or more latent factors (common factors) that employ causal effect on these observed variables. Hence, we can differentiate or categorize the variables according to the contributions of the latent factors to individual variables. Mathematically, the EFA equation can be written as [205]:

$$X = LF + R \Leftrightarrow \begin{pmatrix} x_1 \\ x_2 \\ \cdots \\ x_p \end{pmatrix} \tag{3.38}$$

$$= \begin{pmatrix} l_{11} & l_{12} & \cdots & l_{1m} \\ l_{21} & l_{22} & \cdots & l_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ l_{p1} & l_{p2} & \cdots & l_{pm} \end{pmatrix} \begin{pmatrix} f_1 \\ f_2 \\ \cdots \\ f_m \end{pmatrix} + \begin{pmatrix} r_1 \\ r_2 \\ \cdots \\ r_m \end{pmatrix} \quad , m \leq p \tag{3.39}$$

where the observations with p variables are $X = \{x_1, x_2, ..., x_p\}$ and $F = \{f_1, f_2, ..., f_m\}$ are the common factor matrix for the number of factors m. $L = \{l_{11}, l_{12}, ..., l_{pm}\}$ is the factor loading matrix. $R = \{r_1, r_2, ..., r_m\}$ is the specific factor or residual errors. From this model, we can obtain factor loading value L for common factors F that affect the original variables X with a factor method. The common EFA model in Eq. 3.39 is derived based on two assumptions. First, the error terms r_i are independent of one another and are such that $E(r_i) = 0$ and $Var(r_i) = \psi_i$, where E denotes the expected value (mean value) of the variable for all the observed data set, and j is the specific variance. Second, common factors f_i are independent of one another and of the error terms and are such that $E(f_i) = 0$ and $Var(f_i) = 1$.

From these assumptions, we can define the covariance matrix in EFA as:

$$Cov(X) = Cov(LF + R) = L\,Cov(F)L' + Cov(R) = LL' + \Psi \tag{3.40}$$

where, $\Psi = diag(\psi_1, \psi_2, ..., \psi_p)$.

The covariance matrix $\sum$ can be expressed as:

$$\Sigma_{ij} = Cov(x_i, x_j) = E\left[(x_i - \overline{x}_i)(x_j - \overline{x}_j)\right] \tag{3.41}$$

$$\Sigma = \begin{bmatrix} E\left[(x_1 - \overline{x}_1)(x_1 - \overline{x}_1)\right] & E\left[(x_1 - \overline{x}_i)(x_2 - \overline{x}_2)\right] & \cdots & E\left[(x_1 - \overline{x}_i)(x_p - \overline{x}_p)\right] \\ E\left[(x_2 - \overline{x}_2)(x_1 - \overline{x}_1)\right] & E\left[(x_2 - \overline{x}_2)(x_2 - \overline{x}_2)\right] & \cdots & E\left[(x_2 - \overline{x}_i)(x_p - \overline{x}_p)\right] \\ \vdots & \vdots & \ddots & \vdots \\ E\left[(x_P - \overline{x}_P)(x_1 - \overline{x}_1)\right] & E\left[(x_P - \overline{x}_P)(x_2 - \overline{x}_2)\right] & \cdots & E\left[(x_P - \overline{x}_p)(x_p - \overline{x}_p)\right] \end{bmatrix} \tag{3.42}$$

The eigenvalues $(\lambda_1, \lambda_2, ..., \lambda_p)$ and corresponding eigenvectors $(e_1, e_2, ..., e_p)$ can be obtained from Eq. 3.42.

3.3.7. Structural equation modeling (SEM)

Structural equation modeling (SEM) is a very effective tool to show the relationships between the dependent and the independent variables using statistical data and qualitative assumptions. The dependent variables are called endogenous variables (observed variable) and are denoted by a rectangle in the structure model, whereas the independent variables are called exogenous variables (unobserved variable) and are denoted by an ellipse in the model. Unlike other statistical tools such as regression, SEM aids to answer a set of related research questions in a single, organized, and extensive way by modeling relationships between several constructs simultaneously (a predictive model of days) [256,257].

Another cause that SEM is the favored model compared to methods of conventional multiple regressions is SEM's usually fragment nature to generate separate and individually distinct coefficients. The SEM technique permits checking and inspecting an entire model by producing goodness-of-fit tests and assessing the overall fit. Another characteristic of SEM that distinguishes it from other models is its capacity to permit the inclusion of each measurement and latent variables into the same evaluation. As a result, the incorporation of those variables provides a stronger assessment of the suggested model and, thus, results in improved evaluations. Furthermore, SEM has the capacity to help in two other ways as it can cope with complicated data information (with non-normality and multi-collinearity) and it can allow for the modeling of graphical interfaces. Overall, there are several vital reasons as to why SEM is favored over other available conservative multivariate methods. As multiple regression models, SEM permits researchers to model the mediator variables, to check and test the models with multiple dependent and independent indicators, to model mediator factors, and to examine entire structures of indicators, thus allowing the establishment of more realistic models that require simultaneous evaluation. Moreover, it can be concluded that SEM is an effective and ideal method for checking and checking out the relationships amongst mediator variables [214].

In simple terms, SEM involves the evaluation of two models: a path model and measurement model. They are described below:

i. **Path model:** Path analysis is an extension of multiple regression in that it involves numerous multiple regression models or equations that are estimated at the same time. This offers an effective way of modeling mediation, indirect effects, and other complicated relationships amongst variables. Path evaluation can be considered a special case of SEM in which structural relationships amongst the observed and the latent variables are modeled i.e., path analysis is SEM with a structural model, but no measurement model. In path analysis, the structural relations are hypotheses about directional effects or causal relations of multiple variables (e.g., how the dependent variable is affected by independent variable). Therefore, path analysis is often called causal modeling. Because analyzing interrelations among variables is a main part of SEM and those interrelations are hypothesized to generate unique observed covariance (or correlation) patterns between the variables, SEM is also sometimes called as covariance structure analysis. In path analyses, observed variables are treated as if they are measured without error, which is an assumption that does not likely hold in most social and behavioral sciences. When observed variables contain error, estimates of path coefficients may be biased in unpredictable ways, especially for complex models.

ii. **Measurement model:** Statistical techniques, such as factor analysis, exploratory or confirmatory, are widely used to study the number of latent constructs underlying the observed responses and to assess the adequacy of individual items or variables as indicators for the latent constructs they're supposed to measure. The measurement model in SEM is evaluated through confirmatory factor analysis (CFA). CFA differs from EFA such that in CFA the factor structures are hypothesized a priori and tested empirically rather than derived from the records. EFA generally allows all indicators to load on all factors or elements and does not allow correlated residuals. Solutions for different factors are often tested in EFA and the maximum sensible solution is interpreted. Indifference, the number of factors in CFA is believed to be recognized. In SEM, those elements corresponding to the latent constructs represented in the model. CFA permits an indicator to load on numerous factors (if it is believed to measure multiple latent constructs). It also allows residuals or errors to correlate (if these indicators are believed to have common causes other than the latent factors included in the model. Once the measurement model has been identified, structural relations of the latent factors are then modeled essentially the same manner as they are in path models.

The combination of CFA models with structural path models on the latent constructs represents the general SEM framework in analyzing covariance structures.

3.3.8. Two-way assessment

A systems thinking approach is suitable when improving business processes to fit customer needs. Various techniques offered by systems engineering can be used to model and improve business processes, in which utility theory is one of the effective technique [258]. Two-way assessment is based on utility theory and AHP and is useful in measuring the impact or effectiveness of performance indicators in a vaccine supply chain. Two-way assessment is a very useful method that uses an expert’s opinion and converts the qualitative judgment data of experts into quantitative data. The method determines the effectiveness of the performance indicators in phrases of the numerical score and highlights the low performing attributes. Using the outcomes of Two-way assessment, decision-makers can identify the low performing attributes and take corrective actions on them [219] to improve the vaccine supply chain performance; hence the overall immunization programs' effectiveness. In the Two-way assessment, the performance indicators are ranked from 1 to 5, where 5 is the highest rank and 1 being the lowest rank. These ranks are further attached with scores of 10, 8, 6, 4 and 2 respectively starting from the highest rank of 5 to least rank of 1. Using the expert's opinions, the indicators are assigned rank, which helps in constructing the 'Current' utility of the performance indicators. Further, the three utility scenarios, i.e. 'Ideal', 'Worst' and 'Optimum' are calculated to compare the current maturity with these scenarios [219,222]. It is expected that the current utility score calculated on expert's opinions should lie in the optimum range. Hence, using a Two-way assessment, we get a general framework to test the effect of these performance indicators. The current, ideal, worst and optimum utility measure value was calculated by incorporating the values of priority weight (W_i), Rank Index (I_j), and Rank Score (S_j) and. Below are the equations for calculating these utility measures.

Expected weight; $EW_i = W_i \times \left(\sum_{j=1}^{5} (S_j \times I_j) \right) \quad i = 1, 2, \ldots, n;$ (3.43)

n is number of factors;

The value of Rank Score (S_j) lies between "2" and "10", where, "Rank1; (S_1) = *10,* Rank2; (S_2) = *8,* Rank3; (S_3) = *6,* Rank4; (S_4) = *4, and* Rank5; (S_5) = *2".* The value of Rank Index (I_j) depends upon the opinions of experts. For example, if 20 experts participated in any study and 10 experts suggest that 'A' factor should be assigned Rank 1, 5 suggest Rank 2, 3 suggest Rank 3, 1 suggest Rank 4 and 1 suggest Rank 5, then the Rank Index (I_1) becomes (10/20=0.50). Similarly, I_2 = 0.25; I_3 = 0.15; I_4 = 0.05; and I_5 = 0.05.

Finally, the utility measure is calculated using Eq. 3.44.

Utility measure; $U = \sum EW_i \quad i, = 1, 2, \ldots, n;$ (3.44)

3.4. Conclusion

In Chapter 3, the description of various methodologies, used in attaining the research objectives has been discussed. The application of these techniques in various chapters of the present work is shown in Table 3.1.

Table 3.1. Application of research methodologies in present work.

S.No.	Methodology	Application
1.	Delphi	Delphi approach has been used in Chapter 4 for finalization of key issues of VSC.
2.	ISM	Using ISM, a hierarchical model of VSC issues is developed in Chapter 4 to show interrelationships among issues.
3.	Fuzzy MICMAC	Fuzzy MICMAC has been used in Chapter 4 to calculate the driving power and dependence of VSC issues.
4.	Fuzzy ANP	Issues and its domain have been prioritized in Chapter 4 using fuzzy ANP.
5.	AHP	Weights of causes of vaccine shortages have been calculated using AHP.
6.	COPRAS-G	Alternatives have been ranked in Chapter 5 using COPRAS-G.
7.	Fuzzy AHP	Barriers of NGVSCs have been ranked using fuzzy AHP in Chapter 6.
8.	Fuzzy MOORA	Solution to design NGVSCs has been prioritized using Fuzzy MOORA in Chapter 6.
9.	EFA	Key performance indicators and sustainable practices criteria's of VSC have been finalized using EFA in Chapter 7.
10.	SEM	Using SEM, the hypothetical model has been tested in Chapter 7.
11.	Two-way assessment	Two-way assessment has been performed in Chapter to measure the impact of KPIs on VSCP

Chapter 4

ANALYSIS OF VACCINE SUPPLY CHAIN ISSUES

Summary

In recent years, the demand to improve child immunization coverage globally, and the development of the latest vaccines and technology has made the vaccine market very complex. The rise in such complexities often gives birth to numerous issues in the vaccine supply chain, which are the primary cause of its poor performance. Figuring out the cause of poor performance can help you decide how to address it. The main goal of chapter 4 is to identify and analyze important issues in the supply chain of basic vaccines required for child immunization in India also in other developing countries. From the field survey and literature review, 40 vaccine supply chain issues have been identified. The Delphi method that uses expert's opinion in decision-making has been employed for finalization of 25 key issues as factors of the vaccine supply chain. Using interpretive structural modeling (ISM) approach a hierarchical structure has been developed to show interrelationships among various issues. Then, using ISM and fuzzy matrix cross-reference multiplication applied to a classification (FMICMAC) methods, an integrated ISM-FMICMAC methodology is developed to classify the 25 key issues into four regions (based on their driving power and dependence). Finally, by integrating another two approaches ISM and fuzzy analytic network process (FANP), a new integrated ISM-FANP methodology is designed to prioritize the 25 key issues and five issues domain. Based on the results and discussion with the experts it has been found that six issues come in the region (out of four regions) of driving factors, whereas, economic issue domain is the most important domain. Further, three factors: better demand forecast, communication between the supply chain members, and proper planning and scheduling have been identified as the critical issues of the vaccine supply chain. The critical issues should be given special care to improve vaccine supply chain performance.

4.1. Introduction

The pharmaceutical industry is among the biggest industries in the world, and it has a direct influence on the quality of life of people in each country. The pharmaceutical industry is accountable for the development, production, advertising and marketing of medicines. Hence, its tremendous importance as a global sector is evident [259]. One of the main sectors of the pharmaceutical industry and its business drivers are the vaccine market [20]. The vaccine market is reasonably small and complex, but important and focused on each supply and demand sides.

It is very much regulated and dependent on public purchasers and donor policies. The business of vaccines is soon to come to be a leading source of earnings for the world's greatest pharmaceutical companies. *A press release published by marketwatch.com says that the pharmaceutical businesses who produce vaccines will reach an estimated $61 billion in profits by way of 2020* [260]. New vaccines are being introduced in the routine immunization programs of developing countries due to the rise in various infectious diseases. For example, India added four new vaccines; inactivated poliomyelitis vaccine (IPV) for polio, rotaviral vaccine, a vaccine against rubella, and Japanese encephalitis vaccine in its immunization program. In a similar way, other developing countries as Tanzania also included the bacillus calmette guerin (BCG), oral polio, diphtheria tetanus pertussis–hepatitis B–Haemophilus influenza type B (pentavalent), measles, and tetanus toxoid vaccines in the year 2012 in its expanded program on the immunization schedule. Likewise, in addition to these vaccines, Kenya administers a yellow fever vaccine to children in select districts and introduced the pneumococcal conjugate vaccine into routine immunization in 2011 [27,32]. As new, more refined and high-priced vaccines become available, many developing countries supply and logistics system, which was designed 40 years ago when vaccines were limited in number and very cheap are struggling to deliver the full schedule of WHO-recommended basic vaccines; resulting in low child immunization coverage [261,262].

Immunization currently prevents an estimated 2 to 3 million deaths each year. Another 1.5 million deaths could be evaded, nonetheless, if global immunization coverage improves. Approximately 19.4 million babies worldwide are still lacking out on basic vaccines [1]. In recent years, developing countries are facing the issue of low immunization coverage, the primary reason being inefficiencies in the vaccine supply chain. Successful immunization programs are constructed on efficient, end-to-end supply chain and logistics systems [5]. The vaccine supply chain, which incorporates all personnel, systems, equipment, and activities involved in making sure that vaccines are effectively delivered right from the stage of manufacturing to the people who need them. However, for several reasons, developing countries supply chains are already strained, and the possible inability to distribute new vaccines will position lives at risk [7].

Better logistics and supply systems are necessary to reach the millions of children in developing countries who are still not protected from vaccine-preventable diseases with basic vaccines. Many countries come across serious issues in vaccine supply and logistics, from an incapability to preserve vaccines at the correct temperature, to report retaining which allows community wellness employees to make sure the right vaccines reach the kids who need them. Of particular concern is that these issues have been reported for a substantial number of children who miss out on their prescribed vaccination schedules. These issues contribute to millions of cases of death from vaccine-preventable diseases, most of which occur in developing countries. The primary child immunization includes vaccines of bacillus calmette-guerin (BCG), diphtheria, pertussis, and tetanus (DPT), polio, and measles. Identification and proper management of important issues can help to improve immunization supply chain efficiencies thus improving the vaccines delivery performance. A report commissioned by project optimize on immunization supply system efficiency identified vaccine supply and logistics domain as one of the four important areas where knowledge and information gaps exist and need to be addressed [262]. Thus, the main aim of the present study is to identify the key issues in vaccine supply chain system of basic vaccines. Through the survey and systematic literature review, a total of 40 issues influencing vaccine supply and delivery were identified. Using the Delphi method 25 key issues have been finalized. Further, by ISM, a hierarchical structure of key issues has been developed to show interrelationships among them. Subsequently, ISM-FMICMAC methodology has been employed for the categorization of key issues into four domains, while the prioritization of key issues based on the weights has been done using ISM-FANP.

Out of the eight research objectives, this chapter focuses on four main objectives:

- ***To identify the key issues in the supply chain of basic vaccines required for the child immunization in India and other developing countries.***
- ***To establish interrelationships among the issues and classify the issues based on their driving power and dependence to help decision-makers differentiate between independent and dependent issues and their mutual relationships.***
- ***To prioritize the issues and its domain based on their relative importance in the vaccine supply chain to help decision-makers drive their efforts and resources on mitigating/eliminating the most important issues.***
- ***To figure out the critical issues which have maximum influence on vaccine supply chain performance.***

4.2. Proposed integrated framework

The flowchart of the proposed integrated framework consists of four phases that are depicted in Figure 4.1. The framework starts with the identification and finalization of key issues and further developing an interrelationship between these issues using field survey, literature review, Delphi, and ISM in Phase 1. In Phase 2, integrated ISM-FMICMAC is applied for the classification of the key issues into four main regions based on their driving power and dependence. In Phase 3, ISM-FANP methodology is applied for the prioritization of the key issues. Finally, in Phase 4, the critical issues of the vaccine supply chain have been identified.

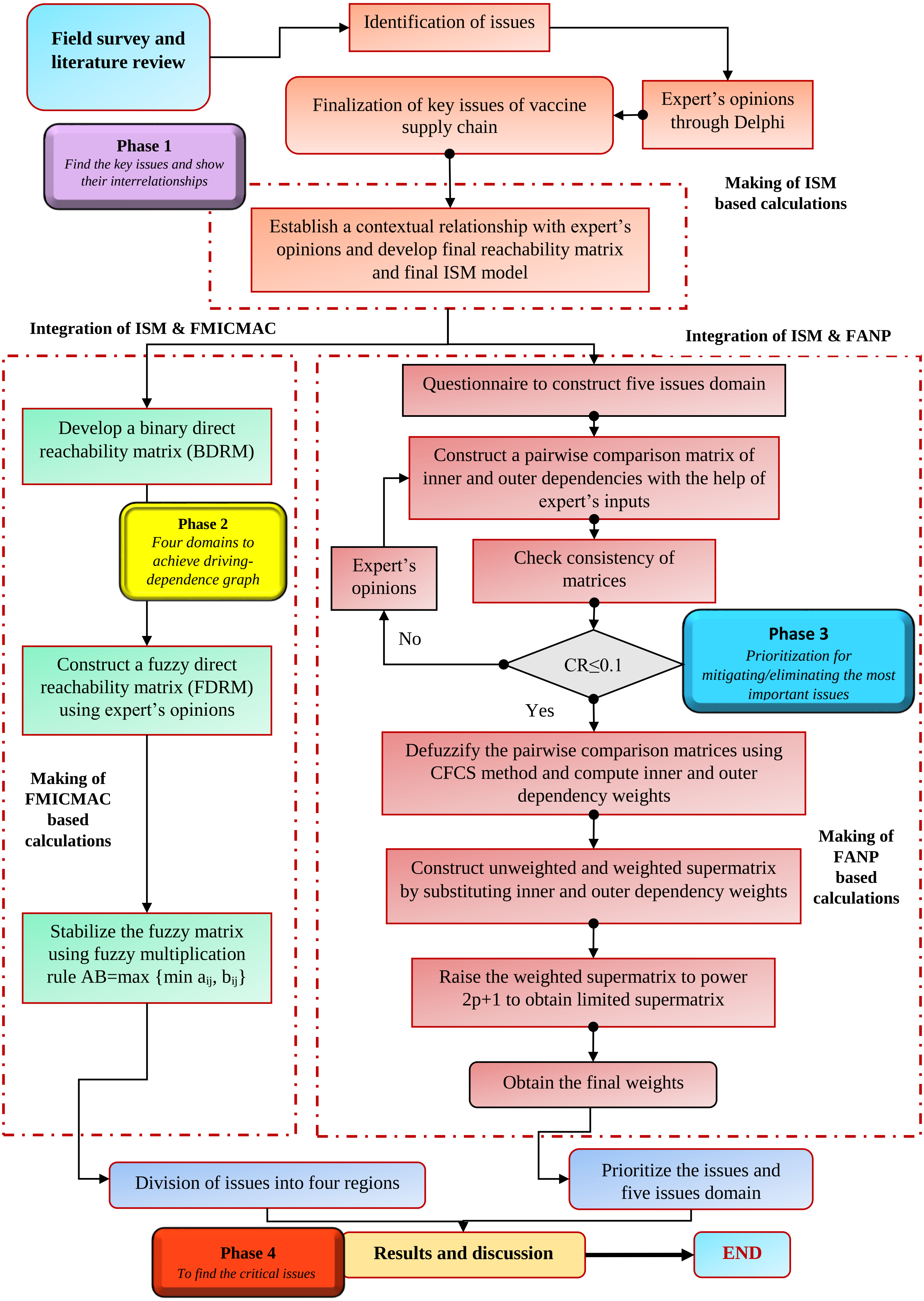


Figure 4.1: Flowchart of the proposed integrated framework.

4.3. Identification of VSC issues

4.3.1. Survey design and procedure

A survey was conducted in Nainital, a district of Uttarakhand, India. The district consists of 11 towns/SIHC (sub-immunization health center) where the vaccine has to be supplied by the district vaccine store or IHC (immunization health center) for the child immunization program. The IHC procure vaccines from the divisional store located in Rudrapur, which in turn procure vaccines from the state vaccine store at Dehradun. The vaccines to Dehradun is supplied by regional vaccine store at Chandigarh that purchase vaccines from the central level. Health workers, which consisted of senior immunization program officers, additional research officers, senior consultants, auxiliary nurse midwife (ANM), and Anganwadi workers were interviewed face-to-face at each vaccine store.

In addition to collecting data from 1 district and 1 divisional store, data was also collected from another divisional store of the state, i.e., Bageswar. Five survey experts of district vaccine store Nainital conducted the interviews. The sample questions asked to the health workers during the interview in each SIHC consisted: "what different issues you face in routine immunization from the stage of procuring the vaccine from the upper level (IHC) till vaccinating a child?" The similar questions were asked to the health workers of IHC, divisional and regional vaccines store. With the consent of the interviewee, the responses were recorded by the digital recorder and later transcribed with the word-processing document. The survey helped in identifying various problems being faced by the immunization program officials from the stage of purchasing until the delivery of vaccines.

4.3.2. Literature collection procedure

Through literature the material collection as one of the key steps of content analysis is employed in this study for collecting the material, defining and delimiting the unit of analysis [263]**.** For the evaluation and selection of the papers, the literature is searched according to the three criteria:

- The paper must be written in the English language and published in peer-reviewed journals covering the fifteen-year-period from 2001 to 2016.
- Paper focusing on immunization and vaccine supply chain issues of developing countries.
- White papers, presentations, and annual reports of important organizations working on human healthcare (e.g., WHO, UNICEF) and covering the five-year period from 2011-2016.

In a first step, databases for the study were selected which includes Elsevier, Springer, Scopus, Taylor & Francis Online, Inderscience, Ebsco, Mendeley, National Center for Biotechnology Information, and Web of Science due to the availability of high volume of indexed papers. Two important keywords of the study (vaccine and immunization) were performed on the databases, and eleven journals/libraries emerged and served as the basis for the literature survey. These are *Vaccine, Expert Review of Vaccines, Operations Research for Health Care, Chemical Engineering Research and Design, PubMed, PubMed Central, Biomed Central, IEE Pervasive Computing, Bulletin of the World Health Organization, Health Affairs,* and *National Journal of Community Medicine.* Additionally, Google search for white papers, presentations, and annual reports was also performed with the same keywords. Thus, websites/documents of important organizations: *WHO, WHO's EVM Tool, UNICEF, PATH, Project Optimize (the five years' collaborative project between WHO, PATH Institute and Gates Foundation), Ministry of Health & Family Welfare (Government of India), Centers for Disease Control and Prevention (CDC), Center for Global Development (CGD),* and *GAVI* were selected for the study.

In a second step, a broader search string with the keywords and their combination were employed in the selected journals/libraries and websites using the following filters: vaccine, vaccination, supply, chain, healthcare, health care (two words), delivery, developing countries, cold, issues, factors, and immunization. Based on three criteria for material collection, the method for the study analysis and collection was centered on four important phases: (i) read the paper title (ii) read the paper abstract and keywords, (iii) read its introduction and conclusion, and (iv) read the entire paper and select for study. By following the procedure for study analysis, 786 papers (including white papers, presentations, and reports) titles matched with the study and were retrieved. 515 papers (65.6%) had their abstract and keyword analyzed, while 298 papers (58.2% of the previous step) had been analyzed for introduction and conclusion and 47 papers were read and in the end selected, representing 15.77% of the beforehand chosen papers.

In a third step, bibliometric software *HistCite*^{TM} (version 12.3.17) was employed for getting some additional papers. The paper collection in the third step was centered on two phases. (i) select the papers cited in at least two manuscripts, and (ii) if the first phase of step 3 is fulfilled, based on three criteria add the selected paper to the final literature. By using the third step, none of the paper met the criteria for selection in the study. At last, 47 papers were finalized for the study. The 47 chosen ones (out of 786 papers) symbolize a yield of 5.97%. Figure 4.2 illustrates the literature extraction procedure.

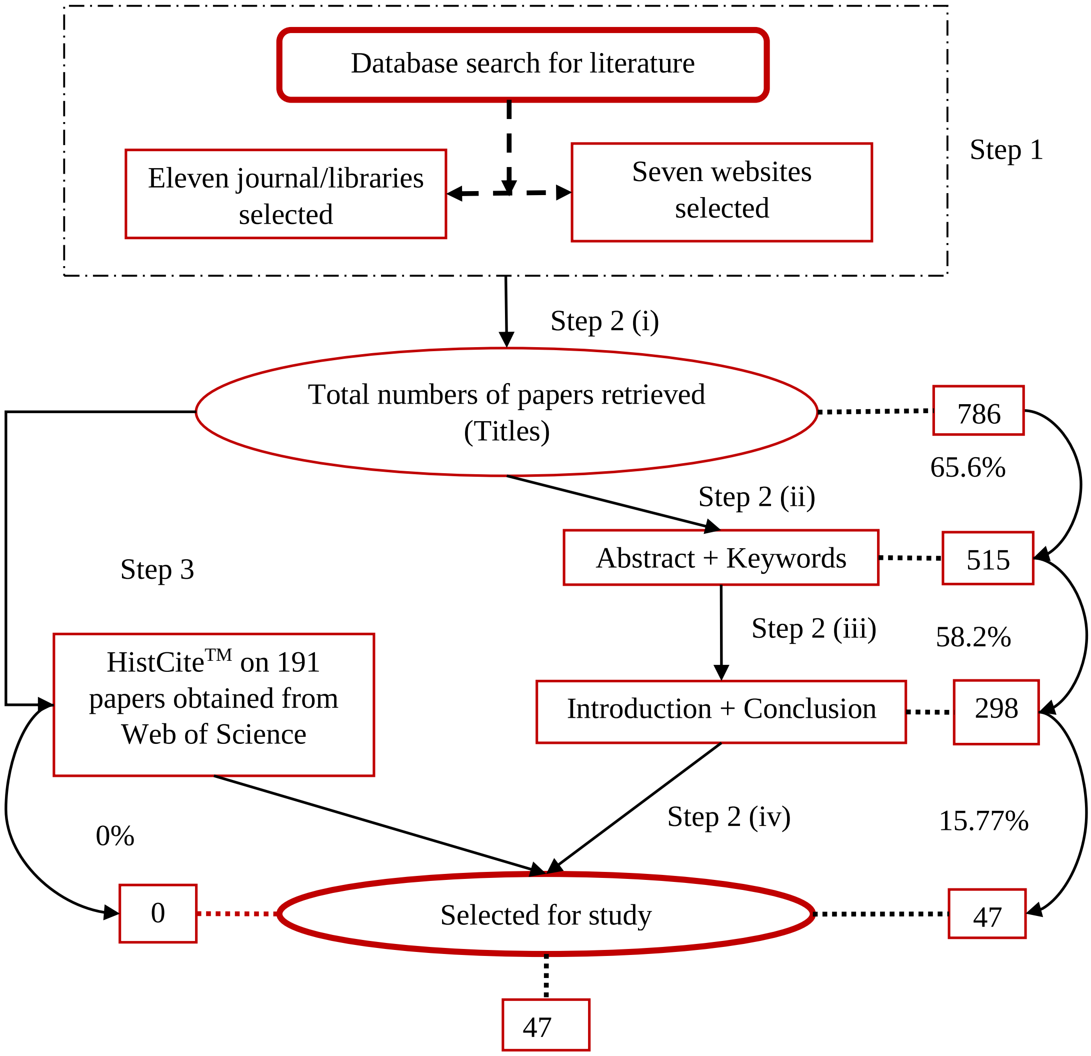


Figure 4.2: Literature extraction procedure for vaccine supply chain issues.

Hence, based on the field survey and literature review, 40 vaccine supply chain issues were identified, which are discussed in the next section.

4.4. A brief description of vaccine supply chain issues

Through field survey and literature, 40 issues in the vaccine supply chain were identified, which are discussed below.

4.4.1. *Immunization costs*

The costs consist of vaccine storage, transportation, salaries, and per diems. In many developing countries like India, there is a lack of technology and a proper mechanism to assess immunization costs. As a result, small issues that can make a significant impact on immunization costs are often ignored.

4.4.2. *Vaccine wastage*

Wastage of vaccine is one of the important issues faced globally. If storage and distribution methods usually are not sufficient, or if too much of the vaccine is ordered, valuable vaccines could eventually go waste.

4.4.3. *Demand forecast*

Vaccine and cold chain equipment forecasting is a necessary step to ensure adequate immunization supplies.

4.4.4. *Need to improve immunization program monitor indicators and gaps in data management*

It is important that immunization programs are monitored frequently and better data management techniques are also followed. This can help to measure and improve immunization programs performance and will ensure accurate data and information flows across the vaccine supply chain**.**

4.4.5. *Replenishment*

Poor replenishment process to refill the vaccine stock at the right time, right quantity, and at the right place is one of the issues faced by the immunization programs frequently. It is one of the important criteria that may help in vaccinating more children as a missed opportunity to vaccinate a child can be reduced by improving replenishment performance.

4.4.6. *Vaccine hesitancy*

Vaccine hesitancy is a complex issue, spreading rapidly globally that requires ongoing monitoring. It refers to delay or refusal in acceptance of vaccines despite its availability. Due to vaccine hesitancy, most of the vaccines go waste. Such wastages increase the manufacturing cost because of producing the same vaccine, which could have been utilized.

4.4.7. *Sustainable financing*

Financial incentives are necessary to protect the existing vaccine supplies, as well as to encourage the development of new vaccines.

4.4.8. *Temperature and exposure control*

The world health organization (WHO) recommends that childhood vaccines should be kept at a temperature of 2–8 °C. Exposure to high or low temperatures can damage the vaccine, thus creating an extra burden to the distributing agency.

4.4.9. *Availability of human resource*

The shortage of health workers in the immunization programs is identified as one of the most critical issues in the improvement of vaccination rates.

4.4.10. *Vaccination schedule*

One of the reasons that children miss the vaccine dose and many vaccines go waste in the supply chain is because the parents do not remember the childhood vaccination schedule. It is important, therefore, that the parents should be reminded of child vaccination schedule through SMS, mobile apps, etc.

4.4.11. *Monitoring of vaccinated population*

India still lacks a robust system for monitoring vaccine-preventable diseases. Better monitoring of coverage trends will help in proper forecasting of vaccines, and also to identify the potential for outbreaks of vaccine-preventable diseases.

4.4.12. *Inventory management*

A good inventory management strategy can improve the accuracy of inventory orders, a more organized warehouse, and save time and money.

4.4.13. *Vaccine shortages*

Vaccine shortages have been a frequent issue faced globally. Reasons for vaccine shortages are manufacturing or production problems, insufficient stockpile, transportation delays, vaccine wastages.

4.4.14. *Vaccine advocacy and education*

Advocacy and education for the immunization programs maintain the confidence of stakeholders and should be suitable for particular audiences, whether policymakers, industry or the community. It is important for the community to accept the new vaccine and also for maintaining their confidence in the existing vaccines.

4.4.15. *Monitoring of vaccine cold chain*

Cold chain monitoring for various vaccines and its equipment is necessary at every stage of the supply chain. Different vaccines have different sensitivity towards heat and freezing. This phenomenon makes it necessary to monitor the temperature of vaccines during storage and transportation.

4.4.16. *Disease and epidemiological dynamics*

The vaccine demand is dependent on the type of disease and how it propagates. Because of various sources of uncertainty to forecast the vaccine demand, for example, childbirth rate, vaccine immunization schedule, types of vaccines, etc. together with the rise in new diseases, it becomes difficult for immunization programs to know the actual demand and to carry out epidemiological investigations.

4.4.17. *Equity of humanitarian logistics*

The role of humanitarian logistics is to distribute vaccines and other important vaccines related materials to the required place and also in the case of an emergency. Equity is an equality measure that attempts to satisfy the same percentage of each demand node by avoiding humanitarian aid to be delivered only to the more accessible areas and hard-to-reach areas to be neglected. In India and other developing countries, often it is observed that humanitarian logistics is weak in rural and remote areas as compared to urban areas. It is important that equity should be maintained in human logistics as they are the one responsible to deliver vaccines effectively and efficiently and for administering vaccines to the children.

4.4.18. *Coordination with local administration*

Coordination with local government will help the immunization program managers to communicate easily with the local people. It will revamp the connections between people and service to improve outcomes for individuals, families, communities, and societies.

4.4.19. *Vaccine supply quality*

An important issue is the quality of vaccines administered in India. In a universal immunization program for routine immunizations, most of the vaccines are procured from the manufacturers which are not WHO prequalified. It must be ensured that the supply of vaccines should be of high quality, reliable and affordable. According to WHO, the only vaccine of assured quality should be regarded for use in national immunization programs by the risk/benefit ratio for the precise population.

4.4.20. *Storage and handling of vaccines*

Vaccines must be stored and handled properly right from the stage of manufacturing until they are administered.

4.4.21. *Geographical barriers*

In most of the areas, especially the rural where the facilities are limited, it becomes tough for the health care workers to reach the location point for administering the vaccines.

4.4.22. *Risk of natural/unnatural causes*

Natural causes like earthquakes, floods, landslides, rain, etc. and unnatural causes like terrorism, fast developing epidemics, etc. can make the delivery of vaccines difficult, thus causing disruptions in immunization programs.

4.4.23. *Responsiveness*

Quick response enables the supply chain to meet customer demands with shorter lead times.

4.4.24. *Transportation disruption*

Disruptions in transportation due to any external/internal cause have a great impact on vaccine supply chain performance as a time to deliver vaccines may get affected.

4.4.25. *Planning and scheduling*

Proper planning helps in reducing uncertainties as it involves anticipation of the future. Running a vaccine supply chain requires proper planning and scheduling, the two key elements of the effective immunization program.

4.4.26. *Communication between the supply chain members*

It has been found from the study that the communication between the upper and lower level of vaccine supply chain members is almost negligible. This lack of communication often results in the mismatch between the supply and demand of vaccines.

4.4.27. *Inadequate or lacking safeguards*

Safety during vaccine administering, delivering vaccination products to the health centers, together with the safety of the health workers is important for gaining the confidence of parents and health workers in vaccinations programs and also for the social sustainability development of immunization programs.

4.4.28. *Location of vaccine stores and immunization camp*

From the survey, it has been found that the place given to the healthcare workers for storing the vaccines on the vaccination day is very far from the immunization camp where the vaccines are to be administered to the children. As the location is very far, there are chances that the ILRs (ice-lined refrigerators) on which the vaccines are kept may get damaged during travel, thus resulting in vaccine wastages.

4.4.29. *Lack of system checks*

It is important that vaccinate systems are checked for accuracy, and properly prepared vaccine in order to improve vaccine delivery performance and quality of vaccines. However, few developing countries still lack proper system checks, which results in inaccurate data and information flow.

4.4.30. *Order visibility*

Due to less technological applications in the vaccine supply chain, it becomes challenging for the immunization programs to track the exact order status and locations of vaccine products in the supply chain.

4.4.31. *Disaster/emergency management*

Immunization programs should be well prepared in advance to manage regular child immunization programs in case of an outbreak like a disaster or emergency. However, in India and other developing countries, such as a disaster or emergency management training are given less importance due to which regular immunization programs can get affected. For example, a sudden outbreak due to flu in 2018 in many developing and developed countries caused Hepatitis B vaccine shortage and also affected the child immunization programs.

4.4.32. *Cold chain vehicles*

The optimum number of cold chain vehicles will overcome delivery problems. The coverage area can also be improved if there are an optimum number of cold chain vehicles.

4.4.33. *Vaccine regulatory management*

New regulations imposed on the vaccine by the government at any point in time makes it difficult for the immunization program officials to plan its proper demand and supply.

4.4.34. *Disability-adjusted life years (DALY)*

One DALY represents one year of life lost due to illness or death. Considering DALY during vaccination programs can help in gaining the trust and confidence of parents towards immunization. For example, the sale of 1,000 pre-packed treatment (PPT) for pneumonia in Mali averts 207 DALY or 207 years of a healthy life, that would have been lost without PSI's intervention.

4.4.35. *Yield uncertainty*

In the supply chain, yield uncertainty refers to a type of operational issue with respect to the supply side in which often high profit-maximizing manufacturers under-produces the quantity ordered, resulting in supply shortages. The example of yield uncertainty is a shortage of influenza vaccines across the globe in 2018.

4.4.36. *Inadequate response to temperature excursions*

Temperature excursion is necessary to maintain the quality of vaccine products. Hence, it's important that the concept of temperature excursion, its reasons, outcomes, and dealing mechanism should be well imparted to the health workers through the quality management system.

4.4.37. *Flexibility*

It is necessary that the vaccine supply chain have greater flexibility in order to deal with changes such as sudden vaccine demand, differing supplier lead-time, quality of vaccine products, etc.

4.4.38. *Procurement lead-time*

There is a substantial lack of coordination between those people and organization who procure vaccines for shipments to developing countries and storekeepers to supply chain managers who are in charge of receiving and distribution. This lack of coordination often results in an increase in procurement lead-time.

4.4.39. *Facility disruptions*

Facility disruptions are one of the issues that a vaccine supply chain can experience. Past studies have highlighted that due to such disruptions, vaccines have been out of stock at regional, state and district vaccine level stores. It is important to improve the reliabilities of such facilities to improve VSC performance.

4.4.40. *Lack of confidence in vaccination programs*

Confidence in benefit of the vaccination programs is an important component of child health programs to deliver life-saving vaccines. Lack of confidence in vaccination programs is one of the issue mostly faced in the low-and-middle-income countries, due to which often the children are completely unvaccinated, resulting in higher child mortality and morbidity rates.

4.5. Finalization of key issues of VSC using the Delphi approach

To identify the key issues from the list of 40 issues, this research included a three-round Delphi e-survey discussed below [139,231,264].

Round 1: The process starts with the selection of vaccine supply chain experts. The panelists had been carefully decided on the basis of their strong knowledge and experience of the subject. Each chosen expert has greater than 10 years of expertise and is well familiar with problems of the vaccine supply chain. Of the potential 34 experts who received an invitation and reminders, 27 agreed to participate in the study in which 23-member panel participated until the final round. The twenty-three expert's team consisted of one head officer of UIP, Nainital as a senior expert, ten additional research officer, and twelve senior consultants.

Round 2: In the second round, the agreed participants (N=27) were emailed a questionnaire prepared in '*Google Forms'* containing a list of 40 issues identified in the survey and literature review. It required approximately ten minutes to complete the questionnaire. The questions had been phrased as follows: "Do you agree that the factor vaccine wastage should be considered as a vaccine supply chain issue?" The experts were asked to rate each of the questions on a 5-point Likert scale (1=strongly disagree, 2=disagree, 3=neutral, 4=agree, 5=strongly agree). With two respondent reminders, panel members (N=23) replied to the questionnaire. Cronbach's alpha (α) was applied to test the reliability of the questionnaire. If α is near 0 then the quantified answers are not any secure at all, and if it is close to 1 the solutions are very secure [265]. As a thumb rule, if $\alpha \geq 0.7$, then the solutions are considered risk-free [266]. The statistical package for the social sciences (SPSS) V.23.0 was used to perform the statistical analysis. The Cronbach's alpha was 0.710, which is acceptable and is therefore viewed as reliable. Then a consensus score was calculated based on the responses received from the expert. Barnes and Mattsson; Walker et al. [140,267] Suggest that consensus can be achieved on a question to question basis if more than 70% of the respondents rate them positively (above neutral) and where the median is more than neutral. Thus for the selection of issues, two selection criteria were applied: at least 70% experts should consider the issue important (rated as 4 or 5) and the mean and median score of the responses for each issue should be at least 4.00. Hence, by following the selection criteria, from the list of 40 issues, the stage 2 of the process returned a consensus-level agreement on 29 issues (mean and median score >4.00) presented in Table 4.1.

Table 4.1: Ranking of 40 issues with their percentage response, median and mean (Second round).

Issues	Response					4 & 5	Median	Mean	SD	Consensus level
	1	2	3	4	5	(%)				
Demand forecast	0	0	0	9	14	100	5	4.61	0.49	Consensus achieved
Vaccine shortages	0	0	1	8	14	96	5	4.57	0.58	Consensus achieved
Planning and scheduling	0	0	1	8	14	96	5	4.57	0.58	Consensus achieved
Vaccine wastage	0	0	0	11	12	100	5	4.52	0.50	Consensus achieved
Inventory management	0	1	1	9	12	91	5	4.39	0.77	Consensus achieved
Vaccine advocacy and education	0	1	1	9	12	91	5	4.39	0.77	Consensus achieved
Communication between the supply chain members	0	1	0	11	12	96	4	4.39	0.71	Consensus achieved
Coordination with local administration	0	1	2	9	11	87	4	4.30	0.80	Consensus achieved
Sustainable financing	0	0	2	12	9	91	4	4.30	0.62	Consensus achieved
Availability of human resource	0	0	4	8	11	83	4	4.30	0.75	Consensus achieved
Geographical barriers	0	2	2	7	12	83	5	4.26	0.94	Consensus achieved
Monitoring of vaccine cold chain	1	0	1	12	9	91	4	4.22	0.88	Consensus achieved
Immunization costs	0	1	1	14	7	91	4	4.17	0.70	Consensus achieved
Monitoring of vaccinated population	1	2	0	11	9	87	4	4.09	1.06	Consensus achieved
Transportation disruptions	1	2	2	7	11	78	4	4.09	1.14	Consensus achieved
Procurement lead-time	0	2	2	11	8	83	4	4.09	0.88	Consensus achieved
Storage and handling of vaccines	0	0	5	11	7	78	4	4.09	0.72	Consensus achieved
Vaccine regulatory management	0	2	2	11	8	83	4	4.09	0.88	Consensus achieved
Risk of natural/unnatural causes	0	3	2	9	2	78	4	4.04	1.00	Consensus achieved
Temperature and exposure control	0	3	1	11	8	83	4	4.04	0.95	Consensus achieved
Cold chain vehicles	2	1	1	9	10	83	4	4.04	1.20	Consensus achieved
Vaccine supply quality	0	3	2	10	8	78	4	4.00	0.98	Consensus achieved
Location of vaccine stores and immunization camp	1	3	1	8	10	78	4	4.00	1.18	Consensus achieved
Vaccine hesitancy	1	1	1	14	6	87	4	4.00	0.93	Consensus achieved
Responsiveness	2	1	2	8	10	78	4	4.00	1.22	Consensus achieved

Table 4.1 (continued): Ranking of 40 issues with their percentage response, median and mean (Second round).

Issues	Response					4 & 5	Median	Mean	SD	Consensus level
	1	2	3	4	5	(%)				
Need to improve immunization program monitor indicators and gaps in data management	0	2	5	7	9	70	4	4.00	0.98	Consensus achieved
Replenishment	0	2	4	9	8	70	4	4.00	0.93	Consensus achieved
Facility disruptions	0	1	6	8	8	70	4	4.00	0.88	Consensus achieved
Order visibility	0	4	1	9	9	78	4	4.00	1.06	Consensus achieved
Disaster/emergency management	1	1	7	4	0	61	4	3.91	1.14	Consensus not achieved
Disability-Adjusted Life Years (DALY)	1	4	7	4	7	48	3	3.52	1.21	Consensus not achieved
Flexibility	5	0	6	8	4	52	4	3.26	1.36	Consensus not achieved
Disease and epidemiological dynamics	7	8	5	3	0	13	2	2.17	1.01	Consensus not achieved
Equity of humanitarian logistics	9	9	0	5	0	22	2	2.04	1.12	Consensus not achieved
Yield uncertainty	9	9	2	3	0	13	2	1.96	1.00	Consensus not achieved
Vaccination schedule	11	7	0	5	0	22	2	1.96	1.16	Consensus not achieved
Lack of system checks	9	11	0	3	0	13	2	1.87	0.95	Consensus not achieved
Inadequate or lacking safeguards	9	11	1	2	0	9	2	1.83	0.87	Consensus not achieved
Inadequate response to temperature excursions	10	9	3	1	0	4	2	1.78	0.83	Consensus not achieved
Lack of confidence in vaccination programs	14	7	0	2	0	9	1	1.57	0.88	Consensus not achieved

Round 3: In the third round, the same twenty-three Delphi panelist were sent a questionnaire that includes the issues and the individual response of the experts in the preceding round and were asked to revise or remain fixed to his/her judgments. After repeated mailing and follow up all the 23 experts responded to the questionnaire. To achieve the consensus the same procedure was followed as mentioned in stage 2. After following the selection criteria, 4 issues (replenishment, need to improve immunization program monitor indicators and gaps in data management, facility disruptions, order visibility) from the list of 29 issues got a low mean score (<4.00), hence they were discarded from the list. In this way, the third stage of the process narrowed down the list from 29 issues to 25, which is shown in Table 4.2. We also validated the degree of consensus among the experts using Kendall's coefficient of concordance (W). The coefficient provides a measure of the consensus among the raters [268]. Kendall's coefficient of concordance ranges from 0 to 1, indicating the degree of consensus reached by the panel (strong consensus for $W > 0.7$; moderate consensus for $W = 0.5$; and weak consensus for $W < 0.3$) [269]. SPSS version 23.0 was employed for calculating the Kendell's (W) and the results were within the acceptable range (N=23, W=0.714, Sign=0.000). The Cronbach's alpha for the 25 issues was 0.713, which is acceptable and shows that the issues are reliable and can be considered for the study.

Since the experts (not the researchers) were those choosing the most important issues [270]***, hence no further steps were utilized in order reduce the number of issues and 25 issues were finalized as key issues for the study.***

Further, an online survey questionnaire was designed for the vaccine supply chain experts of various developing countries to validate our results in order to know whether the key issues taken for the study are relevant or not. The questionnaire was designed in English, as it is the most commonly used official language for communication in various countries. It consisted of 25 questions dealing with the vaccine supply chain issues as identified by the Delphi method. The sample questions consist of "How important do you think the issue 'vaccine wastage' can be considered as vaccine supply chain issue". Moreover, each question was evaluated on the 5-point scale in such a way that it would be one of the scales of "not important" (1) to "very important" (5).

The questionnaire was developed in 'Google Forms' and it required approximately eight minutes to complete the questionnaire. It was sent by e-mail to immunization program centers in twenty developing countries. After repeated mailing and follow-up, we received 14 responses, which were analyzed for the final study. Cronbach's alpha was 0.730, which is acceptable and shows that the issues are reliable and can be considered for the study.

Table 4.2: Ranking of 29 issues with their percentage response, median and mean (third round).

Issues	Response					4 & 5	Median	Mean	SD	Consensus level
	1	2	3	4	5	(%)				
Demand forecast	0	0	0	7	16	100	5	4.70	0.46	Consensus achieved
Vaccine wastage	0	0	0	7	16	100	5	4.70	0.46	Consensus achieved
Vaccine shortage	0	0	0	8	15	100	5	4.65	0.48	Consensus achieved
Planning and scheduling	0	0	0	9	14	100	5	4.61	0.49	Consensus achieved
Communication between the supply chain members	0	0	1	10	12	96	5	4.48	0.58	Consensus achieved
Monitoring of vaccine cold chain	0	0	0	12	11	100	4	4.48	0.50	Consensus achieved
Vaccine advocacy and education	0	0	2	9	12	91	5	4.43	0.65	Consensus achieved
Inventory management	0	1	0	10	12	96	5	4.43	0.71	Consensus achieved
Availability of human resource	0	0	2	9	12	91	5	4.43	0.65	Consensus achieved
Coordination with local administration	0	1	1	9	12	91	5	4.39	0.77	Consensus achieved
Sustainable financing	0	0	2	12	9	91	4	4.30	0.62	Consensus achieved
Geographical barriers	0	2	1	8	12	87	5	4.30	0.91	Consensus achieved
Transportation disruptions	1	1	1	9	11	87	4	4.22	1.02	Consensus achieved
Storage and handling of vaccines	0	0	3	13	7	87	4	4.17	0.64	Consensus achieved
Vaccine hesitancy	1	1	1	10	10	87	4	4.17	1.01	Consensus achieved
Procurement lead-time	0	2	1	12	8	87	4	4.13	0.85	Consensus achieved
Immunization costs	0	1	3	12	7	83	4	4.09	0.78	Consensus achieved
Vaccine regulatory management	0	2	2	11	8	83	4	4.09	0.88	Consensus achieved
Vaccine supply quality	0	2	2	11	8	83	4	4.09	0.88	Consensus achieved
Risk of natural/unnatural causes	0	3	2	9	9	78	4	4.04	1.00	Consensus achieved
Temperature and exposure control	0	3	1	11	8	83	4	4.04	0.95	Consensus achieved
Cold chain vehicles	2	1	1	9	10	83	4	4.04	1.20	Consensus achieved
Location of vaccine stores and immunization camp	1	3	1	7	11	78	4	4.04	1.20	Consensus achieved
Responsiveness	2	1	2	7	11	78	4	4.04	1.23	Consensus achieved
Monitoring of vaccinated population	1	2	2	9	9	78	4	4.00	1.10	Consensus achieved
Replenishment	0	1	8	6	8	61	4	3.91	0.93	Consensus not achieved
Need to improve immunization program monitor indicators and gaps in data management	0	4	4	7	8	65	4	3.83	1.09	Consensus not achieved
Facility disruptions	0	4	4	8	7	65	4	3.78	1.06	Consensus not achieved
Order visibility	0	4	5	8	6	61	4	3.70	1.04	Consensus not achieved

Finally, after the validation of results, 25 key issues as factors of the vaccine supply chain were selected that are shown in Table 4.3.

Table 4.3: Key issues in vaccine supply chain.

Issue/factor	Denotation
Immunization costs	1
Temperature and exposure control	2
Vaccine wastage	3
Vaccine hesitancy	4
Demand forecast	5
Sustainable financing	6
Procurement lead-time	7
Transportation disruptions	8
Availability of human resource	9
Monitoring of vaccinated population	10
Vaccine regulatory management	11
Inventory management	12
Vaccine shortages	13
Vaccine advocacy and education	14
Monitoring of vaccine cold chain	15
Coordination with local administration	16
Storage and handling of vaccines	17
Responsiveness	18
Geographical barriers	19
Risk of natural/unnatural causes	20
Vaccine supply quality	21
Planning and scheduling	22
Communication between the supply chain members	23
Cold chain vehicles	24
Location of vaccine stores and immunization camp	25

4.6. Modeling of VSC issues using ISM

In this section, VSC issues have been analyzed to develop a hierarchical structure and show interrelationships among the issues using the ISM approach. Various steps involved in the ISM process are:

4.6.1. *Development of structural self-interaction matrix (SSIM)*

To develop the SSIM, a structural self-interaction matrix sheet without notation was once given to twenty-three experts. Guidelines for filling the SSIM sheet are given below:

- Use symbol V if the factor i has an influence on factor j.
- Use symbol A if the factor j has an influence on factor i.
- Use symbol X if both the factors i and j has an influence on each other.
- Use symbol O if there is no relation to the factors.

The responses had been then discussed with each expert, and a final matrix was performed, reflecting the expert's consensus centered on their judgment. The SSIM is presented in Table 4.4.

Table 4.4: Structural self-interactive matrix (SSIM).

Factors	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2
1	O	A	O	O	O	A	A	A	O	O	A	O	A	A	O	A	A	O	O	X	O	O	A	A
2	O	O	O	A	O	O	O	O	O	O	A	A	V	O	O	O	O	O	O	A	O	O	V	
3	A	A	A	A	A	A	A	A	A	O	A	A	V	A	O	A	O	A	O	O	A	A		
4	O	O	O	O	O	O	O	O	O	A	O	A	O	O	O	V	O	O	O	O	O			
5	O	O	A	A	O	O	O	O	O	O	O	O	V	V	O	V	O	O	O	O				
6	V	V	V	O	O	O	O	V	V	V	V	V	V	O	O	V	V	V	O					
7	O	O	O	A	O	A	A	A	O	O	O	O	V	V	O	V	O	A						
8	O	A	A	A	O	A	A	A	O	A	A	O	V	A	O	V	O							
9	O	O	O	V	O	O	O	V	V	V	V	O	O	O	O	V								
10	A	A	A	A	A	A	A	A	A	A	A	A	A	O	A									
11	O	O	O	O	V	O	O	O	O	A	A	O	V	O										
12	O	O	A	A	V	O	O	O	V	O	O	A	V											
13	O	O	O	A	X	A	O	V	O	O	A	O												
14	O	O	O	O	O	O	O	O	V	V	V													
15	O	O	O	A	O	O	O	O	O	O														
16	V	O	O	A	O	O	O	O	O															
17	O	O	O	A	O	O	O	O																
18	O	O	A	A	O	A	A																	
19	V	O	O	O	O	A																		
20	O	O	O	O	O																			
21	O	O	A	A																				
22	O	O	V																					
23	O	O																						
24	O																							

4.6.2. *Development of reachability matrix*

The symbols of SSIM (V, A, X, and O) are now changed into a binary matrix, called the initial reachability matrix (IRM) based on the rules discussed below:

- If the SSIM contains symbol V in the cell (i, j), then this entry turns into 1 within the cell (i, j) and the cell (j, i) becomes 0 in the IRM.

- If the SSIM contains symbol A in the cell (i, j), then this entry turns into 0 within the cell (i, j) and the cell (j, i) becomes 1 in the IRM.

- If the SSIM contains symbol X in the cell (i, j), then this entry turns into 1 within the cell (i, j) and the cell (j, i) also becomes 1 in the IRM.

- If the SSIM contains symbol O in the cell (i, j), then this entry turns into 0 within the cell (i, j) and the cell (j, i) also becomes 0 in the IRM.

The initial reachability matrix is developed based on the above rules and is presented in Table 4.5. If the factor i leads to j and the factor j leads to k, then factor i must lead to factor k. This process of bridging the gaps between the factors is known as transitivity check. For the transitivity check, Warshall's Algorithm is used. After incorporating the transitivity check, a final reachability matrix (FRM) is shown in Table 4.6. In the FRM, transitivity is marked as 1*.

Table 4.5: Initial reachability matrix (IRM).

Factors	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
3	1	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	1	0	1	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
6	1	1	0	0	0	1	0	1	1	1	0	0	1	1	1	1	1	1	0	0	0	0	1	1	1
7	0	0	0	0	0	0	1	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	1	0	0	0	1	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
9	1	0	0	0	0	0	0	0	1	1	0	0	0	0	1	1	1	1	0	0	0	1	0	0	0
10	1	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0
12	1	0	1	0	0	0	0	1	0	0	0	1	1	0	0	0	1	0	0	0	1	0	0	0	0
13	1	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	1	0	0	1	0	0	0	0
14	0	1	1	1	0	0	0	0	0	1	0	1	0	1	1	1	1	0	0	0	0	0	0	0	0
15	1	1	1	0	0	0	0	1	0	1	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0
16	0	0	0	1	0	0	0	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1
17	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
18	1	0	1	0	0	0	1	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
19	1	0	1	0	0	0	1	1	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1
20	1	0	1	0	0	0	1	1	0	1	0	0	1	0	0	0	0	1	1	1	0	0	0	0	0
21	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0
22	0	1	1	0	1	0	1	1	0	1	0	1	1	0	1	1	1	1	0	0	1	1	1	0	0
23	0	0	1	0	1	0	0	1	0	1	0	1	0	0	0	0	0	1	0	0	1	0	1	0	0
24	1	0	1	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
25	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Table 4.6: Final reachability matrix (FRM).

Factors	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	1	0	0	0	0	1	0	1*	1*	1*	0	0	1*	1*	1*	1*	1*	1*	0	0	0	0	1*	1*	1*
2	1	1	1	0	0	1*	0	0	0	1*	0	0	1	0	0	0	0	1	0	0	1*	0	0	0	0
3	1	0	1	0	0	1*	0	0	0	1*	0	0	1	0	0	0	0	1	0	0	1*	0	0	0	0
4	1*	0	1	1	0	0	0	0	0	1	0	0	1*	0	0	0	0	0	0	0	0	0	0	0	0
5	1*	0	1	0	1	0	0	1*	0	1	0	1	1	0	0	0	1*	1*	0	0	1*	0	0	0	0
6	1	1	1*	1*	1*	1	1*	1	1	1	1*	1*	1	1	1	1	1	1	0	0	1*	0	1	1	1
7	1*	0	1	0	0	0	1	1*	0	1	0	1	1	0	0	0	1*	1*	0	0	1*	0	0	0	0
8	1*	0	1	0	0	0	1	1	0	1	0	0	1	0	0	0	0	0	0	0	1*	0	0	0	0
9	1	1*	1*	1*	1*	1*	1*	1*	1	1	1*	1*	1*	0	1	1	1	1	0	0	1*	1	0	0	1*
10	1	0	1	0	0	1*	0	0	0	1	0	0	1*	0	0	0	0	0	0	0	0	0	0	0	0
11	1*	0	1*	0	0	0	0	0	0	1	1	0	1	0	0	0	0	1*	0	0	1	0	0	0	0
12	1	0	1	0	0	1*	0	1	0	1	0	1	1	0	0	0	1	0	0	0	1	0	0	0	0
13	1	0	1*	0	0	1*	1*	1*	0	1	0	0	1	0	0	0	0	1	0	0	1	0	0	0	0
14	1*	1	1	1	0	0	0	1*	0	1	1*	1	1*	1	1	1	1	0	0	0	1*	0	0	0	1*
15	1	1	1	0	0	1*	1*	1	0	1	1	0	1	0	1	0	0	0	0	0	1*	0	0	0	0
16	1*	0	1*	1	0	0	1*	1	0	1	1	0	1*	0	0	1	0	0	0	0	1*	0	0	0	1
17	1*	0	1	0	0	0	0	0	0	1	0	0	1*	0	0	0	1	0	0	0	0	0	0	0	0
18	1	0	1	0	0	1*	1	1	0	1	0	1*	1*	0	0	0	0	1	0	0	0	0	0	0	0
19	1	0	1	0	0	1*	1	1	0	1	0	1*	1*	0	0	0	0	1	1	0	0	0	0	0	1
20	1	0	1	0	0	1	1	1	0	1	0	1	1	0	0	0	0	1	1	1	1*	0	0	0	1*
21	1*	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0
22	1*	1	1	1*	1	0	1	1	0	1	1*	1	1	0	1	1	1	1	0	0	1	1	1	0	1*
23	1*	0	1	0	1	0	1*	1	0	1	0	1	1*	0	0	0	1*	1	0	0	1	0	1	0	0
24	1	0	1	0	0	1*	1*	1	0	1	0	0	1*	0	0	0	0	0	0	0	0	0	0	1	0
25	1*	0	1	0	0	0	0	0	0	1	0	0	1*	0	0	0	0	0	0	0	0	0	0	0	1

4.6.3. ***Level partition and Canonical matrix***

The final reachability matrix is used for developing the reachability and antecedent sets for each factor. The reachability set for any factor is obtained after collection all the ones from its row. Whereas, the antecedent set is obtained after collecting all the ones from its column. The elements that are similar in reachability and antecedent sets are placed in the intersection set. If the elements in the reachability set and intersection set are common, then that factor occupies the topmost level (Level I group). These factors are now excluded while forming the next set of tables. This procedure is repeated until finding all the levels for each factor. All these levels are made use in constructing a digraph and further its ISM model. This process is completed in twelve iterations and is shown in Table 4.7. Further, a canonical matrix which is a lower triangular matrix is developed by placing all the factors together in the same level, throughout rows and columns of the FRM. Table 4.8 shows the canonical matrix.

4.6.4. ***Development of final ISM model***

The structural model is produced by the level partitioning of the factors and the FRM (Table 4.6). If the factors i and j have any relationship, this is appeared by using an arrow which aspects from i to j. This graph is called a directed graph, or digraph. By removing the transitivity among the factors, the digraph is at last changed over into the ISM-based model as shown in Figure 4.3.

Table 4.7: Iterations with the level of factors.

Factor	Reachability set	Antecedent set	Intersection set	Level
1	1,6,8,9,10,13,14,15, 16,17,18,23,24,25	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25	1,6,8,9,10,13,14,15,16,17,18,23,24,25	1
10	1,3,6,10,13	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25	1,3,6,10,13	1
13	1,3,6,7,8,10,13,18,21	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25	1,3,6,7,8,10,13,18,21	1
3	3,6,18,21	2,3,4,5,6,7,8,9,11,12,14,15,16,17,18, 19,20,21,22,23,24,25	3,6,18,21	2
21	3,21	2,3,5,6,7,8,9,11,12,14,15,16,20,21,22,23	3,21	2
4	4	4,6,9,14,16,22	4	3
8	7,8	5,6,7,8,9,12,14,15,16,18,19,20,22,23, 24	7,8	3
17	17	5,6,7,9,12,14,17,22,23	17	3
25	25	6,9,14,16,19,20,22,25	25	3
12	6,12	5,6,7,9,12,14,18,19,20,22,23	6,12	4
18	6,7,18	2,5,6,7,9,11,18,19,20,22,23	6,7,18	5
5	5	5,6,9,22,23	5	6
7	7	6,7,9,15,16,19,20,22,23,24	7	6
11	11	6 9 11 14 15 16 22	11	6
16	16	6,9,14,16,22	16	7
23	23	6,22,23	23	7
24	6,24	6,24	6,24	7
6	2,6,9,15	2,6,9,15,19,20	2,6,9,15	8
2	2	2,9,14,15,22	2	9
19	19	19,20	19	9
15	15	9,14,15,22	15	10
20	20	20	20	10
14	14	14	14	11
22	9,22	9,22	9,22	11
9	9	9	9	12

Table 4.8: Canonical matrix.

Factors	1	10	13	3	8	21	18	6	7	12	17	25	11	2	4	15	16	5	23	9	14	24	19	22	20	DP
4	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	**5**
10	1	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**5**
17	1	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**5**
21	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**5**
25	1	1	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	**5**
3	1	1	1	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**7**
8	1	1	1	1	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**7**
11	1	1	1	1	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	**7**
2	1	1	1	1	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	**8**
24	1	1	1	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	**8**
12	1	1	1	1	1	1	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**9**
13	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**9**
18	1	1	1	1	1	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**9**
5	1	1	1	1	1	1	1	0	0	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	**10**
7	1	1	1	1	1	1	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**10**
15	1	1	1	1	1	1	0	1	1	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	**11**
16	1	1	1	1	1	1	0	0	1	0	0	1	1	0	1	0	1	0	0	0	0	0	0	0	0	**11**
19	1	1	1	1	1	0	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	**11**
23	1	1	1	1	1	1	1	0	1	1	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	**12**
20	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	1	0	1	**13**
1	1	1	1	0	1	0	1	1	0	0	1	1	0	0	0	1	1	0	1	1	1	1	0	0	0	**14**
14	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	0	0	0	1	0	0	0	0	**15**
22	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1	0	**19**
9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	1	0	**20**
6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	**22**
DEP.	**25**	**25**	**25**	**24**	**17**	**17**	**14**	**13**	**13**	**11**	**10**	**9**	**7**	**6**	**6**	**6**	**6**	**5**	**4**	**3**	**3**	**3**	**2**	**2**	**1**	

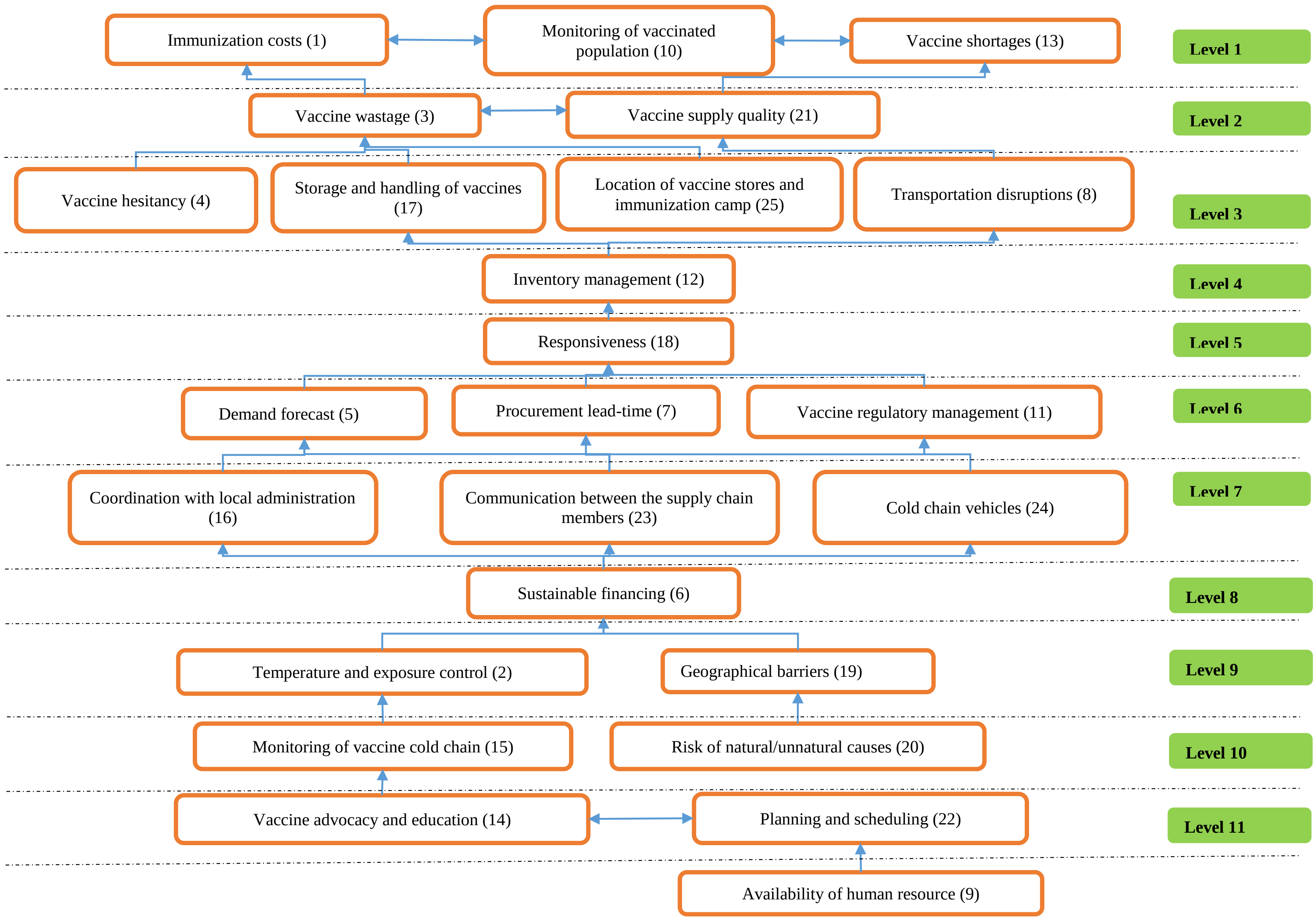


Figure 4.3: ISM-based model for vaccine supply chain key issues.

4.7. Analysis of key issues using integrated ISM-FMICMAC methodology

In ISM the indirect relationships between the factors are not revealed. Therefore, MICMAC is needed to further improve the ISM by evaluating indirect relationships. Duperrin and Godet in 1973 introduced MICMAC to study the role and behavior and to analyze the inter-relationships among the factors. MICMAC (Matrice d'Impacts Croisés Multiplication Appliquée á un Classement, i.e., cross-impact matrix – multiplication applied to classification) is used for the analysis of hidden and indirect relationships between various components of the system. The fuzzy set theory is applied to conventional MICMAC to increase the sensitivity of the result. Whereas MICMAC studies only binary type of relationships, i.e., 0 or 1, in fuzzy-MICMAC a different input of the likelihood of relations between the factors is presented [151]. The possibility of relationships is defined in the scale of 0-1. The integrated ISM-FMICMAC methodology consists of five steps discussed below:

Step I: ***Identify and define factors.*** The approach starts by identifying the factors relevant to the problem and selecting the key factors using the Delphi method. Therefore, based on the survey, literature study, and expert's opinion 25 key factors were finalized.

Step II. ***Establish a contextual relationship.*** Based on the expert's opinion a relation is chosen among factors, and an SSIM is obtained through pairwise comparison of factors. Contextual relation and interpretation of the relationship as SSIM is taken as per Table 4.4.

Step III. ***Initial reachability matrix and the binary direct relationship matrix*****.** SSIM is now transformed into an IRM by replacing the variables with 0 and 1. The initial reachability matrix (IRM) diagonal elements are converted to zero, and it works as the basic input to FMICMAC for obtaining binary direct relationship matrix (BDRM). The BDRM is shown in Table 4.9.

Step IV. ***Fuzzy direct relationship matrix.*** The fuzzy direct relationship matrix (FDRM) is achieved by including in BDRM the possibility of relations on the scale of 0-1. Experts opinions are considered to show the relationships between the two factors. The scale for the possibility of a relationship is designed in a way that it is one of the measure ("No=0", "Negligible=0.1", "Low=0.3", "Medium=0.5", "High=0.7", "Very high=0.9", "Full=1"). The values obtained from the expert's opinions are then superimposed on the BDRM to obtain FDRM, which is given in Table 4.10.

Table 4.9: Binary direct relationship matrix (BDRM).

Factors	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
3	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	1	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
6	1	1	0	0	0	0	0	1	1	1	0	0	1	1	1	1	1	1	0	0	0	0	1	1	1
7	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	1	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
9	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	1	1	0	0	0	1	0	0	0
10	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0
12	1	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0	0
13	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0
14	0	1	1	1	0	0	0	0	0	1	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0
15	1	1	1	0	0	0	0	1	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	1	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
17	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	1	0	1	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	1	0	1	0	0	0	1	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
20	1	0	1	0	0	0	1	1	0	1	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0
21	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
22	0	1	1	0	1	0	1	1	0	1	0	1	1	0	1	1	1	1	0	0	1	0	1	0	0
23	0	0	1	0	1	0	0	1	0	1	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0
24	1	0	1	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 4.10: Fuzzy direct relationship matrix (FDRM).

Factors	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	0	0	0	0	0	0.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0.5	0	0.9	0	0	0	0	0	0	0	0	0	0.9	0	0	0	0	0	0	0	0	0	0	0	0
3	0.9	0	0	0	0	0	0	0	0	0	0	0	0.9	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0.3	0	0	0	0	0	0	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0.7	0	0	0	0	0	0	0.3	0	0.3	0.5	0	0	0	0	0	0	0	0	0	0	0	0
6	0.5	0.3	0	0	0	0	0	0.3	0.7	0.3	0	0	0.1	0.7	0.7	0.3	0.7	0.7	0	0	0	0	0.5	0.9	0.7
7	0	0	0	0	0	0	0	0	0	0.5	0	0.1	0.7	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0.9	0	0	0	0.9	0	0	0.7	0	0	0.9	0	0	0	0	0	0	0	0	0	0	0	0
9	0.7	0	0	0	0	0	0	0	0	0.7	0	0	0	0	0.5	0.5	0.3	0.7	0	0	0	0.3	0	0	0
10	0.5	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0.1	0	0	0.7	0	0	0	0	0	0	0	0.5	0	0	0	0
12	0.3	0	0.7	0	0	0	0	0.1	0	0	0	0	0.9	0	0	0	0.3	0	0	0	0.9	0	0	0	0
13	0.7	0	0	0	0	0	0	0	0	0.9	0	0	0	0	0	0	0	0.9	0	0	0.9	0	0	0	0
14	0	0.7	0.7	0.9	0	0	0	0	0	0.3	0	0.7	0	0	0.9	0.1	0.7	0	0	0	0	0	0	0	0
15	0.3	0.9	0.9	0	0	0	0	0.1	0	0.7	0.1	0	0.9	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0.7	0	0	0	0.1	0	0.7	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7
17	0	0	0.5	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0.5	0	0.3	0	0	0	0.9	0.9	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0.9	0	0.7	0	0	0	0.9	0.9	0	0.9	0	0	0	0	0	0	0	0.9	0	0	0	0	0	0	0.5
20	0.7	0	0.9	0	0	0	0.9	0.9	0	0.7	0	0	0.9	0	0	0	0	0.9	0.9	0	0	0	0	0	0
21	0	0	0.7	0	0	0	0	0	0	0.5	0	0	0.9	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0.3	0.3	0	0.1	0	0.7	0.3	0	0.7	0	0.5	0.7	0	0.5	0.9	0.3	0.5	0	0	0.7	0	0.7	0	0
23	0	0	0.7	0	0.7	0	0	0.1	0	0.7	0	0.7	0	0	0	0	0	0.9	0	0	0.9	0	0	0	0
24	0.5	0	0.3	0	0	0	0	0.7	0	0.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0.5	0	0	0	0	0	0	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Step V. ***Stabilization of the fuzzy matrix.*** In FMICMAC analysis fuzzy matrix multiplication rule is followed instead of using Boolean matrix multiplication. Fuzzy matrix multiplication is generally a simplification of Boolean matrix multiplication [271]. According to the fuzzy multiplication rule, the product of two fuzzy matrices is also a fuzzy matrix.

Mathematically,

$$AB = \max \{\min a_{ij}, b_{ij}\} \tag{4.1}$$

Where, $A = [a_{ij}]$ and $B = [b_{ij}]$ are two fuzzy matrices.

For multiplication, the FDRM is taken as the initial matrix to start the process. The matrix is repeatedly multiplied until the hierarchy of the driving power and dependence is not stable. Suppose we define FDRM as matrix A. Now the matrix A will be multiplied with itself based on the fuzzy multiplication rule to obtain matrix A^2 (0^{th} iteration). Likewise, matrix A^3, A^4, A^5, and other higher order matrices are obtained. In each step of the multiplication process, the sum of rows (R) and columns (C) also called the driving power and dependence is taken. Whenever the new matrix generated in each step will be multiplied by the original matrix A, new driving power and dependence will be obtained. During this process, a stage is reached when the driving power and dependence starts repeating either in consecutive step or the alternate step. This stage of repletion of the driving power and dependence is called the stabilization of the fuzzy matrix. The given fuzzy matrix is stabilized in seven iterations (A^7). Table 4.11 shows the sum of driving power and dependence at each iteration of the matrix multiplication process. Finally, based on fuzzy multiplication rule, the fuzzy stabilized matrix is obtained, shown in Table 4.12.

Table 4.11: Driving power and dependence at different iterations for matrix stability.

Iteration / Factor	R0	C0	R1	C1	R2	C2	R3	C3	R4	C4	R5	C5	R6	C6	R7	C7	R8	C8
1	7.4	16.3	11.3	16.7	11.8	17.3	13.9	17.9	14.5	18.5	14.5	18.9	14.5	18.9	14.5	18.9	14.5	18.9
2	5.0	2.9	11.8	4.7	15.5	10.9	16.1	15.9	16.3	16.3	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5
3	4.3	13.3	11.3	14.9	15.5	17.3	15.1	18.5	15.7	18.9	16.3	18.9	16.3	18.9	16.5	18.9	16.5	18.9
4	1.3	2.0	2.4	1.5	7.8	7.1	10.9	15.5	10.9	15.7	10.9	16.3	10.9	16.5	10.9	16.5	10.9	16.5
5	3.6	1.3	5.5	0.9	11.1	5.7	14.3	12.5	13.7	12.5	14.1	12.5	14.5	12.5	14.5	12.5	14.5	12.5
6	11.3	7.0	11.8	16.3	13.9	16.7	14.5	17.3	14.5	17.9	14.5	18.5	14.5	18.9	14.5	18.9	14.5	18.9
7	3.6	7.4	4.7	13.8	11.1	18.3	13.7	18.9	14.1	18.9	14.5	18.9	14.5	18.9	14.5	18.9	14.5	18.9
8	5.1	6.1	7.8	12.2	13.3	17.5	16.1	18.9	16.3	18.9	16.5	18.9	16.5	18.9	16.5	18.9	16.5	18.9
9	7.9	0.7	11.6	6.6	13.5	15.5	12.9	15.7	13.9	16.3	14.5	16.5	14.5	16.5	14.5	16.5	14.5	16.5
10	1.5	15.1	7.0	17.5	10.9	18.7	10.9	18.9	10.9	18.9	10.9	18.9	10.9	18.9	10.9	18.9	10.9	18.9
11	3.8	0.4	5.5	0.3	11.3	1.3	13.7	2.5	14.1	2.5	14.5	2.5	14.5	2.5	14.5	2.5	14.5	2.5
12	5.4	2.4	10.3	2.5	14.3	7.7	16.1	15.5	16.3	15.7	16.5	16.3	16.5	16.5	16.5	16.5	16.5	16.5
13	5.1	15.6	12.3	18.1	15.1	18.7	15.7	18.9	16.3	18.9	16.3	18.9	16.5	18.9	16.5	18.9	16.5	18.9
14	5.5	0.7	6.2	6.6	13.3	15.5	16.3	15.7	16.3	16.3	16.3	16.5	16.5	16.5	16.5	16.5	16.5	16.5
15	5.8	1.7	10.7	7.3	14.7	15.9	16.3	16.3	16.3	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5
16	2.0	1.1	2.4	4.1	7.6	9.5	10.9	12.5	10.9	12.5	10.9	12.5	10.9	12.5	10.9	12.5	10.9	12.5
17	1.3	3.0	2.8	8.0	8.4	15.9	10.9	16.3	10.9	16.5	10.9	16.5	10.9	16.5	10.9	16.5	10.9	16.5
18	4.5	10.6	10.0	17.1	14.1	18.9	15.5	18.9	16.1	18.9	16.3	18.9	16.5	18.9	16.5	18.9	16.5	18.9
19	6.0	0.0	12.9	0.0	16.1	0.0	16.3	0.0	16.3	0.0	16.3	0.0	16.5	0.0	16.5	0.0	16.5	0.0
20	8.5	0.0	13.5	0.0	16.5	0.0	16.5	0.0	16.5	0.0	16.5	0.0	16.5	0.0	16.5	0.0	16.5	0.0
21	4.6	11.2	6.9	16.0	12.9	18.5	15.9	18.9	16.1	18.9	16.3	18.9	16.3	18.9	16.5	18.9	16.5	18.9
22	8.9	0.3	6.9	0.3	11.7	3.6	14.5	7.5	14.5	7.5	14.5	7.5	14.5	7.5	14.5	7.5	14.5	7.5
23	5.9	0.8	7.3	5.6	13.1	12.5	16.1	12.5	16.3	12.5	16.3	12.5	16.5	12.5	16.5	12.5	16.5	12.5
24	3.8	0.9	9.0	7.0	12.7	16.3	13.9	16.7	14.5	17.3	14.5	17.9	14.5	18.5	14.5	18.9	14.5	18.9
25	1.5	2.8	3.0	6.9	8.6	15.5	10.9	15.7	10.9	16.3	10.9	16.5	10.9	16.5	10.9	16.5	10.9	16.5

Table 4.12: Fuzzy stabilized matrix.

Factors	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19	F20	F21	F22	F23	F24	F25	DP.
F1	0.7	0.7	0.7	0.7	0.5	0.7	0.7	0.7	0.7	0.7	0.1	0.7	0.7	0.7	0.7	0.5	0.7	0.7	0	0	0.7	0.3	0.5	0.7	0.7	**14.5**
F2	0.9	0.7	0.9	0.7	0.5	0.9	0.9	0.9	0.7	0.9	0.1	0.7	0.9	0.7	0.7	0.5	0.7	0.9	0	0	0.9	0.3	0.5	0.9	0.7	**16.5**
F3	0.9	0.7	0.9	0.7	0.5	0.9	0.9	0.9	0.7	0.9	0.1	0.7	0.9	0.7	0.7	0.5	0.7	0.9	0	0	0.9	0.3	0.5	0.9	0.7	**16.5**
F4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0	0	0.5	0.3	0.5	0.5	0.5	**10.9**
F5	0.7	0.7	0.7	0.7	0.5	0.7	0.7	0.7	0.7	0.7	0.1	0.7	0.7	0.7	0.7	0.5	0.7	0.7	0	0	0.7	0.3	0.5	0.7	0.7	**14.5**
F6	0.7	0.7	0.7	0.7	0.5	0.7	0.7	0.7	0.7	0.7	0.1	0.7	0.7	0.7	0.7	0.5	0.7	0.7	0	0	0.7	0.3	0.5	0.7	0.7	**14.5**
F7	0.7	0.7	0.7	0.7	0.5	0.7	0.7	0.7	0.7	0.7	0.1	0.7	0.7	0.7	0.7	0.5	0.7	0.7	0	0	0.7	0.3	0.5	0.7	0.7	**14.5**
F8	0.9	0.7	0.9	0.7	0.5	0.9	0.9	0.9	0.7	0.9	0.1	0.7	0.9	0.7	0.7	0.5	0.7	0.9	0	0	0.9	0.3	0.5	0.9	0.7	**16.5**
F9	0.7	0.7	0.7	0.7	0.5	0.7	0.7	0.7	0.7	0.7	0.1	0.7	0.7	0.7	0.7	0.5	0.7	0.7	0	0	0.7	0.3	0.5	0.7	0.7	**14.5**
F10	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0	0	0.5	0.3	0.5	0.5	0.5	**10.9**
F11	0.7	0.7	0.7	0.7	0.5	0.7	0.7	0.7	0.7	0.7	0.1	0.7	0.7	0.7	0.7	0.5	0.7	0.7	0	0	0.7	0.3	0.5	0.7	0.7	**14.5**
F12	0.9	0.7	0.9	0.7	0.5	0.9	0.9	0.9	0.7	0.9	0.1	0.7	0.9	0.7	0.7	0.5	0.7	0.9	0	0	0.9	0.3	0.5	0.9	0.7	**16.5**
F13	0.9	0.7	0.9	0.7	0.5	0.9	0.9	0.9	0.7	0.9	0.1	0.7	0.9	0.7	0.7	0.5	0.7	0.9	0	0	0.9	0.3	0.5	0.9	0.7	**16.5**
F14	0.9	0.7	0.9	0.7	0.5	0.9	0.9	0.9	0.7	0.9	0.1	0.7	0.9	0.7	0.7	0.5	0.7	0.9	0	0	0.9	0.3	0.5	0.9	0.7	**16.5**
F15	0.9	0.7	0.9	0.7	0.5	0.9	0.9	0.9	0.7	0.9	0.1	0.7	0.9	0.7	0.7	0.5	0.7	0.9	0	0	0.9	0.3	0.5	0.9	0.7	**16.5**
F16	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0	0	0.5	0.3	0.5	0.5	0.5	**10.9**
F17	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0	0	0.5	0.3	0.5	0.5	0.5	**10.9**
F18	0.9	0.7	0.9	0.7	0.5	0.9	0.9	0.9	0.7	0.9	0.1	0.7	0.9	0.7	0.7	0.5	0.7	0.9	0	0	0.9	0.3	0.5	0.9	0.7	**16.5**
F19	0.9	0.7	0.9	0.7	0.5	0.9	0.9	0.9	0.7	0.9	0.1	0.7	0.9	0.7	0.7	0.5	0.7	0.9	0	0	0.9	0.3	0.5	0.9	0.7	**16.5**
F20	0.9	0.7	0.9	0.7	0.5	0.9	0.9	0.9	0.7	0.9	0.1	0.7	0.9	0.7	0.7	0.5	0.7	0.9	0	0	0.9	0.3	0.5	0.9	0.7	**16.5**
F21	0.9	0.7	0.9	0.7	0.5	0.9	0.9	0.9	0.7	0.9	0.1	0.7	0.9	0.7	0.7	0.5	0.7	0.9	0	0	0.9	0.3	0.5	0.9	0.7	**16.5**
F22	0.7	0.7	0.7	0.7	0.5	0.7	0.7	0.7	0.7	0.7	0.1	0.7	0.7	0.7	0.7	0.5	0.7	0.7	0	0	0.7	0.3	0.5	0.7	0.7	**14.5**
F23	0.9	0.7	0.9	0.7	0.5	0.9	0.9	0.9	0.7	0.9	0.1	0.7	0.9	0.7	0.7	0.5	0.7	0.9	0	0	0.9	0.3	0.5	0.9	0.7	**16.5**
F24	0.7	0.7	0.7	0.7	0.5	0.7	0.7	0.7	0.7	0.7	0.1	0.7	0.7	0.7	0.7	0.5	0.7	0.7	0	0	0.7	0.3	0.5	0.7	0.7	**14.5**
F25	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0	0	0.5	0.3	0.5	0.5	0.5	**10.9**
DEP.	**18.9**	**16.5**	**18.9**	**16.5**	**12.5**	**18.9**	**18.9**	**18.9**	**16.5**	**18.9**	**2.5**	**16.5**	**18.9**	**16.5**	**16.5**	**12.5**	**16.5**	**18.9**	**0**	**0**	**18.9**	**7.5**	**12.5**	**18.9**	**16.5**	

4.8. Prioritization of key issues and its domain using integrated ISM-FANP methodology

To prioritize the key issues and its domain, an integrated ISM-FANP methodology has been used. ISM helps to develop a direct and indirect relationship between the elements of complex systems to gain a better understanding of the entire system. It identifies the interdependencies among the elements of the system (SSIM matrix) through the expert's opinions. FANP an extension of the conventional analytic network process (ANP) uses fuzzy logic to handle uncertainties in the problem-solving through importing information such as knowledge, experience, and human judgment into the decision-making process [272–274]. Then, these decisions of experts are used in FANP to prioritizes/rank the factors/criteria. One of the basic assumptions in using FANP is the interdependency among the criteria's. Hence, by integrating ISM and FANP, the interdependency between the VSC issues and its domain can be identified through ISM and instead of comparing each issue while designing pairwise comparison matrices in FANP, only those issues can be compared, where the interdependence from ISM has been identified. It may help to improve the quality and efficiency of problem solving of the decision-makers by reducing the computational complexities.

The steps of the methodology to achieve the objectives are discussed below:

Step 1: Identify the main domains and their relevant key issues

As mentioned in section 1, based on the field survey, literature review and from further discussion with experts, 25 key issues as factors of the VSC have been finalized. Further, based on the studies of various authors five main domains of issues were identified (operational; environmental; economic; social; management) [69,275–284]. Then, the opinions of experts were taken to classify these issues into five domains. A questionnaire was designed in English and sent to the immunization program of 3 states of India i.e. Uttarakhand, Delhi, and Uttar Pradesh. Among the 123 questionnaires distributed to respondents, 65 were returned, and out of 65 returning questionnaires, 52 were accepted and analyzed; representing a satisfactory response rate of 42.27% [285]. The listed main domains and key issues are shown as the fish-bone diagram in Figure 4.4. Finally, the evaluation model structure (Step 1) of VSC issues can be seen in Figure 4.5.

Step 2: Establish a contextual relationship matrix and reachability matrix

In this step, the consecutive steps of ISM are applied to analyze the contextual interrelationships between elements. Step 2 of the process comprises of the development of SSIM and final reachability matrix (IRM). The results of ISM were taken as an input for the SSIM and FRM matrix. The initial reachability matrix for domains and issues is shown in Table E.1&E.2 in Appendix E. After incorporating the transitivity check, a final reachability matrix (FRM) is shown in Table E.4. The final reachability matrix presents a clear relationship among all of the main domains to vaccine supply chain issues, depicted in Figure 4.6 & 4.7.

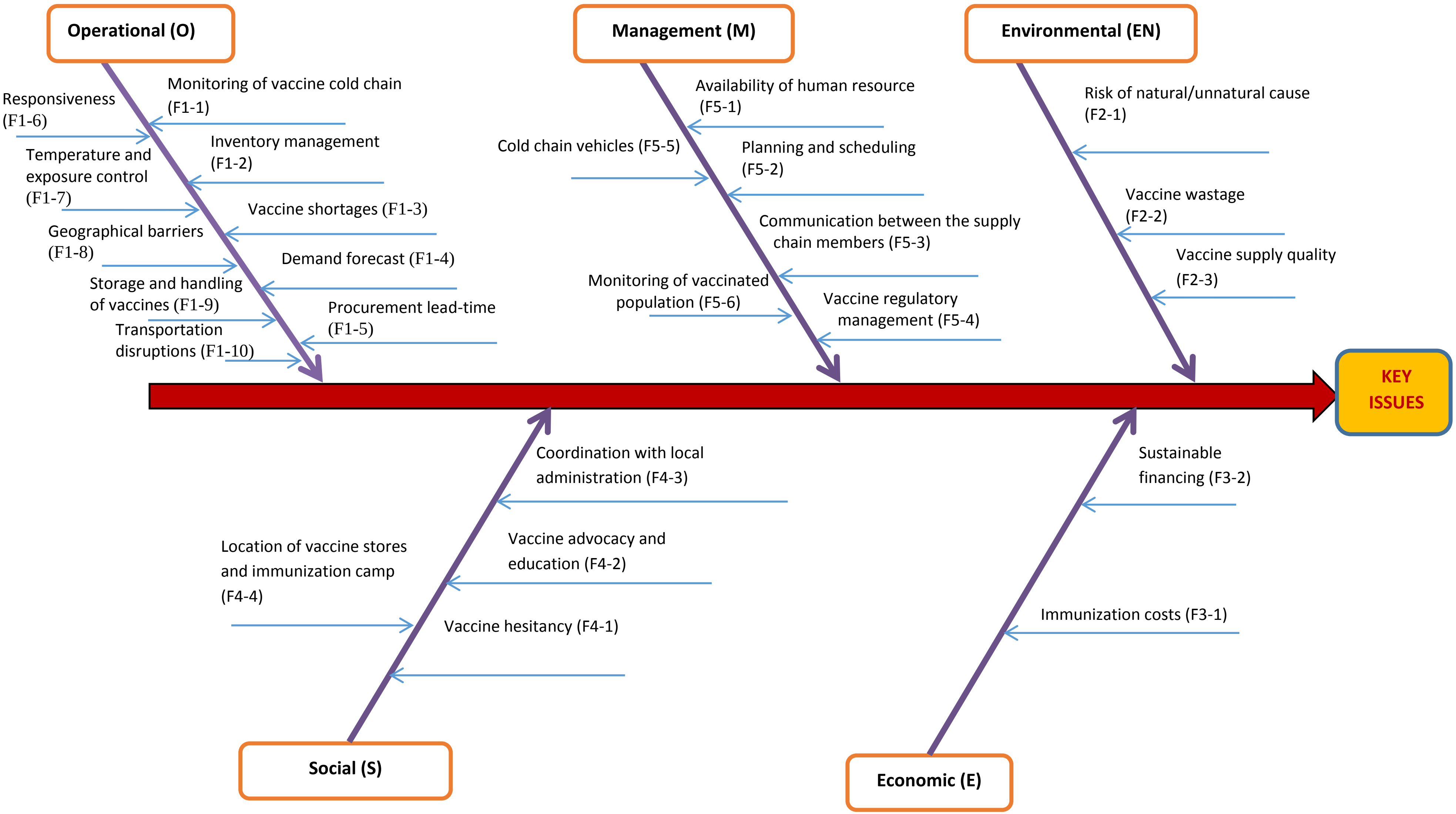


Figure 4.4: Fish-bone diagram of five main domains and its key issues.

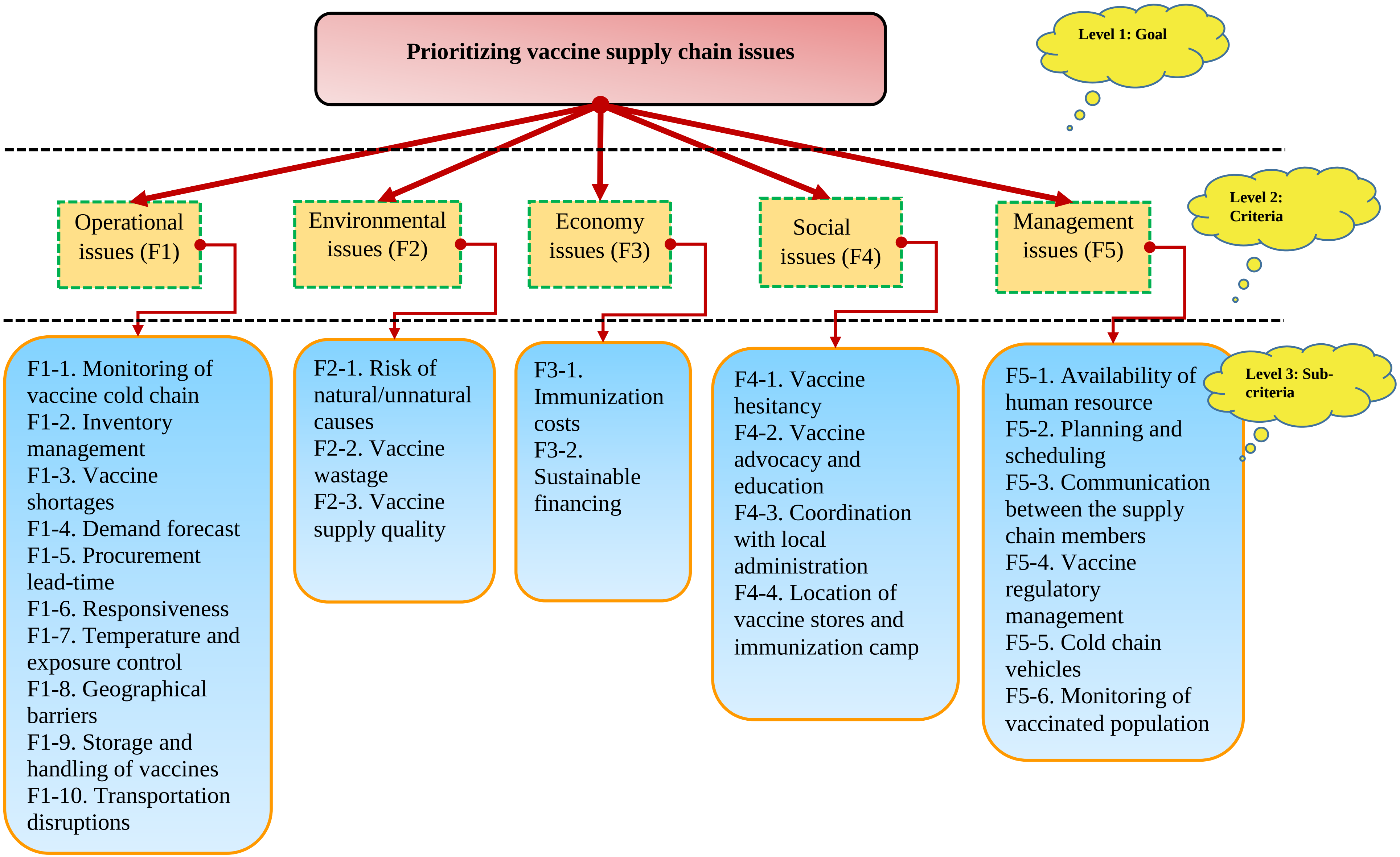


Figure 4.5: Evaluation model structure of vaccine supply chain issues.

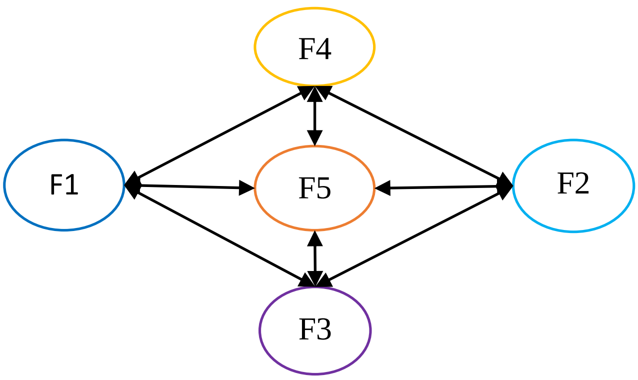


Figure 4.6: Relationship between the main domains.

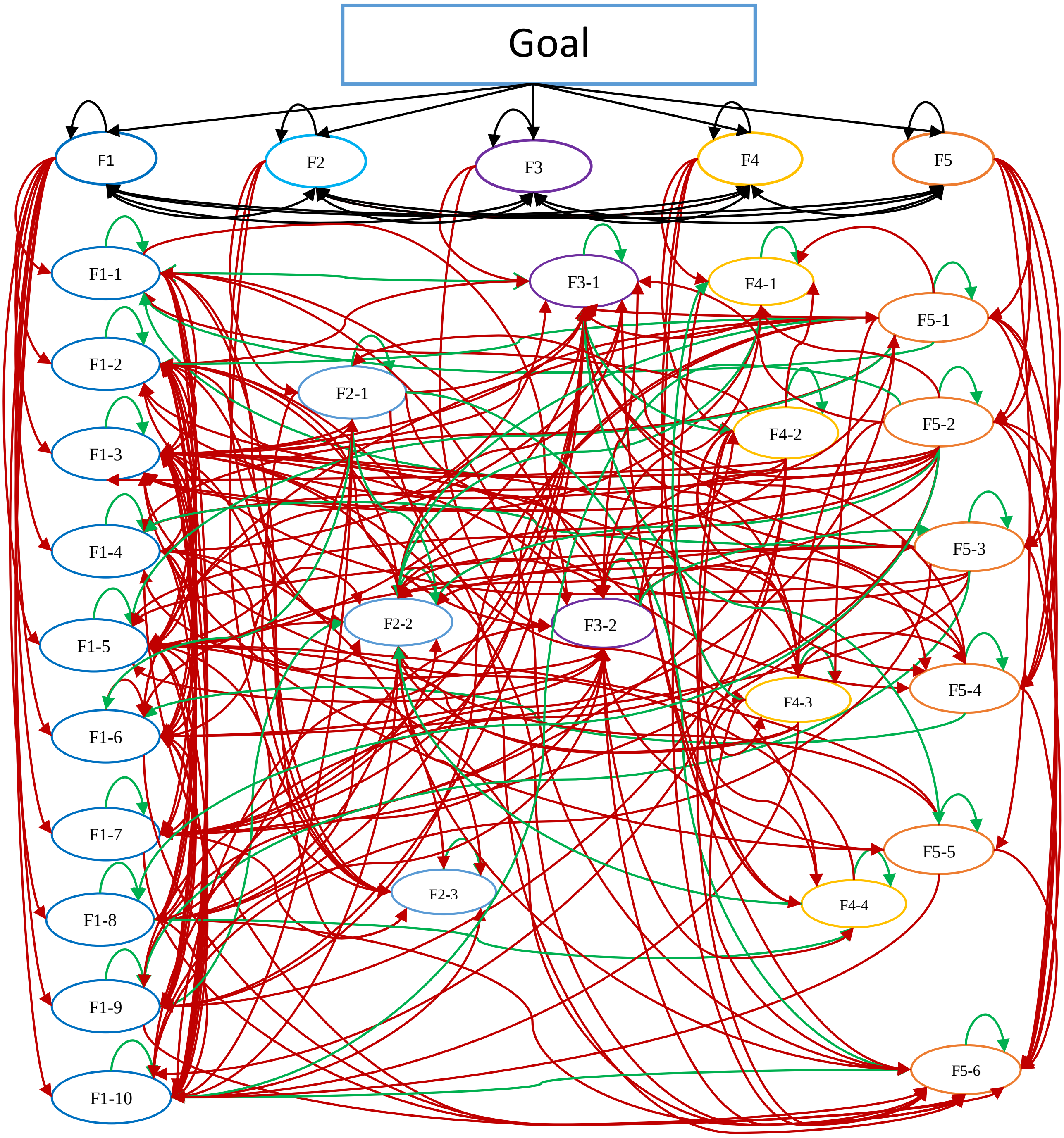


Figure 4.7: Relationship of the main domains and their relevant issues (the network scheme).

Step 3: Construct a pairwise comparison matrix and check the consistency ratio

Develop a pairwise comparison matrix for the inner dependencies (within elements) and outer dependencies (between clusters). In the present study, a three-level hierarchy (sub-criteria) is taken ignoring the fourth level, i.e. alternatives. To show the outer dependencies, the relations between elements from different clusters are considered. For acquiring inner dependencies, elements within the same cluster are considered, and their interrelationship is obtained from the SSIM shown in Table E.1 (for domains) and Table E.2 (for issues) in Appendix E. Further, sixteen experts have given their inputs in the form of a verbal questionnaire for pairwise comparison matrix, and their responses as linguistic variables have been converted into triangular fuzzy numbers based on the scales mentioned in Table E.5. For example, the pairwise comparison matrix for one expert concerning goal and organization is presented in Table E.6 & E.7. To check the consistency of each pairwise comparison matrix, Eq. 3.3-3.4 is used. The method of calculating the consistency ratio in the case of triangular fuzzy numbers is shown in Appendix E.2.

Step 4: Defuzzification of the pairwise comparison matrix

Using the CFCS method discussed in Appendix E.3, the triangular fuzzy numbers of the pairwise comparison matrix are converted into crisp numbers.

Step 5: Construct unweighted, weighted and limited supermatrix and calculate the final weights

This is the last step of the proposed integrated ISM-FANP method. It starts with obtaining an unweighted supermatrix through the steps described in Appendix E.4. The unweighted supermatrix is shown in Table 4.13. After normalizing the unweighted supermatrix, i.e. the sum of each column is equal to 1, the weighted supermatrix is obtained and is shown in Table 4.14. Raising the weighted supermatrix to the power of 2p+1, the limited supermatrix is acquired. For convergence of the weighted supermatrix, visual basic applications (VBA) programming language is used in Microsoft Excel 16.0. The weighted supermatrix started converging (column values repeating) after the 47^{th} power, i.e. p=23. The limited supermatrix and final weights of the twenty-five key issues and five domains are shown in Table 4.15 & 4.16.

Table 4.13: The unweighted supermatrix.

	Goal	F1	F2	F3	F4	F5	F1-1	F1-2	F1-3	F1-4	F1-5	F1-6	F1-7	F1-8	F1-9	F1-10	F2-1	F2-2	F2-3	F3-1	F3-2	F4-1	F4-2	F4-3	F4-4	F5-1	F5-2	F5-3	F5-4	F5-5	F5-6
Goal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F1	0.281	0	0.394	0.398	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F2	0.138	0	0	0.263	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F3	0.218	0.536	0.409	0	0.602	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F4	0.089	0	0	0.166	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F5	0.274	0.464	0.197	0.174	0.398	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F1-1	0	0.085	0	0	0	0	0	0	0.074	0	0	0	0.327	0	0	0.071	0	0.073	0	0.078	0	0	0	0	0	0	0	0	0.488	0	0.029
F1-2	0	0.200	0	0	0	0	0	0	0.161	0	0	0	0	0	0.162	0.068	0	0.106	0.117	0.135	0	0	0	0	0	0	0	0	0	0	0
F1-3	0	0.130	0	0	0	0	0	0	0	0	0	0.130	0	0	0	0	0	0	0.099	0.147	0	0	0	0	0	0	0	0	0	0	0.031
F1-4	0	0.188	0	0	0	0	0	0.320	0.172	0	0	0	0	0	0	0	0	0.129	0	0	0	0	0	0	0	0	0	0	0	0	0.031
F1-5	0	0.080	0	0	0	0	0	0.105	0.065	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.022
F1-6	0	0.050	0	0	0	0	0	0	0	0	0.297	0	0	0	0	0.075	0	0.031	0	0.043	0	0	0	0	0	0	0	0	0	0	0.050
F1-7	0	0.082	0	0	0	0	0	0	0.079	0	0	0	0	0	0	0	0	0.075	0	0.103	0	0	0	0	0	0	0	0	0	0	0
F1-8	0	0.059	0	0	0	0	0	0	0	0	0.166	0.190	0	0	0	0.160	1	0.039	0	0.060	0	0	0	0	0.212	0	0	0	0	0	0.064
F1-9	0	0.072	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.070	0	0	0	0	0	0	0	0	0	0	0	0	0.026
F1-10	0	0.056	0	0	0	0	0	0	0.060	0	0.206	0	0	0	0	0	0	0.046	0	0	0	0	0	0	0	0	0	0	0	0	0.063
F2-1	0	0	0.450	0	0	0	0	0	0	0	0.200	0.210	0	0.248	0	0.141	0	0.041	0	0.043	0	0	0	0	0	0	0	0	0	0	0.066
F2-2	0	0	0.317	0	0	0	0	0	0.168	0	0	0	0	0	0	0	0	0	0	0.088	0	0	0	0	0	0	0	0	0	0	0
F2-3	0	0	0.233	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.064	0	0	0	0	0	0	0	0	0	0	0	0	0.028
F3-1	0	0	0	0.471	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
F3-2	0	0	0	0.529	0	0	0.118	0	0.051	0	0	0.105	0.165	0	0.187	0.098	0	0	0	0.072	0	0	1	0.313	0.491	1	0	0.589	0	1	0.082
F4-1	0	0	0	0	0.266	0	0	0	0	0	0	0	0	0	0	0	0	0.040	0	0	0	0	0	0	0	0	0	0	0	0	0.033
F4-2	0	0	0	0	0.330	0	0.246	0.139	0	0	0	0	0.365	0	0.197	0	0	0.054	0	0	0	0.667	0	0.147	0	0	0	0	0	0	0.038
F4-3	0	0	0	0	0.223	0	0	0	0	0	0	0	0	0	0	0.044	0	0	0	0	0	0.333	0	0	0.297	0	0	0	0.512	0	0.047
F4-4	0	0	0	0	0.182	0	0	0	0	0	0	0	0	0	0	0	0	0.038	0	0	0	0	0	0	0	0	0	0	0	0	0.039
F5-1	0	0	0	0	0	0.248	0.402	0	0	0	0	0.107	0	0	0.215	0	0	0	0	0.097	0	0	0	0.215	0	0	1	0	0	0	0.126
F5-2	0	0	0	0	0	0.192	0.234	0.229	0.129	0.660	0.131	0.151	0.143	0.752	0.239	0.081	0	0.063	0.289	0	0	0	0	0.325	0	0	0	0.411	0	0	0.096
F5-3	0	0	0	0	0	0.258	0	0.207	0	0.340	0	0.107	0	0	0	0.083	0	0.061	0.278	0	0	0	0	0	0	0	0	0	0	0	0.094
F5-4	0	0	0	0	0	0.081	0	0	0.041	0	0	0	0	0	0	0	0	0	0.217	0	0	0	0	0	0	0	0	0	0	0	0
F5-5	0	0	0	0	0	0.130	0	0	0	0	0	0	0	0	0	0.179	0	0.043	0	0.084	0	0	0	0	0	0	0	0	0	0	0.035
F5-6	0	0	0	0	0	0.091	0	0	0	0	0	0	0	0	0	0	0	0.027	0	0.050	0	0	0	0	0	0	0	0	0	0	0

Table 4.14: The weighted supermatrix.

	Goal	F1	F2	F3	F4	F5	F1-1	F1-2	F1-3	F1-4	F1-5	F1-6	F1-7	F1-8	F1-9	F1-10	F2-1	F2-2	F2-3	F3-1	F3-2	F4-1	F4-2	F4-3	F4-4	F5-1	F5-2	F5-3	F5-4	F5-5	F5-6
Goal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F1	0.281	0	0.197	0.199	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F2	0.138	0	0	0.131	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F3	0.218	0.268	0.205	0	0.301	0.500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F4	0.089	0	0	0.083	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F5	0.274	0.232	0.099	0.087	0.199	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F1-1	0	0.042	0	0	0	0	0	0	0.074	0	0	0	0.327	0	0	0.071	0	0.073	0	0.078	0	0	0	0	0	0	0	0	0.488	0	0.029
F1-2	0	0.100	0	0	0	0	0	0	0.161	0	0	0	0	0	0.162	0.068	0	0.106	0.117	0.135	0	0	0	0	0	0	0	0	0	0	0
F1-3	0	0.065	0	0	0	0	0	0	0	0	0	0.130	0	0	0	0	0	0	0.099	0.147	0	0	0	0	0	0	0	0	0	0	0.031
F1-4	0	0.094	0	0	0	0	0	0.320	0.172	0	0	0	0	0	0	0	0	0.129	0	0	0	0	0	0	0	0	0	0	0	0	0.031
F1-5	0	0.040	0	0	0	0	0	0.105	0.065	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.022
F1-6	0	0.025	0	0	0	0	0	0	0	0	0.297	0	0	0	0	0.075	0	0.031	0	0.043	0	0	0	0	0	0	0	0	0	0	0.050
F1-7	0	0.041	0	0	0	0	0	0	0.079	0	0	0	0	0	0	0	0	0.075	0	0.103	0	0	0	0	0	0	0	0	0	0	0
F1-8	0	0.029	0	0	0	0	0	0	0	0	0.166	0.190	0	0	0	0.160	1	0.039	0	0.060	0	0	0	0	0.212	0	0	0	0	0	0.064
F1-9	0	0.036	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.070	0	0	0	0	0	0	0	0	0	0	0	0	0.026
F1-10	0	0.028	0	0	0	0	0	0	0.060	0	0.206	0	0	0	0	0	0	0.046	0	0	0	0	0	0	0	0	0	0	0	0	0.063
F2-1	0	0	0.225	0	0	0	0	0	0	0	0.200	0.210	0	0.248	0	0.141	0	0.041	0	0.043	0	0	0	0	0	0	0	0	0	0	0.066
F2-2	0	0	0.158	0	0	0	0	0	0.168	0	0	0	0	0	0	0	0	0	0	0.088	0	0	0	0	0	0	0	0	0	0	0
F2-3	0	0	0.116	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.064	0	0	0	0	0	0	0	0	0	0	0	0	0.028
F3-1	0	0	0	0.236	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
F3-2	0	0	0	0.264	0	0	0.118	0	0.051	0	0	0.105	0.165	0	0.187	0.098	0	0	0	0.072	0	0	1	0.313	0.491	1	0	0.589	0	1	0.082
F4-1	0	0	0	0	0.133	0	0	0	0	0	0	0	0	0	0	0	0	0.040	0	0	0	0	0	0	0	0	0	0	0	0	0.033
F4-2	0	0	0	0	0.165	0	0.246	0.139	0	0	0	0	0.365	0	0.197	0	0	0.054	0	0	0	0.667	0	0.147	0	0	0	0	0	0	0.038
F4-3	0	0	0	0	0.111	0	0	0	0	0	0	0	0	0	0	0.044	0	0	0	0	0	0.333	0	0	0.297	0	0	0	0.512	0	0.047
F4-4	0	0	0	0	0.091	0	0	0	0	0	0	0	0	0	0	0	0	0.038	0	0	0	0	0	0	0	0	0	0	0	0	0.039
F5-1	0	0	0	0	0	0.124	0.402	0	0	0	0	0.107	0	0	0.215	0	0	0	0	0.097	0	0	0	0.215	0	0	1	0	0	0	0.126
F5-2	0	0	0	0	0	0.096	0.234	0.229	0.129	0.660	0.131	0.151	0.143	0.752	0.239	0.081	0	0.063	0.289	0	0	0	0	0.325	0	0	0	0.411	0	0	0.096
F5-3	0	0	0	0	0	0.128	0	0.207	0	0.340	0	0.107	0	0	0	0.083	0	0.061	0.278	0	0	0	0	0	0	0	0	0	0	0	0.094
F5-4	0	0	0	0	0	0.041	0	0	0.041	0	0	0	0	0	0	0	0	0	0.217	0	0	0	0	0	0	0	0	0	0	0	0
F5-5	0	0	0	0	0	0.065	0	0	0	0	0	0	0	0	0	0.179	0	0.043	0	0.084	0	0	0	0	0	0	0	0	0	0	0.035
F5-6	0	0	0	0	0	0.046	0	0	0	0	0	0	0	0	0	0	0	0.027	0	0.050	0	0	0	0	0	0	0	0	0	0	0

Table 4.15: The limited supermatrix.

	Goal	F1	F2	F3	F4	F5	F1-1	F1-2	F1-3	F1-4	F1-5	F1-6	F1-7	F1-8	F1-9	F1-10	F2-1	F2-2	F2-3	F3-1	F3-2	F4-1	F4-2	F4-3	F4-4	F5-1	F5-2	F5-3	F5-4	F5-5	F5-6
Goal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F1-1	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311
F1-2	0.0377	0.0377	0.0377	0.0377	0.0377	0.0377	0.0377	0.0377	0.0377	0.0377	0.0377	0.0377	0.0377	0.0377	0.0377	0.0377	0.0377	0.0377	0.0377	0.0377	0.0377	0.0377	0.0377	0.0377	0.0377	0.0377	0.0377	0.0377	0.0377	0.0377	0.0377
F1-3	0.0335	0.0335	0.0335	0.0335	0.0335	0.0335	0.0335	0.0335	0.0335	0.0335	0.0335	0.0335	0.0335	0.0335	0.0335	0.0335	0.0335	0.0335	0.0335	0.0335	0.0335	0.0335	0.0335	0.0335	0.0335	0.0335	0.0335	0.0335	0.0335	0.0335	0.0335
F1-4	0.0213	0.0213	0.0213	0.0213	0.0213	0.0213	0.0213	0.0213	0.0213	0.0213	0.0213	0.0213	0.0213	0.0213	0.0213	0.0213	0.0213	0.0213	0.0213	0.0213	0.0213	0.0213	0.0213	0.0213	0.0213	0.0213	0.0213	0.0213	0.0213	0.0213	0.0213
F1-5	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063
F1-6	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127
F1-7	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265
F1-8	0.0459	0.0459	0.0459	0.0459	0.0459	0.0459	0.0459	0.0459	0.0459	0.0459	0.0459	0.0459	0.0459	0.0459	0.0459	0.0459	0.0459	0.0459	0.0459	0.0459	0.0459	0.0459	0.0459	0.0459	0.0459	0.0459	0.0459	0.0459	0.0459	0.0459	0.0459
F1-9	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020
F1-10	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052	0.0052
F2-1	0.0269	0.0269	0.0269	0.0269	0.0269	0.0269	0.0269	0.0269	0.0269	0.0269	0.0269	0.0269	0.0269	0.0269	0.0269	0.0269	0.0269	0.0269	0.0269	0.0269	0.0269	0.0269	0.0269	0.0269	0.0269	0.0269	0.0269	0.0269	0.0269	0.0269	0.0269
F2-2	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244	0.0244
F2-3	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019
F3-1	0.2132	0.2132	0.2132	0.2132	0.2132	0.2132	0.2132	0.2132	0.2132	0.2132	0.2132	0.2132	0.2132	0.2132	0.2132	0.2132	0.2132	0.2132	0.2132	0.2132	0.2132	0.2132	0.2132	0.2132	0.2132	0.2132	0.2132	0.2132	0.2132	0.2132	0.2132
F3-2	0.2130	0.2130	0.2130	0.2130	0.2130	0.2130	0.2130	0.2130	0.2130	0.2130	0.2130	0.2130	0.2130	0.2130	0.2130	0.2130	0.2130	0.2130	0.2130	0.2130	0.2130	0.2130	0.2130	0.2130	0.2130	0.2130	0.2130	0.2130	0.2130	0.2130	0.2130
F4-1	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013
F4-2	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260	0.0260
F4-3	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025
F4-4	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014
F5-1	0.1254	0.1254	0.1254	0.1254	0.1254	0.1254	0.1254	0.1254	0.1254	0.1254	0.1254	0.1254	0.1254	0.1254	0.1254	0.1254	0.1254	0.1254	0.1254	0.1254	0.1254	0.1254	0.1254	0.1254	0.1254	0.1254	0.1254	0.1254	0.1254	0.1254	0.1254
F5-2	0.0884	0.0884	0.0884	0.0884	0.0884	0.0884	0.0884	0.0884	0.0884	0.0884	0.0884	0.0884	0.0884	0.0884	0.0884	0.0884	0.0884	0.0884	0.0884	0.0884	0.0884	0.0884	0.0884	0.0884	0.0884	0.0884	0.0884	0.0884	0.0884	0.0884	0.0884
F5-3	0.0199	0.0199	0.0199	0.0199	0.0199	0.0199	0.0199	0.0199	0.0199	0.0199	0.0199	0.0199	0.0199	0.0199	0.0199	0.0199	0.0199	0.0199	0.0199	0.0199	0.0199	0.0199	0.0199	0.0199	0.0199	0.0199	0.0199	0.0199	0.0199	0.0199	0.0199
F5-4	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018
F5-5	0.0203	0.0203	0.0203	0.0203	0.0203	0.0203	0.0203	0.0203	0.0203	0.0203	0.0203	0.0203	0.0203	0.0203	0.0203	0.0203	0.0203	0.0203	0.0203	0.0203	0.0203	0.0203	0.0203	0.0203	0.0203	0.0203	0.0203	0.0203	0.0203	0.0203	0.0203
F5-6	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114

Table 4.16: Final weights and ranking of the key issues.

Issues domain	Weights	Key issues	Issues denotation	Final weights	Global rank
Operational (O)	0.2222	Monitoring of vaccine cold chain	F1-1	0.0311	**8**
		Inventory management	F1-2	0.0377	**6**
		Vaccine shortages	F1-3	0.0335	**7**
		Demand forecast	F1-4	0.0213	**13**
		Procurement lead-time	F1-5	0.0063	**18**
		Responsiveness	F1-6	0.0127	**16**
		Temperature and exposure control	F1-7	0.0265	**10**
		Geographical barriers	F1-8	0.0459	**5**
		Storage and handling of vaccines	F1-9	0.0020	**21**
		Transportation disruptions	F1-10	0.0052	**19**
Environmental (EN)	0.0532	Risk of natural/unnatural causes	F2-1	0.0269	**9**
		Vaccine wastage	F2-2	0.0244	**12**
		Vaccine supply quality	F2-3	0.0019	**22**
Economic (EC)	0.4262	Immunization costs	F3-1	0.2130	**2**
		Sustainable financing	F3-2	0.2132	**1**
Social (S)	0.0312	Vaccine hesitancy	F4-1	0.0013	**25**
		Vaccine advocacy and education	F4-2	0.0260	**11**
		Coordination with local administration	F4-3	0.0025	**20**
		Location of vaccine stores and immunization camp	F4-4	0.0014	**24**
Management (M)	0.2672	Availability of human resource	F5-1	0.1254	**3**
		Planning and scheduling	F5-2	0.0884	**4**
		Communication between the supply chain members	F5-3	0.0199	**15**
		Vaccine regulatory management	F5-4	0.0018	**23**
		Cold chain vehicles	F5-5	0.0203	**14**
		Monitoring of vaccinated population	F5-6	0.0114	**17**

4.9. Results

The results of the analysis have been discussed below.

- The results of the Delphi approach shown in Table 4.3 are the key issues in the supply chain of basic vaccines. These 25 key issues are the primary reasons that hamper the delivery of basic vaccines to the health-centers and children.
- The ISM model developed in Figure 4.3 is a causal diagram, which shows how the issues are interrelated in the VSC system, i.e. the cause and effect of the issues in the system. The developed ISM model can help decision-makers in taking quick actions regarding which issue to focus on based on their position on the hierarchical level.
- The fuzzy stabilized matrix (see Table 4.12) obtained from the integrated ISM-FMICMAC analysis indicates the driving power and dependence of each VSC issue. These issues can be classified into four main regions (each level has its own significance) based on their driving power and dependence. The four regions are presented in Figure 4.8 as driver-dependence graph and discussed below:

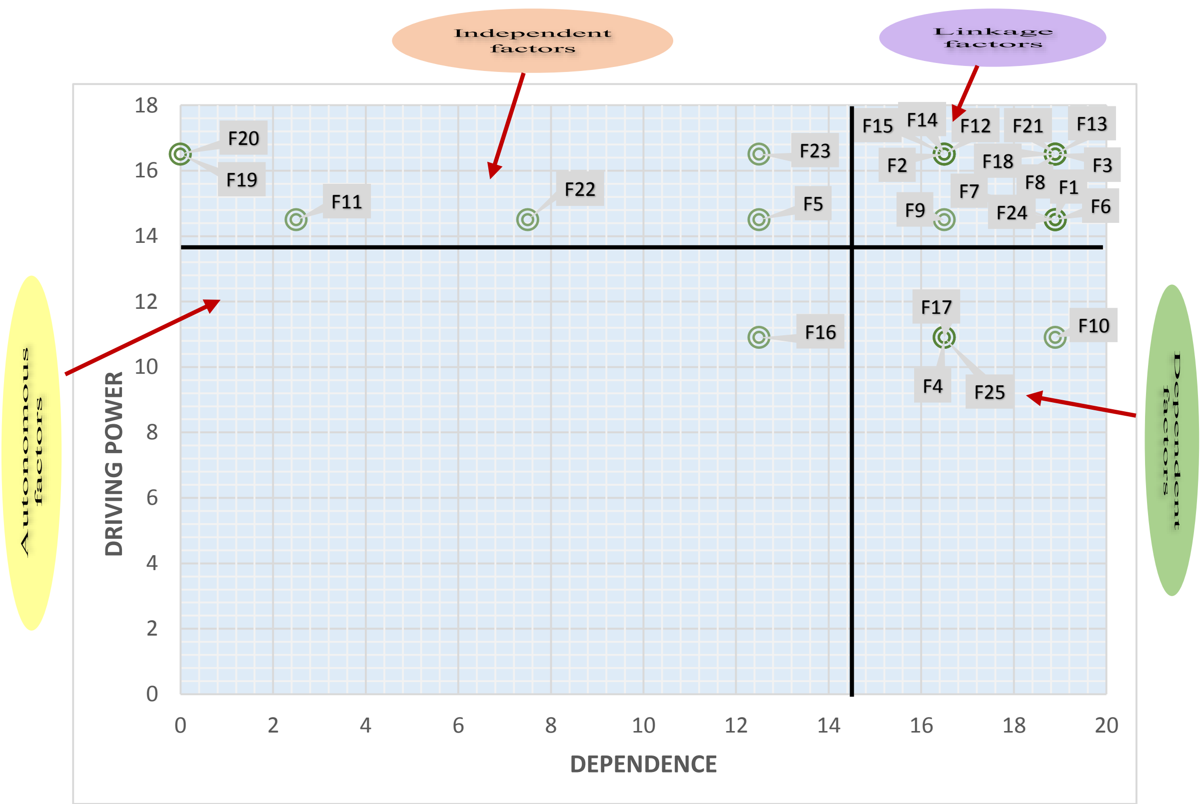


Figure 4.8: Driver-dependence graph.

1. ***Autonomous (I)*:** They have a weak driving power and dependence. They are close to the origin and moderately disengaged from the system. Autonomous factors do not have

much influence on the system. These factors neither affect the system nor are they affected by the system. ***Coordination with local administration (16)*** is the autonomous factor because of the less dependence (12.5) and less driving power (10.9).

2. ***Dependent (II)*****:** Dependent factors are characterized by their weak driving power and high dependence on other factors. Their strong dependence shows that they need the whole other factors to come together for reducing their effect on the vaccine supply chain. ***vaccine hesitancy (4)*** with low driving (10.9) and high dependency (16.5), ***monitoring of vaccinated population (10)*** (10.9, 18.9), ***storage and handling of vaccines (17)*** (10.9, 16.5), and ***location of vaccine stores and immunization camp (25***) (10.9, 16.5) are the dependent factors.

3. ***Linkage (III)*****:** The third sector consists of the linkages factors that have strong driving power and dependence. These factors are unsteady in nature and are connected to each other in either way. Any effect on these factors will affect other factors and provide feedback on them. In our study, factors ***immunization costs (1)*** with high driving power (14.5) and high dependence (18.9), ***temperature and exposure control (2)*** (16.5, 16.5), ***vaccine wastage (3)*** (16.5, 18.9), ***sustainable financing (6)*** (14.5, 18.9), reduction in ***procurement lead-time (7)*** (14.5, 18.9), ***transportation disruptions (8)*** (16.5, 18.9), ***availability of human resource (9)*** (14.5, 16.5), ***inventory management (12)*** (16.5, 16.5), ***vaccine shortages (13)*** (16.5, 18.9), ***vaccine advocacy and education (14)*** (16.5, 16.5), ***monitoring of vaccine cold chain (15)*** (16.5, 16.5), ***responsiveness (18)*** (16.5, 18.9), ***vaccine supply quality (21)*** (16.5, 18.9), and ***cold chain vehicles (24)*** (14.5, 18.9) constitutes to linkage factors.

4. ***Independent (IV)*****:** The fourth sector comprises independent factors (also called driving factors) with high driving power and low dependence. Six factors come into the category of independent factors. These factors can have an effect on other factors to the extreme degree in the system so that they are carefully handled. ***Demand forecast (5)*** along with high driving power and low dependence (14.5, 12.5), ***vaccine regulatory management (11)*** (14.5, 2.5), ***geographical barriers (19)*** (16.5, 0), ***risk of natural/unnatural causes (20)*** (16.5, 0), ***planning and scheduling (22)*** (14.5, 7.5), and ***communication between the supply chain members (23)*** (16.5, 12.5) are the independent factors in our study.

- The integrated ISM-FMICMAC analysis also helped in the creation of a more improved and simpler integrated model of vaccine supply chain issues shown in Figure 4.9. The model developed is a defuzzified and enhanced binary model than the basic ISM as it can be seen that the decision of whether a factor is driving another factor or not can be made either by yes or no. The integrated model has been developed after making the hierarchical structure of three sectors obtained from the ISM-FMICMAC analysis. The autonomous factors have been discarded from the model in the light of their property of not having much impact on the system. The independent factors or the driving factors have been placed at the bottom of the hierarchy, the linkage factors occupy the intermediate position, and finally, the dependent factors are positioned at the top of the hierarchy.

- Based on the integrated ISM-FANP analysis, the final weights of twenty-five key issues is obtained from the limited supermatrix (see Table 4.15); provided in Table 4.16. Figure 4.10 depicts the weight of five issues domain. From Figure 4.10, the ranking of the five domains of vaccine supply chain issues according to their weight obtained from the analysis are ***'Economic' (0.4620)***, followed by ***'Management' (0.2672)***, ***'Operational' (0.2222)***, ***'Environmental' (0.0532)*** and ***'Social' (0.0312).*** Due to the high value of weights, the economic, management and operational are the most important domains of vaccine supply chain issues. Discussion with the experts also confirmed the importance of these three domains on immunization programs. Thus, it is expected that giving priority to these domains in decision-making may help decision-makers to drive their efforts and resources on eliminating the most important issues. In the present case, because of getting a low rank on the priority list, the environmental and social domains issues will not have a significant effect in improving system performance. In some circumstances, however, such as focusing on building a green or agile vaccine supply chain these issues may have a noteworthy impact on the supply chain performance.

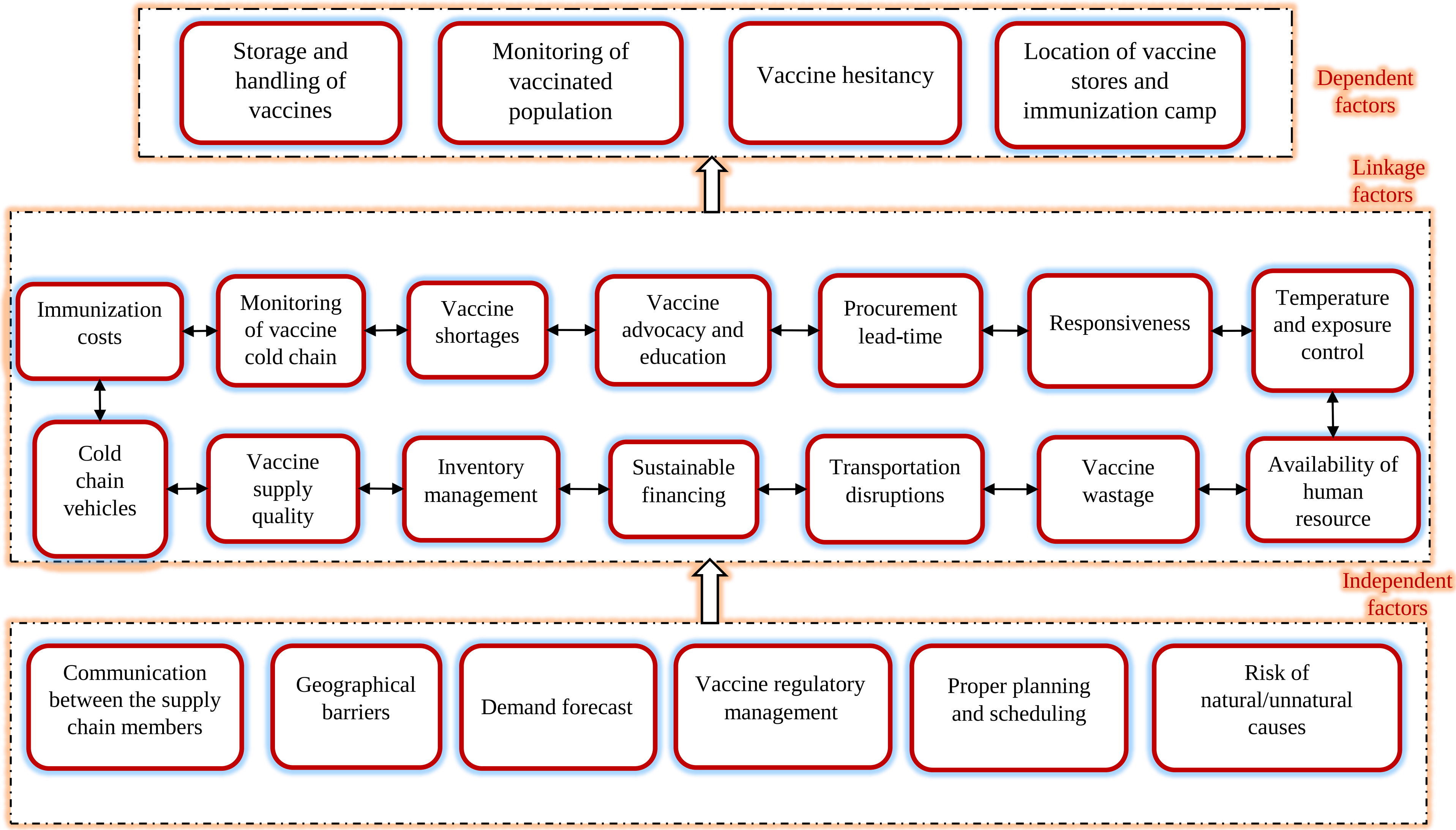


Figure 4.9: Integrated model of vaccine supply chain issues.

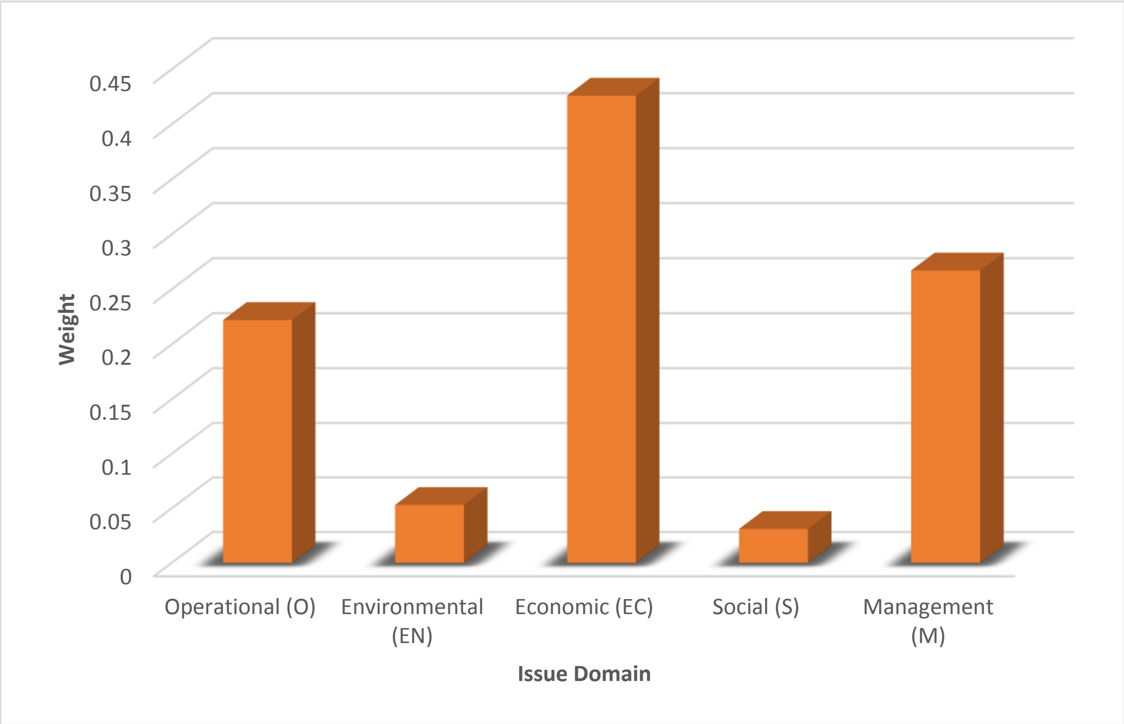


Figure 4.10: Weights of the five issues domain.

Prior to the findings of the study, during the field survey, when the vaccine supply chain issues were discussed with the staff and experts of the immunization program, most of them emphasized on operational and financial issues for the primary reasons for the delay in vaccines delivery. When we deliberated that managerial issues like communication, planning can be important issues that may affect the vaccine supply chain performance, then, neither we nor the experts were certain with this proposed hypothesis. After conducting ISM-FMICMAC and ISM-FANP analysis, the results confirmed that managerial issues affect the other issues of vaccine supply chain and its performance. Thereafter, when the results were presented to the experts, the experts pointed out that often managerial issues arise in VSC, but they never thought from the perspective of interrelationships among the factors, i.e. managerial issues can lead to other issues. Intuitively the officials thought that operational issues are the reasons for the delay in vaccines delivery. Hence, the immunization programs senior experts pointed out on three factors as the most important and the primary reasons for other issues to arise, and henceforth these factors were classified as critical factors. Consequently, from the analysis and from further discussions with the experts, factors ***'demand forecast'***, ***'communication between the supply chain members'*** and ***'planning and scheduling'*** are three most critical issues and thus directly or indirectly drive every other factor. To improve vaccine supply chain performance in order to improve child immunization coverage it is important that the decision-makers give special attention to the critical factors. The critical factors are shown in Figure 4.11.

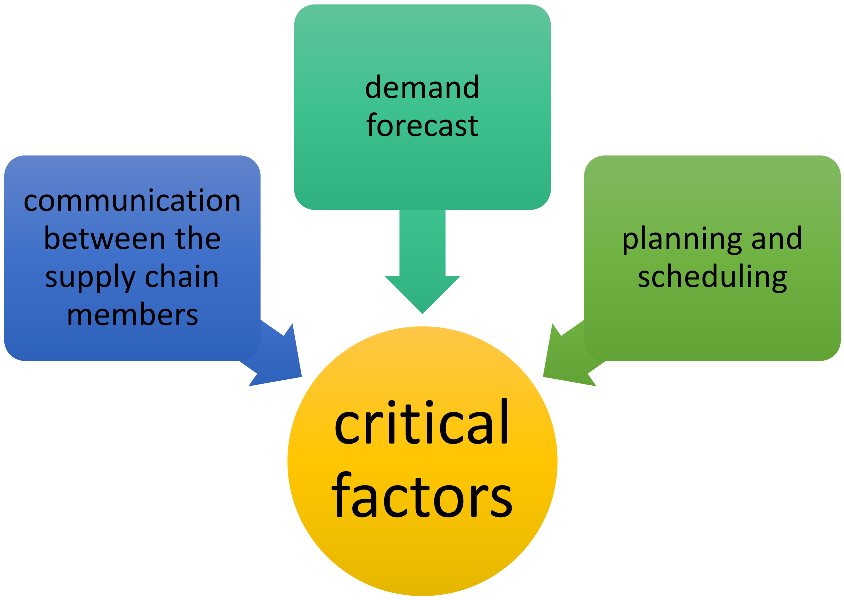


Figure 4.11: Critical issues of vaccine supply chain.

4.9.1. Sensitivity analysis

Applying sensitivity analysis to such decision-making methods is essential to make sure that there is consistency in the final decision. Through sensitivity analysis, distinct "what-if" situations may be visualized which can be helpful to observe the stability of the optimal solution under possible changes in parameters [286,287]. In this work, to perform sensitivity analysis, a simulation is carried out by changing the weights of the input parameter, i.e. unweighted supermatrix and obtaining the limited supermatrix in the similar means to test the ranking of the criteria. To do so, Monte Carlo simulation with uniform probability distribution in Microsoft Excel 16.0 is used with the following calculation formula:

$$X_k^b = X_{0,k} \pm [X_{0,k} * \delta * rand()] \quad (4.2)$$

Where b = 1,2,……, B is the number of experiments in simulation run, B denotes the total number of experiments, k = 1,2….., K is the number of criteria in the model; K is the total number of criteria; $X_{0,k}$ is the initial weight of the criteria k in decision matrix (unweighted supermatrix); δ (10%, 20%,….,60%) is the variations in estimating criteria weights; *rand()* generates uniformly distributed random criteria weights in the interval [0,1]; the resulting values X_k^b denotes the weight of criteria k in experiment b.

Simulation is performed in six different cases. In case 1, four sets of simulation experiments are conducted, in which, 2 sets of experiments are done with a positive change and 10% variation, and remaining two with a negative change and same 10% variation to the initial weights of unweighted supermatrix. Then, the steps used in FANP are performed to obtain the final rankings from the limited supermatrix. Next, the variations are changed with a step size increase of 10%. During the simulation, while moving from 50% to 60% variation, it has been observed that in 60% variation, there is not much difference in the final weights of the factors, i.e. weights in limited supermatrix. In addition, in 70% variation, there is a negligible change in the final weights of the twenty-five factors. Further, during simulation, it is also observed that when variation is kept 70% and above, some unrealistic weights are being generated, i.e. weights of certain factors in unweighted supermatrix are exceeding above 1. Since it is assumed that 60% variations will serve the purpose of simulation and due to the complexity in solving FANP models with such large number of factors, the variations have been restricted to 60% with 24 simulation run. Hence, the remaining five cases are obtained with a variation of 20%, 30%, 40%, 50%, and 60%. With four possibilities of weights for any factor in each case, 24 scenarios are obtained, and a limited supermatrix is acquired for each situation that is shown in Table 4.17. Finally, based on the issues constituting its respective domain, the weights of each domain is obtained using values of the limited supermatrix (Table 4.17) shown in Table 4.18.

Table 4.17: Values of limited supermatrix after sensitivity analysis.

	Case 1 (±10%)				Case 2 (±20%)				Case 3 (±30%)				Case 4 (±40%)				Case 5 (±50%)				Case 6 (±60%)			
	Ex .1	Ex .2	Ex. 3	Ex. 4	Ex .1	Ex .2	Ex. 3	Ex. 4	Ex .1	Ex .2	Ex. 3	Ex. 4	Ex .1	Ex .2	Ex. 3	Ex. 4	Ex .1	Ex .2	Ex. 3	Ex. 4	Ex .1	Ex .2	Ex. 3	Ex. 4
F1-1	0.02757	0.02925	0.02792	0.03295	0.02038	0.03706	0.04119	0.03228	0.02483	0.03138	0.03682	0.03544	0.03037	0.03294	0.02821	0.01964	0.03371	0.03285	0.02219	0.01421	0.02911	0.04162	0.04076	0.02919
F1-2	0.03370	0.02767	0.02627	0.03771	0.03271	0.02461	0.02554	0.02733	0.02190	0.02113	0.03596	0.03365	0.03167	0.03214	0.02615	0.03986	0.01295	0.03888	0.01980	0.02466	0.02094	0.01351	0.02499	0.01987
F1-3	0.03324	0.03304	0.03014	0.03161	0.02175	0.02491	0.02449	0.03910	0.03142	0.01939	0.01443	0.03226	0.02508	0.01578	0.02978	0.02065	0.01485	0.03491	0.01311	0.02661	0.01405	0.01854	0.03491	0.01895
F1-4	0.01783	0.01374	0.01183	0.01800	0.01357	0.01303	0.01564	0.01536	0.01268	0.01230	0.01169	0.01136	0.01532	0.01371	0.01154	0.01157	0.00638	0.01643	0.00819	0.00824	0.00571	0.00779	0.01290	0.00903
F1-5	0.00749	0.00717	0.00666	0.00688	0.00840	0.00692	0.00618	0.00404	0.00640	0.00358	0.00552	0.00827	0.00514	0.00912	0.00994	0.00663	0.00708	0.01213	0.00459	0.00436	0.00769	0.00505	0.00557	0.00173
F1-6	0.02003	0.01996	0.02305	0.01112	0.02491	0.02485	0.01109	0.02547	0.00889	0.02928	0.01275	0.02024	0.02603	0.02173	0.02932	0.03061	0.02140	0.00794	0.02606	0.02440	0.02077	0.02409	0.01772	0.02726
F1-7	0.02359	0.02549	0.02642	0.02171	0.02302	0.02435	0.02728	0.01918	0.01568	0.02393	0.02009	0.03455	0.03085	0.01507	0.03052	0.02390	0.01588	0.02238	0.02971	0.01028	0.02766	0.03070	0.03597	0.03294
F1-8	0.05251	0.05544	0.06013	0.04756	0.05314	0.06152	0.05249	0.05691	0.07729	0.06506	0.05695	0.04843	0.06724	0.04954	0.06754	0.05839	0.08415	0.07175	0.08974	0.10226	0.09032	0.06967	0.05080	0.06950
F1-9	0.00291	0.00207	0.00141	0.00227	0.00085	0.00154	0.00176	0.00213	0.00150	0.00177	0.00112	0.00124	0.00042	0.00328	0.00118	0.00411	0.00210	0.00204	0.00090	0.00095	0.00156	0.00075	0.00297	0.00327
F1-10	0.00614	0.00723	0.00625	0.00559	0.00480	0.00299	0.00679	0.00591	0.00797	0.00425	0.00654	0.00862	0.00357	0.00675	0.00773	0.00348	0.00618	0.00372	0.00483	0.00281	0.00438	0.00521	0.00710	0.00331
F2-1	0.02820	0.02886	0.03404	0.03036	0.02537	0.03849	0.02341	0.03011	0.05706	0.04293	0.03394	0.03096	0.03035	0.03062	0.05286	0.04214	0.05584	0.04559	0.05534	0.07133	0.06250	0.04519	0.03016	0.04186
F2-2	0.02620	0.02357	0.01938	0.02055	0.01623	0.01586	0.02643	0.03175	0.02021	0.02729	0.01737	0.02089	0.01247	0.02000	0.01185	0.02056	0.02270	0.01071	0.02105	0.01662	0.02004	0.01306	0.03344	0.01479
F2-3	0.00204	0.00210	0.00202	0.00174	0.00188	0.00181	0.00273	0.00269	0.00248	0.00336	0.00258	0.00191	0.00053	0.00257	0.00044	0.00395	0.00358	0.00079	0.00379	0.00134	0.00218	0.00094	0.00170	0.00046
F3-1	0.20805	0.21043	0.21130	0.21525	0.22328	0.21300	0.22061	0.20520	0.21214	0.21260	0.22130	0.21305	0.21330	0.21900	0.20324	0.20530	0.20440	0.20250	0.20620	0.20060	0.20030	0.21380	0.21050	0.21660
F3-2	0.20807	0.21045	0.21134	0.21534	0.22330	0.21321	0.22063	0.20522	0.21215	0.21265	0.22150	0.21327	0.21374	0.22001	0.20327	0.20560	0.20444	0.20257	0.20644	0.20077	0.20042	0.21418	0.21056	0.21693
F4-1	0.00247	0.00235	0.00187	0.00169	0.00227	0.00152	0.00138	0.00148	0.00263	0.00130	0.00130	0.00080	0.00098	0.00265	0.00077	0.00312	0.00288	0.00147	0.00358	0.00091	0.00132	0.00259	0.00303	0.00077
F4-2	0.02315	0.02518	0.02520	0.02477	0.02325	0.02549	0.02603	0.02416	0.01700	0.02596	0.02914	0.03121	0.02485	0.02099	0.02353	0.02716	0.02282	0.02832	0.02323	0.01016	0.02575	0.02537	0.03599	0.02804
F4-3	0.00435	0.00501	0.00477	0.00337	0.00455	0.00269	0.00253	0.00345	0.00376	0.00229	0.00453	0.00424	0.00219	0.00241	0.00241	0.00296	0.00521	0.00303	0.00301	0.00335	0.00199	0.00577	0.00520	0.00323
F4-4	0.00240	0.00227	0.00218	0.00069	0.00192	0.00178	0.00179	0.00163	0.00211	0.00213	0.00178	0.00067	0.00032	0.00223	0.00159	0.00165	0.00204	0.00108	0.00197	0.00224	0.00099	0.00148	0.00022	0.00299
F5-1	0.12368	0.12021	0.12275	0.13098	0.12837	0.13314	0.13136	0.12409	0.12823	0.11688	0.11848	0.11220	0.12591	0.12011	0.12409	0.12607	0.11351	0.11915	0.11159	0.13885	0.11165	0.11384	0.12428	0.11360
F5-2	0.09074	0.08725	0.08787	0.08899	0.08570	0.08898	0.08273	0.09249	0.08699	0.09083	0.08306	0.07988	0.09141	0.08304	0.08114	0.08236	0.08918	0.09141	0.08997	0.10055	0.09447	0.08359	0.07849	0.08883
F5-3	0.01961	0.01761	0.01661	0.01948	0.01971	0.01278	0.01463	0.01750	0.01609	0.02064	0.01685	0.01833	0.01456	0.01806	0.01229	0.02385	0.01289	0.01847	0.01412	0.01195	0.01566	0.01224	0.01438	0.01725
F5-4	0.00324	0.00365	0.00362	0.00169	0.00323	0.00126	0.00208	0.00353	0.00306	0.00143	0.00189	0.00464	0.00231	0.00062	0.00243	0.00111	0.00110	0.00182	0.00118	0.00361	0.00056	0.00224	0.00507	0.00259
F5-5	0.01952	0.02253	0.02106	0.01506	0.01989	0.01516	0.01983	0.01890	0.01690	0.01021	0.02291	0.02873	0.02828	0.03039	0.01838	0.00723	0.02556	0.01580	0.01535	0.01396	0.02605	0.02417	0.00899	0.01809
F5-6	0.01327	0.01747	0.01591	0.01464	0.01752	0.01305	0.01138	0.01009	0.01063	0.01743	0.02150	0.00516	0.00311	0.02724	0.01980	0.02810	0.02917	0.01426	0.02406	0.00498	0.01393	0.02461	0.00430	0.01892

Table 4.18: Ranking of the main domains after sensitivity analysis.

	Case 1 (±10%)								Case 2 (±20%)							
	Exp .1		Exp .2		Exp. 3		Exp. 4		Exp .1		Exp .2		Exp. 3		Exp. 4	
	W	R	W	R	W	R	W	R	W	R	W	R	W	R	W	R
Operational (F1)	0.22500	**3**	0.22104	**3**	0.22008	**3**	0.21541	**3**	0.20353	**3**	0.22180	**3**	0.22500	**3**	0.22104	**3**
Environmental (F2)	0.05644	**4**	0.05453	**4**	0.05543	**4**	0.05266	**4**	0.04348	**4**	0.05616	**4**	0.05644	**4**	0.05453	**4**
Economic (F3)	0.41613	**1**	0.42089	**1**	0.42264	**1**	0.43057	**1**	0.44659	**1**	0.42620	**1**	0.41613	**1**	0.42089	**1**
Social (F4)	0.03236	**5**	0.03481	**5**	0.03402	**5**	0.03053	**5**	0.03199	**5**	0.03148	**5**	0.03236	**5**	0.03481	**5**
Management (F5)	0.27006	**2**	0.26873	**2**	0.26783	**2**	0.27084	**2**	0.27441	**2**	0.26435	**2**	0.27006	**2**	0.26873	**2**

	Case 3 (±30%)								Case 4 (±40%)							
	Exp .1		Exp .2		Exp. 3		Exp. 4		Exp .1		Exp .2		Exp. 3		Exp. 4	
	W	R	W	R	W	R	W	R	W	R	W	R	W	R	W	R
Operational (F1)	0.22008	**3**	0.21541	**3**	0.20353	**3**	0.22180	**3**	0.21245	**3**	0.22770	**3**	0.20855	**3**	0.21207	**3**
Environmental (F2)	0.05543	**4**	0.05266	**4**	0.04348	**4**	0.05616	**4**	0.05257	**4**	0.06455	**4**	0.07975	**4**	0.07359	**4**
Economic (F3)	0.42264	**1**	0.43057	**1**	0.44659	**1**	0.42620	**1**	0.44126	**1**	0.41043	**1**	0.42430	**1**	0.42523	**1**
Social (F4)	0.03402	**5**	0.03053	**5**	0.03199	**5**	0.03148	**5**	0.03173	**5**	0.03072	**5**	0.02550	**5**	0.03169	**5**
Management (F5)	0.26783	**2**	0.27084	**2**	0.27441	**2**	0.26435	**2**	0.26199	**2**	0.26660	**2**	0.26190	**2**	0.25742	**2**

	Case 5 (±50%)								Case 6 (±60%)							
	Exp .1		Exp .2		Exp. 3		Exp. 4		Exp .1		Exp .2		Exp. 3		Exp. 4	
	W	R	W	R	W	R	W	R	W	R	W	R	W	R	W	R
Operational (F1)	0.20187	**3**	0.23406	**3**	0.23569	**3**	0.20007	**3**	0.24189	**3**	0.21884	**3**	0.20468	**3**	0.24303	**3**
Environmental (F2)	0.05389	**4**	0.05375	**4**	0.04334	**4**	0.05320	**4**	0.06515	**4**	0.06666	**4**	0.08212	**4**	0.05708	**4**
Economic (F3)	0.44280	**1**	0.42632	**1**	0.42704	**1**	0.43899	**1**	0.40651	**1**	0.41090	**1**	0.40883	**1**	0.40507	**1**
Social (F4)	0.03675	**5**	0.03692	**5**	0.02834	**5**	0.02828	**5**	0.02830	**5**	0.03489	**5**	0.03296	**5**	0.03390	**5**
Management (F5)	0.26469	**2**	0.24894	**2**	0.26559	**2**	0.27946	**2**	0.25814	**2**	0.26871	**2**	0.27141	**2**	0.26091	**2**

The results of the sensitivity analysis shown in Figure 4.12 indicates that after changing the input weights, the rank of the issues has changed, but there is not much difference in the ranking. For example, in each of the 24 experiments, the issues ‘sustainable financing’ and ‘immunization costs’ occupied the topmost rank as obtained in the original results (i.e. rank 1 & 2). Similarly, the ranking of most of the issues has not changed in the simulation run.

It can also be seen that, although the ranking of issues has changed slightly, the ranking of the main domains of issues remains unaffected (see Figure 4.13). In each experiment, the economic domain has acquired the highest priority among all of the five domains. The corresponding ranking order for the main domains is ***EC* > *M* > *O* > *EN* > *S***. The sensitivity analysis indicates that the ranking remains consistent in the simulation run, suggesting the stability of the results. Overall, it can be concluded that the final decision is consistent and reliable.

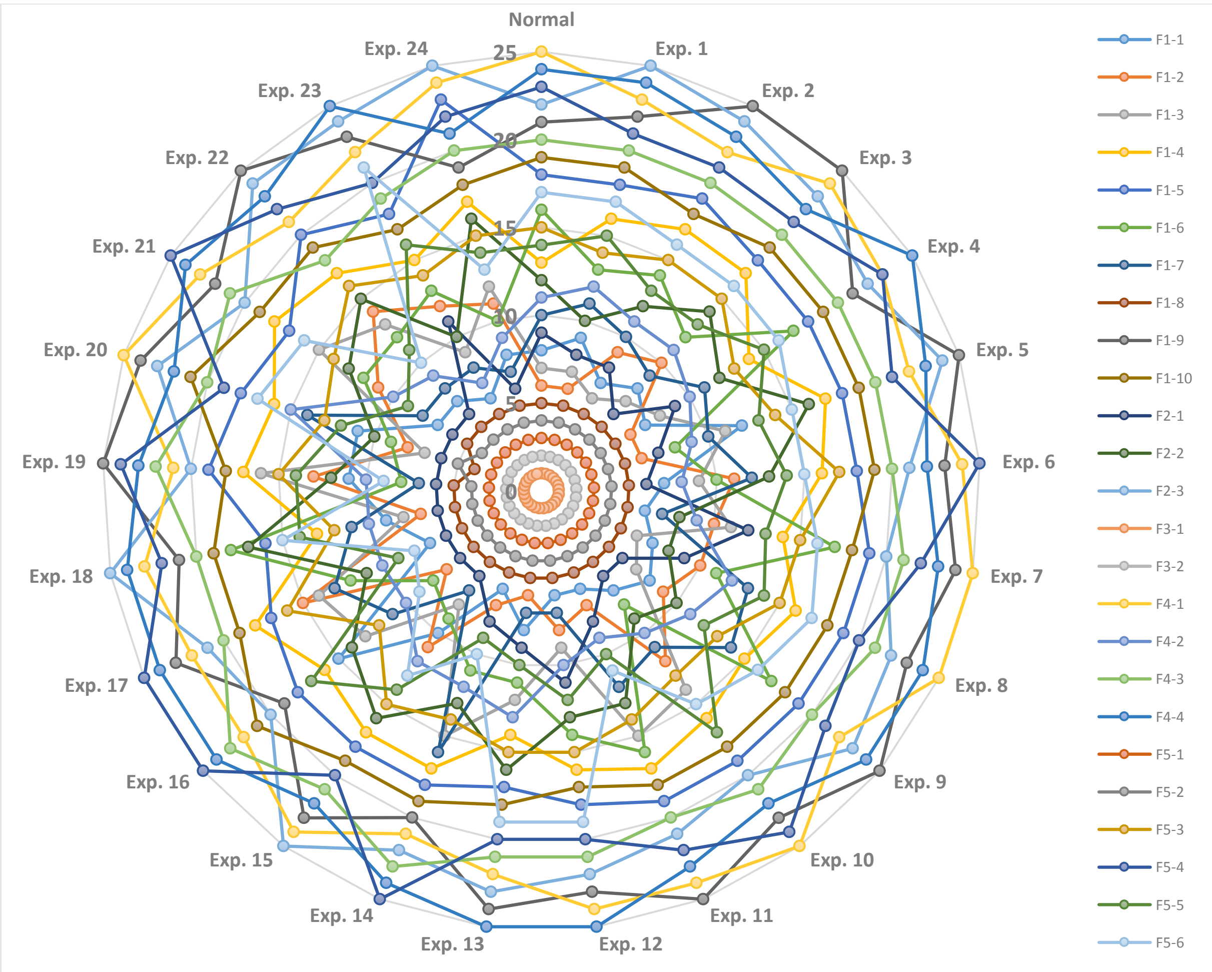


Figure 4.12: Result of the sensitivity analysis for key issues.

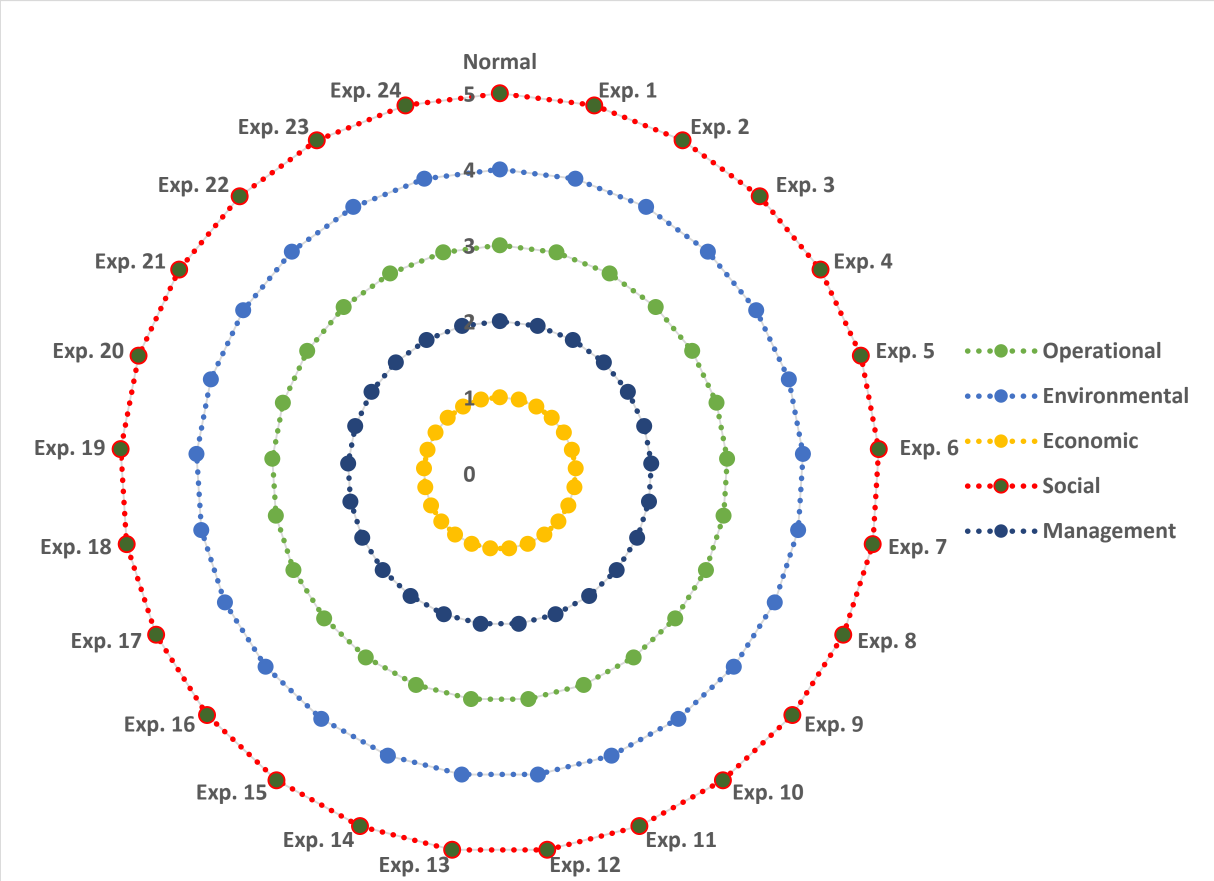


Figure 4.13: Result of the sensitivity analysis for main domains.

4.10. Discussion of results

Identifying and deciphering vaccine supply chain issues can play a vital role in delivering vaccines to every child who needs them. By analyzing the issues categories using ISM, ISM-FMICMAC, and ISM-FANP important issues that affect vaccine supply chain can be extracted. The findings of the present study can be useful to the immunization program officials of various developing countries to take better decisions to help improve VSC performance and child immunization coverage. From the ISM model, based on the driving power and dependence of the VSC issues, the decision-makers can take quick decisions in situations when there are less time and resources. From Figure 4.9, which is an integrated and improved model then ISM, it is evident that issues under the independent category have a greater influence on all remaining categories as they are positioned in the root of the model. Therefore, factors communication between the supply chain members, geographical barriers, demand forecast, better vaccine regulatory management, planning and scheduling and risk of natural/unnatural causes are significant issues that can be considered by immunization programs to improve vaccination coverage.

Better demand forecasting is the first step to ensure adequate immunization supplies and is the base of vaccine security. Mueller et al. [43] investigated the low-income country's supply chain and found that implementing demand forecasting system with increased storage and transport frequency elevated the variety of efficaciously administered vaccine doses and lowered the logistics cost per dose as much as 34%. Our findings are in line with the results of the study and show the reason why forecasting assumes significant importance in the vaccine supply chain. Recently, Huber et al. [288] and Klemm & McPherson [289] found that because of the better communication between the supply chain members, forecasting accuracy improved and resulted in a less shortage of items. Demand forecasting should be considered as an integral part of the planning processes [290,291]. Kochhar et al. [284] suggested that macro & micro planning and communication is necessary for successful immunization programs. Planning helps in reducing uncertainties as it involves anticipation of the future. From the survey conducted, it has been found that the communication between the upper and lower level of vaccine supply chain members was very less. This lack of communication often resulted in the mismatch between the supply and demand of vaccines. Running a vaccine supply chain requires proper planning and communication, the two key elements of the effective immunization program. In most of the developing countries geographical and natural/unnatural conditions acts as a barrier to proper communication. Distance and long travel time for the health workers in the last mile or by the children to the immunization centers is one of the key barriers to improve immunization rate, especially in rural areas. Transportation facilities, unavailability of human resource, maintaining the temperature of the cold chain, etc. are some of the issues, which arise because of the adverse geography. Natural causes like earthquakes, floods, landslides, rain, etc. and unnatural causes like terrorism, fast developing epidemics, etc. can make the delivery of vaccines difficult, thus causing disruptions in immunization programs. Studies in various developing countries have shown that people do not like to travel to immunization centers if the distance is beyond five kilometers [292–294]. A good planning strategy designed by the immunization programs, therefore, will be effective in delivering vaccines to the geographically hard-to-reach areas. One of the strategies suggested by WHO is to use outreach when the distance of location to serve is more than five kilometers. Outreach is the last critical link in the supply chain where health workers travel to a remote location for vaccination and the results have shown that utilization of outreach immunization services is beneficial in improving child immunization rates. A good planning strategy by the immunization programs will be effective in dealing with natural disasters so that the vaccination program does not stop. Proper planning and management are also essential for the vaccine regulatory authorities of any developing country.

Better vaccine regulatory management plays an important role in the vaccine supply. The highest priority of any regulatory body should be the protection and efficacy of vaccines. The WHO prequalification processes should be executed in a manner that avoids unnecessary delays. Gupta et al. [49] suggest the establishment of a quick-track mechanism for regulatory clearance of vaccines with the use of new platforms, might be immensely helpful, especially for vaccines required urgently in emergencies. The linkage factors come next, placed at an intermediate level in the hierarchy (Figure 4.9). The factors in the linkage category have the property of instability because any step taken on them can affect the system due to a feedback effect. From our findings, fourteen factors fall into this category. Firstly, in this category, monitoring of the vaccine cold chain and temperature and exposure control are important obstacles in improving vaccine supply. Today, many developing countries are facing the challenge of monitoring and controlling the temperature of the cold chain due to lack of technology and better equipment. Nelson et al. [295] found that in developing countries keeping vaccines at a controlled temperature is often a difficult task. The cold chain system across the developing countries is struggling to efficiently support immunization programs in ensuring the accessibility of safe and potent vaccines [6]. Thus, skilled health workers and the use of advanced technological devices will be required in the future to ensure a continuous supply of quality vaccines, so that vaccine wastage is less.

One alternative is to use radio-frequency identification (RFID) technology in immunization programs. The use of RFID technology can help to speed up operational processes such as tracking, shipping, improved inventory flows and accurate information thus resulting in a gain in overall vaccine supply chain effectiveness [296]. Vaccine wastage is one of the important issues faced globally. WHO estimates that in some countries, 50% of all vaccine doses are wasted both earlier than or after a vial is opened. Most closed-vial vaccine wastage may be attributed to supply chain issues including unintended freezing, expiry, vaccine vial monitor indication, breakage, theft, and loss [33]. Rishnappa [46] investigated an urban city of India and found that during primary care settings, vial size is statistically considerably related to vaccine wastage. Parmar et al. [297] found that the ideal vial size relies upon country-specific wastage rates. However, these vital data are missing for maximum GAVI-eligible countries [298]. Proper vaccine wastage management techniques in developing countries can be one of the solutions to overcome wastage issues. Sharma et al. [299] point out that the most important objective of waste management in developed countries is to protect the environment. All other objectives are, by far, less important. For a developing country like India, the situation with regard to the objectives of waste management is not so simple. Environmental protection, productivity improvement, employment generation, resource recovery, the welfare needs of a huge population, and so on are also important with respect to waste management. Thus the problem of ascertaining the objectives of waste management in such cases is many faceted. Soda et al. [300] point out that green supply chain management (GSCM) practices can help developing countries like India to make a supply chain eco-friendly without diluting the organizational objectives. Another alternative to reduce waste in VSC is to introduce concepts of the lean supply chain. A lean supply chain strategy is one aimed at creating a cost-efficient supply chain, with a focus on reducing inventory lead times and waste [301]. However, implementing lean concepts in VSC is not any task and requires commitment from management and financial support and resources. But, outsourcing parts of the supply chain such as transportation or inventory to lean supply chain companies in India can be helpful in reducing wastage. Hence, it becomes important that the immunization programs have trained and educated supply chain managers and skilled health workers so that important issues such as vaccine wastages, monitoring of cold chain, vaccine hesitancy, low coverage, etc. can be solved.

Today, the growing complexity of immunization programs increases the need for a properly-skilled, capable health worker. One of the challenges for accomplishing universal health coverage is making sure that everyone, mainly people in vulnerable groups and remote areas has access to properly trained and capable health group of workers. Technical abilities should be adequate to administer vaccines to any age groups. According to WHO, the world will be short of 12.9 million health workers by 2035 [302]. A 2013 study conducted in India found out that there is almost a 40% shortage of certified medical graduates for healthcare facilities at the grassroots stage. The immunization coverage stepped forward wherein it was properly supported by additional providers [49]. One advantage of having skilled and educated health workers is that they can advocate for immunization programs. Baleta et al. [303] suggest that advocacy and education for the immunization programs maintain the confidence of stakeholders. It is important for the community to accept the new vaccine and for maintaining their confidence in the existing vaccines. Kochhar et al. [284] suggest that health workers and local vaccine administrators have to be well educated about new modes of vaccine administration.

Another important linkage factors are sustainable financing, procurement lead-time, transportation disruptions, responsiveness, vaccine supply quality, and cold chain vehicles. Often vaccines are required in an emergency, therefore, it should reach with minimum time to the government agencies and to the health centers. Hence, the lead time is an important factor in the vaccine supply chain. Jha and Shanker [304] also point out that when the demand is stochastic, lead time becomes an important issue and its control leads to many benefits. Shorter lead time reduces the safety stock and the loss caused by stock-out, improves customer service level and increases the competitive advantage of the business. Another important factor in the list of linkage factors is the supply of high-quality vaccines to the immunization programs. The purpose of immunizing children through vaccination is to make them stronger so to fight against various diseases instead of making ill. Thus, it must be ensured that the supply of vaccines should be of high quality, reliable and affordable. According to WHO, the only vaccine of assured quality should be regarded for use in national immunization programs by the risk/benefit ratio for the precise population. Development and supply of quality vaccines are possible if the government provides financial support. Having a sustainable financing plan for the advent of the latest vaccines and permitting the non-public sector to play a significant position alongside the public sector, may help in improving the child immunization coverage[49]. According to Kochhar et al. [284], introducing a new vaccine in a developing country may face several financial and logistical challenges because the newer generation vaccines are often too expensive. Yadav [305] suggest that supplying health products quickly to the patients who need them requires a supply chain that is responsive. Quick response enables the supply chain to meet customer demands with shorter lead times [69]. A vaccine supply chain can be responsive if there are an adequate number of cold chain vehicles. As suggested by the experts the optimum number of cold chain vehicles can overcome delivery problems. The coverage area can also be improved if there are an optimum number of cold chain vehicles.

Moving to the topmost level in Figure 4.9 is the dependent factors. However, being at the top of the hierarchy does not mean that the factors are more important, but more dependent on other factors, that is, they are considered a consequence of the system. In this category, four factors vaccine hesitancy, storage and handling of vaccines, monitoring of vaccinated population and location of vaccine stores and immunization camp are superficial influence factors. Their performance is influenced by driving and linkage factors. If the driving and linkage factors can be properly addressed, the overall performance of these factors will be improved accordingly. As an example, poor or inadequate communication, confidence, complacency, and convenience can negatively affect vaccination uptake and contribute to vaccine hesitancy [58,306]. To counter vaccine hesitancy, it requires educated health workers who can advocate for immunization. Therefore, the availability of human resource and vaccine advocacy and education, which are linkage factors, supported in dealing with vaccine hesitancy. In turn, the same linkage factors can also help in proper storage and handling of vaccines and monitoring the number of people vaccinated. Proper vaccine storage and handling practices play a crucial function in protecting individuals and groups from vaccine-preventable diseases. Failure to store and handle vaccines well can lessen vaccine potency, ensuing in insufficient immune responses in patients and poor safety against disease [307]. There are few vaccination issues more significant than the proper storage and handling of vaccines in developing countries. Our findings are in line with the study of [308]. The study pointed out various literature published in the analysis of freezing of vaccine in the cold chain in 16 developing and 19 developed countries in the last 20 years. During storage, the incidence of exposure to freezing temperatures became observed to be 13.5% in developed countries as against 21.9% in developing countries.

Chiodini [74] found that proper storage and handling of vaccines is dependent on other important issues such as staff involved, vaccine ordering and delivery, equipment's, and inventory management. Kochhar et al. [284] suggest that monitoring of the vaccine trends with awareness on the public health issues would allow government health authorities, healthcare companies, parents and decision-makers to comprehend the health benefits of vaccination in lowering the burden of severe disease. Better monitoring of vaccinated population will also help in proper forecasting of vaccines, and to identify the potential for outbreaks of vaccine-preventable diseases. The location of vaccine stores and immunization camp (25) is one of the important dependent factors. As suggested by the experts the issue is mainly faced by those developing countries, which have a large population residing in the rural region. From the survey, it has been found that the place given to the healthcare workers for storing the vaccines on the vaccination day is very far from the immunization camp, where the vaccines are to be administered to the children. As the location is very far, therefore, many health workers especially women face the problem of staying and transportation. Due to remote locations, there are chances that the ILRs (ice-lined refrigerators) on which the vaccines are kept may get damaged during travel, thus resulting in vaccine wastages. The failure of vaccines kept on ILRs can be because the ILRs are not able to maintain the required temperature due to traveling for a long period. If the government provides better transportation facilities for immunization programs, then the chances of vaccine wastages will be less due to a reduction in vaccine travel time. Therefore, in the present case, the vaccines waste is not dependent on the distance of remote areas but the temperature. In our study, 'transportation disruption' is the linkage issue and it resulted in other linkage issue 'temperature and exposure control', which in turn the 'vaccine wastage', which is another linkage issue. Hence, our study shows that affecting any linkage factor can affect other factors and disturb the whole system.

The location of vaccine stores and immunization camp (factor 25) is mainly dependent on transportation and infrastructure facilities. If transportation facilities are proper with better infrastructure, then it will not make much difference of whether the distance is optimum or not. However, in maximum developing countries better logistics and infrastructure is not available because of insufficient funds from the government. Because of few driving or linkage factors, factor 25 exist; hence, for the ease of the health workers, the distance should be optimum to travel and stay. The location of vaccine stores and immunization camp depends upon several other factors and can be covered under the optimization models for coverage location problems. In

Figure 4.9, the autonomous factors have been excluded because of their property of not influencing the system to much extent. Their effect on improving the performance of the system will not be much significant. Instead, the decision-makers can save their time and cost by focusing on other issues, which have a greater effect on the system. Coordination with the local administration is the autonomous factor in our study.

Kochhar et al. [284] suggest that the vaccination program should set up a coordinating committee and thematic sub-committees and examine epidemiological statistics to decide the goal regions and population. The coordinating committee needs to engage all related individuals and departments at the extent of the Ministry of Health, other ministers at local and state levels. To properly communicate with the state and local administration financial support will be required for hiring human resource who can travel to urban/remote locations, purchasing better-communicating devices and setting up proper infrastructure. However, as most of the developing countries are already facing the issue of insufficient funding [75,309], therefore, proper coordination with the local government cannot guarantee better services and improvement in vaccination rate. Hence, the decision-makers should not pay much attention to autonomous factors. Finally, from the model, and from further discussions with the expert's, it has been found that there are three most critical factors, and these directly or indirectly drive every other factor. Therefore, the critical factors should be given more attention to enhancing the vaccine supply chain performance. The three critical factors identified in the study are 'demand forecast', 'planning and scheduling', and 'communication between the supply chain members'. These factors are shown in Figure 4.11. One of the most critical factors of the VSC is better demand forecasting, which plays a major role in fulfilling the vaccine demand and improving the vaccination coverage. The purpose of vaccine forecasting is to estimate the number of products and economic needs essential to conduct immunization programs. The forecasting for vaccines is mainly based on the target population, time-period of estimation, and previous consumption [310]. However, many developing countries do not have reliable data about past vaccine consumption, proper methodologies for data analysis, or accurate projections of target populations and their locations [7,311]. The lack of real-time vaccine consumption data, inappropriate analysis of trends in vaccine utilization rates and incorrect assumptions about the uptake of new vaccines makes demand forecasting vulnerable to inaccurate estimates. Because census data are typically updated in every ten years, even in the nice organized developing countries, the combination of inaccurate estimates means that inaccurate vaccine forecasts are replicated year after year. Unnecessary logistical burdens and expense are the results when an excessive amount of or too little vaccine is ordered because of the inaccuracies [7].

During the survey, it was identified that there was no proper mechanism for vaccine forecasting from the local (town/cities) to the district and finally the divisional level. This odd way of forecasting often created a bullwhip effect in the supply chain, mostly found for polio and BCG vaccines. The bullwhip effect is defined as the magnification of demand fluctuations along the upstream supply chain and leads to excess inventory or stock-outs [288]. The primary reason being the flow of distorted information flow from one end of a supply chain to the other [312]. The issue of vaccine stock-outs due to poor forecasting is with not only India but also other countries are facing similar problems. Lydon et al. [50] investigated the availability of essential vaccines in 194 WHO member states. The results conclude that 65 countries reported a national level stock-out for at least one vaccine and for at least one month during 2015. The vaccines most affected are DTP and BCG, which account for 43% and 31% respectively. Both lower and upper-middle-income countries reported the majority of stock-outs. A total of 58 countries reported subnational-level stockouts at the district level, 49 countries indicated sub-national stock-outs were due to national level stockout. More concerning is that 47 of the 49 countries reported that the district level stockout resulted in an interruption of immunization services. This implies that there is a 96% chance that a stockout at the district level will cause an interruption of vaccination services. The cause for stockouts at country level was found 18% due to poor forecasting and stock management. Supply chain experts have recognized that the bullwhip effect is a problem in forecast-driven supply chains, and careful management of the uncertainty to reduce its effect is an important goal for supply chain managers [313]. Some degree of uncertainty exists in every supply chain. Many researchers suggest that information sharing through communication and coordination are essential elements to manage uncertainty in the supply chain [314–316]. Thereby, it helps to increase the responsiveness of the supply chain and to make demand more seen through sharing information that in turn helps to mitigate bullwhip effect [317,318]. In this regard, Agarwal and Shanker [319] in their study found that information sharing can benefit the supply chain by reducing the bullwhip effect. Likewise, Ali et al.[320] have conducted a study to compare the performance of a two-stage supply chain using two strategies, i.e. forecast information sharing and no information sharing. The results show that forecast information sharing outperforms no information sharing on reducing the mean square error of forecast and inventory cost. Irrespective of the forecasting technique used, sharing information might continually be beneficial because the upstream supply chain members would be using the real consumer data in their planning structure. Information sharing builds healthier partnerships and promotes integration among suppliers and manufacturers in the supply chain, leading to higher performance [321]. High degrees of internal communication and planning tend to be lots more productive in problem-solving and objective attainment [322].

According to Kaipia [323], the lack of integrated planning processes is a critical shortcoming because it ends in many supply chain inefficiencies. Typically it results in, unused inventory, difficulties in coping with seasonal demand patterns, insufficient demand forecasting, long planning horizons, and the incapability to seize supply constraints regarding capacity or materials availability[324]. Galasso et al. [325] suggest that tactical planning can help to improve supply chain performance, especially in the presence of uncertainty. Tactical plans are medium-term plans in which decisions related to demand forecast, procurement of materials, production, and delivery are made for a time horizon of 1-2 years[87]. A study by Kaipia [323] found that supply chains, which are required to supply products to customers at high speed are also required to develop efficient forecasting processes to manage the uncertainty in demand. Makatsoris and Chang [326] found that forecast centered planning supplied a better guide for achieving organization desires than order-based planning. Comelli et al. [327] proposed an approach to evaluate the financial benefits of supply chain tactical planning regarding cash flow and found that proper planning leads to a reduction in cash flow. Kwon et al.[328] suggest the concept of collaborative planning and forecasting replenishment in the healthcare industry that can result in increased inventory turns and customer care. Another possibility to alleviate the bullwhip effect is the utility of more advanced forecasting techniques, which are capable of managing sudden demand changes [329]. Nevertheless, to cope with the issues of the vaccine supply chain, strategic planning is required for building a better communication channel between the vaccine supply chain members. It will help in addressing the key issues faced in the delivery of basic vaccines in developing countries. Also, the support from the government is also very important to strengthen the immunization supply chain.

Apart from this, if decision-makers want to concentrate on the group of issues, instead of focusing only on one or a few issues, then the results of ISM-FANP, which divides issues into five domains and prioritize them, can be very helpful. Based on the results, the economic issues (E) domains holds first place in the priority list and it clear that economic issues are the important constraints in the improvement of vaccination coverage. Donnell [281] point out that in developing countries economic resources are often insufficient to support the essential health care services. Similarly, Kochhar et al. [284] highlight that due to lack of economic and political instability vaccination coverage remains unsatisfactory in many parts of the developing countries. Immunization programs with weak economic, or political stability have a higher risk of decision-makers making decisions that negatively impact the supply chain performance, such as vaccine wastage due to the use of cheap and outdated equipment's, too much vaccine ordering at once due to fluctuations in funds from government, etc. Management issues (M) holds the second rank on the priority list. With the rising costs of vaccine and the complexity of immunization programs, a consistently high standard of supply chain management is required that can only be accomplished if all of the links in the supply chain follow current standards for storage and distribution [330].

Operational issues (O) dimension comes next on the priority list with a weight of 0.222. Finally, environmental issues (E) and social issues (S) domain occupies the lowest position in the priority list. Because of the fewer weights, they will not have a major impact on system performance. During discussions, most of the field experts also agreed with the results, while few argued the importance of social issues in improving immunization coverage in rural areas. The experts pointed out that considering few relevant links of the environment and social issues such as vaccine wastage, uncertainties of natural/unnatural causes, vaccine advocacy and education, proper coordination with local administration, etc. together with good support from the government through incentives could help to obliterate these barriers. Few experts added two important issues in the list ‘coordination with local administration’ and ‘location of vaccine stores and immunization camp’, which is often neglected in India and most of the developing countries. They suggested that these issues should be given special care as it can help in improving coverage, especially in rural areas.

4.10.1. Recommendations for decision-makers to improve VSCP

- The decision-makers should first give priority to the economic issue and management issue domain because they are the primary reasons for which the issues of the vaccine supply chain issues arise.
- In Figure 4.9, the factors placed on the bottom level are the driving factors of the vaccine supply chain and have more capability of influencing other factors. These factors need the maximum attention and focus. They refer to the strategic issues in improving vaccine supply chain performance.
- Three factors in the group of driving factors have been identified as the critical factors and are the most crucial of all factors in affecting vaccine supply chain performance. The decision-makers should give special priority to critical factors while taking corrective actions. The results of better management of critical factors can help in designing a supply chain that is optimized and works efficiently and effectively.
- The linkage factors placed in the intermedium-level in Figure 4.9 are the next important factors after the driving factors to improve supply chain performance. These actors are strong both in driving power and dependence. They are sensitive factors and have less influencing power compared to the driving factors. These factors assume a linkage role

with getting the influence and actions from the driving factors, and in turn, applying effects on those dependent factors.

- The dependent factors in Figure 4.9 are less important as compared to the other factors placed below its level. They are more dependent on other factors, and if driving and linkage factors are addressed correctly, their performance will be improved accordingly. Therefore, they are generally accepted as less important in improving supply chain performance, and decision-makers should not pay much attention to them.
- The autonomous factors having weak driving power and dependence and do not have much influence on the system performance and have been excluded from the integrated model shown in Figure 4.9. Their effect on improving the performance of the system will not be much significant. Instead, the decision-makers can save their time and cost by focusing on other issues, which have a greater effect on the system.
- The sequence with which decision-makers should focus on the issues/domain is the economic issue domain then critical factors followed by the remaining driving factors and in the end the linkage factors to improve system performance. The effect of five issues domain of ISM-FANP to mitigate VSC issues and four regions of ISM-FMICMAC on vaccine supply chain performance is shown in Figure 4.14 & 4.15.

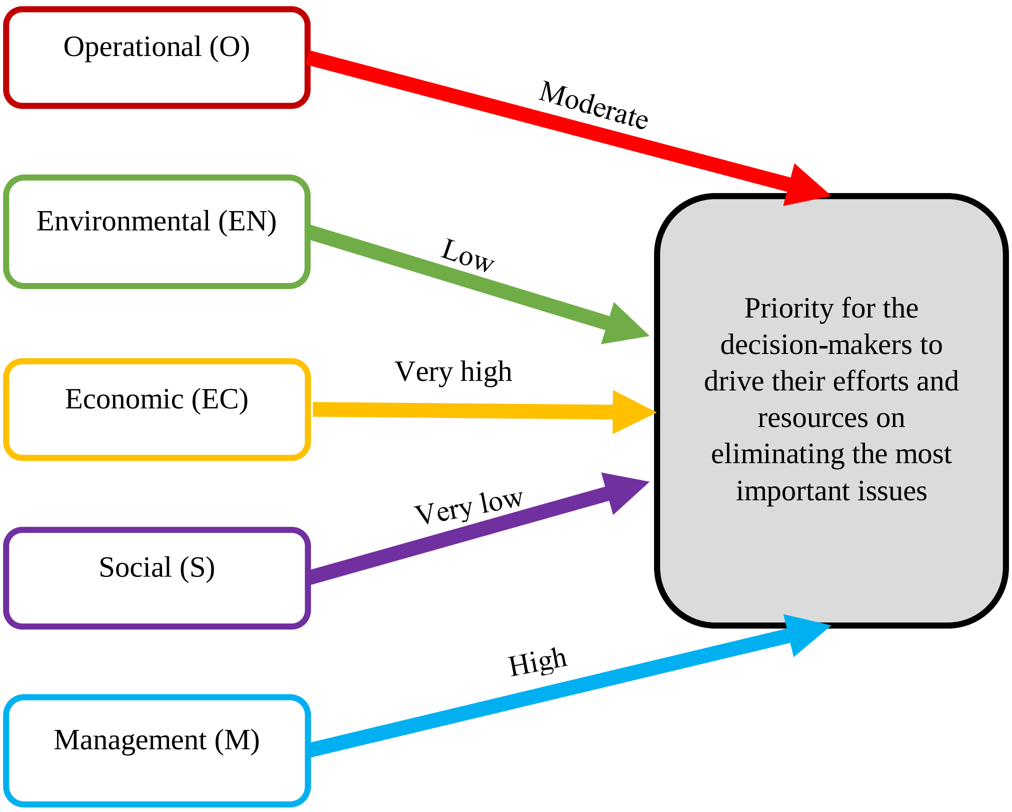


Figure 4.14: Priority of five issues domain to mitigate/eliminate vaccine supply chain issues.

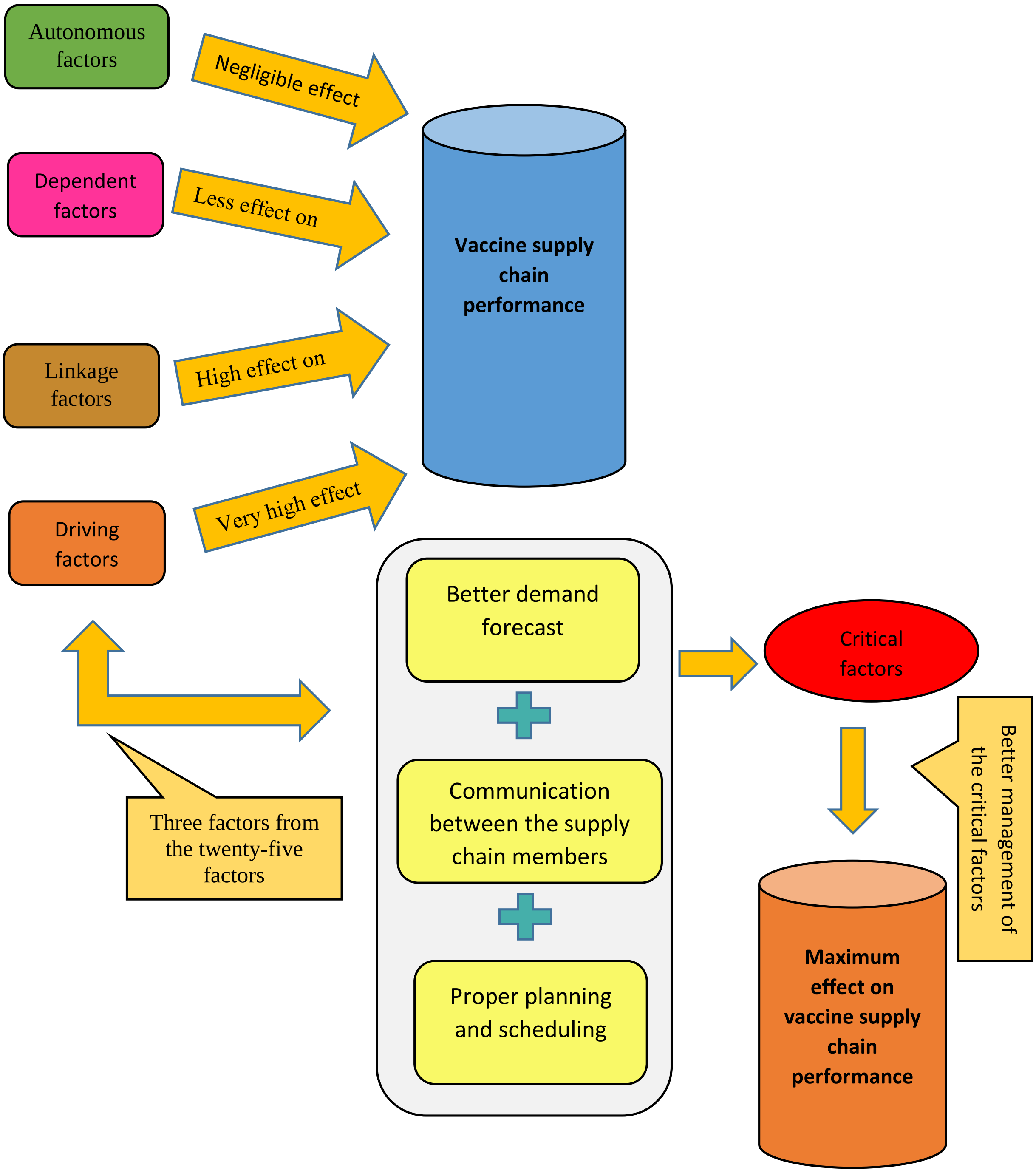


Figure 4.15: Effects of key issues/factors on vaccine supply chain performance.

4.11. Conclusion

In this chapter, 25-key issues of vaccine supply are identified from field survey, literature review and Delphi approach. Using ISM, integrated ISM-FMICMAC these issues are analyzed, first for making a hierarchical model to determine the interrelationships among the issues, and second for allocating these issues into four groups based on their level of importance (driving power and dependence). Next, these 25 issues are categorized into 5 main domain of issues and then prioritized using integrated ISM-FANP. Based on the discussion with experts and also from the results of the study, three factors are identified as critical factors that are the primary reasons for the delay in the delivery of vaccines. These critical factors need special care as they have maximum effect on vaccine supply chain performance.

Further, from the ISM-FMICMAC analysis results, it can be observed that factor vaccine shortages is among the important issues of vaccine supply chain as it occupies the linkage domain in the driver-dependence graph. The same can be confirmed from ISM-FANP analysis where the factor occupied the 7^{th} rank among the twenty-five key issues. Experts also pointed out that often due to improper forecasting and several other factors, vaccine shortages arises in not only in India but in other developing and developed countries. The purpose of focusing only on factor vaccine shortages from the list of key issues is because during literature survey, first, it was found that in recent years, experts from around the world have constantly expressed concern over the vaccine shortage problem, and second, very few researchers have focused on the problem of vaccine shortages. Therefore, vaccine shortages can be considered as one of the important areas that needs attention to improve immunization coverage. Although demand forecast and other critical issues identified in this study are also important for the vaccine supply chain, however, researchers have already started to focus on these areas and suggested different mathematical models and other solutions to handle these issues [47,48,57,331]. Therefore, based on study findings, expert's opinions, and scarcity of literature associated with the vaccine shortages, the present research work has given emphasis on the analysis of vaccine shortages domain.

Chapter 5

STUDY OF VACCINE SHORTAGES

Summary

Shortages of basic vaccines are one of the key issues, which affects the child immunization programs of not only India but also other developing countries. This chapter discusses, the major causes of vaccine shortages and possible solutions to overcome the problem of the shortage. The ten causes indicating the basic vaccine shortages and 12 solutions to overcome the shortages have been identified from the literature review, field survey, and expert's opinions. Using AHP, the weights of criteria's have been obtained. Next, hybrid AHP-COPRAS-G has been applied for prioritizing the alternatives. Analysis results reveal that 'uncertainty in demand' is the most important cause for vaccine shortages and 'setting up monitoring and reporting systems for shortages' is one of the key solutions to overcome vaccine shortages problems.

5.1. Introduction

One of the main objectives of the national immunization programs is to maintain a continuous supply of basic vaccines to the health centers so that it can be made available to all the children at the right time. Vaccines unavailability not only leads to missed opportunities to vaccinate the child but also put their life at risk. Hence, it is very important that the vaccines are always available in the stock in order to have uninterrupted immunization program scheduled. Despite various efforts by the international health agencies such as WHO, UNICEF, etc. vaccine shortages still occur not only in the developing countries but also in the developed countries. Experts point out that these shortages affect the immunization programs for a long time because due to such shortages, the regular immunization programs and the specific group of children to be vaccinated gets delayed, and when the shortages are over not only the immunization programs have to cover the population that has to be immunized, but also the specific group of children left unvaccinated. So shortages not only increases the vaccine demand for vaccines but also causes extra burden to the immunization programs [332].

Vaccine shortages are defined as the inability of the countries to meet national needs, which includes population needs and buffer. In supply chains, the shortages may occur at multiple points, right from the supplier to manufacturer until distribution. It happens not only once a year, but it also happens very often and is everywhere around the world that affects countries of all income groups and regions. A recent flu outbreak in the USA caused the shortage of flu vaccine that resulted in the deaths of many children and infants [333]. The global shortage of hepatitis B vaccine in 2017 is another example that indicates the manufacturers are struggling to produce vaccines to meet global demand. India also experienced a shortage of inactivated poliomyelitis vaccine (IPV) because of the worldwide shortfall.

India is one of the largest suppliers of vaccines to WHO, UNICEF and to the globe and is considered as the epicenter for vaccine manufacturing in the world. According to a report "Indian Vaccine Market Report and Forecast 2017-2022", the market of the vaccine in India reached a value of around INR 59 Billion in 2016, with a CAGR of nearly 18% during 2009-2016. Indian vaccine industry with best manufacturing facilities has earned India the recognition of having the largest global capacity for WHO prequalified vaccine manufacturing. In spite of being a manufacturing hub, India is also home to one-third of the world's unimmunized children. According to Mckinsey & Company report, the primary reason for the low immunization coverage in India is the limitations in distribution, public health delivery system, and supply in basic vaccines. The distribution of life-saving vaccines is hampered by insufficient cold chain equipment's and constraints to last-mile distribution together with the shortage of vaccines, which has limited delivery of basic vaccines to 60-70% [334]. Recently, Andhra Pradesh state of India faced an acute shortage of Rotavirus, IPV, OPV, and Pentavalent vaccines because of the inadequate supply from the central system. Figure 5.1 shows that vaccine shortages problem in not only in India, but it is a global phenomenon.

Experts indicate that vaccine shortages are global and complex phenomena and the solutions to overcome shortages needs to be addressed globally. Since the vaccine shortages depend upon the vaccine type and other internal and external factors, therefore, the aim of the study is to focus on the causes of basic vaccine shortages in India. Based upon the literature review, field survey and expert's opinions, 10 causes or criteria's of basic vaccine shortages and 12 solutions or alternatives that can help to overcome vaccines shortages have been identified. AHP has been applied to calculate the weights of the causes, while a hybrid framework with AHP and COPRAS-G methodologies aids to prioritize the alternatives based on their utility values. For the analysis purpose, COPRAS-G is used because COPRAS-G is completely logical and useful mathematically for processing incomplete data about the system and is supposed to upsurge the performance and enhance the accuracy stage of the process within the decision-making system. 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 illustrates the degree to which one alternative is considered as higher as or worse than the set of existing alternatives. Other MCDM techniques do no longer have such features and that is the cause why COPRAS-G succeeded in the decision--making the process. COPRAS-G helps the decision-makers to make more decisions that are accurate. COPRAS-G is accepted for efficiently managing the problems of uncertainty, subjectivity and imprecise information [227,228].

The purpose of integrating COPRAS-G and AHP is that in order to rank sub-criteria's/alternatives; it is required to give weights to the criteria's so that these weights can serve as an input to the COPRAS-G method. In this condition, often researchers assume arbitrary weights, which, may lead to wrong results. Therefore, in such situations, instead of putting arbitrary weights, getting weights through the expert's opinions with the AHP method can be helpful in obtaining more realistic weights of the criteria; hence better decision-making results. Thus, in this study, AHP has been used to obtain weights of the criteria using expert's opinions and then these weights have been used in COPRAS-G to rank alternatives. The findings of the analysis may help the policy-makers to take a better decision on reducing/eliminating the impact of vaccine shortages on immunization programs performance.

The objectives of this Chapter are:

- ***To identify the major causes of vaccine shortages and solutions to overcome shortages.***
- ***To prioritize the causes and solutions to help policy-makers to reduce or eliminate the impact of shortages on the immunization programs performance.***

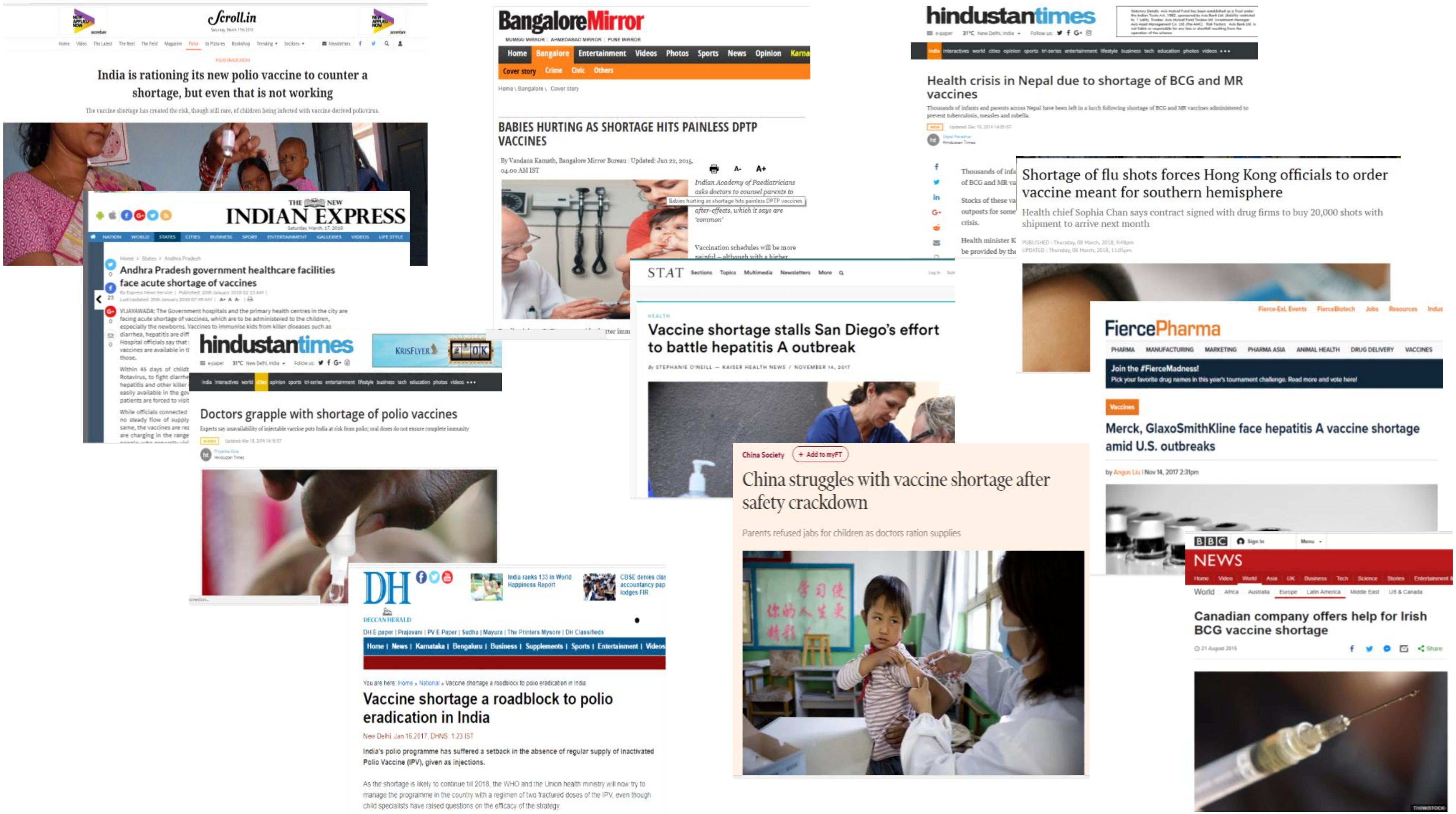


Figure 5.1: Reports of vaccine shortages in India and worldwide (2015-2018).

5.2. Hybrid framework

The hybrid framework consists of three phases as shown in Figure 5.2. It starts with the literature review, field survey and expert's opinions in phase 1. In phase 2, based on expert's opinions, weights of causes of vaccine shortage as various criteria's are calculated using AHP. Then in phase 3, a hybrid AHP-COPRAS-G method is applied to obtain the final ranking of alternatives, followed by the simulation to check the stability of the results.

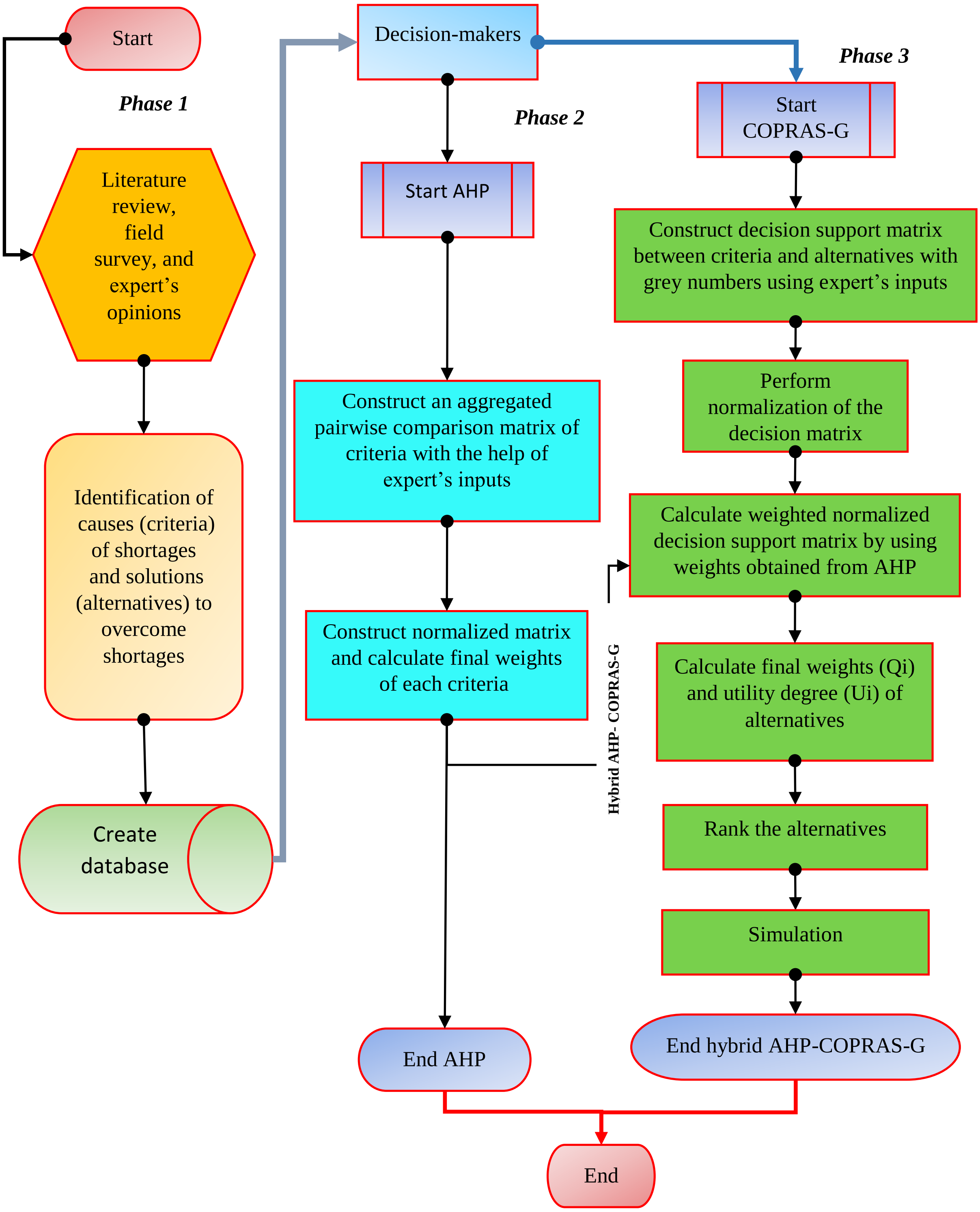


Figure 5.2: Flowchart of the hybrid framework.

5.3. Application of the methodology

Based on the hybrid framework presented in Figure 5.2, an evaluation process to weight the criteria's and prioritize the alternatives to overcome the vaccine shortages have been followed that is given below.

Phase 1: ***Research instrument and data collection***

In phase 1, data collection was done to identify the causes of vaccine shortage and solutions using two steps discussed below:

Step 1: Literature review

An organized and comprehensive literature survey was performed to identify various causes and solutions for the study. The schematic of the finalization of papers that deals with the vaccine shortages problem are depicted in Figure 5.3.

Step 2: Field survey and expert's opinions

The study used a field survey and expert's opinions as a second instrument to explore various causes and solutions. In rural and urban health centers, fifteen health facilities were surveyed in three states of India: Uttarakhand, Delhi, Uttar Pradesh to ascertain the condition of vaccine shortages in the child immunization services. Interviews were organized with the healthcare staff that consisted of senior immunization program officers, additional research officers, senior consultants, auxiliary nurse midwife (ANM), and Anganwadi workers. The health workers were asked to provide information on shortages of basic vaccines. The survey helped in identifying various causes of basic vaccine shortages in the immunization program.

Further, eleven senior experts from the same three states gave their valuable inputs in identifying the solutions that can help in overcoming vaccine shortages. Lastly, from the survey and literature review, a total of 10 causes (shown in Figure 5.4) and 12 solutions were identified. The identified vaccine shortages causes and solutions with their descriptions have been discussed in Table 5.1 & 5.2.

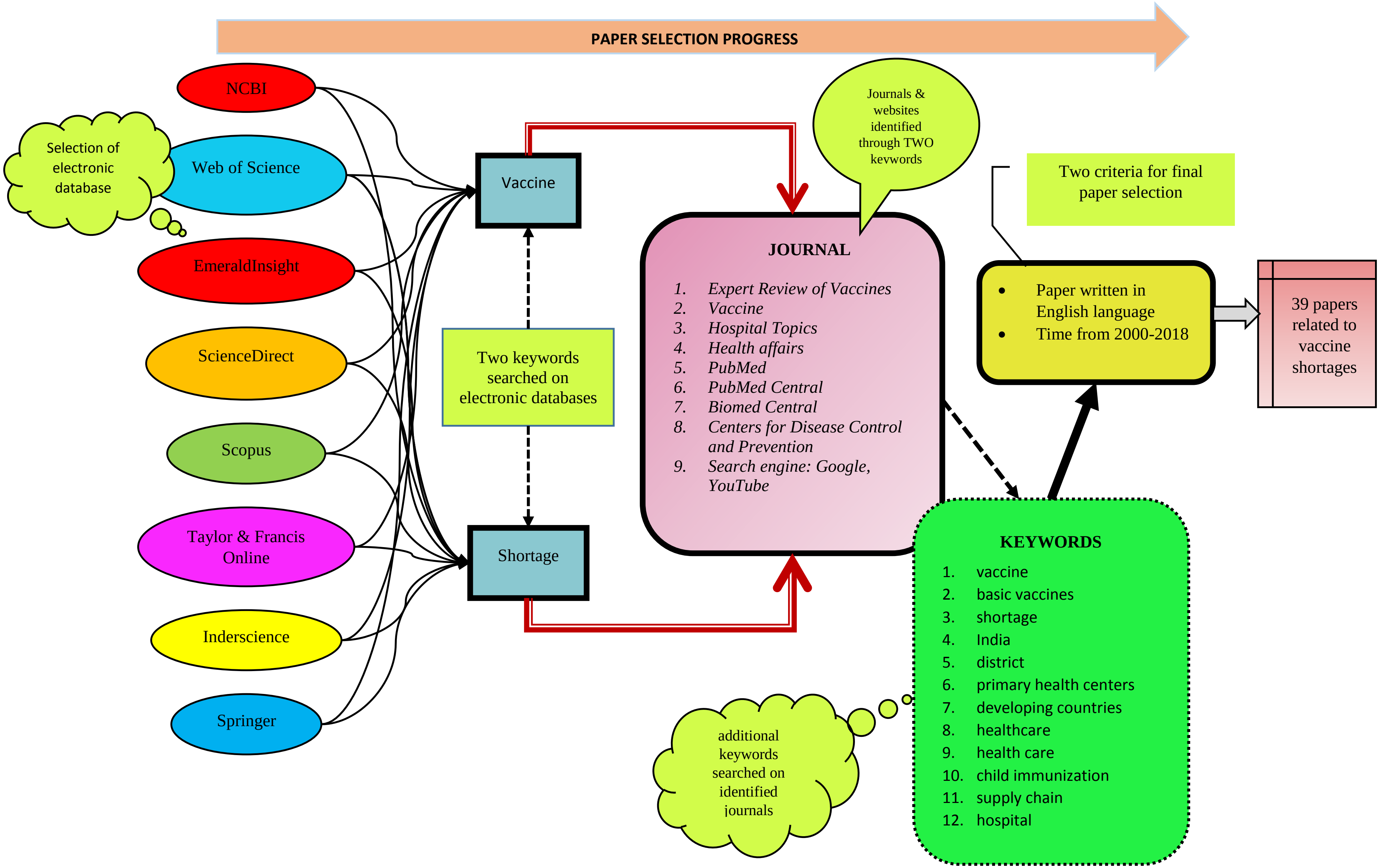


Figure 5.3: Identification of causes and solutions through literature review.

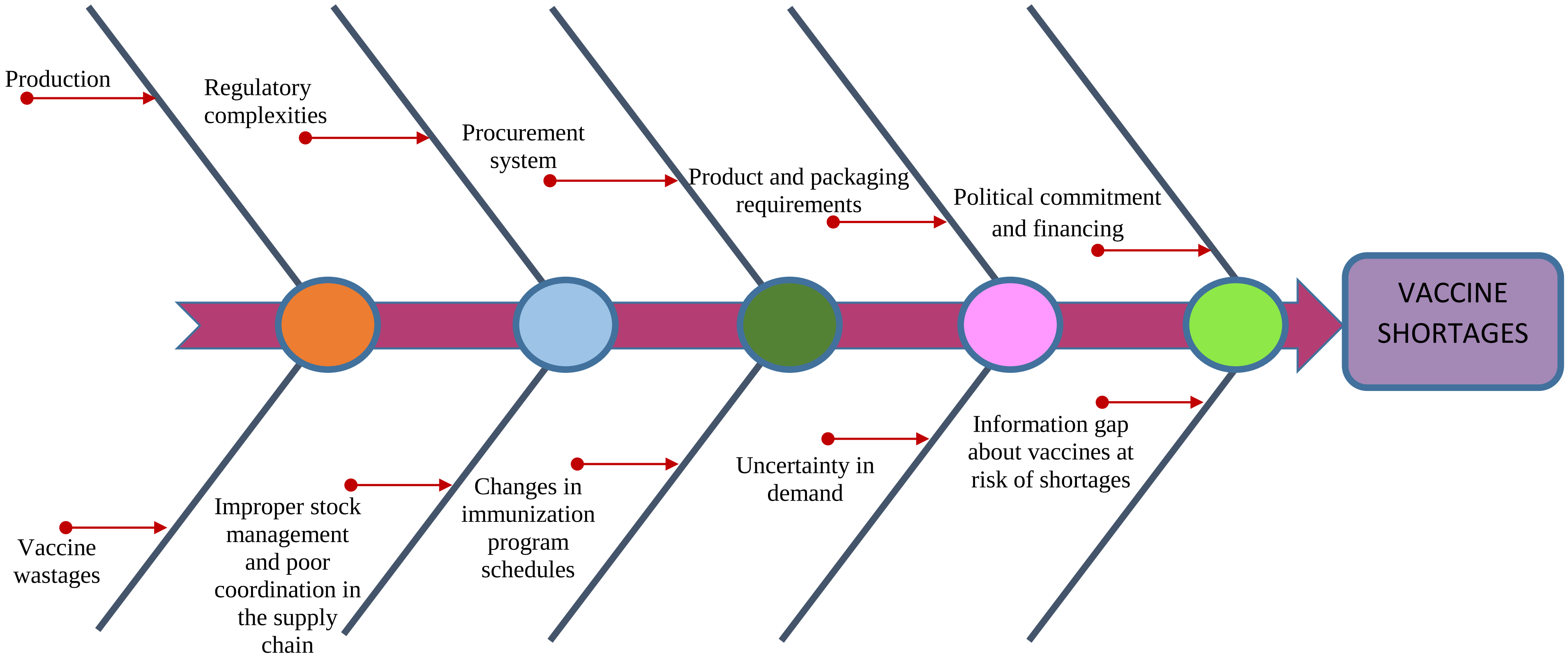


Figure 5.4: Cause-Effect diagram for vaccine shortages.

Table 5.1: List of causes and their description.

Cause	Denotation	Description
Production	C1	Due to the complex and rigorous process for vaccine manufacturing companies to qualify as WHO prequalified vaccine manufacturers, and due to high startup investment, technology, and knowledge requirements, there is a limited number of vaccine manufacturers globally. Since vaccine manufacturers are limited, the production of vaccines to meet the global demand for national immunization programs is also limited, which is one of the primary causes for vaccine shortages.
Regulatory complexities	C2	India has very complex vaccine regulatory procedures for procuring vaccines to be used in national immunization programs. Such regulatory issues impose difficulty for the manufacturing companies and immunization programs to supply and purchase vaccines, which leads to shortages.
Procurement system	C3	Inflexible procurement mechanism causes vaccine shortages to occur at different levels of VSC in most of the developing countries.
Product and packaging requirements	C4	Diverse country product and packaging requirements create complexities for the vaccine manufacturers to consolidate and meet the actual demand. For example, in many countries, BCG 10 dose vial is used and somewhere 20 dose vial.
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 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.
Political commitment and financing	C7	Because of the poor political commitment towards the healthcare sector especially immunization programs, the required budget is not allocated to the immunization sector. This is one of the main reason that causes a delay in payments to purchase vaccines, and thus causes vaccine shortages.
Changes in immunization program schedules	C8	Each developing country has its immunization program schedule, which changes from time to time. This change often leads to a shortage of specific vaccines required in urgency.

Cause	Denotation	Description
Improper stock management and poor coordination in the supply chain	C9	Due to the improper stock management and poor coordination between the supply chain members, vaccine shortages occur at various levels of VSC.
Information gap about vaccines at risk of shortages	C10	Due to lack of information available on current and future supply capacity of manufacturers; due to lack of technological development and no authorized authority frame to report the vaccine shortages issues, often there is an information gap between the supplier and the receiver regarding the information on vaccines that are at risk of shortage. Hence, such information gaps are often the cause of shortages in most of the countries.
Source: Identified from literature and experts opinion		

Table 5.2: List of solutions and their descriptions.

Solution	Denotation	Description
Better information system	A1	Establishing a robust information system to report the shortages, severity of the shortages and for better information sharing between the VSC members can help in overcoming shortages problems.
Analyzing the risk of nonproduction	A2	The pharmaceutical companies producing vaccines and other medicines should analyze the risk of not producing vaccines in the first priority. Hence, it is required that these vaccines should be in the list of critical products by the manufacturers, and if due to any reason the manufacturer is not able to produce it, the collective effort is required from country to help them produce it.
High-quality active procurement process	A3	Sometimes the immunization programs get interrupted due to delay in realizing order to procure vaccines or batch of specific vaccines. Therefore, it must be ensured that the procurement process should be strengthened to high-quality procurement in order to support immunization programs not only in quality vaccines but also for a sustainable supply.
Removing all the regulatory barriers	A4	Because of the regulatory complexities of each country, it is imperative that regulatory barriers should be removed to make it easier for the producers to supply a batch of vaccines to any country.

Solution	Denotation	Description
Authorized body in charge of shortage issues	A5	As each country has an official body to handle child immunization programs, in the same way, it is also important that countries should set up an official authorized body in charge of shortage issues with whom all the communication regarding vaccine shortages can take place.
Better demand forecasting	A6	A better demand forecasting system should be designed by the manufactures and the child immunization programs in order to meet the necessary demands of the vaccine.
Introduction of new technologies and new platforms	A7	Many developing countries like India still lack well-equipped technologies for supporting the immunization programs in case of shortages. It is required, therefore, that better technology and new platforms for information sharing, demand forecasting, cold chain equipment's, storing vaccine, etc. are introduced in future to cope with such shortages issues and strengthened the immunization programs.
The industry should be transparent of notifying of shortages	A8	Sometimes industries to not inform about the incapacity to fulfill the order or shortages in the supply of specific vaccine because of fear of losing order and money. Hence, it is important that industries should be transparent regarding vaccines shortages so that country can be well prepared in advance to handle shortages.
Incentivize more manufacturers to enter into the specific vaccine supply market	A9	Because of the high R&D cost, higher manufacturing lead-times, the pressure to supply quality products, vivo testing, and due to various other important factors, many companies avoid entering into the vaccine market. The result is that there is a shortage of vaccine manufacturer, which results in shortages of vaccines. Hence, the government should support the pharmaceutical companies to produce basic vaccines to meet the demand globally.
Constructing technology infrastructure at various levels of supply chains for buffer stocks	A10	Poor infrastructure is one of the main cause in India and other developing countries due to which vaccines go waste. Therefore, constructing technology infrastructure at various levels of supply chains for buffer stocks can help to stock more vaccines that can be used in case of shortages.

Solution	Denotation	Description
Incorporate supply chain experts, stakeholders, governments organizations, healthcare professionals, pharmacists, etc. to work together	A11	Information and knowledge sharing by involving every player such as supply chain experts, stakeholders, government's organizations, healthcare professionals, pharmacists, etc. to work together can help in overcoming shortages issues.
Setting up monitoring and reporting systems for shortages	A12	Vaccine stocks should be monitored in a time-to-time basis and if in case there is a chance that a shortage is likely to occur or in future, it should be immediately reported to the authorized body.

Source: Identified from literature and experts opinion

Phase 2: ***Criteria's weight calculation using AHP***

During the second phase, a questionnaire was supplied to the same eleven VSC experts of Uttarakhand, Uttar Pradesh, and Delhi, India to obtain the relative importance between two criteria's. It comprised of questions: With respect to weighting/ranking important reasons/criteria's for basic vaccine shortages: "How important is the criteria 'production (C1)' when it is compared with the factor 'regulation (C2)'"? Then, the expert's opinions were recorded in the Saaty's 9-Point scale of "Equally important (EI)", "Moderately important (MI)", "Strongly important (SI)", and "Extremely important (EXI)", and "Extremely more important (EXMI)" presented in Table 5.3. Based on the responses obtained from the supplied questionnaire, an aggregated final pairwise comparison matrix between criteria's is created using Eq. 3.1-3.2, as shown in Table 5.4. The consistency ratio is 0.0887 for the matrix (using Eq. 3.3-3.4), which is less than 0.1 and acceptable. Finally, using Eq. 3.5 the normalized matrix and priority weight is obtained, representing the weight of each of the criteria shown in Table 5.5.

Table 5.3: 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

Table 5.4: 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
λmax = 11.1899, CI = 0.1322, RI = 1.49, CR = 0.0887;CR ≤ 0.1 consistency										

Table 5.5: 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**

Phase 3*: Prioritization of solutions using AHP-COPRAS-G and simulation for the stability of results*

Step 1: In step 1 of phase 3, the same 11 experts were yet again supplied a second questionnaire to evaluate the importance of the alternatives. The sample question consisted: With respect to 'prioritizing/ranking important solutions that can help in overcoming basic vaccine shortages problems': "How important is the effect of the solution/alternative 'better information system (A1)' to overcome the vaccine shortage issue/criteria 'production (C1)'"? The responses of the experts in terms of linguistics variable were converted into the grey numbers using the scale shown in Table 5.6. Then, based upon expert's opinions a decision support matrix is formulated with grey numbers, which are shown in Table 5.7.

Table 5.6: Linguistic variables and grey numbers for evaluating the alternatives [255]**.**

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

Table 5.7: 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]

Then, using Eq. 3.26-3.27 of COPRAS-G approach, the normalized decision support matrix is obtained shown in Table 5.8. Next, using weights of each criterion obtained in Phase 2 from AHP, a weighted normalized decision matrix is calculated that is shown in Table 5.9. At last, using Eq. 3.29-3.37, the final ranking of alternatives is obtained shown in Table 5.10.

Table 5.8: 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 5.9: 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 5.10: 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**

Step 2: A sensitivity analysis is performed to check for robustness and validate the feasibility of AHP-COPRAS-G outcomes. To do so, Monte Carlo simulation with uniform probability distribution in the domain of [0, 1] is carried out by simulating the randomly generated criterion weights 150 times in such a manner that the criteria weight satisfies the condition $0 \leq w_j \leq 1; \sum_{i=1}^{n} w_j = 1$. After the simulation, the qualitative criteria chosen for robustness as mentioned by Saaty and Ergu [335] is 'less variation in final rankings of the factors' or 'consistent ranking'. The results of the simulation for alternatives weights Q_i for 150 cases is shown in Figure 5.5.

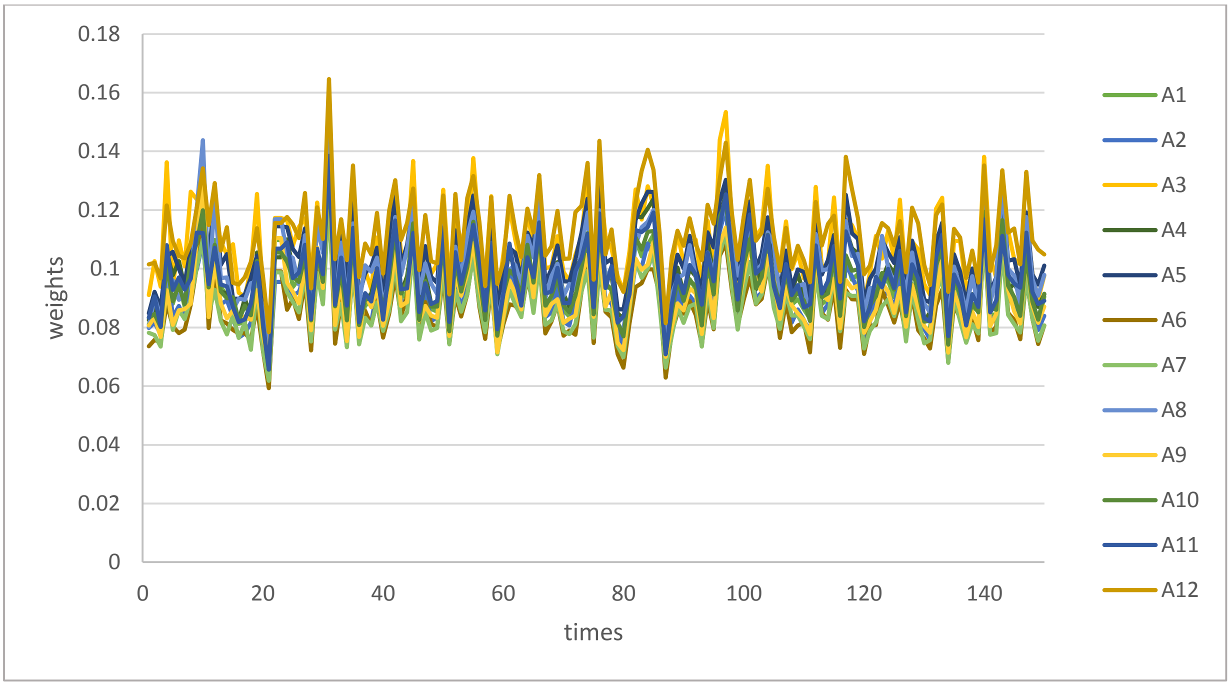


Figure 5.5: Weights of twelve alternatives in one hundred fifty times simulation.

The results show that although the weights of the alternatives Q_i have changed by changing the input weight q_j, there is not much difference in the final results, and the alternatives A12, A3, and A5 always capture the top position, accept fewer cases. Figure 5.6 depicts the rank of alternatives in the first 50 cases. Overall, it can be concluded that the final decision is consistent and reliable.

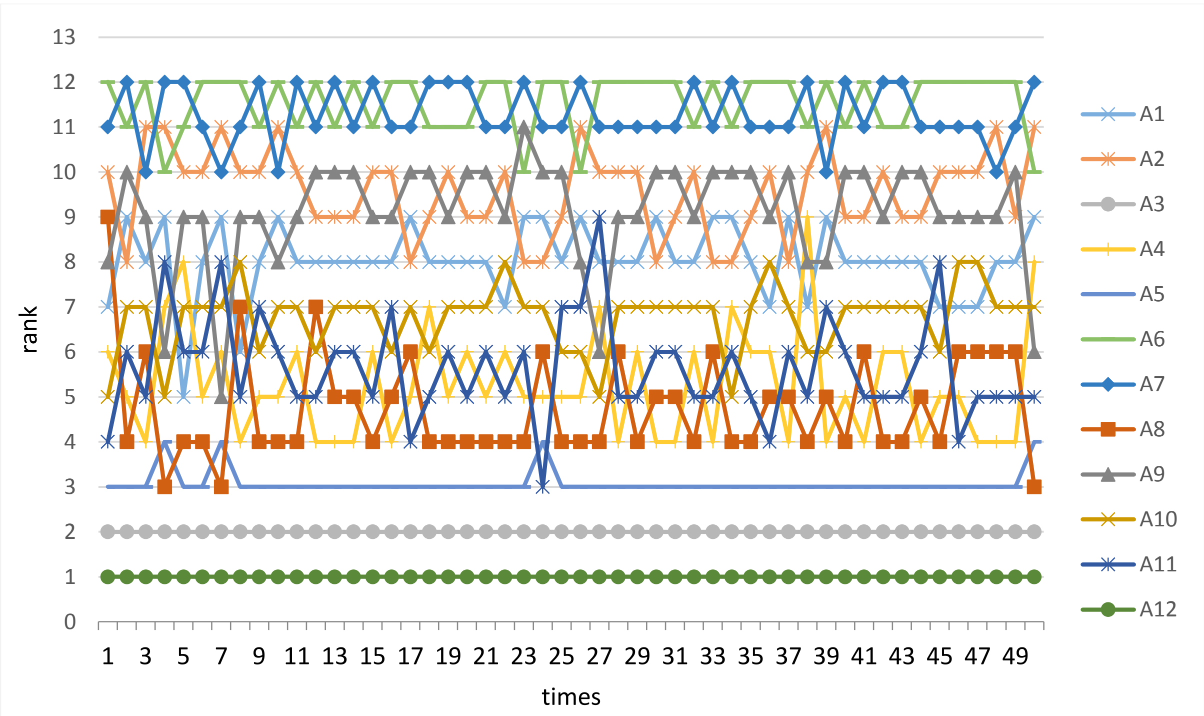


Figure 5.6: Ranking of alternatives for fifty cases.

5.4. Results

This section discusses the results obtained from the analysis.

- The results of the AHP analysis are depicted in Figure 5.7. Based on the results, the priority of causes of vaccine shortages according to their weights is, **C5** > **C9** > **C2** > **C6** > **C1** > **C7** > **C8** > **C10** > **C3** > **C4**. Therefore, the top five causes of vaccine shortages are:

    i. Uncertainty in demand

    ii. Improper stock management and poor coordination in the supply chain

    iii. Regulatory complexities

    iv. Vaccine wastages

    v. Production

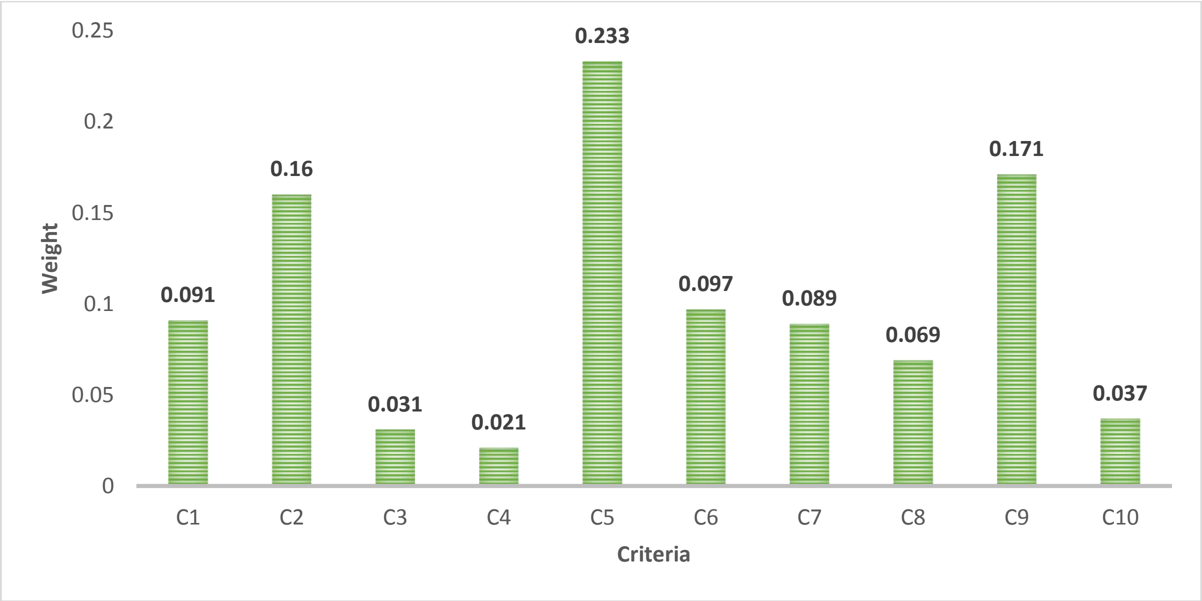


Figure 5.7: Weight of ten criteria for vaccine shortages.

- *The results derived using the hybrid AHP-COPRAS-G methodology for ranking the alternatives is depicted in Figure 5.8. Based on the results, the order of priority for the alternatives is* ***A12 > A3 > A5 > A11 > A10 > A4 > A1 > A9 > A8 > A2 > A7 > A6****. The results generated by the hybrid approach indicates that, among the list of 12 solutions, the top 5 solutions are,* ***'setting up monitoring and reporting systems for shortages (A12)'*** *is the best solution for overcoming shortages problems and after that* ***'high-quality active procurement process (A3)****' is next followed by* ***'authorized body in charge of shortage issues (A5)'****, then* ***'incorporate supply chain experts, stakeholders, governments organizations, healthcare professionals, pharmacists etc. to work***

together (A11)', *and finally* ***'constructing technology infrastructure at various levels of supply chains for buffer stocks (A10)'***.

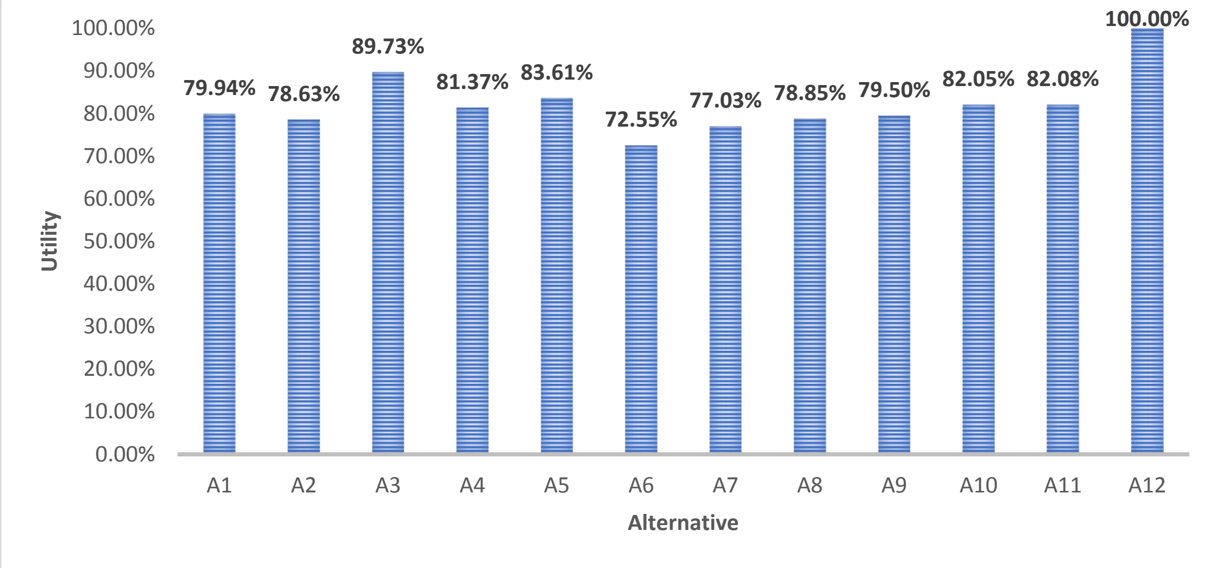


Figure 5.8: Utility score of twelve alternatives.

5.5. Discussion of results

Based on the results, ***'uncertainty in demand'*** with a weight of 0.233 is the most important reason for vaccine shortages. Studies and experts opinions indicate that vaccine demand is one of the biggest issues in child immunization programs [7,47,311]. Because of the various complexities in the UIP India due to such large-scale operations, the uncertainty in vaccine demand is inevitable and hence, it becomes challenging for the Indian vaccine manufacturing companies and UIP to anticipate the real demand. The consequence of such mismatch is often the companies and UIP ends up producing and ordering less than what is required. To overcome such demand issues and other problems, the results suggest that ***'setting up monitoring and reporting systems for shortages'*** can be one of the best solutions that can be implemented by the policy-makers to reduce or eliminate shortages problems and improve UIP performance. Experts also suggested that a robust centralized information system may be more useful, where demand for each region/country can be monitored and reported by the policy-makers to the manufactures to forecast the demand. This process may also be used at various state/district level to obtain more real vaccine shortages information. Another important solution may be to consider a ***'high-quality active procurement process'***. The immunization program of India was designed almost 30 years ago and it is still going in a similar manner. Today, the scenario of child immunization is very different, and therefore, it is important that the immunization programs modify their procurement processes to strengthen its vaccine stock availability. For strengthening the procurement process, it is important that UIP India emphasizes not only the quality of the procured product but also in the sustainable supply of vaccines and its equipment's. Therefore, factors such as tender, costing, forecasting, information sharing, etc. should be of high quality so that the vaccines and its usage equipment's are always available in stock [332]. The third important solution that can be considered by UIP policy-makers is designing an '***authorized body in charge of shortage issues***' so that all the important information regarding shortages can be obtained from the official authorized body rather than collecting it at various levels of immunization programs. This will not only help in designing better strategies to tackle shortages but also in avoiding interruptions in immunization program operations because of the unavailability of vaccines. Nevertheless, it is important that the immunization programs officials start giving importance to vaccine shortages and ensure that continuous and sustainable of the vaccine is designed so that no child go unimmunized from the health centers due to the unavailability of basic vaccines.

5.6. Conclusion

In this chapter, causes for vaccine shortages and an important solution that can help in overcoming these shortages problems were discussed. Using AHP and hybrid AHP-COPRAS-G methodologies, the causes of vaccine shortages and solutions were analyzed. The results show that 'uncertainty in demand' is the main cause of vaccine shortages, whereas, 'setting up monitoring and reporting systems for shortages' is the main solution to overcome shortages. The policy-makers should focus on the aforementioned factors to reduce/eliminate the impact of vaccine shortages.

Studying various issues in VSC such as demand forecast, vaccine shortages, and solutions to overcome them can help the decision-makers in improving the performance of conventional/outdated VSC system. Hence, after overcoming the VSC issues, the decision-makers can now think of designing a supply chain which is more efficient and effective. Therefore, it is important that now the focus of decision-makers should be on moving forward in the direction of a next-generation vaccine supply chain system (NGVSCs) from the conventional vaccine supply chain system. NGVSCs are improved and well performing VSC, which are designed to meet the immunization programs needs in the present and future.

Chapter 6

FRAMEWORK TO DESIGN NEXT-GENERATION VACCINE SUPPLY CHAIN SYSTEM

Summary

Due to the old and outdated vaccine supply chain (VSC) system, together with increasing population and rise in new infectious diseases, India and other developing countries are struggling to meet the basic vaccines demands of the large population. There is, therefore, an urgent need to reform their current VSC system with an improved/modern system called next generation vaccine supply chain system (NGVSCs). This NGVSCs may prove to be more useful in improving the child immunization coverage and its performance. Hence, this study discusses the design of NGVSCs to help the decision-makers help in planning of logistics and supply chain as per the need of today. By collecting the opinions of field experts and the information through the literature, barriers and solutions pertaining to the design of this new system are identified. The, using an integrated fuzzy analytical hierarchical processes (FAHP) and fuzzy multi-objective optimization on the basis of ratio analysis (FMOORA) approach, the barriers and solutions are analyzed. The outcome of the analysis contends that demand forecasting is the topmost barrier in designing NGVSCs and sustainable financing is the most important solution to facilitate the implementation of next-generation vaccine supply chain systems.

6.1. Introduction

The conventional VSC system of India was designed almost 30 years ago when vaccines were limited and less costly. Today, new vaccines are being introduced into the routine immunization programs of India and other developing countries for the prevention and treatment of emerging infectious diseases [262]. Due to such introduction of vaccines and many in the pipeline, VSC of India is struggling to efficiently support national immunization programs in ensuring the availability of safe and potent vaccines [6]. To cope with such complexities, it is important that India and other developing countries start focusing on moving from the conventional vaccine supply chain system to next-generation vaccine supply chain system (NGVSCs).

NGVSCs are designed to optimize safety, reliability, and efficiency of immunization programs in order to deliver vaccines to all the children at the right time. In a supply chain, getting the "last mile" delivery is certainly one of the biggest challenge, which many countries face whether for vaccines or other health commodities. Next-generation supply chains will have the capability to overcome these problems [336]. Today, however, even the conventional vaccine supply chains around the world have not received the same degree of attention. The supply chain components in many countries regularly constitute bottlenecks, which results in a delay of vaccines to the communities [337,338]. These bottlenecks are nothing but the supply chain barriers that are generally ignored or neglected by the decision-makers. Hence, in order to manage the changes and prepare immunization programs for future vaccine needs, it is important to start thinking about the new solutions for designing NGVSC to maximize efficacy and agility in vaccine supply systems [262]. Identifying and deciphering NGVSCs barriers can help in forming a robust and efficient supply chain and logistics system, which may be the first step towards improving the vaccine distribution performance.

Therefore, due to the importance of designing NGVSCs, the study, based on the data collected from the literature review, field survey, and expert's opinions, suggests ten solutions to mitigate the fifteen key barriers in designing NGVSCs. Using FAHP and integrated FAHP and FMOORA methodology, the topmost barriers and solutions to design NGVSCs have been identified. The analysis may serve as a guideline for the VSC managers and policy-makers of immunization programs to help design better and improved immunization strategies to reduce or remove the new system supply chain constraints. This study may also provide a suitable environment to develop a new system to cater to the needs of present and future immunization programs in a better way.

The objectives discussed in this chapter are:

- ***To identify key barriers and solutions in the design of NGVSC in India.***
- ***To prioritize key solutions to assist decision-makers to mitigate/remove key barriers to designing next-generation vaccine supply chain system (NGVSCs) in India.***

6.2. Proposed integrated framework

Based on the integrated framework presented in Figure 6.1, an evaluation process of three phases to give preference to key barriers and its solutions have been followed, which is discussed in the next section.

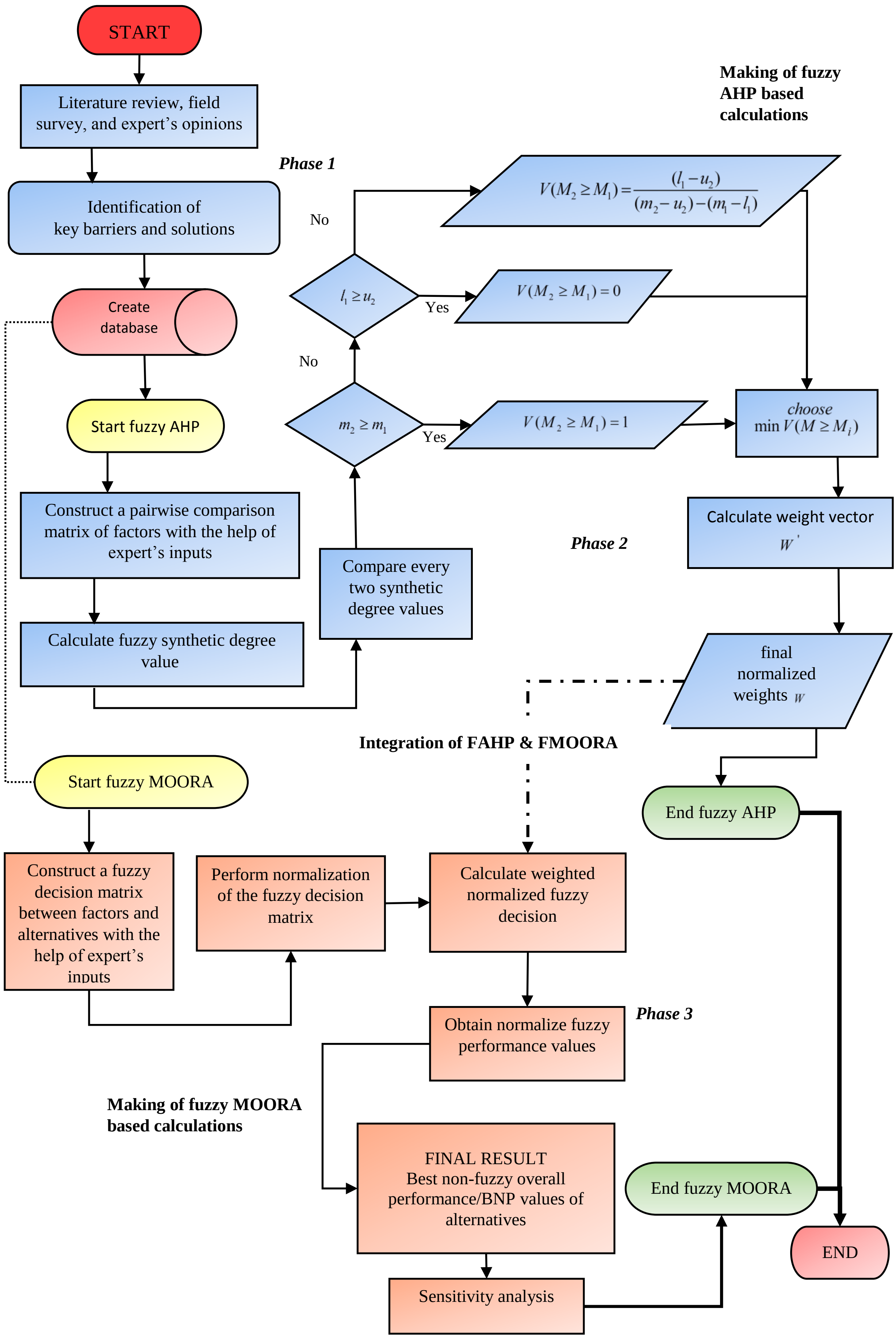


Figure 6.1: Flowchart of the integrated framework.

6.3. Analysis of barriers and its solutions using integrated FAHP-FMOORA

The analysis steps used in the integrated framework are as follows:

Phase 1: Identification of key barriers and solutions

The phase 1 of the methodology consist of the three steps conversed below:

Step 1: Literature collection procedure

Literature collection was used as the first tool to identify key barriers and solutions to support the present work. The method of literature collection used in the current study involved three important stages, which are discussed below.

Stage 1 – Time horizon

The period of study covered the 26 years from 1992 to early 2018.

Stage 2 – Journal/libraries selection

The journals and libraries finalized in Chapter 4 and using SciMAT software were again taken for the study to identify relevant papers in the field of NGVSCs.

Stage 3 – Paper selection

For the assessment and assortment of the relevant papers, two inclusion criteria were described. The paper must: (i) be written in the English language and published in peer-reviewed journals (ii) focuses on vaccine supply chain issues of developing countries and solutions to overcome them. Further, a broader search string with the keywords and their combination was conducted in the selected journals/libraries and websites using the following filters: vaccine, immunization, next generation, vaccination, supply, chain, problems, barriers, healthcare, health care, delivery, developing countries, and cold. Based on the inclusion criteria, the paper selection procedure involved two rounds. In the first round, the papers were identified based on the title, abstract, and keywords. Next, the papers identified were reviewed to recognize and remove duplication arising from references determined in multiple databases. In the second round, the papers were inspected based on the introduction, conclusion and full texts.

Out of 1223 papers (including white papers, presentations, and reports) identified in phase 2, 740 papers (60.50%) that focuses on the vaccine supply chain, cold chain, and healthcare barriers and its solutions were selected in the first round of phase 3. Out of 740 papers, 407 (55% of the previous step) had been analyzed for introduction and conclusion and finally, 100 papers were read and in the end selected, representing 24.57% of the beforehand chosen papers. From the total number of retrieved papers, the 100 selected ones represent a yield of 8.17%.

Step 2: Field survey and expert' opinions

Various districts situated in Uttarakhand, Delhi, Uttar Pradesh, and Karnataka were surveyed to find the condition of how the child immunization services are being provided through various health centers. Twenty-three health facilities were selected from rural and urban health centers. Five divisional vaccine stores and three state vaccine stores were also included for collecting the information. Thirty-eight vaccine supply chain experts of the aforementioned states gave their valuable inputs to identify the barriers and solutions to assist decision-makers in designing NGVSCs. The experts were selected based on their subject expertise and work experience. In the team, senior experts have experience of more than 15 years, while junior experts have experience in their current positions for about 5 to 10 years. The profile of the 38 experts is shown in Table 6.1.

Table 6.1: Profile of experts involved in decision-making.

Designation	**Organization**	**Number of experts**	**Role in the study**
National Professional Officer	WHO, India	2	Senior experts
Chief Medical Officer	UIP, Nainital & Haridwar District, India	2	
Additional Research Officers	UIP Bengaluru, Nainital, Dehradun, Haridwar, Bulandshahr District, India	16	Junior experts
Senior Consultants	UIP Bengaluru, Nainital, Dehradun, Haridwar, Bulandshahr District, India	14	
Surveillance Medical Officer	WHO, India	4	

Finally, Step 1 & 2 of Phase 1 led to the finalization of fifteen key barriers and ten solutions. The key barriers and solutions are demonstrated in Table 6.2 & 6.3.

Table 6.2: List of key barriers.

Key barriers	Denotation	Description
Improper monitoring of temperature-controlled supply chain	B1	Due to improper monitoring of the temperature controlled chain, many vaccines in between the stage of manufacturing until the delivery goes waste, which leads to poor delivery performance.
Improper stock management	B2	The ability to properly manage VSC inventory is a critical factor for the success of immunization programs. However, due to poor stock management, the conventional VSCs gets inefficient in fulfilling the vaccination order that leads to delay in the delivery of vaccines.
Unavailability of vaccines and equipment's	B3	Due to less number of vaccines manufacturers together with the improper planning and coordination between the immunization programs and vaccine suppliers, the essential vaccines are often unavailable, which delay the regular immunization schedule.
Poor demand forecast	B4	Vaccine, device and cold chain forecasting is an important step to ensure adequate immunization supplies. The accuracy of the forecast is important – overestimation results in extra stock, which in turn increases the manufacturer's cost, underestimating the requirements results in vaccine shortages or shortfalls in delivery. The objective of vaccine forecasting is to estimate the number of goods and financial needs for smoother functioning of immunization programs.
Higher lead-time gaps	B5	The time between placing an order to the upper-level immunization program center and receiving it to the health centers is very high that often results in immunizing the children at the right time.

Key barriers	Denotation	Description
Inadequate cool innovations for vaccine handling and storage	B6	India and other developing countries still lack cool innovations that can store the vaccines and maintain its temperature for a longer period of time. The results are most of the vaccines go unused or waste.
Environmental uncertainties	B7	Sometimes environmental uncertainties obstruct the delivery of vaccines and many children are deprived of vaccination. For example, 2018 flood in Kerala hindered the delivery of basic vaccines to the state, leaving children unimmunized.
Improper transportation management	B8	Because of improper transportation management, issues such as transportation disruptions and lack of vaccine carrying vehicles arises, which is the primary reasons for the delay in vaccines delivery.
High vaccine wastage	B9	The high rate of vaccine wastage for vaccines such as BCG, DPT etc. contributes to the poor performance of immunization programs in delivering vaccines.
Outdated methods of collecting and managing data and information on child vaccination	B10	India and other developing countries still rely on collecting and managing data and information through paper-based work. Therefore, due to the lack of technological infrastructure support, extracting the important data and information in a timely manner becomes difficult for the decision-makers, which often results in sharing of wrong data and information in VSC.
High rate of vaccine hesitancy	B11	Sometimes due to vaccine hesitancy that could get evolved by way of perception of parents towards ill-effect of immunization programs on children, the vaccines are left unused despite the availability of vaccination services. It is therefore important that immunization programs focus on training and educating health workers to reduce the vaccine hesitancy, which will be also important in designing NGVSCs.

Key barriers	Denotation	Description
Inadequate training and programs for upgrading employee skills and education	B12	Training and educating VSC employees has many benefits like improving VSC performance and designing NGVSCs. Therefore, it is vital that more vaccine healthcare workers, supply managers, and leaders come in the future; with proper training and education for the staff to help improve delivery performance and design of NGVSCs.
Unavailability of healthcare workers	B13	India still lacks in healthcare workers, whether it is for child immunization programs or any other health services. One of the primary reasons for shortages of healthcare workers in India is poor salary and incentives programs, and poor work culture that is often the primary cause in the design of NGVSCs.
Vaccine regulatory complexities	B14	India has very complex vaccine regulatory procedures for procuring vaccines to be used in national immunization programs. Such regulatory issues impose difficulty in procuring vaccines, which delays the child immunization services.
Inadequate immunization surveillance, assessment and monitoring	B15	Due to inadequate immunization surveillance, assessment and monitoring, the performance of the VSC can't be measured, and improved. Hence, often the decision-makers, due to lack of surveillance and assessment of immunization programs, are not able to find suitable actions to improve VSC performance that is one of the bottlenecks in the design of NGVSCs.

Table 6.3: List of key solutions.

Key solutions	Denotation	Description
Improve communication between policy-makers and vaccine supply chain experts	S1	Internal and external communication in the supply chain, especially between policy-makers and VSC experts is essential to measure and eliminate the impact of barriers to designing a well-performing VSC system i.e. NGVSCs.
Raise awareness of vaccine supply chain issues	S2	Most of the members of immunization programs either do not know about their vaccine supply chains or are not aware of their issues. If the immunization program members do know about the vaccine supply chains, and its issues then it is not possible to find the root cause of the low performance of immunization programs, as the VSCs are considered the backbone of immunization programs. Hence, understanding VSCs and then, identifying, measuring, and finding solutions to remove VSC issues is essential in removing barriers to designing NGVSCs.
Data visibility and management	S3	If the VSC system has transparency, then it will be easier for the experts to know the actual demand and also for the better planning of VSC. Hence, it is essential that learning and training programs regarding data visibility and management are organized for the VSC members in order to improve VSC performance.
Sustainable financing	S4	Late payments to release purchase order and salary of health workers, no proper incentives, and bonus, etc. are some of the financial issues in VSC in India. Hence, it is important that the government focus on these aspects so that better health force joins immunization programs and employee turnover rate is reduced to improve healthcare services and designing NGVSCs in India.

Key solutions	Denotation	Description
Improve use of technology	S5	Use of better technology is essential in every step of VSC and therefore, should be an integral part of the VSC. The better technology will help to improve the overall efficiency and effectiveness of VSCs, which is crucial for designing NGVSCs.
Leadership and training programs	S6	Most of the developed countries have better leaders and training programs to manage their vaccine supply chains. India and other developing countries should also emphasize on hiring quality employees by giving them proper training and education so that effective vaccine management procedures can be followed to improve VSC performance.
Proper planning and coordination	S7	Proper planning and coordination between the VSC players can help in reducing uncertainties and issues that cause a delay in vaccines delay.
Continuous improvement through effective vaccine management (EVM)	S8	Nine areas of effective vaccine management should be followed properly by the immunization programs to make continuous improvement in vaccine delivery performance and for the design of NGVSCs.
Use of commercial partners for logistics activities	S9	Third-party logistics can be considered as one of the solutions by the immunization programs to improve vaccine delivery performance.
Incorporate supply chain experts and considerations into all vaccine decision	S10	It is important that vaccine supply chain experts are included in all decision making regarding immunization programs, so that the actual scenario of issues and performance of VSCs is known to the policy-makers.

Step 3: Development of decision-hierarchy

Further, based on the fifteen barriers and ten solutions, a decision hierarchy of the NGVSCs is developed to prioritize the solutions. Figure 6.2 shows the decision-hierarchy, where B refers to barrier and S refers to the solution.

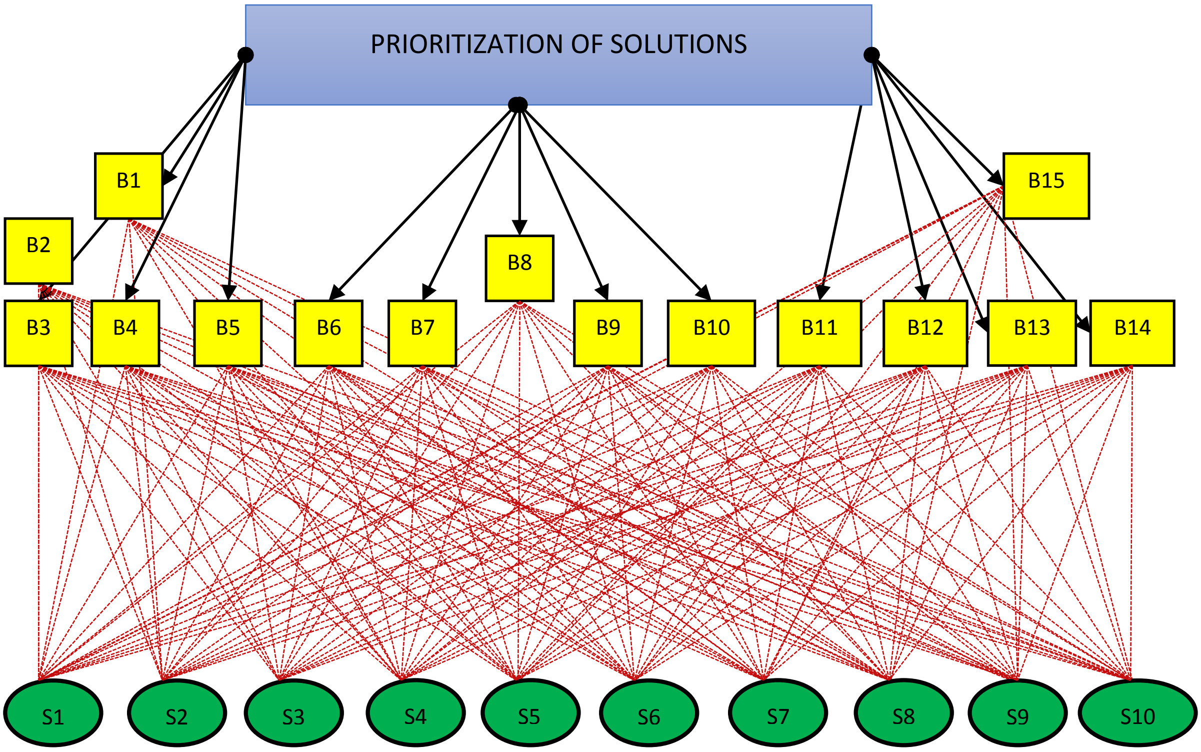


Figure 6.2: Decision hierarchy of NGVSCs for solution selection.

***Phase 2**: Computation of barrier weights using fuzzy AHP*

In this Phase, the identified barriers have been weighted using FAHP. To start the analysis, a questionnaire was supplied to the same 38 experts and their responses were recorded on the scale given in Table 6.4. Then, a fuzzy pairwise comparison matrix (Table 6.5) between barriers is created using the responses obtained from the questionnaire. As an example, 'poor demand forecast' and 'higher lead-time gaps' are compared using the question "How important is poor demand forecast when it is compared with higher lead-time gaps"? and the final answer selected by the expert's committee is "Very strongly more important (VSMI)". Next, fuzzy synthetic values are calculated using Eq. 3.7 and is given in Table 6.6. Using the fuzzy synthetic degrees of Table 6.6, the weight vector (W') is computed. Lastly, the weight vector is converted into a normalized weight vector (W) vector shown in Table 6.7.

Table 6.4: Linguistic scales for the level of importance [339]**.**

Linguistic variables	TFN	Reciprocal TFN	Fuzzy numbers
Just equal (JE)	(1,1,1)	(1,1,1)	1
Equally important (EI)	(1/2,1,3/2)	(2/3,1,2)	1
Weakly more important (WMI)	(1,3/2,2)	(1/2,2/3,1)	3
Strongly more important (SMI)	(3/2,2,5/2)	(2/5,1/2,2/3)	5
Very strongly more important (VSMI)	(2,5/2,3)	(1/3,2/5,1/2)	7
Absolutely more important (AMI)	(5/2,3/1,7/2)	(2/7,1/3,2/5)	9

Table 6.5: Fuzzy pairwise comparison matrix between barriers.

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15
B1	1/1,1/1,1/1	3/2,2/1,5/2	1/2,1/1,3/2	2/5,1/2,2/3	2/1,5/2,3/1	1/2,1/1,3/2	3/2,2/1,5/2	2/1,5/2,3/1	2/5,1/2,2/3	3/2,2/1,5/2	5/2,3/1,7/2	2/5,1/2,2/3	1/3,2/5,1/2	5/2,3/1,7/2	2/1,5/2,3/1
B2	2/5,1/2,2/3	1/1,1/1,1/1	1/2,2/3,1/1	2/5,1/2,2/3	3/2,2/1,5/2	1/3,2/5,1/2	1/2,1/1,3/2	3/2,2/1,5/2	2/5,1/2,2/3	1/2,2/3,1/1	2/1,5/2,3/1	1/3,2/5,1/2	1/3,2/5,1/2	2/1,5/2,3/1	3/2,2/1,5/2
B3	2/3,1/1,2/1	1/1,3/2,2/1	1/1,1/1,1/1	2/5,1/2,2/3	2/1,5/2,3/1	3/2,2/1,5/2	5/2,3/1,7/2	5/2,3/1,7/2	1/1,3/2,2/1	3/2,2/1,5/2	5/2,3/1,7/2	3/2,2/1,5/2	1/1,3/2,2/1	2/1,5/2,3/1	2/1,5/2,3/1
B4	3/2,2/1,5/2	3/2,2/1,5/2	3/2,2/1,5/2	1/1,1/1,1/1	2/1,5/2,3/1	3/2,2/1,5/2	5/2,3/1,7/2	5/2,3/1,7/2	1/1,3/2,2/1	3/2,2/1,5/2	5/2,3/1,7/2	3/2,2/1,5/2	1/1,3/2,2/1	5/2,3/1,7/2	5/2,3/1,7/2
B5	1/3,2/5,1/2	2/5,1/2,2/3	1/3,2/5,1/2	1/3,2/5,1/2	1/1,1/1,1/1	1/3,2/5,1/2	2/5,1/2,2/3	1/2,1/1,3/2	1/3,2/5,1/2	1/1,3/2,2/1	3/2,2/1,5/2	1/3,2/5,1/2	2/7,1/3,2/5	3/2,2/1,5/2	3/2,2/1,5/2
B6	2/3,1/1,2/1	2/1,5/2,3/1	2/5,1/2,2/3	2/5,1/2,2/3	2/1,5/2,3/1	1/1,1/1,1/1	3/2,2/1,5/2	2/1,5/2,3/1	3/2,2/1,5/2	3/2,2/1,5/2	2/1,5/2,3/1	2/5,1/2,2/3	2/5,1/2,2/3	2/1,5/2,3/1	2/1,5/2,3/1
B8	2/5,1/2,2/3	2/3,1/1,2/1	2/7,1/3,2/5	2/7,1/3,2/5	3/2,2/1,5/2	2/5,1/2,2/3	1/1,1/1,1/1	3/2,2/1,5/2	1/3,2/5,1/2	1/1,3/2,2/1	3/2,2/1,5/2	2/5,1/2,2/3	2/7,1/3,2/5	1/1,3/2,2/1	1/1,3/2,2/1
B8	1/3,2/5,1/2	2/5,1/2,2/3	2/7,1/3,2/5	2/7,1/3,2/5	2/3,1/1,2/1	1/3,2/5,1/2	2/5,1/2,2/3	1/1,1/1,1/1	1/3,2/5,1/2	2/5,1/2,2/3	1/2,2/3,1/1	1/3,2/5,1/2	1/3,2/5,1/2	1/1,3/2,2/1	3/2,2/1,5/2
B9	3/2,2/1,5/2	3/2,2/1,5/2	1/2,2/3,1/1	1/2,2/3,1/1	2/1,5/2,3/1	2/5,1/2,2/3	2/1,5/2,3/1	2/1,5/2,3/1	1/1,1/1,1/1	3/2,2/1,5/2	2/1,5/2,3/1	2/5,1/2,2/3	2/5,1/2,2/3	2/1,5/2,3/1	2/1,5/2,3/1
B10	2/5,1/2,2/3	1/1,3/2,2/1	2/5,1/2,2/3	2/5,1/2,2/3	1/2,2/3,1/1	2/5,1/2,2/3	1/2,2/3,1/1	3/2,2/1,5/2	2/5,1/2,2/3	1/1,1/1,1/1	3/2,2/1,5/2	2/5,1/2,2/3	2/5,1/2,2/3	3/2,2/1,5/2	3/2,2/1,5/2
B11	2/7,1/3,2/5	1/3,2/5,1/2	2/7,1/3,2/5	2/7,1/3,2/5	2/5,1/2,2/3	1/3,2/5,1/2	2/5,1/2,2/3	1/1,3/2,2/1	1/3,2/5,1/2	2/5,1/2,2/3	1/1,1/1,1/1	2/7,1/3,2/5	1/3,2/5,1/2	3/2,2/1,5/2	3/2,2/1,5/2
B12	3/2,2/1,5/2	2/1,5/2,3/1	2/5,1/2,2/3	2/5,1/2,2/3	2/1,5/2,3/1	3/2,2/1,5/2	3/2,2/1,5/2	2/1,5/2,3/1	3/2,2/1,5/2	3/2,2/1,5/2	5/2,3/1,7/2	1/1,1/1,1/1	2/5,1/2,2/3	2/1,5/2,3/1	2/1,5/2,3/1
B13	2/1,5/2,3/1	2/1,5/2,3/1	1/2,2/3,1/1	1/2,2/3,1/1	5/2,3/1,7/2	3/2,2/1,5/2	5/2,3/1,7/2	2/1,5/2,3/1	3/2,2/1,5/2	3/2,2/1,5/2	2/1,5/2,3/1	3/2,2/1,5/2	1/1,1/1,1/1	5/2,3/1,7/2	5/2,3/1,7/2
B14	2/7,1/3,2/5	1/3,2/5,1/2	1/3,2/5,1/2	2/7,1/3,2/5	2/5,1/2,2/3	1/3,2/5,1/2	1/2,2/3,1/1	1/2,2/3,1/1	1/3,2/5,1/2	2/5,1/2,2/3	2/5,1/2,2/3	1/3,2/5,1/2	2/7,1/3,2/5	1/1,1/1,1/1	1/2,1/1,3/2
B15	1/3,2/5,1/2	2/5,1/2,2/3	1/3,2/5,1/2	2/7,1/3,2/5	2/5,1/2,2/3	1/3,2/5,1/2	1/2,2/3,1/1	2/5,1/2,2/3	1/3,2/5,1/2	2/5,1/2,2/3	2/5,1/2,2/3	1/3,2/5,1/2	2/7,1/3,2/5	2/3,1/1,2/1	1/1,1/1,1/1

Table 6.6: Calculation of fuzzy synthetic values.

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	Min.
M1	-	1	0.794	0.650	1	0.974	1	1	0.981	1	1	0.850	0.685	1	1	0.650
M2	0.621	-	0.415	0.270	1	0.590	1	1	0.597	1	1	0.465	0.297	1	1	0.270
M3	1	1	-	0.864	1	1	1	1	1	1	1	1	0.901	1	1	0.864
M4	1	1	1	-	1	1	1	1	1	1	1	1	1	1	1	1
M5	0.350	0.738	0.146	0.001	-	0.315	0.847	1	0.321	0.849	1	0.190	0.021	1	1	0.001
M6	1	1	0.824	0.684	1	-	1	1	1	1	1	0.879	0.719	1	1	0.684
M8	0.536	0.902	0.337	0.196	1	0.506	-	1	0.512	1	1	0.385	0.222	1	1	0.196
M8	0.139	0.509	0	0	0.765	0.103	0.620	-	0.107	0.618	0.946	0	0	1	1	0
M9	1	1	0.813	0.669	1	0.993	1	1	-	1	1	0.869	0.705	1	1	0.669
M10	0.518	0.895	0.315	0.171	1	0.486	0.996	1	0.492	-	1	0.362	0.196	1	1	0.171
M11	0.131	0.524	0	0	0.800	0.092	0.642	1	0.097	0.640	-	0	0	1	1	0
M12	1	1	0.943	0.800	1	1	1	1	1	1	1	-	0.838	1	1	0.800
M13	1	1	1	0.960	1	1	1	1	1	1	1	1	-	1	1	0.960
M14	0	0.205	0	0	0.475	0	0.328	0.721	0	0.318	0.660	0	0	-	1	0
M15	0	0.242	0	0	0.501	0	0.360	0.737	0	0.351	0.679	0	0	1	-	0

Table 6.7: Weight vector and the final normalized weight vector.

Factor	Weight vector ($W^{'}$)	Normalized weight vector (W)
B1	0.650	**0.104**
B2	0.270	**0.043**
B3	0.864	**0.138**
B4	1	**0.160**
B5	0.001	**0.000**
B6	0.684	**0.109**
B7	0.196	**0.031**
B8	0	**0**
B9	0.669	**0.107**
B10	0.171	**0.027**
B11	0	**0**
B12	0.800	**0.128**
B13	0.960	**0.153**
B14	0	**0**
B15	0	**0**

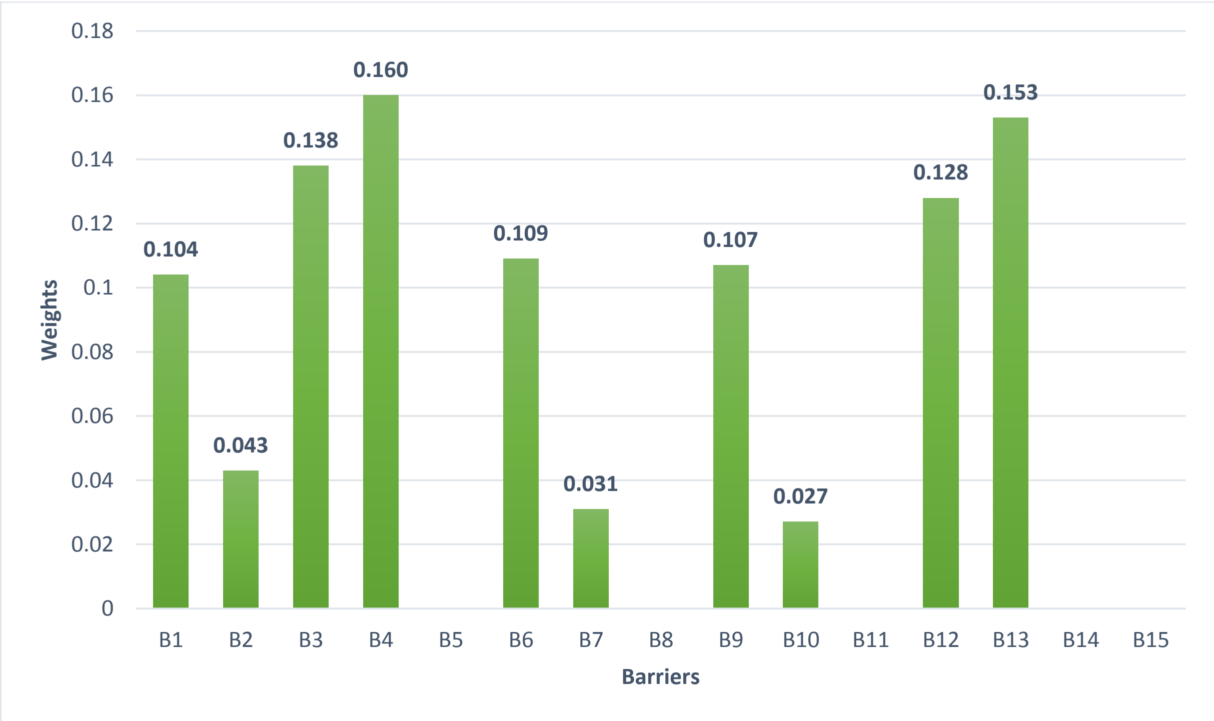


Figure 6.3: Weights of fifteen key barriers.

Phase 3**: **Solutions prioritization using integrated FAHP-MOORA and sensitivity analysis

Step 1: In this phase, fuzzy AHP has been integrated with fuzzy MOORA for the analysis purpose. The second set of questionnaire was prepared and distributed to the same 38 experts to identify the relative importance of the barriers and solution. A fuzzy decision matrix shown in Table 6.8 is then constructed using the expert's responses. Using Eq. 3.16-3.19 of Chapter 3, a normalized fuzzy decision matrix is obtained shown in Table 6.9. The weighted normalized fuzzy decision matrix is calculated from the equalities 3.20, 3.21, and 3.22, and is shown in Table 6.10. Lastly, BNP values for the solutions are calculated with the assist of the equalities 3.23 and 3.24 of Chapter 3 and are presented in Table 6.11.

Table 6.8: Fuzzy decision matrix between barriers and solutions.

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15
S1	2/1,5/2,3/1	5/2,3/1,7/2	2/1,5/2,3/1	5/2,3/1,7/2	1/1,3/2,2/1	1/1,3/2,2/1	1/1,3/2,2/1	3/2,2/1,5/2	3/2,2/1,5/2	1/1,3/2,2/1	1/1,3/2,2/1	1/1,3/2,2/1	3/2,2/1,5/2	1/1,3/2,2/1	3/2,2/1,5/2
S2	5/2,3/1,7/2	5/2,3/1,7/2	5/2,3/1,7/2	3/2,2/1,5/2	3/2,2/1,5/2	5/2,3/1,7/2	3/2,2/1,5/2	5/2,3/1,7/2	1/1,3/2,2/1	5/2,3/1,7/2	2/1,5/2,3/1	2/1,5/2,3/1	3/2,2/1,5/2	1/1,3/2,2/1	1/1,3/2,2/1
S3	1/1,3/2,2/1	5/2,3/1,7/2	5/2,3/1,7/2	5/2,3/1,7/2	3/2,2/1,5/2	3/2,2/1,5/2	1/1,3/2,2/1	1/1,3/2,2/1	5/2,3/1,7/2	5/2,3/1,7/2	1/1,3/2,2/1	1/1,3/2,2/1	1/1,3/2,2/1	1/1,3/2,2/1	5/2,3/1,7/2
S4	5/2,3/1,7/2	2/1,5/2,3/1	3/2,2/1,5/2	5/2,3/1,7/2	5/2,3/1,7/2	5/2,3/1,7/2	2/1,5/2,3/1	3/2,2/1,5/2	2/1,5/2,3/1	2/1,5/2,3/1	3/2,2/1,5/2	5/2,3/1,7/2	5/2,3/1,7/2	1/1,3/2,2/1	5/2,3/1,7/2
S5	5/2,3/1,7/2	5/2,3/1,7/2	2/1,5/2,3/1	5/2,3/1,7/2	1/1,3/2,2/1	5/2,3/1,7/2	5/2,3/1,7/2	1/1,3/2,2/1	2/1,5/2,3/1	3/2,2/1,5/2	1/1,3/2,2/1	1/1,3/2,2/1	1/1,3/2,2/1	1/1,3/2,2/1	5/2,3/1,7/2
S6	5/2,3/1,7/2	5/2,3/1,7/2	5/2,3/1,7/2	5/2,3/1,7/2	3/2,2/1,5/2	5/2,3/1,7/2	3/2,2/1,5/2	1/1,3/2,2/1	5/2,3/1,7/2	5/2,3/1,7/2	5/2,3/1,7/2	5/2,3/1,7/2	1/1,3/2,2/1	1/1,3/2,2/1	5/2,3/1,7/2
S8	3/2,2/1,5/2	5/2,3/1,7/2	5/2,3/1,7/2	3/2,2/1,5/2	5/2,3/1,7/2	3/2,2/1,5/2	2/1,5/2,3/1	5/2,3/1,7/2	2/1,5/2,3/1	1/1,3/2,2/1	1/1,3/2,2/1	1/1,3/2,2/1	1/1,3/2,2/1	5/2,3/1,7/2	5/2,3/1,7/2
S8	5/2,3/1,7/2	5/2,3/1,7/2	5/2,3/1,7/2	5/2,3/1,7/2	2/1,5/2,3/1	5/2,3/1,7/2	1/1,3/2,2/1	1/1,3/2,2/1	2/1,5/2,3/1	3/2,2/1,5/2	1/1,3/2,2/1	5/2,3/1,7/2	1/1,3/2,2/1	1/1,3/2,2/1	3/2,2/1,5/2
S9	1/2,1/1,3/2	1/2,1/1,3/2	1/2,1/1,3/2	1/2,1/1,3/2	5/2,3/1,7/2	1/2,1/1,3/2	5/2,3/1,7/2	5/2,3/1,7/2	1/2,1/1,3/2	1/2,1/1,3/2	1/2,1/1,3/2	1/2,1/1,3/2	1/2,1/1,3/2	1/2,1/1,3/2	2/1,5/2,3/1
S10	3/2,2/1,5/2	5/2,3/1,7/2	3/2,2/1,5/2	5/2,3/1,7/2	5/2,3/1,7/2	3/2,2/1,5/2	1/1,3/2,2/1	1/1,3/2,2/1	3/2,2/1,5/2	3/2,2/1,5/2	1/1,3/2,2/1	1/1,3/2,2/1	1/1,3/2,2/1	3/2,2/1,5/2	1/1,3/2,2/1

Table 6.9: Normalized fuzzy decision matrix.

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15
S1	0.1441	0.1605	0.1399	0.1682	0.0743	0.0734	0.0823	0.1251	0.1158	0.0797	0.0970	0.0841	0.1504	0.1030	0.1071
	0.1802	0.1925	0.1748	0.2018	0.1114	0.1101	0.1235	0.1668	0.1544	0.1196	0.1455	0.1261	0.2005	0.1545	0.1428
	0.2162	0.2246	0.2098	0.2354	0.1486	0.1467	0.1647	0.2085	0.1930	0.1595	0.1940	0.1681	0.2506	0.2060	0.1785
S2	0.1802	0.1605	0.1748	0.1009	0.1114	0.1834	0.1235	0.2085	0.0772	0.1994	0.1940	0.1681	0.1504	0.1030	0.0714
	0.2162	0.1925	0.2098	0.1345	0.1486	0.2201	0.1647	0.2502	0.1158	0.2392	0.2425	0.2102	0.2005	0.1545	0.1071
	0.2523	0.2246	0.2447	0.1682	0.1857	0.2568	0.2058	0.2919	0.1544	0.2791	0.2910	0.2522	0.2506	0.2060	0.1428
S3	0.0721	0.1605	0.1748	0.1682	0.1114	0.1101	0.0823	0.0834	0.1930	0.1994	0.0970	0.0841	0.1003	0.1030	0.1785
	0.1081	0.1925	0.2098	0.2018	0.1486	0.1467	0.1235	0.1251	0.2316	0.2392	0.1455	0.1261	0.1504	0.1545	0.2141
	0.1441	0.2246	0.2447	0.2354	0.1857	0.1834	0.1647	0.1668	0.2702	0.2791	0.1940	0.1681	0.2005	0.2060	0.2498
S4	0.1802	0.1284	0.1049	0.1682	0.1857	0.1834	0.1647	0.1251	0.1544	0.1595	0.1455	0.2102	0.2506	0.1030	0.1785
	0.2162	0.1605	0.1399	0.2018	0.2228	0.2201	0.2058	0.1668	0.1930	0.1994	0.1940	0.2522	0.3008	0.1545	0.2141
	0.2523	0.1925	0.1748	0.2354	0.2600	0.2568	0.2470	0.2085	0.2316	0.2392	0.2425	0.2942	0.3509	0.2060	0.2498
S5	0.1802	0.1605	0.1399	0.1682	0.0743	0.1834	0.2058	0.0834	0.1544	0.1196	0.0970	0.0841	0.1003	0.1030	0.1785
	0.2162	0.1925	0.1748	0.2018	0.1114	0.2201	0.2470	0.1251	0.1930	0.1595	0.1455	0.1261	0.1504	0.1545	0.2141
	0.2523	0.2246	0.2098	0.2354	0.1486	0.2568	0.2882	0.1668	0.2316	0.1994	0.1940	0.1681	0.2005	0.2060	0.2498
S6	0.1802	0.1605	0.1748	0.1682	0.1114	0.1834	0.1235	0.0834	0.1930	0.1994	0.2425	0.2102	0.1003	0.1030	0.1785
	0.2162	0.1925	0.2098	0.2018	0.1486	0.2201	0.1647	0.1251	0.2316	0.2392	0.2910	0.2522	0.1504	0.1545	0.2141
	0.2523	0.2246	0.2447	0.2354	0.1857	0.2568	0.2058	0.1668	0.2702	0.2791	0.3395	0.2942	0.2005	0.2060	0.2498
S7	0.1081	0.1605	0.1748	0.1009	0.1857	0.1101	0.1647	0.2085	0.1544	0.0797	0.0970	0.0841	0.1003	0.2575	0.1785
	0.1441	0.1925	0.2098	0.1345	0.2228	0.1467	0.2058	0.2502	0.1930	0.1196	0.1455	0.1261	0.1504	0.3090	0.2141
	0.1802	0.2246	0.2447	0.1682	0.2600	0.1834	0.2470	0.2919	0.2316	0.1595	0.1940	0.1681	0.2005	0.3605	0.2498
S8	0.1802	0.1605	0.1748	0.1682	0.1486	0.1834	0.0823	0.0834	0.1544	0.1196	0.0970	0.2102	0.1003	0.1030	0.1071
	0.2162	0.1925	0.2098	0.2018	0.1857	0.2201	0.1235	0.1251	0.1930	0.1595	0.1455	0.2522	0.1504	0.1545	0.1428
	0.2523	0.2246	0.2447	0.2354	0.2228	0.2568	0.1647	0.1668	0.2316	0.1994	0.1940	0.2942	0.2005	0.2060	0.1785
S9	0.0360	0.0321	0.0350	0.0336	0.1857	0.0367	0.2058	0.2085	0.0386	0.0399	0.0485	0.0420	0.0501	0.0515	0.1428
	0.0721	0.0642	0.0699	0.0673	0.2228	0.0734	0.2470	0.2502	0.0772	0.0797	0.0970	0.0841	0.1003	0.1030	0.1785
	0.1081	0.0963	0.1049	0.1009	0.2600	0.1101	0.2882	0.2919	0.1158	0.1196	0.1455	0.1261	0.1504	0.1545	0.2141
S10	0.1081	0.1605	0.1049	0.1682	0.1857	0.1101	0.0823	0.0834	0.1158	0.1196	0.0970	0.0841	0.1003	0.1545	0.0714
	0.1441	0.1925	0.1399	0.2018	0.2228	0.1467	0.1235	0.1251	0.1544	0.1595	0.1455	0.1261	0.1504	0.2060	0.1071
	0.1802	0.2246	0.1748	0.2354	0.2600	0.1834	0.1647	0.1668	0.1930	0.1994	0.1940	0.1681	0.2005	0.2575	0.1428

Table 6.10: Weighted normalized fuzzy decision matrix.

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15
S1	0.0150	0.0069	0.0193	0.0268	0.0000	0.0080	0.0026	0.0000	0.0124	0.0022	0.0000	0.0107	0.0231	0.0000	0.0000
	0.0187	0.0083	0.0241	0.0322	0.0000	0.0120	0.0039	0.0000	0.0165	0.0033	0.0000	0.0161	0.0307	0.0000	0.0000
	0.0224	0.0097	0.0289	0.0376	0.0000	0.0160	0.0052	0.0000	0.0206	0.0044	0.0000	0.0215	0.0384	0.0000	0.0000
S2	0.0187	0.0069	0.0241	0.0161	0.0000	0.0200	0.0039	0.0000	0.0082	0.0054	0.0000	0.0215	0.0231	0.0000	0.0000
	0.0224	0.0083	0.0289	0.0215	0.0000	0.0240	0.0052	0.0000	0.0124	0.0065	0.0000	0.0268	0.0307	0.0000	0.0000
	0.0262	0.0097	0.0338	0.0268	0.0000	0.0280	0.0064	0.0000	0.0165	0.0076	0.0000	0.0322	0.0384	0.0000	0.0000
S3	0.0075	0.0069	0.0241	0.0268	0.0000	0.0120	0.0026	0.0000	0.0206	0.0054	0.0000	0.0107	0.0154	0.0000	0.0000
	0.0112	0.0083	0.0289	0.0322	0.0000	0.0160	0.0039	0.0000	0.0247	0.0065	0.0000	0.0161	0.0231	0.0000	0.0000
	0.0150	0.0097	0.0338	0.0376	0.0000	0.0200	0.0052	0.0000	0.0289	0.0076	0.0000	0.0215	0.0307	0.0000	0.0000
S4	0.0187	0.0055	0.0145	0.0268	0.0000	0.0200	0.0052	0.0000	0.0165	0.0044	0.0000	0.0268	0.0384	0.0000	0.0000
	0.0224	0.0069	0.0193	0.0322	0.0000	0.0240	0.0064	0.0000	0.0206	0.0054	0.0000	0.0322	0.0461	0.0000	0.0000
	0.0262	0.0083	0.0241	0.0376	0.0000	0.0280	0.0077	0.0000	0.0247	0.0065	0.0000	0.0376	0.0538	0.0000	0.0000
S5	0.0187	0.0069	0.0193	0.0268	0.0000	0.0200	0.0064	0.0000	0.0165	0.0033	0.0000	0.0107	0.0154	0.0000	0.0000
	0.0224	0.0083	0.0241	0.0322	0.0000	0.0240	0.0077	0.0000	0.0206	0.0044	0.0000	0.0161	0.0231	0.0000	0.0000
	0.0262	0.0097	0.0289	0.0376	0.0000	0.0280	0.0090	0.0000	0.0247	0.0054	0.0000	0.0215	0.0307	0.0000	0.0000
S6	0.0187	0.0069	0.0241	0.0268	0.0000	0.0200	0.0039	0.0000	0.0206	0.0054	0.0000	0.0268	0.0154	0.0000	0.0000
	0.0224	0.0083	0.0289	0.0322	0.0000	0.0240	0.0052	0.0000	0.0247	0.0065	0.0000	0.0322	0.0231	0.0000	0.0000
	0.0262	0.0097	0.0338	0.0376	0.0000	0.0280	0.0064	0.0000	0.0289	0.0076	0.0000	0.0376	0.0307	0.0000	0.0000
S7	0.0112	0.0069	0.0241	0.0161	0.0000	0.0120	0.0052	0.0000	0.0165	0.0022	0.0000	0.0107	0.0154	0.0000	0.0000
	0.0150	0.0083	0.0289	0.0215	0.0000	0.0160	0.0064	0.0000	0.0206	0.0033	0.0000	0.0161	0.0231	0.0000	0.0000
	0.0187	0.0097	0.0338	0.0268	0.0000	0.0200	0.0077	0.0000	0.0247	0.0044	0.0000	0.0215	0.0307	0.0000	0.0000
S8	0.0187	0.0069	0.0241	0.0268	0.0000	0.0200	0.0026	0.0000	0.0165	0.0033	0.0000	0.0268	0.0154	0.0000	0.0000
	0.0224	0.0083	0.0289	0.0322	0.0000	0.0240	0.0039	0.0000	0.0206	0.0044	0.0000	0.0322	0.0231	0.0000	0.0000
	0.0262	0.0097	0.0338	0.0376	0.0000	0.0280	0.0052	0.0000	0.0247	0.0054	0.0000	0.0376	0.0307	0.0000	0.0000
S9	0.0037	0.0014	0.0048	0.0054	0.0000	0.0040	0.0064	0.0000	0.0041	0.0011	0.0000	0.0054	0.0077	0.0000	0.0000
	0.0075	0.0028	0.0096	0.0107	0.0000	0.0080	0.0077	0.0000	0.0082	0.0022	0.0000	0.0107	0.0154	0.0000	0.0000
	0.0112	0.0041	0.0145	0.0161	0.0000	0.0120	0.0090	0.0000	0.0124	0.0033	0.0000	0.0161	0.0231	0.0000	0.0000
S10	0.0112	0.0069	0.0145	0.0268	0.0000	0.0120	0.0026	0.0000	0.0124	0.0033	0.0000	0.0107	0.0154	0.0000	0.0000
	0.0150	0.0083	0.0193	0.0322	0.0000	0.0160	0.0039	0.0000	0.0165	0.0044	0.0000	0.0161	0.0231	0.0000	0.0000
	0.0187	0.0097	0.0241	0.0376	0.0000	0.0200	0.0052	0.0000	0.0206	0.0054	0.0000	0.0215	0.0307	0.0000	0.0000

Table 6.11: Best non-fuzzy performance value (BNP) and ranking of solutions.

Solution	y_i^l	y_i^u	y_i^m	BNP (y_i)	Rank
S1	0.1269	0.1658	0.2047	0.1658	**7**
S2	0.1479	0.1868	0.2257	0.1868	**4**
S3	0.1321	0.1710	0.2098	0.1710	**6**
S4	0.1768	0.2157	0.2546	0.2157	**1**
S5	0.1441	0.1829	0.2218	0.1829	**5**
S6	0.1687	0.2076	0.2465	0.2076	**2**
S7	0.1203	0.1592	0.1980	0.1592	**8**
S8	0.1611	0.2000	0.2389	0.2000	**3**
S9	0.0440	0.0829	0.1218	0.0829	**10**
S10	0.1158	0.1547	0.1935	0.1547	**9**

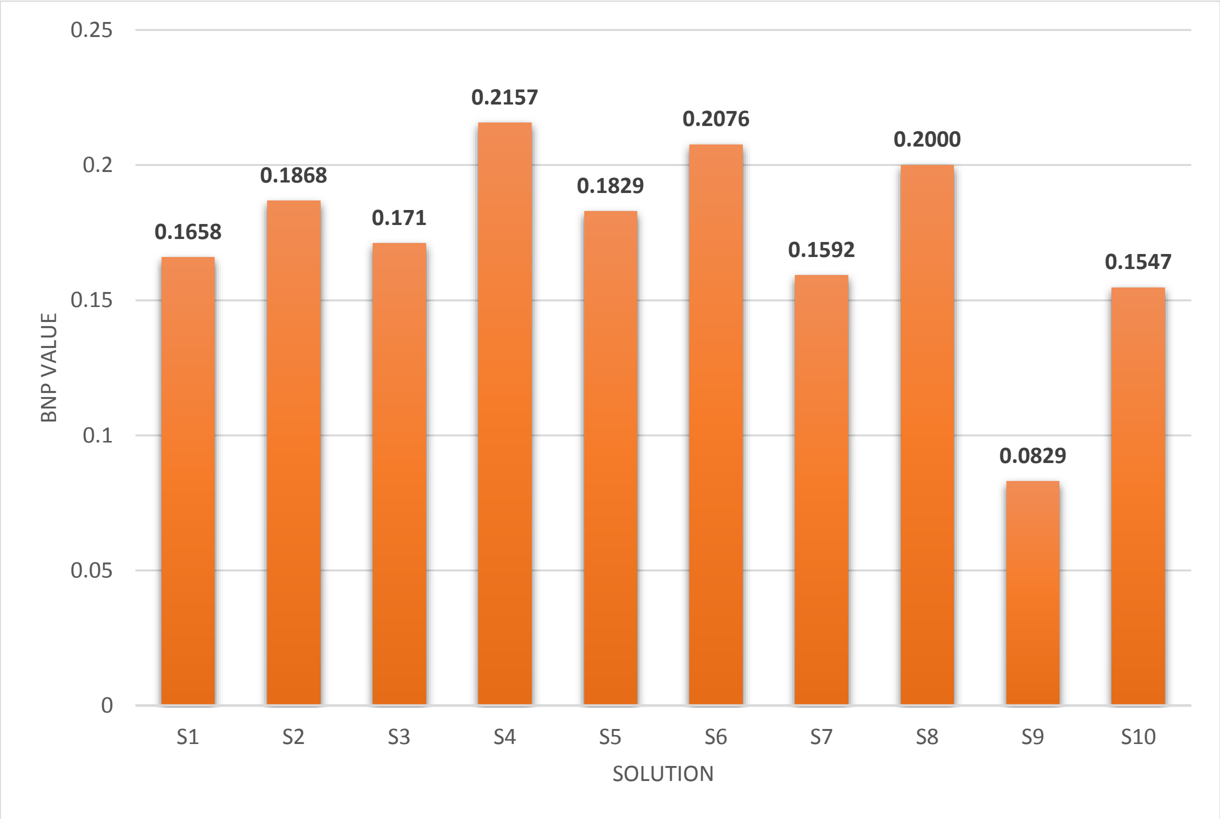


Figure 6.4: BNP values of ten key solutions.

Step2: Sensitivity analysis

To check the stability of the results, Monte Carlo simulation with uniform probability distribution is performed using the same formula discussed in Equation 4.2 i.e.,

$$X_k^b = X_{0,k} \pm [X_{0,k} * \delta * rand()]$$

However, in the present situation, δ is kept constant at 10% and in each case, the normalized weight of a barrier in Table 6.7 is increased by δ while the weight of other factors remains unchanged. The factors having zero weights are not taken into account because they will not affect the input weights in order to perform the sensitivity analysis. Ten sets of experiments are performed and resulting results are shown in Table 6.12. The results illustrate the effect of 10% growth in the barriers weight on the final ranking of the alternatives. As it can be seen from Figure 6.5 & 6.6, the solution weights have changed in each experiment, but the ranking always remains the same implying that FMOORA outcomes are stable.

Table 6.12: BNP values and ranking of key solutions by sensitivity analysis.

	Exp. 1		Exp. 2		Exp. 3		Exp. 4		Exp. 5	
	y_i	RANK	y_i	RANK	y_i	RANK	y_i	RANK	y_i	RANK
S1	0.1677	**7**	0.1666	**7**	0.1682	**7**	0.1682	**7**	0.1670	**7**
S2	0.1890	**4**	0.1876	**4**	0.1897	**4**	0.1897	**4**	0.1892	**4**
S3	0.1721	**6**	0.1718	**6**	0.1739	**6**	0.1739	**6**	0.1726	**6**
S4	0.2180	**1**	0.2164	**1**	0.2176	**1**	0.2176	**1**	0.2181	**1**
S5	0.1852	**5**	0.1838	**5**	0.1854	**5**	0.1854	**5**	0.1853	**5**
S6	0.2098	**2**	0.2084	**2**	0.2105	**2**	0.2105	**2**	0.2100	**2**
S7	0.1607	**8**	0.1600	**8**	0.1621	**8**	0.1621	**8**	0.1608	**8**
S8	0.2022	**3**	0.2008	**3**	0.2029	**3**	0.2029	**3**	0.2024	**3**
S9	0.0837	**10**	0.0832	**10**	0.0839	**10**	0.0839	**10**	0.0837	**10**
S10	0.1562	**9**	0.1555	**9**	0.1566	**9**	0.1566	**9**	0.1563	**9**
	Exp. 6		Exp. 7		Exp. 8		Exp. 9		Exp. 10	
	y_i	RANK	y_i	RANK	y_i	RANK	y_i	RANK	y_i	RANK
S1	0.1662	**7**	0.1674	**7**	0.1661	**7**	0.1674	**7**	0.1689	**7**
S2	0.1873	**4**	0.1880	**4**	0.1875	**4**	0.1895	**4**	0.1899	**4**
S3	0.1714	**6**	0.1734	**6**	0.1716	**6**	0.1726	**6**	0.1733	**6**
S4	0.2164	**1**	0.2178	**1**	0.2163	**1**	0.2189	**1**	0.2203	**1**
S5	0.1837	**5**	0.1850	**5**	0.1834	**5**	0.1845	**5**	0.1852	**5**
S6	0.2081	**2**	0.2101	**2**	0.2082	**2**	0.2108	**2**	0.2099	**2**
S7	0.1598	**8**	0.1612	**8**	0.1595	**8**	0.1608	**8**	0.1615	**8**
S8	0.2004	**3**	0.2021	**3**	0.2004	**3**	0.2032	**3**	0.2023	**3**
S9	0.0837	**10**	0.0837	**10**	0.0831	**10**	0.0840	**10**	0.0845	**10**
S10	0.1550	**9**	0.1563	**9**	0.1551	**9**	0.1563	**9**	0.1570	**9**

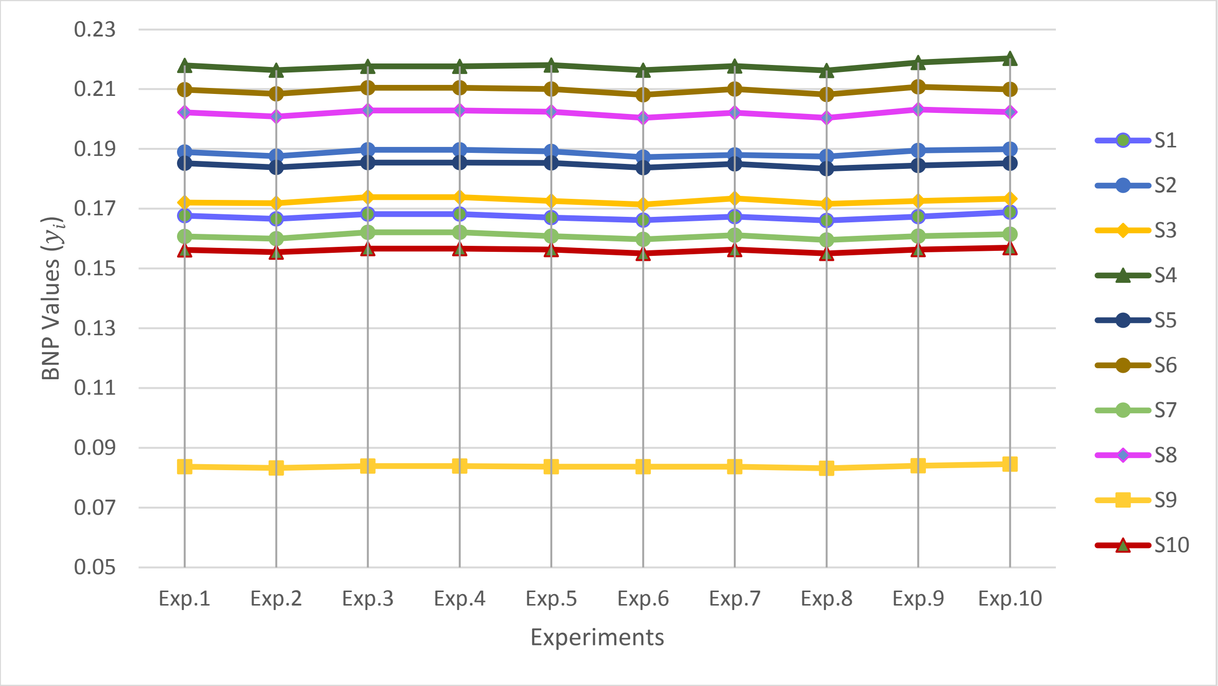


Figure 6.5: Results of sensitivity analysis for BNP values of solutions.

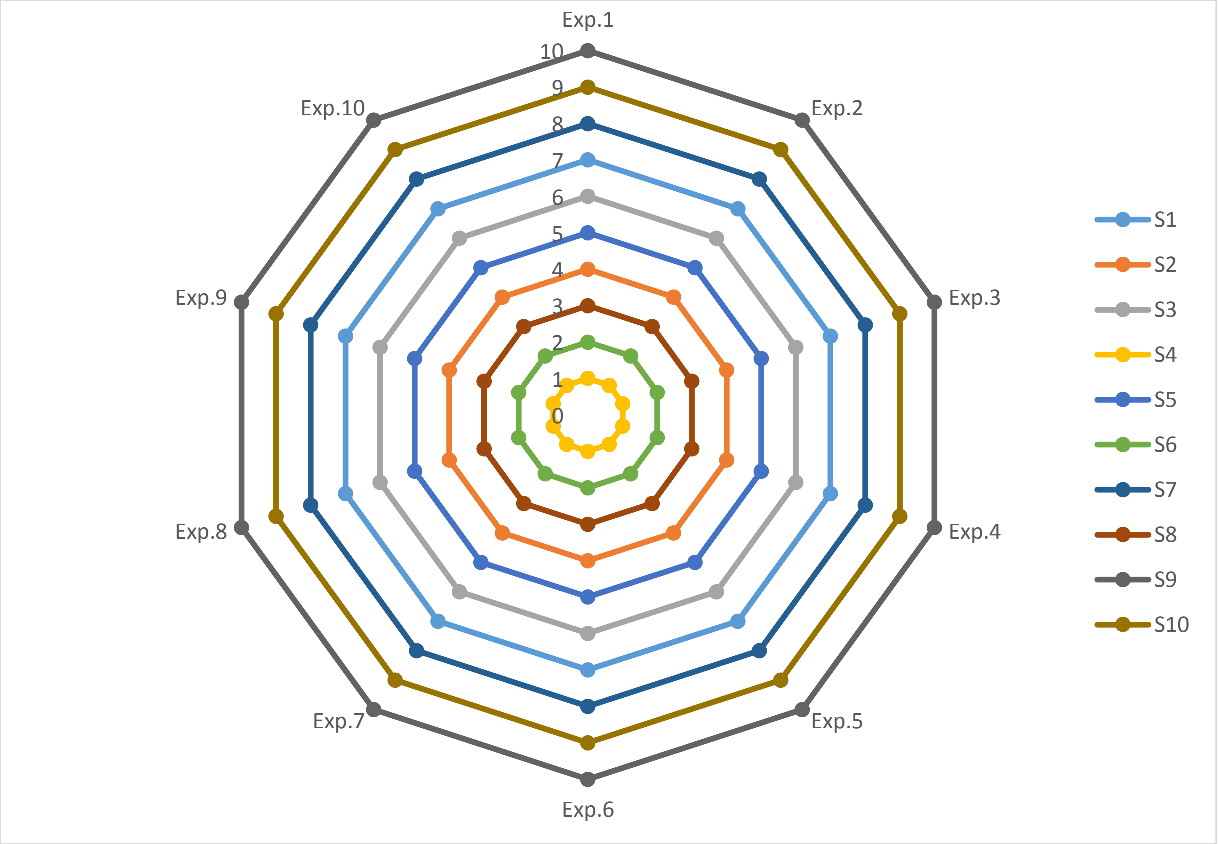


Figure 6.6: Results of sensitivity analysis for ranking of solutions.

6.4. Discussion of results

Due to the increase in the population of India and associated complexities in UIP operations, it is the time that the policy-makers of immunization programs start focussing on building next-generation vaccine supply chain system (NGVSCs) that can help them to achieve six rights of supply chain: right product, right, quantity, right condition, right place, right time and right cost in order to support immunization programs and protect every infant. Process redesign methodologies are an important and potentially fruitful approach to improving the efficiency and effectiveness of hospitals and addressing the broader challenges facing public management in difficult economic times [340].

In the present study, a set of solutions to overcome barriers, which can help in designing a safe, reliable and efficient NGVSCs have been discussed. The next-generation supply chains have the capability to deliver vaccines safely, efficiently and effectively to the children who need them. As pointed out by Numbi and Kupa [341], new or ‘‘next-generation” supply chain designs throughout a number of African countries are demonstrating the flexibility to address present and future necessities dealing with immunization programs. For example, stock-out levels reduced from 80% to less than 1% in Northern Mozambique that helped in increasing the DTP3 coverage rate by 25% [342]. The alternative system design raised vaccine availability (from 66% to 93% in Gaza; from 76% to 84% in Cabo Delgado) and reduced the logistics cost per dose administered (from $0.53 to $0.32 in Gaza; from $0.38 to $0.24 in Cabo Delgado) [343]. Similarly, a study conducted at Cabo Delgado and Niassa Provinces, Mozambique found that the new supply chain design reduced the government operating costs by 20% [344]. Lee et al. [343] point out that re-designing not only helps in improving efficacy but also the efficiency of vaccine supply chains.

6.4.1. *Three critical barriers to NGVSCs*

In order to build well-performing NGVSCs, first, it is important that the barriers which are the main obstacles to design NGVSCs are identified and eliminated. Based on the results of the study, ***“poor demand forecast (B4)”*** with the weight of 0.160 has been identified as one of the most important barriers in the list of critical barriers. In VSC, a better demand forecasting system and inventory management can help to reduce vaccine stock-outs and improve vaccine coverage [345]. A study by Lydon et al. to analyze the stock-outs in 194 WHO members states found that 18% of the vaccine stock-outs at country level was due to poor forecasting and inventory management [50]. The objective of vaccine forecasting is to estimate the number of vaccines, cold chain devices, and capital needs important to conduct immunization program. However, stock-outs in developing countries are unavoidable [346]. Proper forecasting is one the feasible way to avoids vaccine stock-outs when uncertainties in demand arise (for example emergencies and natural failures). Mueller et al. [43] suggest that without proper forecasting systems, those managing a supply chain might have difficulty predicting changes in demand at immunization locations and consequently making an appropriate infrastructure and supply compensatory changes. ***"Unavailability of healthcare workers (B13) (0.153)"*** is identified as the second imperative barrier on the list. Health workers are necessary at every stage of the supply chain for the smooth functioning of immunization programs. However, there is a severe shortage of trained human resources in India [347]. According to WHO, there is a shortage of nearly 4.7 million health workers in 57 developing countries [348].

Anjali explains that Indian health workers are willing to work in the public and rural areas given better conditions, pay, and continued training [347]. Liu et al. [349] point out that in many low and middle-income countries, efforts to scale-up health services to acquire universal health coverage and health improvement goals are faced by acute shortages and inequitable distribution of professional medical examiners that present a binding constraint to delivering important healthcare services. Hence, there is a need for proper funding support that will allow acquiring a better human resource. ***"Unavailability of vaccines and equipment's (B3) (0.138)"*** comes last on the list of critical barriers. Unavailability of vaccines and equipment's due to poor forecasting, stock-outs, etc. have been a frequent problem faced globally. A global shortage of inactivated polio vaccine (IPV) has also affected India, leaving many children unvaccinated [347]. Lydon et al. [50] study in 194 WHO member states found that every year on an average, one in every three states experienced at least one stock-out of at least one basic vaccine for at least one month. Further, in most of the developing countries poor stock management contributed to 18% of the national level stock-outs. The result also revealed that when a national level stock-out occurs, there is an 89% chance that a subnational stock-out will occur at the district level. Proper inventory management is essential for controlling vaccines and equipment's in the stock. Vaccine and storage equipment's stock-outs and their improper use can not only lead to financial losses but also have a significant impact on children health. Uthayakumar and Priyan [350] points out that many health systems and hospitals experience problems in managing inventory as they have not addressed how medicines are managed, provided, and used to save lives and enhance health.

6.4.2. *Discussion on solutions to mitigate barriers to help design NGVSCs*

The result derived for ranking the solutions using integrated fuzzy AHP-MOORA is depicted in Figure 6.4. The order of priority for the alternatives *is* ***S4 > S6 > S8 > S2 > S5 > S3 > S1> S7 > S10 > S9***. Hence, based on the results, the factor ***"sustainable financing (S4)"*** is the most important solution in the priority list of important solutions. Financial support is important to protect the existing vaccine supplies, along with the encouragement in the development of new vaccines. However, in most of the developing countries, the vaccine platform and delivery technologies that can have a substantial impact on the immunization rates are not appropriately funded [7,49,351,352]. According to Chatterjee [347], as the overall useful resource requirement will increase regularly and because of the introduction of new vaccines and development in other programs in India, the government budget on immunization needs to be increased in the coming years to fill the investment gap.

Lydon et al. [50] also point out that government funding was the single largest root cause of the stock-outs of the basic vaccines in 194 WHO member states form the period of 2011 to 2015. Stenberg et al. [353] study in 67 low and middle-income countries estimate that at an extra $274 billion spending on health will be required every year by 2030 to make development towards the sustainable development goals 3 targets, whereas US$371 billion would be required to reach healthcare system targets. Similarly, Ozawa et al. [352] performed an analysis to estimate the full immunization costs and projected available financing in 94 low- and middle-income countries over five years (2016-2020) and found that the delivery of full immunization programs would result in a funding gap of $7.6 billion by 2020, which represents 66% of the projected supply chain costs. A better and robust financial mechanism is necessary for addressing delays in releasing national funds to purchase vaccines, immunization products and strengthening immunization programs. The present funding gap in India and other developing countries shows the necessity for country and donor commitments to mobilize and efficiently assign resources, specifically for the service delivery section of national immunization programs and comparatively underfunded country supply chains [50,352].

"Leadership and training programs (S6)" comes next on the priority list. Brown et al. [354] suggest that because of the addition of new vaccines in EPI schedule and development of new technologies more vaccine supply chain experts with an appropriate technical and leadership abilities will be required in future to run immunization supply chains from end to end. According to Numbi and Kupa [341], a professionalized logistics workforce with authority to make supply chain decisions based on data and actual, on-the-ground circumstances can have a great impact on building next-generation supply chains. Next in the list is ***"continuous improvement through effective vaccine management (EVM) (S8)"***. According to WHO, the EVM initiative provides materials and tools needed to monitor and investigate vaccine management practices including supply chain and help countries to improve their supply chain performance. It requires that the managers must display interest in organizing the EVM method to assist immunization programs to compare the current performance of their vaccine supply chain, and benchmark this performance towards best practice standards [355,356]. UNICEF launched the mobile-based Effective Vaccine Management (EVM) machine in Bihar a state of India in 2014 along with the state authorities to electronically capture information and discover gaps within the existing vaccine management system for suitable action. This initiative resulted in an extended cold chain space from 49% (July 2014) to 87% (September 2015), deployment of enough human resource; 38 cold chain technicians for maintenance of the cold chain equipment's and systems, set up of important equipment's, and advancement of state and regional vaccine stores [357].

India has made enormous progress in reducing stock out since the introduction of electronic vaccine intelligence network (eVIN) in 12 States in 2015/2016 [358]. In Mozambique, results showed reduced stock-outs at health centers from 79% to less than 1% [4]. The coverage rate of DTP3 also increased from 68.9% to 92.8%. However, seeing the enormous benefits of EFV, still, according to the Gavi Vaccine Alliance analysis of recent EVM assessments in 57 countries, the majority do not meet the WHO recommended 80% score across most of the nine categories of supply chain management, with results particularly low for the categories of stock management, maintenance, and distribution [4]. Based on the results, it becomes important that the nine areas (criteria) of effective vaccine management should be followed properly and regularly by the immunization program managers for the continuous improvement in the delivery performance. ***"Raise awareness of supply chain issues (S2)"*** is next on the solution list. Identifying and addressing the supply chain issues can help to improve its efficiency.

One feasible action is the involvement of social media and general media. The efforts on publishing stories by means of the media on vaccine supply chain issues; for example, 'vaccine expired by keeping on shelf led to the loss of US$5 million to a country' via news testimonies, or special reports can raise cognizance among immunization program officials. The next ranked solution is ***"improve use of technology (S5)"***. Major advancements have been made in cold chain equipment technology since 2011 with the introduction of SDD vaccine refrigerators prequalified through the WHO/PQS program, however, still developing countries like India are struggling to store and deliver vaccines efficiently and effectively [6]. Therefore, to improve vaccination coverage in India more innovation in cold chain equipment and digital and logistics technology is required so that vaccines can be stored and delivered safely and more efficiently [70]. Ashok et al. [6] point out that achieving this will require financial support, human resource, effort and political will in the country as well as global level. ***"Data visibility and management (S3)"*** comes next on the priority list. Today many nations still depend upon largely paper-based information collection systems, based on few excellent standards, gathered and processed once in a month and flowing in just one route [338]. Franzel et al. [359] suggest that with rapidly flowing robust data, an efficient information system can be designed, which in turn will assist to simplify the efforts of health workers, saving money and time. For example, Nigeria installed a vaccine dashboard in 774 LGAs, 36 states and 6 zonal stores for stock visibility and management.

As a result, there was a marked improvement from a total of 263 (34%) of the 774 LGA cold stores having adequacy of all antigens at baseline in March 2013 to over 688 (89%) in April 2016 [54]. As pointed out by Numbi and Kupa [341], clear data visibility of vaccine availability and quality until the point of delivery, through appropriate information technology can be successful in designing next-generation vaccine supply chains. The next solution ***"improve communication between policy-makers and vaccine supply chain experts (S1)"*** can play an important role in the VSC to cope with various uncertainties. Communication in the form of information sharing is essential in the immunization programs to reduce uncertainties. It also helps to make health workers more productive as they contribute more and feel better about their contribution in saving child life through vaccine dose. From the survey, it was found that there was very less communication between the supply chain members. Tkalac [360] and Welch [361] suggest that internal communication is essential to the achievement of the organization and it is critical that organizations grasp that speaking with employees is an essential success factor.

Internal communication is generally concerned with the connection among social actors, e.g. the organization and its employees [362]. To achieve the immunization goals, it is important that the government spend more on building modern and robust information sharing systems so that an effective communication channel is built between the supply chain members. Bhaihaqi and Sohal [363] also point out that information sharing is one of the major means to enhance supply chain performance. It allows companies to better coordinate their activities with their supply chain partners, which leads to increased performance. Some important solutions for communication improvement as pointed out by Lee and Haidari [337] are (i) integrating supply chain specialists into different committees, conferences, meetings, etc., (ii) establishing online data sharing websites and communications portals wherein decision-makers and supply chain experts can collaborate, and (iii) harmonizing language between the supply chain world and other vaccine-related disciplines can help policy-makers in a better understanding of vaccine supply chains. ***"Proper planning and coordination (S7)"*** comes next. Proper planning and scheduling are necessary for any stage of the supply chain so that immunization programs can effectively manage processes. In fulfilling customer orders, one of the goals of supply chain planning is to satisfy the customers in phrases of delivery efficiency, delivery quantity accuracy, and on-time shipping. These performance objectives may be impacted by the planning strategy of any organization for the three stages of the supply chain: procurement, production, and distribution [87]. Designing a strategic planning system by the decision-makers can help to coordinate and align resources and action with mission, vision, and goal of the immunization programs in achieving high immunization rate. The next place of importance is ***"incorporate supply chain experts and considerations into all vaccine decision (S10)"***. Lee and Haidari [337] suggest that including vaccine supply chain experts at every stage of vaccine development and decision-making (e.g. Inclusion on committees and regulatory bodies) can help decision-makers better understand and address supply chains. Finally, ***"use of commercial partners for logistics activities (S9)"*** occupies the last position on the list of important solutions. Outsourcing the logistics domain to the companies that are expert in this field can help the immunization programs in improving coverage rate. For example, UNICEF is using logistics companies such as FedEx, DHL, and UPS for managing transportation activities [7]. Sarley et al. [54] study on Nigeria found that the use of 3PLs by the state governments for managing vehicle operations helped in improving stock availability. Therefore, other developing countries should also emphasize outsourcing direct deliveries of vaccines.

6.5. Conclusion

Since the last three decades, UIP India has contributed to unprecedented advances in reducing child mortality and morbidity. Now, another start is needed to ensure that supply chains can address today's issues and future uncertainties and challenges. Few developing countries have already started to show improvements in system performance by re-designing their current supply chain system. India is at the forefront of introducing new strategies to improve supply chain logistics. Further, new and improved strategies are required by India to improve and design the supply chain system, which is strong enough to overcome the issues and challenges that are running in the country, consisting of complexity, range, and systemic barriers. Moreover, the strategy will only be successful if it manages to carry collectively the countries and partners operating to enhance immunization supply chains, and guarantees that their support spans the breadth of the five fundamental components: data, people, equipment, systems and continuous development method [4,338].

In this chapter, an effort has been made to outline the key solutions that can help in mitigating/removing the barriers that come in the direction of designing next-generation vaccine supply chain system (NGVSCs) in India. Using fuzzy AHP and integrated fuzzy AHP-MOORA, the barriers of NGVSCs and its solutions have been analyzed. From the analysis, poor demand forecast has been identified as the most critical barrier and sustainable financing as the most important solution to overcome NGVSCs barrier. The policy-makers of immunization programs need to focus on the aforementioned barriers and solution in order to design a well-efficient NGVSCs. In addition, the results of the sensitivity analysis results indicate that the ranking remains consistent in the simulation run for the solutions categories, which suggests the stability of the results obtained. Overall, it can be concluded that the final decision is consistent and reliable.

Chapter 7

PERFORMANCE FRAMEWORK OF VACCINE SUPPLY CHAIN SYSTEM

Summary

This chapter demonstrates the role of the VSC key performance indicators (KPIs) to achieve the goal of sustainable development (SD) of child immunization program and to improve vaccine supply chain performance (VSCP) and sustainability. Based on the methodology (field expert's opinions and an in-depth review of the literature), 57 performance indicators of VSC and 52 sustainability practices criteria (SPC) have been identified. Using the balanced scorecard (BSC) approach the performance indicators have been assessed in four dimensions: learning and growth (LAG), internal process (INP), customer (CUS), and finance (FIN); whereas SPC has been evaluated in three dimensions: economic (ECS), environmental (ENS), and social (SOS). Then, exploratory factor analysis (EFA) and structural equation modeling (SEM) is applied to finalize the KPIs and the sustainable key practices criteria's (SKPCs) and to test the conceptual model based upon assumptions and hypothesis. Further using expert' responses, the impact of IP, and LAG performance indicators on the vaccine supply chain performance (VSCP) improvement is evaluated using Two-way assessment. The results of the SEM analysis reveal that LAG and IP dimension of BSC has a positive influence on customer satisfaction and also in the sustainable development success of the child immunization program. While, the results of Two-way assessment reveal that the three critical performance indicators having maximum impact on VSCP improvement are: 'Enhancement in employee work satisfaction' (LAG3=10.08%), 'Enhancement in professional vaccine supply chain managers and leaders' (LAG2 = 6.70%) 'Improvement in planning and coordination in the supply chain' (LAG9 = 6.57%). Focus on these three factors may help in improving sustainability in immunization programs.

7.1. Introduction

Vaccination against various childhood infectious diseases is the right of every child. In order to provide this right to every child, the Government of India started the universal immunization program (UIP) in 1985, one of the largest health programs of its kind in the world. In spite of its best efforts during the last three decades, it has been able to vaccinate only 65% of the children population. During the last five years, the increase in immunization coverage has stabilized to an average of 1% every year [3]. In order to improve immunization coverage, it is important for the government to build effective and sustainable child immunization programs in the country to benefit all section of society children for a long time.

In recent years, the term sustainability is being adopted by many non-profit and government organizations. Sustainable development (SD) concept involves social, economic and environmental development [46]. It is believed that sustainability in the future will be a major source of competitive advantage, so, the amount of investments in sustainability is increasing in all industries and organizations [45,389]. However, sustainability achievement in India and other developing countries is not an easy task.

Today, India is considered one of the leading vaccine's producer & supplier and runs one of the largest child vaccination program. Due to such large-scale operations, many complexities, e.g., increasing demand of vaccines, increasing emissions, increasing consumptions of natural resources, etc. arises, which are the primary reason for the inhibition of the sustainable development of the child the immunization programs. Hence, it is important that India finds a way to ensure energy and environmental sustainability without compromising its economic and social development to fulfill the objectives of increased coverage with sustainable development [392,393]. One possible way that can be considered by the immunization programs is to find a positive link between the factors of immunization programs, whose positive outcome can lead to sustainable development of child immunization programs. Many researchers, for example, Lambert et al. [394] and Dotson & Allenby [395] have studied the relationship between customer satisfaction and performance and the results prove that there is a positive correlation between satisfied customers and performance. As VSC is the backbone of immunization programs for vaccination of children, therefore, improvement in VSCP can be considered as one of the ways to improve the performance of immunization programs by satisfying customers, and the leading step towards the direction of sustainable development of child immunization program.

Enhancement in VSCP for immunization programs may help in delivering the right vaccines to the children in the right quantity and condition, at the right place and the right time, and with minimum cost. There are many advantages to a better performing supply chain, but the manager's role in measuring and monitoring performance may be a big question. For this reason, a performance measurement system (PMS) is necessary to collect, analyze and report various information regarding the performance of any organization, business process or system.

In this context, Kaplan and Norton [40] proposed a balanced scorecard (BSC) approach as a PMS to evaluate business performance. The BSC is considered as a strategic planning and management system that is utilized substantially in business and industry, government, and non-profit organizations worldwide to measure and manage organizational performance against strategic goals [396]. According to Kaplan and Norton, the BSC helps the organization to answer the following four questions (Gomes and Liddle, 2009):

1. How does the customer see us? (Customer perspective)
2. What must we excel at? (Internal process perspective)
3. Can we continue to improve and create value? (Learning and growth perspective)
4. How do we view our shareholders? (Financial perspective)

Hence, identifying the KPIs of VSC in terms of BSC and further segregating the KPIs based on the VSCP improvement, i.e. high, medium, and low impact can help the VSC managers to design some better strategies for performance improvement. Two-way assessment plays a suitable role in measuring the impact of each performance indicator on the performance of the supply chain. It is based on utility theory and AHP and enables the managers to focus their priority towards the KPIs having the maximum impact it may result in higher quality and faster turnaround of the immunization programs.

Due to the above discussion, this chapter confers EFA, SEM, and Two-way assessment approaches to illustrate how the performance indicators of VSC will be helpful for the sustainable development of child immunization programs and for improvement of VSCP to improve sustainability. The following objectives are designed for the work:

- ***To identifying and classifying KPIs of VSC in terms of the balanced scorecard (BSC).***
- ***To develop a linkage between the KPIs and sustainable development of child immunization program in India.***
- ***To identify critical performance indicators that have maximum effect on improving VSCP to improve sustainability.***

7.2. Theoretical framework and conceptual model

In order to achieve sustainability in immunization, it is important that the immunization programs experiment with how performance indicators of VSC may be used to create managerial momentum, not only within the direction of improving delivery performance but within also more sustainability. Based on this first assumption, conceptual model 1 is developed shown in Figure 7.1. The model proposes that the performance indicator of the vaccine supply chain will influence and promote sustainability practices in UIP, which will in turn help to achieve sustainable development of child immunization. Based on the opinions of the 38 VSC experts of the four states of India: Delhi, Uttar Pradesh, Uttarakhand, and Karnataka, and exhaustive literature analysis, a set of eight hypotheses has been framed and discussed below.

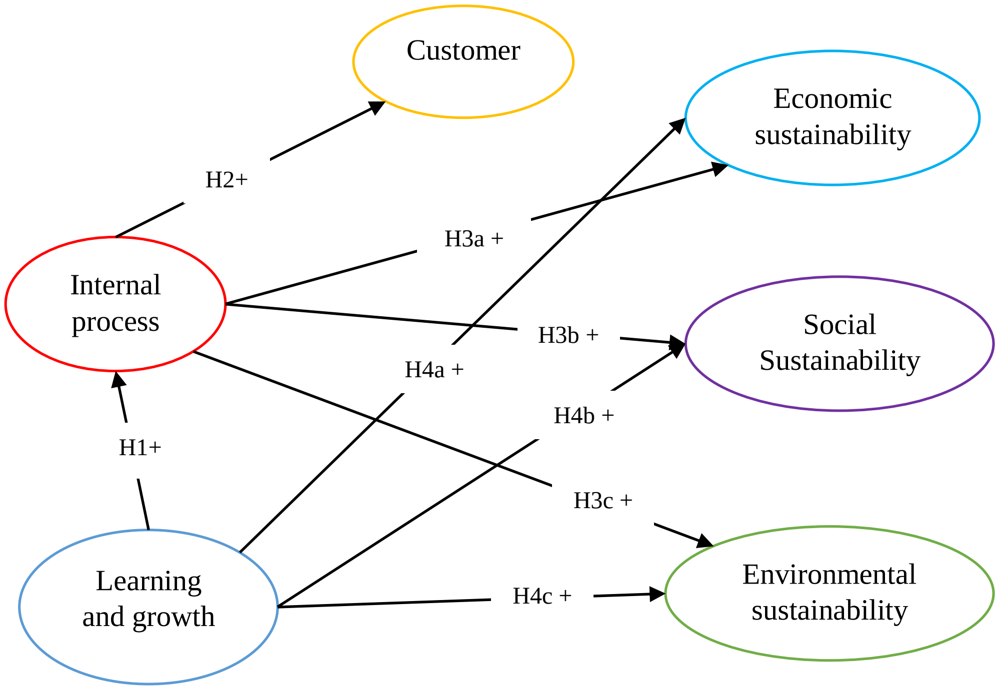


Figure 7.1: Theoretical framework of conceptual model 1.

7.2.1. Hypothesis about the relationship between learning and growth and internal process dimension of BSC

Capability to sustain innovation, exchange, and continuous improvement are the measures related to the learning and growth environment of an organization and the ability to excel in the future. To maintain sustainability and growth of an organization these factors are needed to measure worker satisfaction, motivation, and empowerment, as well as the capabilities of employees and information systems [102]. For any healthcare organization such as immunization programs, the learning and growth dimensions are the important elements to determine and drive the performance of the internal processes. Learning is a crucial factor in immunization programs for its growth and improving supply chain operations to deliver vaccines efficiently, effectively and without waste. As the policy-makers are responsible for the organizational changes and therefore, they should strive for new ideas and innovation for learning and growth, and knowledge sharing to help the health workers to be more skilled, trained, and satisfied. Questions such as ‘as an immunization program what type of culture, skill, training, and technology are we going to develop to support our VSC internal processes?’ should be the primary objective of policy-makers to bring changes in the internal processes.

Lee et al. [103] point out that organizational capability for learning and creating knowledge is the foundation for operating businesses. Organizational learning improves the potential capability for effective actions of organizations and individuals through improved business processes. According to Dutoit [364], organizational development is determined by learning processes and gaining knowledge that requires the addition or trade of mental models. Organizations can create knowledge through continuous inquiry into the understanding of new environments. Nonaka [365] points out that knowledge is created through information flow, so the mutual knowledge generated through the information shared with the supply chain will increase the likelihood of a common understanding of any problem among the supply chain members [366]. As knowledge flows may contribute to higher levels of performance and the performance has the capability to improve dimensions important to the customer, therefore, it is reasonable to expect that improvement in performance will increase customer satisfaction [367]. In this context, Gold et al. [368] also mentioned that better knowledge management practices lead to improved organizational efficiency. Moyano-Fuentes et al. [369], also argued that product and process innovation is ultimately reflective of the organizations learning and growth environment. Therefore, based on the above discussion, hypothesis H1 is proposed:

- **H1: Learning and growth positively affects the internal processes in the VSC.**

7.2.2. Hypothesis about the relationship between internal process and customer satisfaction dimension of BSC

This hypothesis is based upon the assumption that the organization performs well by considering the key internal operational methods. Hence. This may be the second objective of the policy-makers that effective internal business operations are vital to imparting products and services to satisfy customers' needs in a responsible way [102]. The objective of internal processes is to innovate and improve the technique of figuring out and satisfying the customer need for, as well as to offer high-quality consumer management service afterward [103]. If customers are dissatisfied while delivery is late, the organization can focus on the internal processes such as designing a more efficient transport system or refining the current system to improve delivery performance to satisfy customers. Because of the complexity in immunization programs, managers need to adopt a rigorous internal evaluation not only in measuring the inner processes of the immunization programs, but also reviewing innovation in products and services [96,370]. Zine and Kulkarni [371] also point out that in order to meet the need of the ever demanding customers, industries have to adopt new strategies to create innovative products and services. The same concept applies to vaccine manufacturing industries, which should strive to innovate in products and services due to changes in the vaccine market and dynamic demand for basic vaccines.

Therefore, it can be hypothesized that better management of VSC internal processes can be helpful to reach more children to improve the immunization program's performance. This will help in developing confidence and trust in the parent's confidence to bring their children for vaccination, which will result in improving immunization rate. Hence, hypothesis H2 is proposed.

- **H2: Internal process positively affects the customer's satisfaction in the vaccine supply chain.**

7.2.3. Hypothesis about the relationship between internal process and sustainable development dimensions

Recent studies indicate that internal process capabilities drive the change towards sustainability. [372] argues that innovation in products, organizational structures, and business methods can be the key to achieving economic, social, and environmental benefits. Moyano-Fuentes et al. [369] in their study reported that an organization that performs process innovation are more engaged in environmental sustainability. Koster et al. [373] also point out that management innovation is the driving factors for sustainability supply chain management. Continuous improvement is a key performance indicator of sustainability in organizations through energy consumption, air emissions, wastage, etc. Because these can be reaffirming over a period of time in order that continuous improvement leads to improved supply chain performance. The previous studies simply demonstrate that the internal processes such as lean practices, continuous improvement, risk management practices, technological innovation drive the organization to sustainability practices, thus causing higher degrees of sustainable supply chain performance. Soda et al. [374] also point out that green SCM practices are getting more attention as a sustainable development mode for modern enterprises. Thus, the following hypothesis are proposed:

- **H3a. Improvement in the internal process will positively influence economic sustainability.**
- **H3b. Improvement in the internal process will positively influence social sustainability.**
- **H3c. Improvement in the internal process will positively influence environmental sustainability.**

7.2.4. Hypothesis about the relationship between learning and growth and sustainable development dimensions

Organizational learning is an important contributor to the development and adoption of sustainability, and therefore, specific organizational abilities can drastically affect sustainability overall performance [375,376]. Sumane et al. [377] suggest that integrating informal and formal knowledge enhances sustainable practices. Nichols & Mukonoweshuro [378] in their study at the Neonatal unit in a district hospital in the United Kingdom found that a continuing information feedback system was helpful in stimulating and sustaining positive behavior changes in waste management inside the Neonatal unit. Accordingly, the following hypothesis are proposed:

- **H4a. Better learning and growth environment will positively influence economic sustainability.**
- **H4b. Better learning and growth environment will positively influence social sustainability.**
- **H4c. Better learning and growth environment will positively influence environmental sustainability.**

7.3. Flowchart of the research

A flowchart shown in Figure 7.2 is prepared to point out the different steps used to achieve the present research objectives. It starts with the identification of performance indicators and sustainability practices criteria's using field expert's opinions and literature review. Then, the application of various methodologies i.e. exploratory factor analysis (EFA), structural equation modeling (SEM), and Two –way assessment has been presented for the analysis purpose. The detailed description of the analysis steps in the flowchart, to achieve the research objectives is given below:

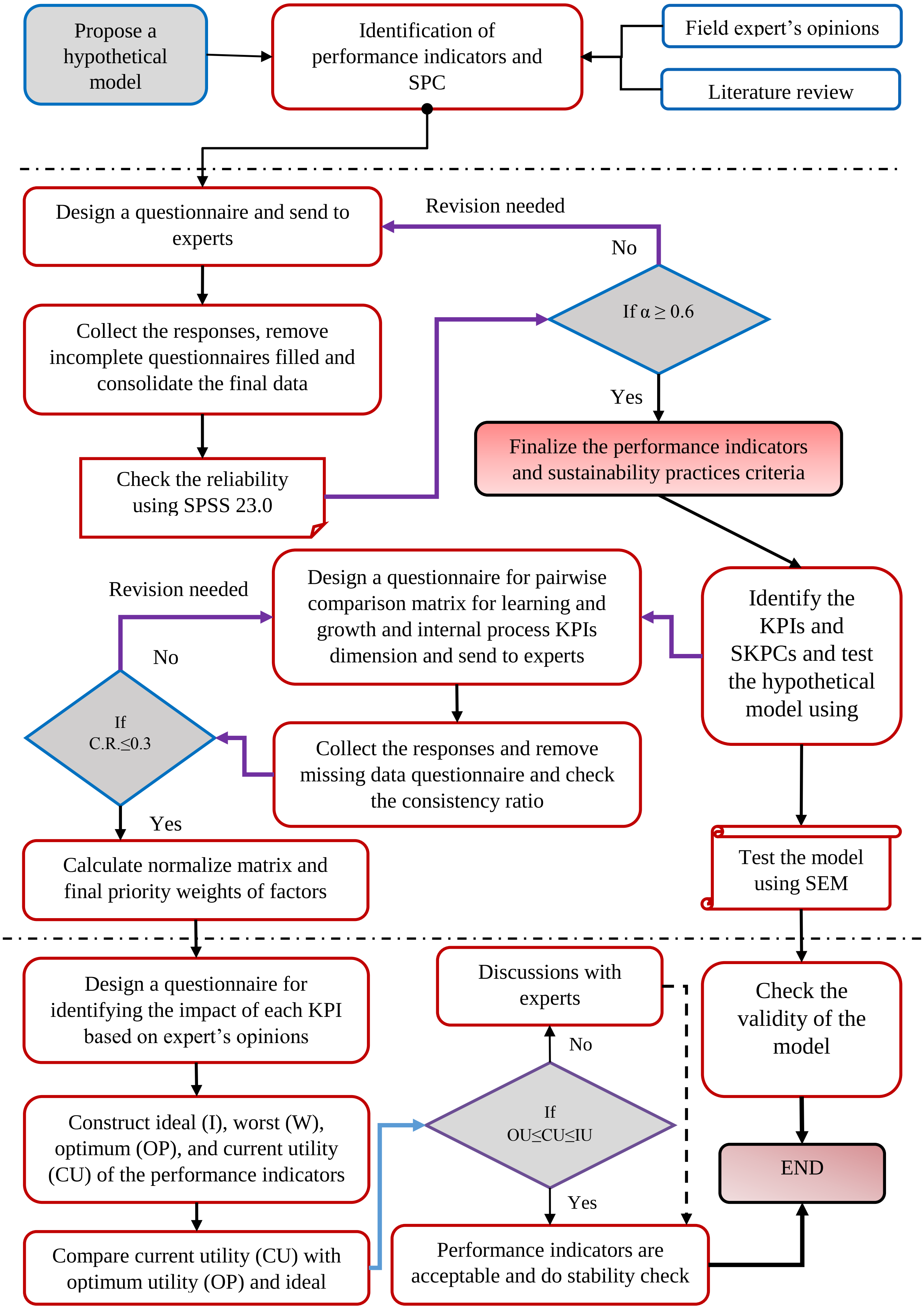


Figure 7.2: Flowchart to achieve the present objectives.

7.4. Research instrument and data collection for testing the conceptual model

The procedure for collecting data, which is used in the testing of the conceptual model is as follows:

7.4.1. Identification of performance indicators and SPC

Step 1. Fields experts from 3 states of India, i.e. Uttarakhand, Delhi, and Uttar Pradesh were contacted for identification of performance indicators and SPC. Through a number of field visits, the opinions of ten vaccine supply chain experts based on their subject expertise and work experience were taken. The selected experts are working in different levels of immunization programs and consist of 2 senior immunization program officers from Delhi, 4 additional research officers and 2 senior immunization program officers from Uttarakhand and 1 additional research officer and 1 senior immunization program officer from Uttar Pradesh. During the survey, BSC was discussed with the experts as one of the important management tools that can be used by the immunization programs for measuring its VSC performance in four different areas. Further, in detail, it was also discussed the role of KPIs in measuring and improving VSC performance. Then after the detail discussions with the experts, questions were asked with them such as 'for measuring the vaccine supply chain performance in each category of BSC, what can be the performance indicators based on your experience and knowledge?' Then the responses of each expert were noted down on 'Evernote mobile app' and later the final compiled list consisting of all expert's responses was prepared on Microsoft word. The expert's opinions helped in identifying and constructing 32 valuable performance indicators and SPC.

Step 2. Further, a literature survey was performed for the identification of some additional VSCP indicators and SPC. Based on thorough literature analysis, 42 papers that had data related to performance indicator and sustainability practices were finalized. Next, the global reporting initiative (GRI) 2017 report, which is an international organization to help businesses and government organizations worldwide follow the best sustainability practices were also identified and finalized for the study.

Finally, from Step 1 & 2, a total of 57 performance indicators and 52 SPC were finalized.
The compiled performance indicators and SPC are shown in Table 7.1 & 7.2.

Table 7.1: Compilation of performance indicators.

Dimension	Objective	Performance indicators
Finance (FIN)	Operating costs	Reduction in total supply chain costs
		Reduction in wastage costs
		Reduction in procurement costs
	Profitability	Improvement of cash flow
		Growth of earnings growth rate
Customer (CUS)	Customer satisfaction degree	Less distance to travel to health centers for vaccination
		Better vaccination services and proper attitude of health workers towards parents
		Reduction in parents complaints
		Enhancement to reply to parents problems
	Effective communication of appropriate healthcare	Provide better knowledge to parents to enhance their awareness regarding vaccination benefits
		Provide reminders of vaccination programs, vaccination dates, and schedule to parents
Internal process (INP)	Agility	Improvement in delivery responsiveness
		Increase in outreach centers
		Enhancement of emergency supply chains
		Reduction in time through system
		Increase in annual number of inventory turns
	Supply	Increase in percentage personnel time dedicated to logistics
		Increase in transport capacity
		Increase in storage capacity
		Increase in personnel
		Increase in doses procured
	Demand	Improvement in operational forecast
		Improvement in vaccine availability
		Increase in number of doses administered
		Reduction in percentage locations experiencing stock-out(s)
		Reduction in percentage time out of stock
		Improvement in percentage shipments completed on time and in full

Dimension	Objective	Performance indicators
	Resource utilization	Increase in percentage cold chain equipment functioning
		Reduction in waste in processes
		Increase in temperature monitoring systems
		Peak storage capacity utilization
		Personnel downtime and overtime
		Peak transport capacity utilization
	Innovation	Enhancement of creativity and innovation development
		Frequency of developing new products or services
	Management	Improvement in stock management systems and procedures
		Improvement in vaccine management policies
		Construction degree of centralized and decentralized process for analytics and reporting
Learning and growth (LAG)	Human capital	Enhancement of professional vaccine supply chain managers and leaders
		Better management training
		Enhancement of degree of employee work satisfaction
		Enhancement of employee motivation and empowerment
		Enhancement of employee productivity
		Reduction of employee turnover rate
	Information capital	Assessing and improvement in data and internal and external information systems
		Better work design
		Improvement in planning and coordination in the supply chain
		Improvement in transparency between supply chain levels
		Improvement in knowledge sharing between and with countries
		Increase in supply chain dashboards
	Organizational capital	Construction degree of technology infrastructure
		Improve awareness of vision, mission, and objectives of immunization programs
		Allow continual feedback and learning process
		Reduction in sickness rate
		Enhancement of employee survey rating
		Better maintenance
		Create an immunization culture for improvement and climate for action

Source: Identified from survey and literature

Table 7.2: Compilation of sustainability practices criteria [Expert's opinions & 18].

Dimension	Objective	Sustainability practices criteria
Social (SOS)	Employment (EP)	Increase in number of employees
		Enhancement of benefits provided to employees
		Enhancement of benefits provided to full-time employees that are not provided to temporary or part-time employees
	Health and safety (HS)	Reduce the incidence of health and safety problems
		Workers representation in formal joint management-worker health and safety committees
		Supply of high-quality vaccines to reduce ill effects
		Establish health and safety committees that help monitor, collect feedback and advise on occupational safety programs
		Reduce Incidents of non-compliance concerning the health and safety impacts of vaccines and vaccination programs
	Training and education	Appropriate training hours for each employee
		Better internal and external training courses or education to improves skill and education of employee
		Regular performance and career development reviews
	Diversity, Equal Opportunity and discrimination	Equal salary and remuneration to promote diversity, eliminate gender bias, and support equal opportunity
		Reduce incidence of discrimination cases
		Diversity of governance bodies and employees
	Local communities	Strong engagement with local communities to understand their expectations and needs for the development programs
		Social and environmental impact assessment of immunization programs to avoid negative impact on local communities
		Manage negative impacts through local community consultation and grievance processes
	Supplier social assessment and social economic compliance	Avoid suppliers having negative social and environmental impacts in supply chain
		Identify and outsource new suppliers using social criteria to deliver vaccine to health centers and local communities
		Reduce non-compliance with laws and regulations in the social and economic area
Environmental (ENS)	Material	Minimizing the size of product and packaging materials
		Maximizing the recycled material used in vaccine vials and sharps
		Maximizing the reclaimed products and packaging material

Dimension	Objective	Sustainability practices criteria
	Energy	Installing solar power and another energy forms
		Minimizing vaccine travel distance or choosing eco-friendly or environmentally-friendly vehicles
		Substituting old, inefficient kerosene and gas refrigerators with the energy-efficient refrigeration system
		Permitting transportation of certain thermostable vaccines in controlled temperature chains without the need for ice packs
	Emissions	Reduce greenhouse gas emissions
		Reduce ozone-depleting substances and other poisonous gases from vaccine manufacturing plants
		Reduce other indirect (Scope 3) GHG emissions
		Reduce energy indirect (Scope 2) GHG emissions
	Effluents and waste	Reduce amount of open and closed vial vaccine wastage
		Develop innovative waste-management strategies
		Reuse, recycling, and recovery of non-sharps waste and packaging materials
		Implementing safe and environmentally sound sharps-disposal procedures
		Reduce transport of hazardous waste
		Reduce waste by type and disposal method
	Environmental compliance	Select vaccine supplier that design products and packaging materials which support green manufacturing
		Design products and process with negative environmental impacts in the supply chain
		Design products and process with non-compliance with environmental laws and regulations
Economic (ECS)	Economic performance	Reduce total costs of immunization programs
		Provide better salary and incentives to employees of immunization programs
		Support community development plans
		Defined benefit plan obligations and other retirement plans
		Increase financial assistance from the government
	Indirect economic impacts	Development of significant immunization infrastructure investments and services supported
		Reduce economic impacts of deteriorating social or environmental conditions
		Maintain changes in the productivity of immunization programs
		Reduce economic impacts from the use of products and services
		Increase economic development in areas of high poverty for better immunization
		Reduce economic impacts from a change in operation or activity location
		Increase availability of products and services for those on low incomes

7.4.2. Questionnaire-based survey

A questionnaire-based survey was done to gather data and information to be used for conducting EFA for finalization of KPIs and SKPCs, and for testing the conceptual model using SEM. The steps used in the analysis are given below:

7.4.2.1. Questionnaire structure

A questionnaire was designed for 26 measures shown in Table 7.1 & 7.2 (as objectives). Brainstorming sessions, which included three research scholars and one senior professor, helped in constructing the relevant questions for the questionnaire. The questionnaire was designed in English and Hindi, as it is the most common language used by most of the people in India. The final questionnaire consisted of two parts: (i) questions about the four areas of balanced scored in measuring vaccine supply performance. The sample questions consist of "Importance of a given factor in measuring vaccine supply chain performance". (ii) questions related to three areas of sustainable practices criteria. They were based on the questions "How important are the sustainability practices criteria listed below in order to develop sustainability in child immunization". Moreover, each question was evaluated on the 5-point scale in such a way that it would be one of the scales of 'not important' (1) to 'very important' (5). After the finalization of the questionnaire structure, it was distributed to the healthcare workers.

7.4.2.2. Questionnaire distribution and response collection

Field visits were again conducted in the same 3 states of India for questionnaire distribution to healthcare workers. Of the three states, 16 health facilities were selected. Apart from this, five districts, three divisional, three state vaccine stores, and five government hospitals were also included in the study. In the initial stage of the study, the questionnaire items for each of the twenty-six constructs were discussed with the three VSC experts of Uttarakhand state India. After the validation of the questionnaire items, questionnaires were circulated to the 350 healthcare workers and sufficient time was given to fill out the questionnaire. Through repeated follow-ups and personal meetings, 265 responses were received in approximately twenty-days. Initial screening of the data removed 17 questionnaires that were deemed unusable due to missing data and multiple responses to a single question. The random sampling method of data collection generated 248 valid responses; yielding a response rate of 70.85%.

7.4.2.3. Validity and reliability of the collected data

The quality of a questionnaire survey can be measured by inspecting its validity and reliability [266]. In this study, the validity and reliability of the questionnaire items are checked through two steps given below:

- Validity refers to the content of the measurement. Two important methods are considered important for examining the validity of the collect data: content validity; and construct validity. Content validity, also known as logical validity, refers to the extent to which a measure shows all aspects of a given construct [379]. This is a subjective criterion and can be adjudicated with experts' opinions and relevant literature. In this study, the questions prepared for the 26 measures, therefore, were constructed based on the literature published in the relevant field and validation from three vaccine supply chain experts, which fulfill the criteria for content validity. The construct validity is used in confirmatory factor analysis (CFA) and can be measured through convergent validity and discriminant validity.

- The reliability of the amassed data through the questionnaire survey is measured by checking the internal consistency of questions that should measure the same concept. Cronbach quantified this reliability by way of proposing a coefficient (namely Cronbach's alpha, α) which theoretically ranges from 0 to 1. If α is near 0, then the quantified answers are not any secure at all, and if it is close to 1, the solutions are very secure [265]. As a thumb rule, if $\alpha \geq 0.7$, then the solutions are considered risk free, but 0.6 is considered acceptable in the case of exploratory study [379].

The results of the construct validity and reliability are shown in Section 7.7.

7.4.2.4. Questionnaire response analysis

EFA and SEM have been used for analyzing the 265 responses collected through a questionnaire. The description of each method is shown in Chapter 3. First, EFA has been conducted to identify and finalize the underlying dimension of 26 measures i.e. the KPIs and SKPCs from the list of 57 performance indicators and 52 SPC (shown in Table 7.1 & 7.2). Then, after finalizing the KPIs and SKPCs, SEM has been used to test the conceptual model.

7.5. Exploratory factor analysis (preliminary analysis)

Exploratory factor analysis (EFA) is a statistical technique that is used to reduce the data to a smaller set of summary variables and to discover the underlining theoretical structure of the phenomena. It discovers the shape of the connection between the variable and the respondent [380]. An advantage of EFA over other classification techniques like clustering is that EFA can recognize properties of correlations [381]. Therefore, EFA is found suitable for the present study to establish the construct variable from different questionnaire items. For conducting EFA SPSS 23.0 was used.

The identified KPIs for each dimension of BSC, i.e., LAG, INP, CUS, and FIN and SKPCs in three dimensions i.e. social, environmental, and economic through EFA method have been discussed below:

7.5.1. Learning and growth dimension KPIs

The first-factor analysis is performed on items of three measures (human capital, information capital, organizational capital) using principal component analysis with varimax rotation. Kaiser-Meyer-Olkin (KMO) test for measuring sample adequacy is applied to check whether the data is suitable for factor analysis. The acceptable value for KMO is 0.50 [381]. The value obtained from the analysis was 0.839, indicating that there are compact correlations and factor analysis will provide different and reliable factors [382]. The criteria used for factor extraction is: the eigenvalue should be greater than one, the total variance explained should be greater than 50%, and the factor loading of each item should be greater than 0.50.

For LAG performance indicators, the eigenvalue of each factor is above one (4.833, 1.277, 1.186); accounting 56.511% of the total variance. The three extracted factors are measured by 19 items, out of which, 6 items (one from human capital, one from information capital and four from organizational capital) are discarded from the list due to factor loading of <0.50. Based on the rotated matrix, factor 1 (human capital (HC)) captured five items; factor 2 (information capital (IC)) captured five items and factor 3 captured three items. The Cronbach alpha for all the three factors is above the threshold value of 0.6. Table 7.3 shows the result of factor analysis with the mean and the factor loading for each item of LAG performance indicators.

Table 7.3: Factor loading and Cronbach alpha for learning and growth dimension KPIs.

Objective	Key performance indicators	Mean	Factor loading	Cronbach alpha
Human capital (HC)	Enhancement of professional vaccine supply chain managers and leaders (HC1)	3.830	0.791	0.788
	Enhancement of degree of employee work satisfaction (HC2)	3.862	0.706	
	Enhancement of employee motivation and empowerment (HC3)	3.871	0.681	
	Enhancement of employee productivity (HC4)	3.806	0.658	
	Reduction of employee turnover rate (HC5)	3.790	0.588	
Information capital (IC)	Assessing and improving data and internal and external information systems (IC1)	3.798	0.868	0.894
	Improvement in planning and coordination in the supply chain (IC2)	3.806	0.850	
	Improvement in transparency between supply chain levels (IC3)	3.830	0.843	
	Improvement in knowledge sharing between and with countries (IC4)	3.782	0.835	
	Increase in supply chain dashboards (IC4)	3.919	0.786	
Organizational capital (OC)	Construction degree of technology infrastructure (OC1)	3.903	0.834	0.722
	Improve awareness of vision, mission, and objectives of immunization programs (OC2)	3.838	0.797	
	Allow continual feedback and learning process (OC3)	3.862	0.599	

7.5.2. Internal process dimension KPIs

The six measures (agility, supply, demand, resource utilization, innovation, management) of the internal process were measured by the healthcare workers through 27 items (questions). KMO obtained is 0.820. The eigenvalue of each factor is above one (6.144, 1.594, 1.340, 1.164, 1.161, 1.030), which accounts for 65.442% of the total variance. Of 27 items measured, 8 items (two from agility, two from supply, one from demand and three from resource utilization) were discarded from the list. Based on the rotated matrix, factor 1 (agility (AG)) captured three items; factor 2 (supply (S)) captured three items, factor 3 (demand (D)) captured five items, factor 4 (resource utilization (RU)) captured three items, factor five (innovation (IN)) captured two items, and factor six (management (MG)) captured three items, and factor 3 captured three items. Table 7.4 shows the factor loading of each item and Cronbach alpha value for each factor.

Table 7.4: Factor loading and Cronbach alpha for internal process dimension KPIs.

Objective	Key performance indicators	Mean	Factor loading	Cronbach alpha
Agility (AG)	Improvement in delivery responsiveness (AG1)	3.814	0.722	0.656
	Increase in outreach centers (AG2)	3.919	0.624	
	Enhancement of emergency supply chains (AG3)	3.943	0.606	
Supply (S)	Increase in percentage personnel time dedicated to logistics (S1)	3.903	0.729	0.670
	Increase in transport capacity (S2)	3.951	0.717	
	Increase in storage capacity (S3)	3.879	0.620	
Demand (D)	Improvement in operational forecast (D1)	3.758	0.708	0.778
	Improvement in vaccine availability (D2)	3.822	0.638	
	Increase in number of doses administered (D3)	3.927	0.637	
	Reduction in percentage locations experiencing stock-out (D4)	3.822	0.612	
	Improvement in percentage shipments completed on time and in full (D5)	3.774	0.561	
Resource utilization (RU)	Increase in percentage cold chain equipment functioning (RU1)	4.064	0.698	0.610
	Reduction in waste in processes (RU2)	3.871	0.646	
	Increase in temperature monitoring systems (RU3)	3.822	0.611	
Innovation (IN)	Enhancement in creativity and innovation development (IN1)	3.961	0.774	0.655
	Frequency of developing new products or services (IN2)	3.871	0.646	
Management (MG)	Improvement in stock management systems and procedures (MG1)	3.903	0.663	0.603
	Improvement in vaccine management policies (MG2)	3.935	0.622	
	Construction degree of centralized and decentralized process for analytics and reporting (MG3)	4.032	0.609	

7.5.3. Customer dimension KPIs

Two measures (customer satisfaction degree, effective delivery of appropriate healthcare) of customer performance were measured by six items and all the items displayed factor loadings of >0.5 with KMO of 0.743. The eigenvalue obtained is (2.765, 1.217), which accounts for 66.365% of the total variance. Based on the rotated matrix, factor 1 (customer satisfaction degree (CS) captured four items, and factor 2 (effective delivery of appropriate health care (EH) captured two items. Table 7.5 shows the factor loading of each item and Cronbach alpha value for each factor.

Table 7.5: Factor loading and Cronbach alpha for customer dimension KPIs.

Objective	Key performance indicators	Mean	Factor loading	Cronbach alpha
Customer satisfaction degree (CS)	Less distance to travel to health centers for vaccination (CS1)	3.959	0.788	0.724
	Better vaccination services and proper attitude of health workers towards parents (CS2)	3.951	0.783	
	Reduction in parents complaints (CS3)	3.983	0.759	
	Enhancement to reply to parents problems (CS4)	4.112	0.740	
Effective communication of appropriate healthcare (EH)	Provide better knowledge to parents to enhance their awareness regarding vaccination benefits (EH1)	3.814	0.873	0.701
	Provide reminders of vaccination programs, vaccination dates, and schedule to parents (EH2)	3.935	0.860	

7.5.4. Financial dimension KPIs

Two measures (operating costs, profitability) of financial were measured by five items. The factor loading results (KMO=0.688) show that profitability obtained an eigenvalue of less than one (0.651); therefore, it is discarded from the list. The eigenvalue of the financial domain (three items) is 2.895; with 57.902% of the total variance. Results of factor loading and Cronbach alpha are presented in Table 7.6.

Table 7.6: Factor loading and Cronbach alpha for financial dimension KPIs.

Objective	Key performance indicators	Mean	Factor loading	Cronbach alpha
Operating costs (C)	Reduction in total supply chain costs (C1)	3.857	0.858	0.770
	Reduction in wastage costs (C2)	3.871	0.835	
	Reduction in vaccine procurement costs (C3)	3.951	0.795	

7.5.5. Social sustainability dimension SKPCs

Six measures (employment, health and safety, training and education, diversity, equal opportunity and discrimination, local communities, supplier social assessment, and social economic compliance) of social dimension were measured by twenty items of the questionnaire. The factor analysis (KMO=0.840) resulted in 17 items with factor loading greater than 0.50. The eigenvalues of the six factors are greater than one (5.660, 1.392, 1.364, 1.130, 1.083, 1.012) with total variance 68.477%. Table 7.7 presents the result of the factor analysis for social sustainability dimension.

Table 7.7: Factor loading and Cronbach alpha for social sustainability dimension SKPCs.

Objective	Sustainable key practices criteria's	Mean	Factor loading	Cronbach alpha
Employment (EP)	Increase in number of employees (EP1)	3.959	0.876	0.618
	Enhancement of benefits provided to employees (EP2)	3.871	0.667	
Health and safety (HS)	Reduce the incidence of health and safety problems (HS1)	3.943	0.711	0.720
	Supply of high-quality vaccines to reduce ill effects (HS2)	3.991	0.660	
	Establish health and safety committees that help monitor, collect feedback and advise on occupational safety programs (HS3)	3.967	0.642	
	Reduce incidents of non-compliance concerning the health and safety impacts of vaccines and vaccination programs (HS4)	3.830	0.523	
Training and education (TE)	Appropriate training hours for each employee (TE1)	3.951	0.761	0.643
	Better internal and external training courses or education to improves skill and education of employee (TE2)	3.943	0.696	
	Regular performance and career development reviews (TE3)	3.830	0.548	
Diversity, Equal Opportunity and discrimination (DE)	Equal salary and remuneration to promote diversity, eliminate gender bias, and support equal opportunity (DE1)	3.967	0.808	0.610
	Reduce incidence of discrimination cases (DE2)	3.790	0.590	
Local communities (LC)	Strong engagement with local communities to understand their expectations and needs for the development programs (LC1)	3.935	0.737	0.701
	Social and environmental impact assessment of immunization programs to avoid negative impact on local communities (LC2)	3.887	0.712	
	Manage negative impacts through local community consultation and grievance processes (LC3)	3.911	0.597	
Supplier social assessment and social economic compliance (SE)	Avoid suppliers having negative social and environmental impacts on supply chain (SE1)	3.871	0.720	0.668
	Identify and outsource new suppliers using social criteria to deliver vaccine to health centers and local communities (SE2)	3.790	0.685	
	Reduce Non-compliance with laws and regulations in the social and economic area (SE3)	4.088	0.676	

7.5.6. Environmental sustainability dimension SKPCs

Five measures (material, energy, emissions, effluents and waste, environmental compliance) were rated by questionnaire, and factor analysis resulted in 16 items (KMO = 0.823); with eigenvalues of five factors (5.255, 1.285, 1.231, 1.088, 1.019); variance explained 61.744%. The results are displayed in Table 7.8.

Table 7.8: Factor loading and Cronbach alpha for environmental sustainability dimension SKPCs.

Objective	Sustainable key practices criteria's	Mean	Factor loading	Cronbach alpha
Material (M)	Minimizing the size of product and packaging materials (M1)	3.911	0.808	0.649
	Maximizing the recycled material used in vaccine vials and sharps (M2)	3.798	0.690	
	Maximizing the reclaimed products and packaging material (M3)	3.903	0.513	
Energy (E)	Installing solar power and another energy forms (E1)	3.838	0.682	0.651
	Minimizing vaccine travel distance or choosing eco-friendly or environmentally-friendly vehicles (E2)	3.798	0.627	
	Substituting old, inefficient kerosene and gas refrigerators with energy-efficient refrigeration system (E3)	3.741	0.606	
	Permitting transportation of certain thermostable vaccines in controlled temperature chains without the need for ice packs (E4)	3.903	0.513	
Emissions (EM)	Reduce greenhouse gas emissions (EM1)	3.895	0.773	0.648
	Reduce ozone-depleting substances and other poisonous gases from vaccine manufacturing plants (EM2)	3.927	0.663	
Effluents and waste (EW)	Reduce amount of open and closed vial vaccine wastage (EW1)	3.846	0.738	0.701
	Develop innovative waste-management strategies (EW2)	3.862	0.669	
	Reuse, recycling and recovery of non-sharps waste and packaging materials (EW3)	3.846	0.626	
	Implementing safe and environmentally sound sharps-disposal procedures (EW4)	3.935	0.506	
Environmental compliance (EN)	Select vaccine supplier that design products and packaging materials which support green manufacturing (EN1)	3.846	0.752	0.710
	Design products and process with negative environmental impacts in the supply chain (EN2)	3.830	0.744	
	Design products and process with non-compliance with environmental laws and regulations (EN3)	3.983	0.654	

7.5.7. Economic sustainability dimension SKPCs

Using factor analysis (KMO = 0.788), two measures (economic performance, indirect economic impacts) were measured by questionnaire items, and 6 items are extracted with eigenvalues (2.852, 1.010); variance explained 64.374%. The results are displayed in Table 7.9.

Table 7.9: Factor loading and Cronbach alpha for economic sustainability dimension SKPCs.

Objective	Sustainable key practices criteria's	Mean	Factor loading	Cronbach alpha
Economic performance (EC)	Reduce total costs of immunization programs (EC1)	3.903	0.835	0.714
	Provide better salary and incentives to employees of immunization programs (EC2)	3.709	0.761	
	Support community development plans (EC3)	3.766	0.721	
Indirect economic impacts (IE)	Development of significant immunization infrastructure investments and services supported (IE1)	3.879	0.827	0.723
	Reduce economic impacts of deteriorating social or environmental conditions (IE2)	3.758	0.764	
	Maintain changes in the productivity of immunization programs (IE3)	3.733	0.730	

7.6. SEM analysis

EFA helped in identifying the KPIs and SKPCs for 26 measures. Now, the data of 26 measures is used to test the conceptual model 1 using the SEM model. Since, the conceptual model 1 has no finance dimension, therefore, out of 26 measures, 24 have been used for analysis purpose. To start SEM, first, a hypothesized measurement model is developed, which is depicted in Figure 7.3. The SEM analysis comprised of three steps (i) testing the measurement model with confirmatory factor analysis (ii) obtaining model coefficients through structural model (iii) data imputation to test the final hypothesized model through path analysis.

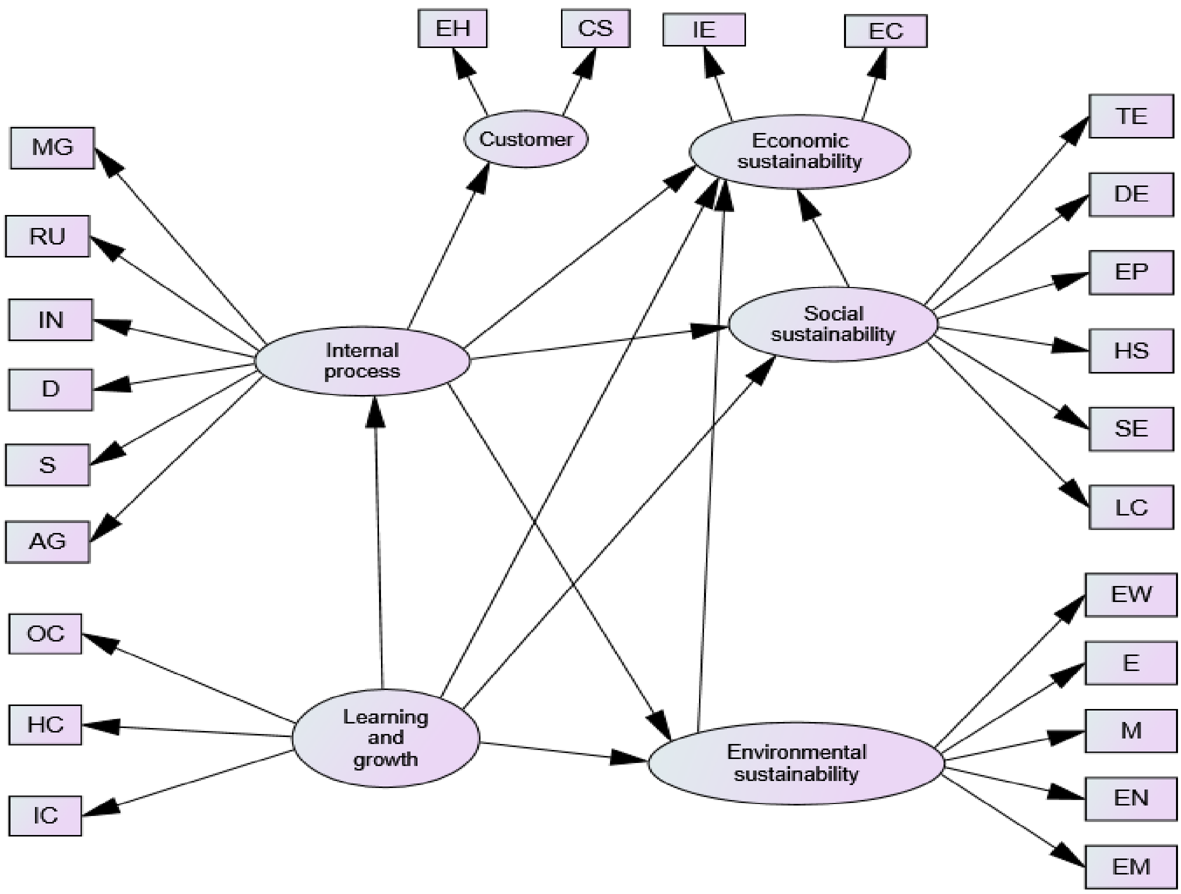


Figure 7.3: Hypothesized measurement model to test eight hypothesis

7.6.1. Testing the measurement model with confirmatory factor analysis

The measurement model indicates that the latent constructs (shown in an ellipse in Figure 7.4), which are essential for testing the proposed structural equation model are estimated successfully from the measures (indicator variable, shown in rectangles) [266]. One of the methods for the analysis of the measurement model is the confirmatory factor analysis (CFA). CFA is used to decide how the proposed model fits the data [214]. In this regard, Kline [383] suggested that a minimum of four tests of model fit should be satisfied for the acceptability and compatibility of the model. These tests consist of chi-square, GFI, AGFI, RFI, NFI, IFI, TLI, CFI, PNFI, and RMSEA. CFA was performed in AMOS 22.0 and the outcome of the results is illustrated in Table 7.10. Based on the analysis, seven statistics, i.e. Chi-square/df = 1.412, CFI = 0.914, IFI = 0.917, TLI = 0.905, AGFI = 0.801, PNFI = 0.653, RMSEA = 0.055, are acceptable. Based on these results it can be concluded that the model fits the data very well.

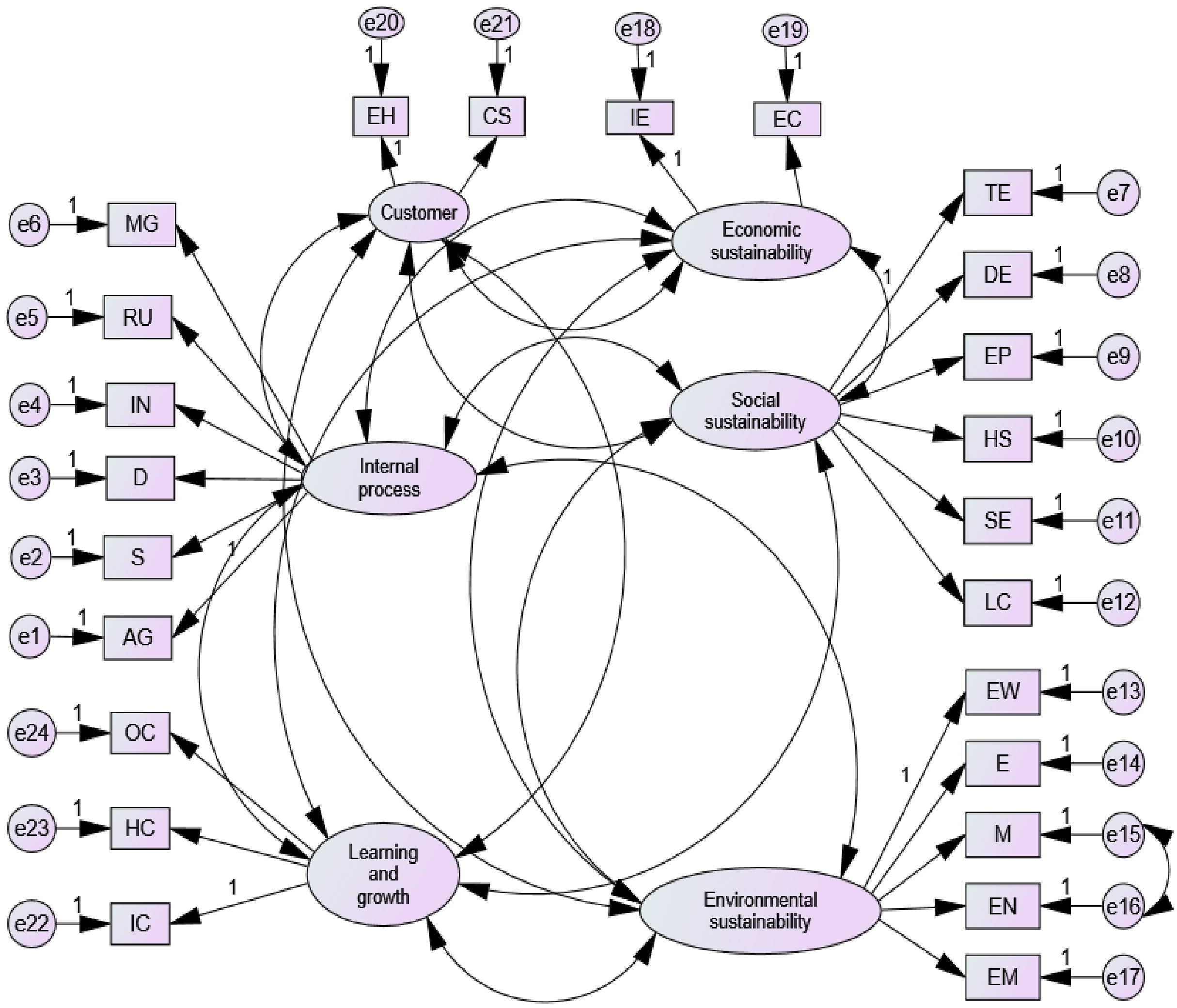


Figure 7.4: Confirmatory factor analysis (Measurement model).

Table 7.10: Fits statistics of the measurement model.

Fit index	Value	Acceptable value	Acceptability
Chi-square	333.28		
df	236		
Chi-square significance (p-value)	0.000	≤0.05	
Chi-square/df	**1.412**	≤5	+
CFI (Comparative fit index)	**0.914**	≥0.9	+
IFI (Incremental fit index)	**0.917**	≥0.9	+
TLI (Tucker Lewis index)	**0.905**	≥0.9	+
AGFI (Adjusted goodness of fit index)	**0.801**	≥0.8	+
PNFI (Parsimonious fit)	**0.653**	≥0.5	+
RMSEA (Root mean square of approximation)	**0.055**	≤0.08	+
GFI (Goodness of fit index)	0.841	≥0.9	-
NFI (Normed fit index)	0.764	≥0.9	-
RFI (Relative fit index)	0.724	≥0.9	-

Then, to examine construct validity, convergent validity and discriminant validity is used. For convergent validity, the three criteria to consider are [384,385]: (1) standardized factor loading must be greater than 0.30; (2) Cronbach alpha (CA) and composite reliability (CR) of the construct must have a value of at least 0.6; and (3) average variance extracted (AVE) must have a value of at least 0.5. The measurement model had convergent validity fulfilled as shown in Table 7.11.

Table 7.11: Assessment of convergent validity.

Construct	Variables	Factor loading	CA	CR	AVE
Economic sustainability (ECS)	Indirect economic impacts	0.755	0.636	0.7322	0.5776
	Economic performance	0.765			
Social sustainability (SSS)	Training and education	0.762	0.811	0.8601	0.5067
	Diversity, Equal Opportunity and discrimination	0.685			
	Employment	0.750			
	Health and safety	0.664			
	Supplier social assessment and social economic compliance	0.691			
	Local communities	0.714			
Environmental sustainability (ENS)	Effluents and waste	0.721	0.737	0.8629	0.5584
	Energy	0.734			
	Material	0.831			
	Environmental compliance	0.691			
	Emissions	0.752			
Customer (CUS)	Effective communication of appropriate healthcare	0.684	0.612	0.7071	0.5483
	Customer satisfaction degree	0.793			
Internal process (INP)	Agility	0.690	0.812	0.8641	0.5156
	Supply	0.651			
	Demand	0.782			
	Innovation	0.756			
	Resource utilization	0.735			
	Management	0.686			
Learning and growth (LAG)	Information capital	0.701	0.717	0.7942	0.5632
	Human capital	0.785			
	Organizational capital	0.763			

According to Fornell & Larcker [386] the discriminant validity can be tested by using two criteria 's: 1) AVE for any construct should be greater than its maximum shared variance (MSV) and average shared variance (ASV); and 2) the square root of AVE of each construct should be greater than the correlation of this construct with any other construct. Table 7.12 shows the result of discriminant validity. For example, internal process has AVE of 0.516, which is greater than MSV = 0.498 and ASV = 0.434. Further, its AVE square root is 0.718, which is greater than its correlation with any other construct. Therefore, the result fulfills the discriminant validity criteria.

Table 7.12: Assessment of discriminant validity.

Construct	AVE	MSV	ASV	Inter-construct correlations					
				CUS	INP	ECS	LAG	SSS	ENS
Customer (CUS)	0.548	0.523	0.371	**0.741**					
Internal process (INP)	0.516	0.498	0.434	0.528	**0.718**				
Economic sustainability (ECS)	0.578	0.523	0.453	0.723	0.660	**0.760**			
Learning and growth (LAG)	0.563	0.493	0.432	0.574	0.702	0.661	**0.751**		
Social sustainability (SOS)	0.507	0.496	0.440	0.608	0.698	0.635	0.671	**0.712**	
Environmental sustainability (ENS)	0.558	0.498	0.459	0.612	0.706	0.686	0.679	0.704	**0.747**

Note: the diagonal bold values indicate the square root of AVE of the construct and the values below diagonal are correlations between construct.

7.6.2. Structural model

The acceptance of the measurement model indicates that the data fits very well with the hypothesized measurement model. The structural model consists of six latent variables shown in an ellipse in Figure 7.5 and 24 observed indicator variables (shown in the rectangle). The purpose of the structural model is to explore the interrelationship among latent variables and to calculate model coefficients. Using AMOS 22.0 it is found that the model fitted the data satisfactorily. The fit indices result is: p-value = 0.000 (≤0.05), Chi-square/df = 1.466 (≤5), CFI = 0.902 (≥0.9), IFI = 0.903 (≥0.9), AGFI = 0.806 (≥0.8), PNFI = 0.660 (≥0.5), RMSEA = 0.059 (≤0.08).

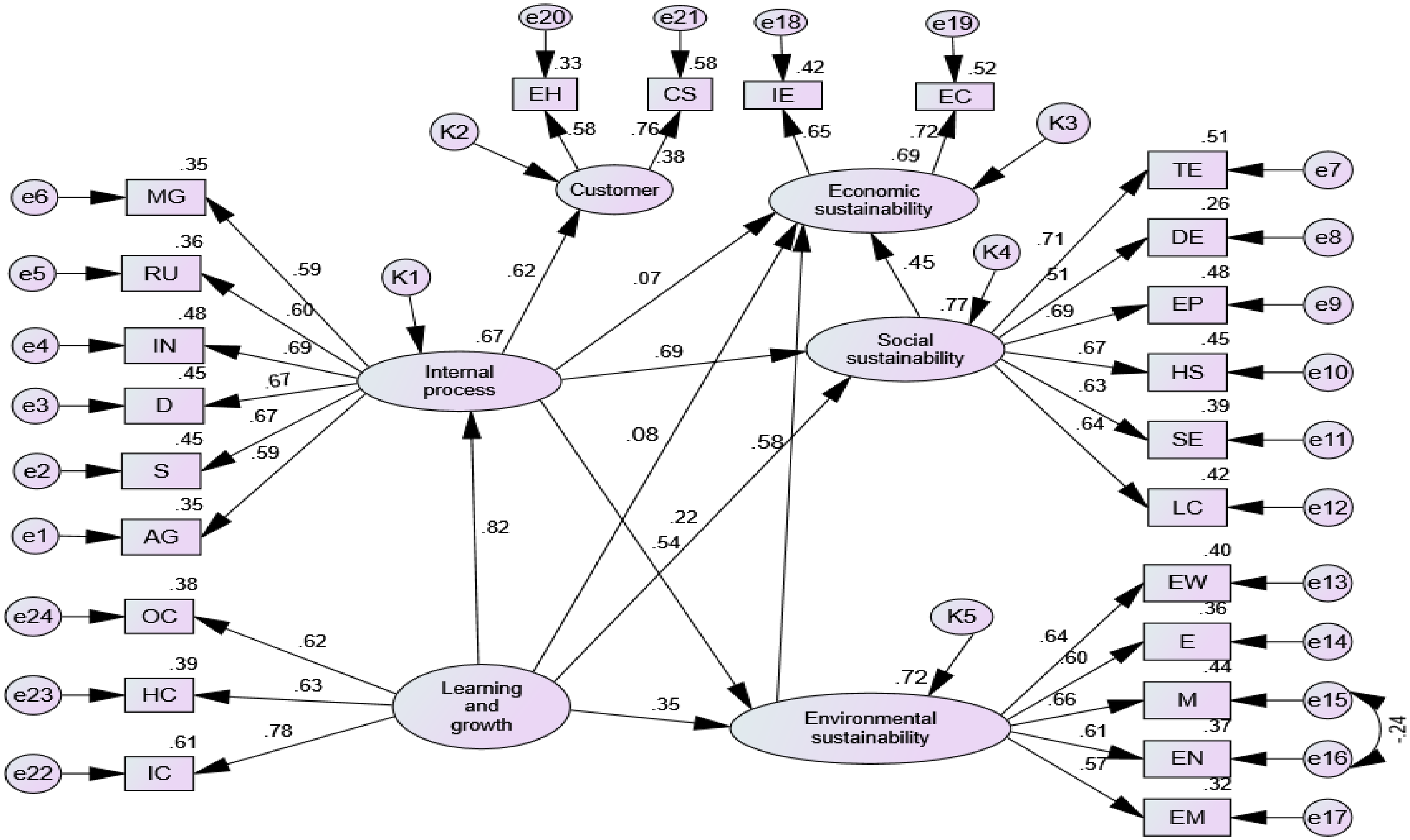
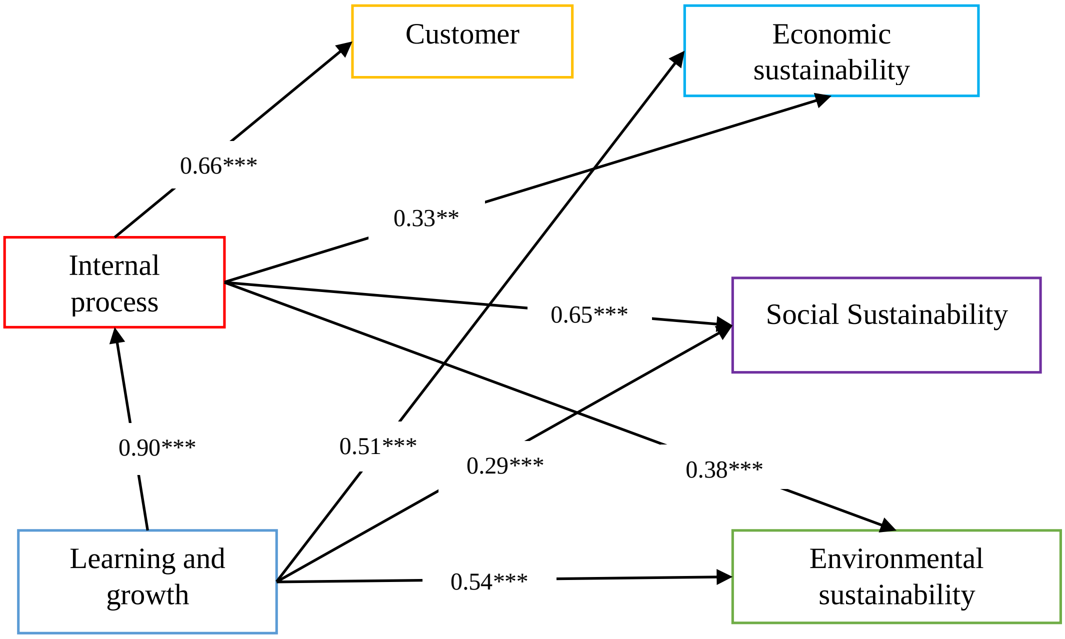


Figure 7.5: Results of structural model showing latent variables and their indicators with loadings.

7.6.3. Path analysis for testing conceptual model 1

Data is imputed in AMOS 22.0 to the test the eight hypotheses of conceptual model 1 shown in Figure 7.1. The final path diagram results with the path coefficients are depicted in Figure 7.6 and Table 7.13. From Figure 7.6, it can be seen that all path coefficients are significant at p<0.001 except for internal process to the economy, which is significant at p<0.01. The results show that Hypothesis 1, Hypothesis 2, Hypothesis 3a, 3b, 3c, and Hypothesis 4a, 4b, 4c are supported at p<0.001, whereas Hypothesis 3a (C.R = 2.866) is supported at p<0.01.



** Significant at P<0.01 level; two-tailed test applied

*** Significant at P<0.001 level; two-tailed test applied

Figure 7.6: Path diagram of conceptual model 1 with coefficients.

Table 7.13: Path coefficient and their significance values for conceptual model 1.

Hs.	Path description			Estimate (E)	Std. error (S.E.)	Critical ratio (C.R.)	*p*-value	Result
H1	Internal process	←	Learning and growth	0.659	0.027	24.555	***	Supported
H2	Customer	←	Internal process	0.538	0.052	10.352	***	Supported
H3a	Economic sustainability	←	Internal process	0.351	0.122	2.866	0.004**	Supported
H3b	Social sustainability	←	Internal process	0.875	0.103	8.532	***	Supported
H3c	Environmental sustainability	←	Internal process	0.367	0.081	4.505	***	Supported
H4a	Economic sustainability	←	Learning and growth	0.390	0.089	4.378	***	Supported
H4b	Social sustainability	←	Learning and growth	0.281	0.075	3.765	***	Supported
H4c	Environmental sustainability	←	Learning and growth	0.377	0.059	6.347	***	Supported

Note: Path significance: ** P<0.01; *** P<0.001; two-tailed test applied.

7.6.4. Standardized conceptual model 2

From conceptual model 1 results, it can be seen that the LAG dimension has a positive effect on the IP dimension and also on the customer satisfaction and sustainability practices dimensions. Therefore, it can be assumed that IP is the key dimension and improvement in this dimension alone may have a positive effect on sustainability practices. Further, many researchers have reported that an improvement in the social and environmental dimension of sustainability will lead to economic sustainability [225,387,388]. Hence, due to the above discussions, a standardized conceptual model 2 shown in Figure 7.7 is developed and tested using SEM. Same steps for SEM analysis are used for testing conceptual model 2. The CFA results and structural model results are all in an acceptable range. Figure 7.8 & 7.9 depicts the final standardized conceptual model 2 and its path diagram.

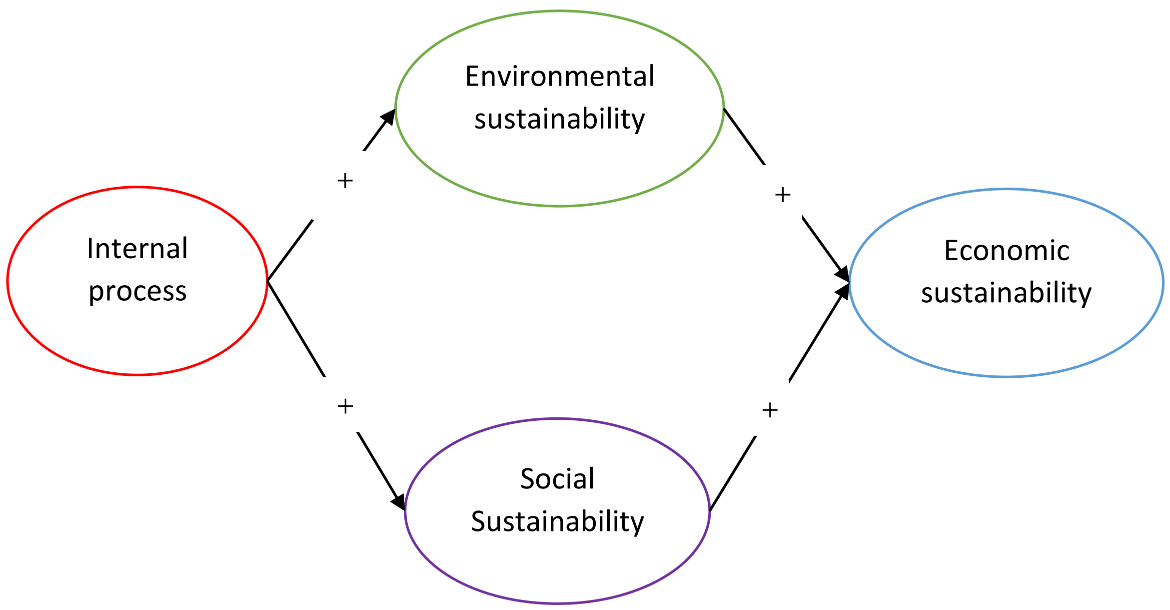


Figure 7.7: Framework of conceptual model 2.

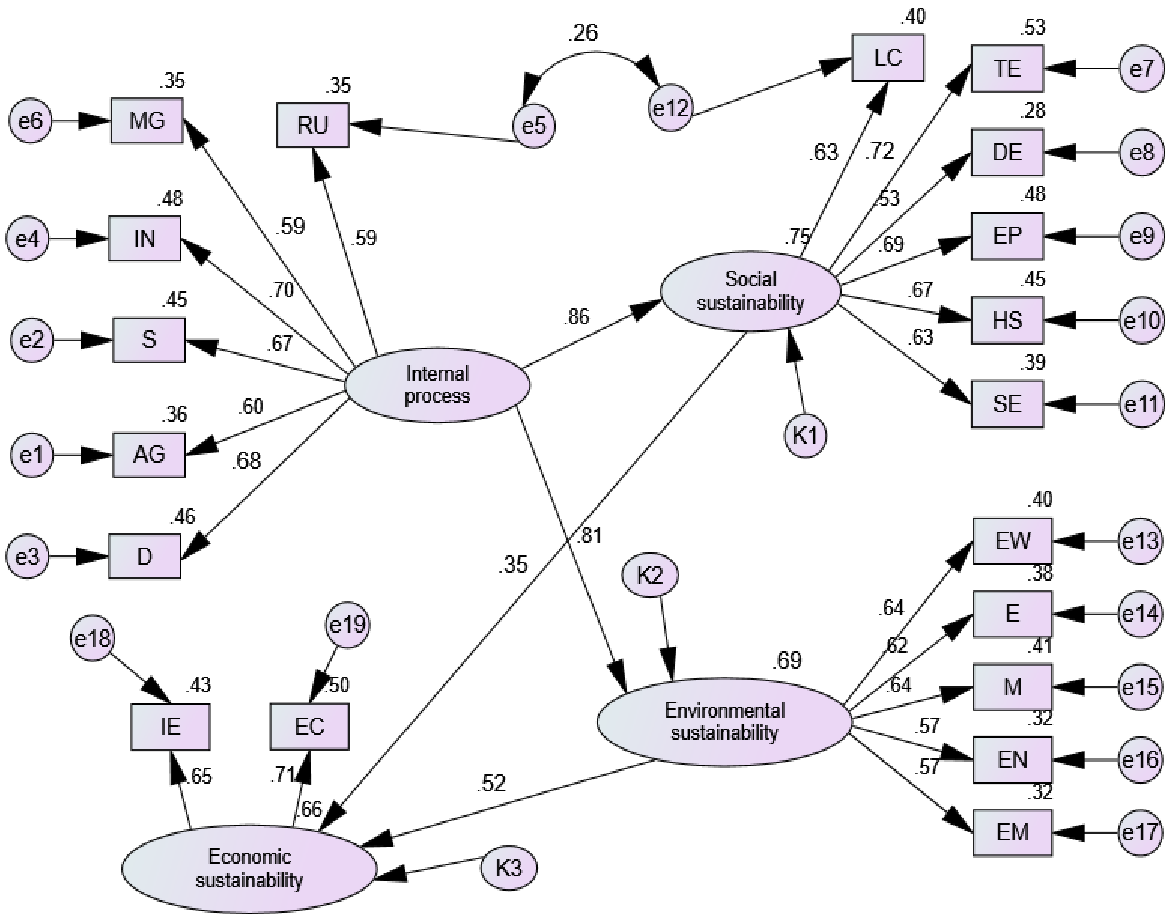
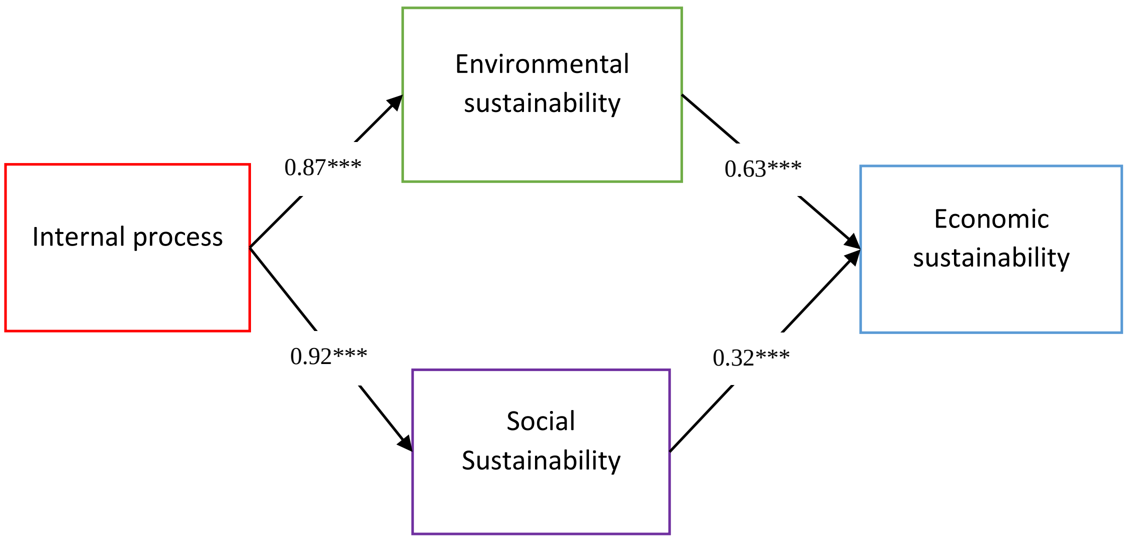


Figure 7.8: Results of standardized conceptual structural equation model 2.



****** Significant at P<0.001 level; two-tailed test applied***

Figure 7.9: Path coefficients of conceptual model 2.

7.7. Evaluation of the impact of KPIs on improving VSCP using Two-way assessment

From the results of SEM, it can be seen that KPIs of VSC have a positive effect on the sustainable development of child immunization programs. Hence, identifying the KPIs based on their impact on improving VSCP will help the immunization programs to focus only on critical performance indicators, which can help to improve sustainability. Therefore, in this context, using Two-way assessment, the KPIs are divided into three zones, i.e. high impact, medium impact, and low impact KPIs, which can help the decision-makers to focus only in the critical performance indicators in order to improve the vaccine delivery performance and sustainability.

Many researchers, like Lee et al. [103] and Moyano-Fuentes [369], have suggested that LAG and IP dimensions of BSC alone have a positive influence on customer satisfaction and financial performance. Therefore, the present study has given emphasis only on LAG and IP dimensions KPIs related to the BSC of VSC. Camp [389] suggests that after the linkage between the customer perspective and its key drivers i.e. internal business and learning and growth perspective has been obtained, the next step will be to prioritize the drivers. According to Gustafsson and Johnson [390], the regions in the business that may be visible as development priorities are the ones which are critical to customers and in which, on the same time, the company is performing poorly. They are of the opinion that managers have to identify the priority regions of the high, medium, and low performance. The steps used in Two-way assessment methodology to achieve the present objectives are given below:

Step 1. Of 41 KPIs identified through EFA and shown in Table 7.3-7.6, 19 belonging to INP dimension, and 13 to LAG dimension were finalized for analysis purpose. The consolidated KPIs are shown in Table 7.14.

Table 7.14: List of 32 KPIs of INP and LAG dimension of BSC.

Dimension	Key performance indicators	Denotation
Internal process (INP)	Improvement in delivery responsiveness	INP1
	Increase in outreach centers	INP2
	Enhancement of emergency supply chains	INP3
	Increase in percentage personnel time dedicated to logistics	INP4
	Increase in transport capacity	INP5
	Increase in storage capacity	INP6
	Improvement in operational forecast	INP7
	Improvement in vaccine availability	INP8
	Increase in number of doses administered	INP9
	Reduction in percentage locations experiencing stock-out(s)	INP10
	Improvement in percentage shipments completed on time and in full	INP11
	Increase in percentage cold chain equipment functioning	INP12
	Reduction in waste in processes	INP13
	Increase in temperature monitoring systems	INP14
	Enhancement of creativity and innovation development	INP15
	Frequency of developing new products or services	INP16
	Improvement in stock management systems and procedures	INP17
	Improvement in vaccine management policies	INP18
	Construction degree of centralized and decentralized process for analytics and reporting	INP19
Learning and growth (LAG)	Enhancement of professional vaccine supply chain managers and leaders	LAG1
	Enhancement of degree of employee work satisfaction	LAG2
	Enhancement of employee motivation and empowerment	LAG3
	Enhancement of employee productivity	LAG4
	Reduction of employee turnover rate	LAG5
	Assessing and improvement in data and internal and external information systems	LAG6
	Improvement in planning and coordination in the supply chain	LAG7

Dimension	Key performance indicators	Denotation
	Improvement in transparency between supply chain levels	LAG8
	Improvement in knowledge sharing between and with countries	LAG9
	Increase in supply chain dashboards	LAG10
	Construction degree of technology infrastructure	LAG11
	Improve awareness of vision, mission, and objectives of immunization programs	LAG12
	Allow continual feedback and learning process	LAG13

Step 2: The description of Step 2 is as follows:

- ✓ In this step, the same 10 VSC experts were supplied a questionnaire that consisted of a list of 32 KPIs of INP and LAG dimension, and an empty pairwise comparison matrix to be filled by the experts. The description of the questionnaire completion is given in Appendix H.3.
- ✓ Using the responses obtained from the supplied questionnaire, an aggregated final pairwise comparison matrix between factors is created by Eq. 3.1-3.2 of AHP, which is shown in Table 7.15.
- ✓ Next, eigenvalue (λmax) is calculated for the pairwise comparison matrix, which is 44.9671. Further, based on the scale of Alonso and Lamata [391], random index (RI) value for a matrix of size n=32 is 1.69.

Table 7.15: Aggregated final pairwise comparison matrix.

	INP1	INP2	INP3	INP4	INP5	INP6	INP7	INP8	INP9	INP10	INP11	INP12	INP13	INP14	INP15	INP16	INP17	INP18	INP19	LAG1	LAG2	LAG3	LAG4	LAG5	LAG6	LAG7	LAG8	LAG9	LAG10	LAG11	LAG12	LAG13
INP1	1.000	5.650	0.226	4.462	0.178	0.226	0.226	0.226	5.650	0.178	0.178	0.226	0.358	0.226	0.193	0.226	0.207	0.207	0.253	0.207	0.184	0.246	0.317	0.246	0.246	0.246	4.095	0.246	0.267	0.246	0.246	2.907
INP2	0.177	1.000	0.301	2.907	0.226	0.301	0.178	0.178	0.226	0.178	0.178	0.301	0.301	0.301	0.226	0.226	0.184	0.184	0.317	0.317	0.184	0.246	0.317	0.317	0.267	0.246	0.246	0.267	0.246	0.314	0.246	0.317
INP3	4.422	3.323	1.000	2.907	0.301	2.907	0.202	0.178	0.202	0.178	0.301	0.233	0.226	0.233	0.226	0.301	0.246	0.246	0.246	0.227	0.184	0.184	0.227	0.184	0.184	0.246	0.246	0.246	0.267	0.246	0.246	0.246
INP4	0.224	0.344	0.344	1.000	0.301	0.301	0.178	4.462	4.462	4.462	2.907	2.907	2.907	4.462	0.226	0.226	0.246	0.246	4.095	0.267	0.246	0.246	0.267	0.246	0.246	0.246	4.095	0.246	0.267	0.246	0.317	4.095
INP5	5.610	4.422	3.323	3.323	1.000	2.907	0.226	0.226	2.907	0.226	0.226	0.301	0.292	0.292	0.253	0.226	0.239	0.246	2.907	0.246	0.246	0.246	0.246	0.246	0.246	0.246	4.095	0.246	0.246	0.317	0.317	2.907
INP6	4.422	3.323	0.344	3.323	0.344	1.000	0.193	0.246	2.907	0.301	0.246	0.301	0.301	0.301	0.246	0.328	0.268	0.268	3.759	0.268	0.200	0.200	0.373	0.373	0.268	0.317	3.477	0.200	0.268	0.317	0.373	2.907
INP7	4.422	5.610	4.953	5.610	4.422	5.173	1.000	5.204	5.204	5.204	0.246	5.204	5.204	4.095	0.301	0.301	3.759	3.759	5.022	0.373	0.200	0.200	0.317	0.317	0.268	0.268	3.759	0.268	0.341	0.268	0.268	3.759
INP8	4.422	5.610	5.610	0.224	4.422	4.063	0.192	1.000	2.907	2.907	0.246	2.907	2.907	2.907	0.246	0.246	0.268	0.268	3.759	0.317	0.268	0.268	0.317	0.317	0.268	0.317	3.759	0.268	0.317	0.268	0.317	3.759
INP9	0.177	4.422	4.953	0.224	0.344	0.344	0.192	0.344	1.000	2.907	0.301	0.301	0.301	0.301	0.276	0.246	0.317	0.317	3.759	0.317	0.200	0.246	0.373	0.373	0.200	0.317	0.268	0.200	0.200	0.268	0.373	2.907
INP10	5.610	5.610	5.610	0.224	4.422	3.323	0.192	0.344	0.344	1.000	4.095	0.301	0.301	0.301	0.246	0.246	0.200	0.200	5.022	0.317	0.200	0.200	0.317	0.317	0.200	0.200	0.268	0.200	0.268	0.200	0.317	3.759
INP11	5.610	5.610	3.323	0.344	4.422	4.063	4.063	4.063	3.323	0.244	1.000	4.095	4.095	4.095	2.907	2.566	2.907	2.462	5.022	0.373	0.184	0.184	0.317	0.317	0.246	0.246	4.095	0.246	0.317	0.317	0.317	3.759
INP12	4.422	3.323	4.296	0.344	3.323	3.323	0.192	0.344	3.323	3.323	0.244	1.000	0.246	4.095	0.246	0.246	2.907	0.268	0.268	2.907	0.184	0.184	0.317	0.373	0.246	0.246	4.095	0.246	0.317	0.317	0.317	0.268
INP13	2.796	3.323	4.422	0.344	3.420	3.323	0.192	0.344	3.323	3.323	0.244	4.063	1.000	4.095	0.246	0.246	0.268	0.268	2.907	0.317	0.184	0.227	0.373	0.317	0.317	0.317	2.907	0.184	0.246	0.200	0.373	0.317
INP14	4.422	3.323	4.296	0.224	3.420	3.323	0.244	0.344	3.323	3.323	0.244	0.244	0.244	1.000	0.193	0.246	0.200	0.200	3.759	0.317	0.184	0.184	0.317	0.373	0.184	0.246	4.095	0.184	0.246	0.200	0.317	0.200
INP15	5.179	4.422	4.422	4.422	3.947	4.063	3.323	4.063	3.627	4.063	0.344	4.063	4.063	5.173	1.000	4.095	3.759	3.759	3.759	0.317	0.246	0.246	0.317	2.907	4.095	0.317	4.095	4.095	4.095	0.268	0.317	5.022
INP16	4.422	4.422	3.321	4.422	4.422	3.051	3.323	4.063	4.063	4.063	0.390	4.063	4.063	4.063	0.244	1.000	0.268	0.268	2.907	0.268	0.184	0.184	0.373	0.317	0.246	0.317	0.317	0.184	0.184	0.268	0.373	2.907
INP17	4.842	5.424	4.063	4.063	4.181	3.733	0.266	3.733	3.157	5.002	0.344	0.344	3.733	5.002	0.266	3.733	1.000	0.317	3.759	0.317	0.246	0.246	0.317	0.317	0.246	0.246	0.184	0.246	0.246	0.317	2.907	5.022
INP18	4.842	5.424	4.063	4.063	4.063	3.733	0.266	3.733	3.157	5.002	0.406	3.733	3.733	5.002	0.266	3.733	3.157	1.000	2.907	0.200	0.200	0.200	0.200	0.317	0.268	0.268	3.759	0.268	0.268	0.317	0.317	3.759
INP19	3.947	3.157	4.063	0.244	0.344	0.266	0.199	0.266	0.266	0.199	0.199	3.733	0.344	0.266	0.266	0.344	0.266	0.344	1.000	0.268	0.268	0.267	0.268	0.317	0.317	0.317	0.317	0.268	0.268	0.268	0.268	3.759
LAG1	4.842	3.157	4.400	3.751	4.063	3.733	2.685	3.157	3.157	3.157	2.685	0.344	3.157	3.157	3.157	3.733	3.157	5.002	3.733	1.000	3.759	0.317	5.022	5.022	3.759	3.759	5.022	3.759	3.477	3.759	3.759	3.477
LAG2	5.424	5.424	5.424	4.063	4.063	5.002	5.002	3.733	5.002	5.002	5.424	5.424	5.424	5.424	4.063	5.424	4.063	5.002	3.733	0.266	1.000	0.268	0.317	0.317	3.759	3.477	3.759	3.759	3.477	3.759	3.759	5.022
LAG3	4.063	4.063	5.424	4.063	4.063	5.002	5.002	3.733	4.058	5.002	5.424	5.424	4.400	5.424	4.063	5.424	4.063	5.002	3.746	3.157	3.733	1.000	3.759	3.759	3.759	3.759	5.022	3.759	3.759	3.759	3.759	5.022
LAG4	3.157	3.157	4.400	3.751	4.063	2.685	3.157	3.157	2.685	3.157	3.157	3.157	2.685	3.157	3.157	2.685	3.157	5.002	3.733	0.199	3.157	0.266	1.000	0.317	0.268	0.268	0.290	0.268	0.268	0.290	0.268	2.907
LAG5	4.063	3.157	5.424	4.063	4.063	2.685	3.157	3.157	2.685	3.157	3.157	2.685	3.157	2.685	0.344	3.157	3.157	3.157	3.157	0.199	3.157	0.266	3.157	1.000	0.268	0.268	0.317	0.268	0.268	0.268	3.759	3.759
LAG6	4.063	3.751	5.424	4.063	4.063	3.733	3.733	3.733	5.002	5.002	4.063	4.063	3.157	5.424	0.244	4.063	4.063	3.733	3.157	0.266	0.266	0.266	3.733	3.733	1.000	2.907	3.759	0.317	2.907	0.268	0.317	3.759
LAG7	4.063	4.063	4.063	4.063	4.063	3.157	3.733	3.157	3.157	5.002	4.063	4.063	3.157	4.063	3.157	3.157	4.063	3.733	3.157	0.266	0.288	0.266	3.733	3.733	0.344	1.000	3.759	0.317	0.317	2.907	0.317	3.759
LAG8	0.244	4.063	4.063	0.244	0.244	0.288	0.266	0.266	3.733	3.733	0.244	0.244	0.344	0.244	0.244	3.157	5.424	0.266	3.157	0.199	0.266	0.199	3.446	3.157	0.266	0.266	1.000	0.268	0.268	0.268	0.268	2.907
LAG9	4.063	3.751	4.063	4.063	4.063	5.002	3.733	3.733	5.002	5.002	4.063	4.063	5.424	5.424	0.244	5.424	4.063	3.733	3.733	0.266	0.266	0.266	3.733	3.733	3.157	3.157	3.733	1.000	2.907	2.907	2.907	3.759
LAG10	3.751	4.063	3.751	3.751	4.063	3.733	2.930	3.157	5.002	3.733	3.157	3.157	4.063	4.063	0.244	5.424	4.063	3.733	3.733	0.288	0.288	0.266	3.733	3.733	0.344	3.157	3.733	0.344	1.000	2.907	3.759	3.759
LAG11	4.063	3.189	4.063	4.063	3.157	3.157	3.733	3.733	3.733	5.002	3.157	3.157	5.002	5.002	3.733	3.733	3.157	3.157	3.733	0.266	0.266	0.266	3.446	3.733	3.733	0.344	3.733	0.344	0.344	1.000	2.907	3.759
LAG12	4.063	4.063	4.063	3.157	3.157	2.685	3.733	3.157	2.685	3.157	3.157	3.157	2.685	3.157	3.157	2.685	0.344	3.157	3.733	0.266	0.266	0.266	3.733	0.266	3.157	3.157	3.733	0.344	0.266	0.344	1.000	3.759
LAG13	0.344	3.157	4.063	0.244	0.344	0.344	0.266	0.266	0.344	0.266	0.266	3.733	3.157	5.002	0.199	0.344	0.199	0.266	0.266	0.288	0.199	0.199	0.344	0.266	0.266	0.266	0.344	0.266	0.266	0.266	0.266	1.000

- ✓ Using Eq. 3.3-3.4, the consistency ratio of the matrix is calculated as 0.247. According to Saaty [392], the consistency ratio should be below 0.2, however, Karapetrovic and Rosenbloom [393] found that it is possible to answer rationally and consistently and obtain a consistency ratio of above 0.1. Also, the consistency ratio depends on the size of the matrix and when the number of objects being observed exceeds (7±2), the consistency can be expected to be very poor and the CR value of >0.1 is acceptable [394,395]. In our study as matrix size was very large (n=32), therefore, CR value 0.247 can be considered as acceptable.
- ✓ Finally, using Eq. 3.5, the priority weight is obtained (see Table 7.16), which represent the weight of each of the KPIs.

Table 7.16: Priority weight of KPIs of INP and LAG.

Denotation of KPIs	Priority weight
INP1	1.25
INP2	0.72
INP3	0.93
INP4	1.96
INP5	1.54
INP6	1.34
INP7	3.32
INP8	2.15
INP9	1.17
INP10	1.75
INP11	3.18
INP12	2.27
INP13	1.76
INP14	1.54
INP15	4.91
INP16	2.48
INP17	2.75
INP18	2.81
INP19	1.19
LAG1	6.89
LAG2	6.74
LAG3	8.49
LAG4	3.58
LAG5	3.81
LAG6	4.64
LAG7	4.45
LAG8	2.03
LAG9	5.66
LAG10	4.82
LAG11	4.73
LAG12	3.93
LAG13	1.20

Step 3: The third steps comprises the following points:

- ✓ In the third phase of the analysis, Ideal Case utility, Worst Case utility, and the Optimum Case utility is calculated using Eq. 3.43-3.44. The Ideal Case utility measure is derived by assuming that each performance indicators is assigned the highest rank of "1" and the numerical score of "10". Ideal Case utility represents the highest value of "1000" as a utility measure [218,219,222], which indicates the best performance of the system and the maximum impact by each performance indicator on improving vaccine supply chain performance.
- ✓ The Worst Case utility measure is derived by assuming each performance indicator is assigned the lowest rank of "5" and the numerical score of "2". Worst Case utility represents the lowest value of "200" which implies that identified performance indicators in this study do not have much impact on improving vaccine supply chain performance.
- ✓ The Optimum Case utility measure is derived by assuming each performance indicator is assigned the rank of "3" and the numerical score of "6". The Optimum Case utility represents the average value of "600" [218,219,222], which indicates the average maturity of performance indicators and an average improvement in vaccine supply chain performance.
- ✓ The complied ideal, worst and optimum case utility measures are presented in Table 7.17. Current utility measure specifies the impact of the performance indicators in vaccine supply chain performance improvement according to the expert's opinions and it should lie between the ideal utility measure and the optimum utility measure.
- ✓ A questionnaire is given to the same experts and is asked to rank the performance indicators in the scale of Rank 1 to Rank 5, where Rank 5 indicates 'very high impact' and Rank 1 'very low impact'. The sample question consisted of "How do you rate the impact of factor 'Improvement in delivery responsiveness' in improving vaccine supply chain performance". Then, based on the expert's opinion the current utility of the performance indicator is calculated as shown in Table 7.18.

Table 7.17: Two-way assessment of INP and LAG KPIs (Ideal, Optimum and Worst Case utility).

			Rank 1	Rank 2	Rank 3	Rank 4	Rank 5						
			10	8	6	4	2	Expected weight			Total utility		
	Factors	Priority weight	Ideal		Optimum		Worst	Ideal	Optimum	Worst	Ideal	Optimum	Worst
Improvement in delivery responsiveness	INP1	1.25	1		1		1	10	6	2	12.54	7.52	2.51
Enhancement of emergency supply chains	INP2	0.72	1		1		1	10	6	2	7.15	4.29	1.43
Increase in outreach centers	INP3	0.93	1		1		1	10	6	2	9.27	5.56	1.85
Increase in storage capacity	INP4	1.96	1		1		1	10	6	2	19.55	11.73	3.91
Increase in percentage personnel time dedicated to logistics	INP5	1.54	1		1		1	10	6	2	15.44	9.26	3.09
Increase in transport capacity	INP6	1.34	1		1		1	10	6	2	13.44	8.06	2.69
Improvement in operational forecast	INP7	3.32	1		1		1	10	6	2	33.25	19.95	6.65
Improvement in vaccine availability	INP8	2.15	1		1		1	10	6	2	21.46	12.87	4.29
Improvement in percentage shipments completed on time and in full	INP9	1.17	1		1		1	10	6	2	11.69	7.01	2.34
Reduction in percentage locations experiencing stock-out(s)	INP10	1.75	1		1		1	10	6	2	17.49	10.49	3.50
Increase in number of doses administered	INP11	3.18	1		1		1	10	6	2	31.82	19.09	6.36
Increase in percentage cold chain equipment functioning	INP12	2.27	1		1		1	10	6	2	22.67	13.60	4.53
Increase in temperature monitoring systems	INP13	1.76	1		1		1	10	6	2	17.59	10.55	3.52
Reduction in waste in processes	INP14	1.54	1		1		1	10	6	2	15.37	9.22	3.07
Enhancement of creativity and innovation development	INP15	4.91	1		1		1	10	6	2	49.12	29.47	9.82
Frequency of developing new products or services	INP16	2.48	1		1		1	10	6	2	24.75	14.85	4.95
Improvement in stock management systems and procedures	INP17	2.75	1		1		1	10	6	2	27.52	16.51	5.50
Improvement in vaccine management policies	INP18	2.81	1		1		1	10	6	2	28.11	16.87	5.62
Construction degree of centralized and decentralized process for analytics and reporting	INP19	1.19	1		1		1	10	6	2	11.85	7.11	2.37
Enhancement of employee motivation and empowerment	LAG1	6.89	1		1		1	10	6	2	68.89	41.33	13.78
Enhancement in professional vaccine supply chain managers and leaders	LAG2	6.74	1		1		1	10	6	2	67.42	40.45	13.48
Enhancement of employee work satisfaction	LAG3	8.49	1		1		1	10	6	2	84.91	50.95	16.98
Reduction of employee turnover rate	LAG4	3.58	1		1		1	10	6	2	35.85	21.51	7.17
Enhancement of employee productivity	LAG5	3.81	1		1		1	10	6	2	38.14	22.89	7.63
Assessing and improving data and internal and external information systems	LAG6	4.64	1		1		1	10	6	2	46.39	27.83	9.28
Improvement in knowledge sharing between and with countries	LAG7	4.45	1		1		1	10	6	2	44.49	26.70	8.90
Increase in supply chain dashboards	LAG8	2.03	1		1		1	10	6	2	20.31	12.18	4.06
Improvement in planning and coordination in the supply chain	LAG9	5.66	1		1		1	10	6	2	56.63	33.98	11.33
Improvement in transparency between supply chain levels	LAG10	4.82	1		1		1	10	6	2	48.21	28.93	9.64
Construction degree of technology infrastructure	LAG11	4.73	1		1		1	10	6	2	47.32	28.39	9.46
Improve awareness of vision, mission, and objectives of immunization programs	LAG12	3.93	1		1		1	10	6	2	39.35	23.61	7.87
Allow continual feedback and learning process	LAG13	1.20	1		1		1	10	6	2	12.00	7.20	2.51
											1000.00	**600.00**	**200.00**

Table 7.18: Two-way assessment of KPIs of IP and LAG (Current Case utility).

		Rank 1	Rank 2	Rank 3	Rank 4	Rank 5			
Factors	**Priority weight**	**10**	**8**	**6**	**4**	**2**	**Expected weight**	**Total utility**	**Ranking of total impact**
INP1	1.25	0.2	0.3	0.3	0.2	0	7.0	8.78 (1.21%)	**25**
INP2	0.72	0	0.2	0.2	0.4	0.2	4.8	3.43 (0.47%)	**32**
INP3	0.93	0.1	0.2	0.3	0.3	0.1	5.8	5.38 (0.74%)	**29**
INP4	1.96	0	0.2	0.2	0.4	0.2	4.8	9.39 (1.30%)	**24**
INP5	1.54	0.4	0.2	0.2	0.1	0.1	7.4	11.43 (1.58%)	**20**
INP6	1.34	0	0.1	0.3	0.4	0.2	4.6	6.18 (0.85%)	**28**
INP7	3.32	0.8	0.2	0	0	0	9.6	31.92 (4.41%)	**9**
INP8	2.15	0.6	0.3	0.1	0	0	9.0	19.31 (2.67%)	**16**
INP9	1.17	0.2	0.3	0.3	0.2	0	7.0	8.18 (1.13%)	**26**
INP10	1.75	0.1	0.2	0.4	0.3	0	6.2	10.84 (1.50%)	**22**
INP11	3.18	0.5	0.3	0.1	0.1	0	8.4	26.73 (3.69%)	**12**
INP12	2.27	0.4	0.3	0.2	0.1	0	8.0	18.14 (2.50%)	**17**
INP13	1.76	0.1	0.2	0.4	0.2	0.1	6.0	10.55 (1.46%)	**23**
INP14	1.54	0	0.2	0.3	0.4	0.1	5.2	7.99 (1.10%)	**27**
INP15	4.91	0.5	0.4	0.1	0	0	8.8	43.23 (5.97%)	**4**
INP16	2.48	0.4	0.4	0.2	0	0	8.4	20.79 (2.87%)	**14**
INP17	2.75	0.4	0.3	0.2	0.1	0	8.0	22.01 (3.04%)	**13**
INP18	2.81	0.1	0.2	0.4	0.2	0.1	6.0	16.87 (2.33%)	**19**
INP19	1.19	0	0	0.3	0.4	0.3	4.0	4.74 (0.65%)	**30**
LAG1	6.89	0.1	0.2	0.4	0.2	0.1	6.0	41.33 (5.71%)	**7**
LAG2	6.74	0.4	0.2	0.2	0.1	0	7.2	48.54 (6.70%)	**2**
LAG3	8.49	0.4	0.5	0.1	0	0	8.6	73.03 (10.0%)	**1**
LAG4	3.58	0.1	0.1	0.4	0.3	0.1	5.6	20.07 (2.77%)	**15**
LAG5	3.81	0	0.1	0.3	0.4	0.2	4.6	17.55 (2.42%)	**18**
LAG6	4.64	0.6	0.4	0	0	0	9.2	42.68 (5.89%)	**5**
LAG7	4.45	0.2	0.4	0.3	0.1	0	7.4	32.92 (4.55%)	**8**
LAG8	2.03	0.1	0.2	0.3	0.2	0.2	5.6	11.37 (1.57%)	**21**
LAG9	5.66	0.5	0.3	0.1	0.1	0	8.4	47.57 (6.57%)	**3**
LAG10	4.82	0.5	0.3	0.2	0	0	8.6	41.46 (5.72%)	**6**
LAG11	4.73	0.1	0.2	0.4	0.3	0	6.2	29.34 (4.05%)	**10**
LAG12	3.93	0.2	0.3	0.4	0.1	0	7.2	28.33 (3.91%)	**11**
LAG13	1.20	0	0	0.2	0.4	0.4	3.6	4.32 (0.60%)	**31**
								724.41 (100.00%)	

Step 4: The results of the Two-way assessment are compared with the decision-making trial and evaluation laborator y (DEMATEL) approach to validate the results. To do so, the impact of one KPI over the other KPI is obtained by the expert's opinions. The experts are asked to rate questions based on the scale of 0–4 depending upon the. The scale of comparison included "0 (No influence), 1 (Very low influence), 2 (Low influence), 3 (High influence), 4 (Very high influence)". On the basis of the experts' response, a pair-wise comparison matrix is constructed. Then, based on expert's opinions, the final ranking of the KPIs using DEMATEL approach is computed, which is shown in Table 7.198. The detailed description of the DEMATEL approach and computational tables have been shown in Appendix H.3.2 as Table H.7 & H.8.

Table 7.19: Ranking of the KPIs of INP and LAG using DEMATEL.

Denotation of KPIs	Prominence $(r+c)$	Relation $(r-c)$	Rank
INP1	18.8626	-0.0705	25
INP2	17.9004	0.2354	32
INP3	18.1387	-0.0784	30
INP4	18.9840	-0.6040	24
INP5	19.2094	-0.1822	20
INP6	18.6948	-0.1258	28
INP7	19.6271	0.3574	8
INP8	19.4702	-0.8941	13
INP9	18.8102	0.8436	26
INP10	19.1095	0.7088	21
INP11	19.4649	-0.5679	14
INP12	19.3427	0.7337	17
INP13	19.0441	0.1332	23
INP14	18.7388	-0.2810	27
INP15	20.3522	-0.5748	4
INP16	19.5103	0.6812	12
INP17	19.2849	-0.4037	18
INP18	19.0890	0.1267	22
INP19	18.0497	-0.1935	31
LAG1	19.5401	-1.1781	9
LAG2	20.4331	0.0380	3
LAG3	20.7408	0.4877	1
LAG4	19.5111	0.5067	11
LAG5	19.3742	-1.1274	16
LAG6	20.0801	-0.0020	5
LAG7	19.7861	-0.6503	6
LAG8	19.2257	0.2786	19
LAG9	20.4958	0.5634	2
LAG10	19.5126	0.7216	10
LAG11	19.7695	0.0187	7
LAG12	19.4401	0.4530	15
LAG13	18.1932	0.0459	29

7.8. Discussion of results

The results of the data analysis shown in Table 7.13 reveal that all the eight hypotheses developed for conceptual model 1 are supported, therefore, signifying that there is a positive relationship between KPIs of VSC and the sustainable development of child immunization program.

Hypothesis 1 ($\beta = 0.90$, $P<0.001$) indicates that there is a positive relationship between learning and growth and the internal process in the VSC. Learning and growth is the first step towards process improvement, which will lead to customer satisfaction. In this category factors ***'assessing and improving data and internal and external information systems (IC1)'***, ***'improvement in planning and coordination in the supply chain (IC2)'***, ***'improvement in transparency between supply chain levels (IC3)'***, ***'improvement in knowledge sharing between and with countries (IC4)'***, ***'construction degree of technology infrastructure (OC1)'***, ***'improve awareness of vision, mission, and objectives of immunization programs (OC2)'*** and ***'enhancement of professional vaccine supply chain managers and leaders (HC1)'*** occupies the maximum factor loading scores.

There is also a positive relationship between the internal process and customer satisfaction according to Hypothesis 2 ($\beta = 0.66$, $P<0.001$). In this category ***'enhancement in creativity and innovation development (IN1)'***, ***'increase in percentage personnel time dedicated to logistics (S1)'***, ***'improvement in operational forecast (D1)'***, ***'improvement in delivery responsiveness (AG1)'***, and ***'increase in percentage cold chain equipment functioning (RU1)'*** are the key factors to improve internal processes to reach number of children. For better working on internal processes of supply chain trained and educated health workers are required, which can work efficiently and effectively. Therefore, it is important that in order to improve internal processes immunization programs should pay attention to the learning and growth factors. However, from the survey and also by expert's opinions, it was noticed that there is a shortage of health workers and managers in India. Chikersal [347] in their study also pointed out there is a severe shortage of trained human resources in India for healthcare. According to WHO, there is a shortage of nearly 4.7 million health workers in 57 developing countries [348]. Anjali points out that Indian health workers are willing to work in the public and rural areas given better conditions, pay, and continued training [347]. Hence, it is important that the Government of India gives proper attention to budget allocation related to the healthcare sector and provides better financial support in the recruitment and training of health workers and vaccine supply chain managers.

Three hypothesis H3a ($\beta = 0.33$, $P<0.01$), H3b ($\beta = 0.65$, $P<0.001$), H3c ($\beta = 0.38$, $P<0.001$) reveal that improvement in internal processes will promote sustainability in economic, social and environmental dimension of child immunization. Also, hypothesis H4a (β = 0.51, P<0.001), H4b (β = 0.29, P<0.001), H4c (β = 0.54, P<0.001) indicates that a better atmosphere of learning and knowledge in immunization programs will help in faster implementation of sustainable practices in criteria's in the child immunization programs. In addition, the conceptual model 2 shows that internal process in alone is the main factor in guiding the program for social and environmental sustainability, which will in turn help to achieve economic sustainability of the child immunization program.

Finally, from Table 7.18 of Two-way assessment, it can be seen that 'e***nhancement in employee work satisfaction (LAG3=10.08%)'***, ***'enhancement in professional vaccine supply chain managers and leaders (LAG2=6.70%)'***, and ***'improvement in planning and coordination in the supply chain (LAG9=6.57%)'*** are the three critical performance indicators that have a high impact (23.35%) on VSCP. These critical performance indicators may have the capability to improve the performance of VSC, and therefore, critical factors should be the priority of the decision-makers for improving sustainability. In addition, the results obtained from the Two-way assessment are compared to the DEMATEL approach. As can be seen from the analysis results that although the ranking of few KPIs has changed, there is not much difference in the ranking when compared to the original ranking obtained from Two-way assessment. This slight difference in the rankings is because the DEMATEL approach is a qualitative technique and the results obtained through DEMATEL is influenced by the perception of decision-makers. Hence, using any qualitative technique one cannot guarantee that the results obtained will be the same in every case. Finally, based on the comparison of the results, it can be concluded that the results obtained through Two-way assessment are stable and reliable.

7.9. Conclusion

In this study, a hypothetical model was developed to check whether the KPIs of VSC can help the immunization programs in the direction of sustainable development of child immunization programs. Using the expert's opinions and literate review, eight sets of hypotheses were framed, which were then tested using EFA and SEM. The results of the analysis supported all the eight developed hypotheses, hence indicating that the KPIs of VSC has a positive influence on customer satisfaction and also in the sustainable development of child immunization program in India. Further, using Two-way assessment, the impact of KPIs on improving VSCP to improve sustainability was identified. The results helped in identifying three factors: enhancement in employee work satisfaction, enhancement in professional vaccine supply chain managers and leaders, and improvement in planning and coordination in the supply chain as the critical performance indicators having maximum effect on VSCP improvement. Hence, to fulfill the goal of building sustainable child immunization programs in India, it is important that the UIP India gives proper attention to the KPIs of VSC, as it has the capability to improve vaccine delivery performance and sustainability. Therefore, UIP managers should design new and improved strategies that can be beneficial to improve the performance of VSC and its three critical performance indicators, for the overall benefit of VSC and sustainable development of child immunization program in India.

Chapter 8

MAJOR OUTCOMES, LIMITATIONS, AND FUTURE SCOPE

In this chapter, triangulation to validate the research results along with the key findings and momentous contributions of the present work are summarized. The limitations of the work with the future directions are also enumerated. Based on the findings as discussed in chapters, various suggestions are made for decision-makers and policy-makers to improve the vaccine supply chain (VSC) performance in order to build sustainable child immunization programs. In the end, some implications to the academicians and managers are given, followed by a meaningful conclusion.

8.1. Introduction

The success of the immunization program depends upon the functional, end-to-end supply chain and logistics systems. A supply chain, which is not efficient and effective, will never deliver the right vaccine in the right quantity, in the right condition, in the right place, in the right time, and in the right cost. Due to a steady rate of immunization programs of India, continuous efforts should be made by the government to improve vaccine supply chain performance to ensure that vaccines reach those who need them, and sustainable child immunization program are built in India. In today's world, the point of interest of many in the vaccine world has been on growing new vaccines and measuring their effects on people, however, failure to apprehend and adequately address vaccine supply chain issues can significantly lessen the effect of any vaccine [337]. Identifying and eliminating or reducing the adverse effect of vaccine supply chain issues can help the decision-makers to design better supply chains such as next-generation vaccine supply chain systems (NGVSCs) to improve its performance. Improvement in VSCP can help in building sustainable development of child immunization in India. With this aim, the present work studied the vaccine supply chain issues and presented various frameworks to analyze the issues and improve VSCP design NGVSCs and for the sustainable development of child immunization program in India.

8.2. Triangulation to validate the results of the research

Triangulation, using the combination of two or more methods, is one of the important techniques, which helps to better corroborate the results. It is a method that allows researchers to be more confident with their obtained results [396]. According to Bekhet and Zauszniewski [397], with triangulation, researchers can utilize two or more research methods or strategies to diminish the shortcomings of an individual technique and reinforce the result of the study. 'Triangulation' lessens the effect of bias because the two sources supplement and confirm each other to validate the results. Four types of triangulation exist in literature namely (i) data triangulation (ii) method triangulation (iii) investigator triangulation, and (iv) theoretical triangulation [396].

In the present research, with triangulation (combination of two or more methods) the legitimacy of the results can be increased so that the research findings look more valid, reliable and generalized. To start with Chapter 4, the 25 key issues of vaccine supply chain have been identified and analyzed using Delphi, ISM-FMICMAC, and ISM-FANP. Since, the 25 key issues have been identified from the thorough literature review, field survey, and expert's opinions of India and other developing countries using Delphi, therefore, it validates the use of variety and reliability of data through data triangulation. In addition, rigor was assured in the qualitative data because the internal consistency (Cronbach's alpha) of the questionnaire was greater than 0.70. With method triangulation using ISM-FMICMAC and ISM-FANP, it is interesting to observe that economic issues like 'immunization cost' and 'sustainable financing' obtained high driving power in ISM-FMICMAC analysis, which can also be confirmed with ISM-FANP where the economic issues occupied first and second rank. Similarly, factor 'coordination with local administration' in ISM-FMICMAC analysis was considered in the bracket of autonomous with low effect on improving VSCP; it can also be observed in ISM-FANP where it occupied 20th rank. In Chapter 5, the data were collected from a variety of sources such as electronic databases ScienceDirect, EmeraldInsight, etc., field survey and expert's opinions, the material collection used in the study is validated as it fulfills the criteria of data triangulation. The application of AHP-COPRAS-G identified the demand uncertainty as the most important reason, which is also noticed in Chapter 4 by ISM-FMICMAC and ISM-FANP. Factor 'incorporating supply chain experts' have been identified as an important solution in Chapter 5, which is also suggested in Chapter 4 as 'improve communication with supply chain experts' as the critical factor. Similarly, in Chapter 6, using FAHP-FMOORA the demand is identified the main barrier to design next-generation vaccine supply chain system in India, which is in conjunction with the results of previous chapters. Hence, it validates the findings of the study and point towards the importance of demand in each aspect of the vaccine supply chain. Finally, Chapter 7, with detailed analysis to collect data, and application of EFA and SEM using various empirical tests such as reliability, construct validity, factor analysis, etc. supports the findings with data triangulation and method triangulation. By highlighting the results of Chapter 7, which identified 'learning and growth' and 'internal process' performance indicators of vaccine supply chain as the main factors for the sustainable development of child immunization program validate the previous results that training and education to health workers with proper focus on internal processes such as demand forecast are important criteria's to improve child immunization coverage

8.3. Major outcomes of the present research

This study focused on the sustainable development of child immunization program by considering the vaccine supply chain as one of the key enablers of sustainability development. Various frameworks are introduced in each chapter that highlight the severity of vaccine supply chain issues and solutions to overcome the issues to design sustainable child immunization program. A sincere attempt has been made towards achieving the research objectives, which is augmented by the key findings of the work.

Summary of the major outcomes of the present research is as followings:

- An extensive literature review has been conducted to identify the research gaps and issues in the supply chain of basic vaccines required for child immunization in India and also in other developing countries.
- In-depth review of literature and field visits that are conducted at various states of India assisted in identifying the key issues faced by the immunization program officials of UIP India.
- Interpretive structural modeling (ISM), fuzzy matrix cross-reference multiplication applied to a classification (FMICMAC), and fuzzy analytic network process (FANP) methodologies are used to segregate the issues based on their driving power and dependence and prioritize/rank them according to their weights in order to improve VSC performance.
- List of important suggestion to overcome supply chain issues, key performance indicators of vaccine supply chain for measuring and improving supply chain performance and sustainability practices criteria for the sustainable development of child immunization program are also extracted through field expert's opinions and literature review.
- A framework based on the analytic hierarchy process (AHP) and complex proportional assessment of alternatives with grey relations (COPRAS-G) methodologies are developed to analyze the issues of vaccine shortages.
- Efforts are made to provide solutions to design next-generation vaccine supply chain system in India, so that vaccine delivery performance can be improved, using an integrated fuzzy analytic hierarchy process (FAHP) and fuzzy multi-objective optimization by ratio analysis (FMOORA) framework.
- A framework using exploratory factor analysis (EFA), structural equation modeling (SEM), and Two-way way assessment is presented, which shows that key performance indicators (KPIs) of vaccine supply chain in terms of the balanced scorecard (BSC) have a positive effect in the sustainable development of child immunization program in India

and also in the improvement of VSCP to improve sustainability.

8.4. Significant research contribution

A research work can be termed as unique if it is capable of answering the three important questions: what, how and why [152]. In the present study, the efforts have been made to answer these queries:

- The present work focuses on key issues of vaccine supply chain of India and other developing countries from the procurement stage until the child is vaccinated.
- The identification and finalization of key issues using field survey, peer-reviewed journals, and expert's opinion. In addition, their statistical validation through the opinions of international experts involved in the process of the vaccine supply chain.
- A contextual relationship among issues is obtained using the expert's opinions. From the literature search and to our knowledge, the work stated here is an initiation to provide a framework for improving vaccine supply chain performance in developing countries.
- Analysis of issues to identify critical issues that have maximum influence on vaccine supply chain performance will be useful to the decision-makers to improve vaccine delivery performance.
- Framework to analyze vaccine shortages will help the policy-makers to gain insight to the shortage issue. It will lead to well-advanced planning along with preventive actions to resolve the issue.
- The present work for the first time has studied the design of next-generation vaccine supply chain system in India that will surely help the vaccine supply chain designers and policy-makers in redesigning its conventional VSC system to NGVSCS for improving delivery performance.
- Identification of KPIs of VSC and sustainability practices criteria's (SPCs) for immunization program through in-depth literature review and expert's opinions are also the part of the author's efforts. Although previous studies have analyzed the performance of healthcare organization using BSC [95,98,100,108,398–404], the researchers have focused mainly on performance measurement and improvement of hospitals and there is still a gap in the research related to VSC performance measurement of VSC. Based on the thorough literature analysis and to our knowledge, it is believed this is the first study that identifies the KPIs of VSC in the context of India, which also applies to most of the developing countries.
- Another major contribution of this work is the measurement of the impact of KPIs on the performance improvement of VSC. The study analyzes the impact of internal

processes and learning and growth performance indicators on the VSC in order to improve performance using a differentiating approach, based on a bidirectional evaluation, in two directions i.e. Two-way assessment. The work offers a different and innovative orientation to seek to improve the vaccination rate through the performance of the VSC. By analyzing the performance of the VSC in the three case scenarios: current, ideal, and worst, the decision-makers can design its planning strategy accordingly so that maximum performance can be achieved and maintained by using minimum resources.

- The present study may also benefit the supply chain analysts of perishable foods and blood supply chain after taking certain assumptions.
- This work is not only beneficial to the vaccination programs, health care organizations, and academicians of the medical fields, but the methods used in the paper can be used by researchers and academics of other areas (such as engineering and management, etc.) in their work for decision making.
- The framework developed for the sustainable development of child immunization program in India will assist the government officials of UIP India and other developing countries to gain familiarity with KPIs and SPCs together with the dominant KPIs for better decision making. It will unify their efforts in the direction of elimination of the same so that improvement in VSC can be made for the success of the child immunization program. It will also assist policy planners to formulate their strategies to cope with the issues of immunization program well in time for the sustainable development of child immunization program.

8.5. Implication of the research work

The present work focusses on the vaccine supply chain for the sustainable development of child immunization program in India. For the overall improvement of the system's performance, it is essential to the immunization program officials to identify and address issues in the supply chain of basic vaccines at every stage, so that sustainable child immunization is built. Hence, to assist UIP officials in better planning and strategy designing, an effort has been made to identify key issues in VSC and categorized them according to their level of importance so that improvement in VSCP can be made for the sustainable development of child immunization program. Following implications are presented as the outcome of the study:

- This study will offer sound comprehension and help the management and top-level administration in deciding to which issues to focus on based on their significance level.

- The identification of supply chain issues, in conjunction with a determination of the priorities and ranking of the issues, can hold great value for policy-makers, supply chain designers, and managers that wish to prioritize their efforts and assets to eliminate the most vital issues and challenges.
- Understanding and prioritizing the performance-related issues of the supply chain would help the decision-makers to measure and benchmark the performance. The performance benchmarking will assist in figuring out whether the immunization program is performing peculiarities and activities efficiently and whether its internal activities and organizational process need improvement. It will also help the decision-makers to recognize the most accurate and efficient method of operating for reducing supply chain and other operational costs.
- Categorization of the issues based on their importance level will help decision analyst to plan decisions at strategic, tactical, and operational levels.
- Apart from addressing operational related issues in the delivery of vaccines, addressing important management issues such as proper planning, better communication, etc. will help the supply chain members in sharing a common goal, developing mutual trust, and respect and careful risk management to ensure sustainable immunization.
- The major contribution is the identified key performance indicators would help the decision-makers to measure and benchmark the performance. The performance benchmarking will assist the managers to perceive the present quality of their organization and with the use of KPIs, they can envision what needs to be done to improve their immunization objectives. It will further help immunization programs become what they deem, i.e. increased immunization coverage through the process of managing, monitoring, and analysis.
- Measuring the system performance using the KPIs of balanced scorecard may assist the managers to compare the system performance from time to time to help identify areas that still need improvements.
- Through benchmarking initiatives, policy-makers can perform comparative analysis in the areas of the supply chain, financial profitability, workforce performance, etc. accordingly, they can adopt the strategic initiative or policies that optimize resources and financial performance and implement best practices with confidence.
- Through analysis of important key performance indicators of VSC, the findings concluded that the learning and growth and internal processes are a major indicator, which means proper training, better forecast, etc. are important factors for the policy-

makers in increasing the performance of the mission when the mission imports sustainable development.

- In this study, the issues, KPIs, and SPCs are gathered from the survey and international literature and are finalized based on the discussions of vaccine supply chain experts in India and other developing countries. Because the issues obtained from expert opinions have been statistically validated, and the supply chain for vaccines is similar in most of the developing countries, therefore, the results of the analysis are equally applicable to India and other developing countries. Hence, the results can be used by immunization program managers in understanding the VSC for better decision-making.
- The present work can be beneficial to not only the immunization program of India, but it can also benefit the immunization programs in other developing countries having similar demography to India on quickly achieving vaccine delivery and coverage results, as Two-way assessment will help to elude complicated planning and data analysis exercises to which KPIs the decision-makers should focus on.
- The present work will raise awareness in the government for the importance of budget allocation in the childhood immunization program, which is the primary cause of the poor performance of immunization coverage in developing countries. It will provide grounds to the healthcare policy-makers in designing a better financial strategy so that none of the issues are overlooked due to lack of finance.
- At last, the work will provide valuable insight to the health-workers, immunization programs, policy-makers and other vaccine-decision-makers about the importance of vaccine supply chains and its KPIs can be useful in the improvement of its performance and for the sustainable development of the mission to improve immunization coverage.

8.6. Conclusion and recommendations

Demographic changes, the introduction of new vaccines and technologies, and treatments along with increased social expectations have put pressure on governments and other funding sources to design more efficient and effective methods of managing hospitals or other government-run health organizations to minimize costs, while in the same time to improve patient care [405]. Due to such issues, the government often finds difficulties in providing vaccines to the children. Without an adequate supply of vaccines at immunization centers, hospitals, etc., children cannot be vaccinated against life-threatening diseases. Today, many developing countries immunization programs are struggling to control large stock volumes and minimize useless wastage while enhancing immunization coverage. Ongoing efforts are required to ensure that developing countries immunization programs make knowledgeable decisions about how to appropriately store, delivery, and supply essential vaccines products now and into the future [406]. The present work highlights key issues in the supply chain of basic vaccine required for child immunization in India and other developing countries. These issues are the primary cause of the poor performance of the vaccine supply chain. Improvement in vaccine supply chain performance can help in developing an efficient and effective vaccine supply chain system, to ensure a high immunization rate, better healthcare facilities, and sustainable child immunization programs. To do so, various frameworks are presented in this research work, which may assist immunization program officials in achieving their healthcare objectives so that no child in India dies of vaccine-preventable diseases and a sustainable child immunization is built. The findings and recommendations of this research may be helpful to UIP India and other developing countries in improving child immunization rate.

8.6.1. Recommendations for UIP India to strengthen vaccine supply chain

From the findings of the present work, field surveys conducted, expert's opinions and a thorough literature review, a set of valuable suggestions have been suggested that will help to strengthen the vaccine supply chain and achieving immunization program objectives: A summary of suggested measures to mitigate or correct supply chain issues and improve its performance for SD of immunization program are as follows:

- ***Raise awareness of supply chain issues:*** Identifying and addressing the supply chain issues are the key to the success of immunization programs. One possible action is the involvement of social media and general media. The efforts on publishing stories by the media on vaccine supply chain issues such as 'vaccine wastage in any country or state led to the loss of thousands of dollars' through news stories, or special reports can raise awareness among people involved in immunization programs.
- ***Proper funding mechanism:*** A better and robust financial mechanism is necessary for addressing delays in releasing national funds to purchase vaccines, immunization products and strengthening immunization programs. The government should not delay in releasing funds for procuring vaccines from UNICEF or other organizations, as vaccine financing is the primary root cause of stockout. Funds should be available in the right amount, right time and at the right place to make delivery of vaccines possible. The present funding gap in the developing countries shows the necessity for country and donor commitments to mobilize and efficiently assign resources, specifically for the service delivery section of national immunization programs and comparatively underfunded country supply chains [50,336,352].

- ***Leadership:*** While a majority of nations have supply chain managers in place, few such managers are professionally trained or educated in supply chain management, nor do they usually have the authority, responsibility, or legal control to improve supply chain performance. Developing countries do not take health logistics seriously as compared to the developed countries, where professionally trained logisticians and supply chain managers are needed to improve the performance of the supply chain. Ministers of Health and immunization program managers should be interested in hiring adequate staff and setting up training and education programs for supply chain and logistics professionals in improving supply chain overall performance. Therefore, an effort should be made for proper training and education of health workers managing the vaccine supply chain and immunization programs, so that better human resource management comes in future for operating and managing vaccine supply chains [7,33,354,356].
- ***Next generation vaccine supply chains****:* To improve immunization equity and coverage, transformative changes in supply chains are required for building next-generation vaccine supply chains. Outlining new supply chains requires a careful examination of options. Numerous supply chains can be merged or streamlined into less level, and a few functions, similar to storage and transportation, can be merged with other health item supply chains or outsourced to the private companies. Designing a highly performing, next-generation supply chains requires the focus of any nation in improving its immunization strategies, which can be made through leadership, continuous improvement, better cold chain equipment, and system design [336,341,354,407].
- ***Information sharing:*** Better information sharing system needs to be developed so that real-time and accurate information about stock, consumption, demand, and shipment is available. Improved supply chain visibility through better information has a notable ability to overcome various issues experienced in public sector supply chains [305].
- ***Improve communication and coordination between vaccine supply chain experts and policy-makers:*** Integrating supply chain specialists into different committees, conferences, meetings, etc., establishing online data sharing websites and communications portals wherein decision-makers and supply chain experts can collaborate, and harmonizing language between the supply chain world and other vaccine-related disciplines can help policy-makers in better understanding of vaccine supply chains [337].
- ***Innovative vaccine technologies:*** To improve vaccination coverage in developing countries, further innovation in cold chain equipment and digital and logistics technology is required so that vaccines can be stored and delivered safely and more efficiently.

Improving the use of technology for activities such as demand forecasting, cold chain, transportation facilities and tracking of shipments can make a supply chain that is responsive in a cost-effective manner [70].

- ***Continuous improvement:*** The effective vaccine management (EVM) process benchmarks the supply chain overall performance against best practices in nine areas of vaccine management at each level of the health system. Hence, it is important that the nine areas (criteria) of effective vaccine management should be followed properly and regularly by the immunization program managers for the continuous improvement in the delivery performance. Further, it can assist immunization programs to evaluate the current performance of their immunization program, and benchmark this performance against best practice standards [355,356].
- ***Use of key performance indicators:*** KPIs provide actionable information because they are always measurable and quantifiable. Setting key performance indicators will help the decision-makers track the results of their efforts in ways that will ensure to make real-time adjustments, better planning and a platform for future strategies.
- ***Emphasis on sustainability practices:*** Embracing sustainable practices will help the immunization program become more efficient and effective. It will benefit everyone in the future, contributing to the economic and social development together with the good environmental practice.

8.7. Limitations of the present work

Although the present study is immensely beneficial to perceive the vaccine supply chain and to understand its relative importance, it is not free from some limitations. Following important limitations have been identified in this work.

- The data collection for the study is mainly based on field surveys. Due to the scarcity of individuals, it was not possible to reach each and every health center and hence many health-centers across India have been ignored.
- The unwillingness of the experts to participate in the study and their reluctance to answer some questions due to the fear of losing government job is one of the important limitations of the present study.
- The research instrument to design questionnaires and collecting data is often a difficult task in field surveys related research, therefore, few questionnaires items that may be important for this study might have been missed.

- As data collected in this study were from less number of states of India, hence, data collection from more states and expert's opinion will give a better sample size and can further improve the results.
- The expert's opinions have been largely responsible for the findings of the results. Thus, the evaluation procedures need to be carried out cautiously.
- Due to the multiple feedback steps that are essential and crucial to the idea and use of the Delphi procedure, the method is very time-consuming and the ability exists for low response rates and striving to maintain robust feedback can be a challenge.
- The iteration characteristics of the Delphi technique can potentially enable investigators to mold opinions.
- The model developed by using the ISM and the FMICMAC has not been statistically validated.
- The SSIM constructed that led to the development of the final fuzzy-MICMAC model and FANP results are based on the decisions of various expert's where the study has been carried out. The findings of the model may vary because of the perception of different decision-makers.
- The study was conducted in one state of India for identifying issues, therefore; some issues that are being faced by immunization program officials of different states may have been overlooked.
- For identifying vaccine supply chain issues, the survey was conducted in a state of India, where the rural population is approximately 70% of the total population. As delivering vaccines to rural areas have certain restrictions such as infrastructure, transportation, etc. Hence, two factors in the fuzzy Micmac model, i.e. 'optimum distance between the vaccine store and immunization camp', and 'geographical barriers' will be more relevant to countries with similar demographic conditions.
- The key performance indicators and sustainability practices have been identified from the expert's opinions and literature, therefore, some important indicators and practices may have been ignored.
- It is important to note that the multi-criteria decision-making techniques such as AHP, ANP, SAW, ELECTRE, TOPSIS etc. include a certain level of subjectivity and decisions could be influenced on decision-maker perception, experience, and its educational background. In that sense, pairwise comparison matrices developed in this study in AHP, FAHP, FANP and judgment matrix in COPRAS-G, FMOORA could be influenced by the experience of the decision-maker.

8.8. Scope for future research

The present work can be extended in the following areas:

- To statistically test the developed ISM an FMICMAC model by using structural equation modeling (SEM) technique.
- To collect data from other states of India to gather more information on vaccine supply chain issues, KPIs, and SKPCs.
- To increase the sample size of the expert's opinions for further improving the results and gaining more insights into the findings.
- Approaches such as weighted interpretive structural modeling and the interpretive ranking process can be used to weight and rank issues in order to fine-tune the decisions.
- During ISM analysis, only first level transitivity is considered. Hence, in the future, the model can be developed using higher order transitivity.
- The Graphical User Interface of the present ISM model can be developed with the use of MATLAB GUI which is a new research area suggested by [408].
- The results obtained from integrated ISM-FANP can be revised using integrated Decision-Making Trial and Evaluation Laboratory (DEMATEL) and ANP methods. This integrated technique may be helpful in better information the purposeful variations of the ISM and DEMATEL strategies regarding defining and spotting the interactions of the barriers to vaccine supply chain issues.
- Using the Total Interpretive Structural Modelling (TISM) technique as opposed to the ISM approach may be powerful for interpretation and clarifying how these relationships behave. This method is an essential step in the direction of extra interpretability of the ISM approach.
- The AHP methodology adopted in the present study has numerous weaknesses, for example, ambiguity, uncertainty, and bias. Therefore, in future work, the AHP method used in frameworks of vaccine shortages and Two-way assessment can be extended to fuzzy AHP to remove the inherent vagueness and uncertainty.
- To compare and check the validity of the MCDM technique results used in the present study with the other MCDM techniques.
- Weighting and prioritizing four regions of BSC using decision-making approaches such as DEMATEL and fuzzy ANP. With the study results, the decision-makers can evaluate the region, which has the most influence on vaccine supply chain performance.

- The BSC can be further extended to second-generation including strategy maps and the third-generation balanced scorecard to address design problems inherent to the conventional balanced scorecard.
- Finally, the identified KPIs of the vaccine supply chain can be analyzed using other decision-making methods and their combinations like TISM, FANP, FELECTRE, FTOPSIS, and FDEMATEL.

Finally, to overcome issues of vaccine supply chains and for sustainable development of child immunization program, a strong emphasis on government support and improvement in current supply chain practices and its redesign is required. Recognizing that different delivery, storage, and staffing configurations might yield better results, countries like Benin, Nigeria, and Mozambique have fundamentally redesigned their supply chains in pilot regions, introducing new staff positions, new cold chain equipment, and new logistics data systems to improve performance. Decision-makers in other lower income countries should be inspired to learn the changes made in these regions such as reduced facility-level stockout, improved staff satisfaction, increased rates of vaccine availability, translating to improved coverage, and in some cases reduced costs for improving their system performance as well [356].

LIST OF PUBLICATIONS

Paper Published in International Journals

***1*. Dheeraj Chandra & Dinesh Kumar (2019)**: Prioritizing the vaccine supply chain issues of developing countries using an integrated ISM-FANP framework. **Journal of Modelling in Management – Accepted for publication *(Emerald, ESCI & Scopus, ABDC – C rating)*.**

2*. Dheeraj Chandra & Dinesh Kumar (2019)**: Two-way assessment of key performance indicators to vaccine supply chain system in India, **International Journal of Productivity and Performance Management,** Vol 68, No. 1, pp.194-230. ***(Emerald, ESCI & Scopus, ABDC – B rating).

3.* Dheeraj Chandra & Dinesh Kumar (2018)**: A fuzzy MICMAC analysis for improving supply chain performance of basic vaccines in developing countries, **Expert Review of Vaccines**, Vol 17, No.3, pp.263-281. ***(Taylor & Francis, SCI Journal, Impact factor 4.271).

4.* Dheeraj Chandra & Dinesh Kumar (2018)**: Analysis of vaccine supply chain issues using ISM approach, **International Journal of Logistics Systems and Management,** Vol 31, No. 4, pp.449-482. ***(Inderscience, Scopus, ABDC – C rating).

First revision submitted

5.* Dheeraj Chandra & Dinesh Kumar (2019)**: Identifying key performance indicators of vaccine supply chain for sustainability development of mission Indradhanush: A Structural Equation Modelling Approach. **Omega – The International Journal of Management Science *(Elsevier, SCI, IF 4.311, ABDC – A* rating).

Paper under review

***6.* Dheeraj Chandra & Dinesh Kumar (2019)**: Key solutions to overcome supply chain issues for designing next-generation vaccine supply chain system in India – A hybrid Fuzzy AHP-MOORA Framework. **Expert Review of Vaccines**.

***7.* Dheeraj Chandra & Dinesh Kumar (2019)**: Analysis of vaccine shortages: An integrated AHP-COPRAS-G framework. **Vaccine (Elsevier).**

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APPENDIX A: Questionnaire based on vaccine supply chain issues

This questionnaire has been designed for analysis purpose to be used for research work under Ph.D. program at Indian Institute of Technology, Roorkee.

The objective of this questionnaire is to identify important or key issues/factors in the supply chain of basic vaccines that impedes the performance of universal immunization program (UIP) India in delivery of basic vaccines to the health centers and children.

Please spare some of your valuable time in filing the questionnaire as your input will be very helpful in achieving our research objective. We assure you that the data will not be disclosed to any person/third party/organization and will solely be used for the research purpose.

The instruction to fill the questionnaire is given below:

Instructions before filling the questionnaire:

1. Kindly read all the questions carefully before filling up the questionnaire. Please attempt all the questions.
2. This questionnaire is to be filled up by the universal immunization program officials.
3. Please try your best to complete the questionnaire within 10 days after receiving it.

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DETAILS OF RESPONDENTS FOR RESEARCH SURVEY

Name:	
Gender:	
Name of UIP center:	
Designation:	
Email id:	
Contact no.:	
Experience(in yrs.):	

Note: Please tick on the circle that corresponds to your answer for each question. Indicate how much you agree or disagree with each of the following statements about the vaccine supply chain issues.

	Strongly Disagree	Disagree	Neutral	Strongly Agree	Agree
1. *To what extent do you think factor **"Demand Forecast"** can be considered as a vaccine supply chain issue?*	○	○	○	○	○
2. *To what extent do you think factor **"Vaccine Shortage"** can be considered as a vaccine supply chain issue?*	○	○	○	○	○
3. *To what extent do you think factor **"Proper Planning and Scheduling"** can be considered as a vaccine supply chain issue?*	○	○	○	○	○
4. *To what extent do you think factor **"Vaccine Wastage"** can be considered as a vaccine supply chain issue?*	○	○	○	○	○
5. *To what extent do you think factor **"Order Visibility"** can be considered as a vaccine supply chain issue?*	○	○	○	○	○
6. *To what extent do you think factor **"Stock Management"** can be considered as a vaccine supply chain issue?*	○	○	○	○	○
7. *To what extent do you think factor **"Vaccine Advocacy and Education"** can be considered as a vaccine supply chain issue?*	○	○	○	○	○
8. *To what extent do you think factor **"Communication Between the Supply Chain Members"** can be considered as a vaccine supply chain issue?*	○	○	○	○	○
9. *To what extent do you think factor **"Need To Improve Immunization Program Monitor Indicators and Gaps In Data Management"** can be considered as a vaccine supply chain issue?*	○	○	○	○	○

10. *To what extent do you think factor* ***"Coordination with Local Administration"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○
11. *To what extent do you think factor* ***"Inadequate Response to Temperature Excursions"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○
12. *To what extent do you think factor* ***"Sustainable Financing"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○
13. *To what extent do you think factor* ***"Availability of Human Resource"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○
14. *To what extent do you think factor* ***"Geographical Barriers"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○
15. *To what extent do you think factor* ***"Monitoring of Vaccinated Population"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○
16. *To what extent do you think factor* ***"Inadequate Response To Temperature Excursions"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○
17. *To what extent do you think factor* ***"Transportation Disruptions"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○
18. *To what extent do you think factor* ***"Procurement Lead-Time"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○
19. *To what extent do you think factor* ***"Storage and Handling of Vaccines"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○
20. *To what extent do you think factor* ***"Disaster/Emergency Management"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○

21. *To what extent do you think factor* ***"Vaccine Regulatory Management"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○
22. *To what extent do you think factor* ***"Risk of Natural/Unnatural Causes"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○
23. *To what extent do you think factor* ***"Optimum Number of Cold Chain Vehicles"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○
24. *To what extent do you think factor* ***"Vaccine Supply Quality"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○
25. *To what extent do you think factor* ***"Location of Vaccine Storage and immunization camp"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○
26. *To what extent do you think factor* ***"Vaccine hesitancy"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○
27. *To what extent do you think factor* ***"Responsiveness"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○
28. *To what extent do you think factor* ***"Facility Disruptions"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○
29. *To what extent do you think factor* ***"Replenishment"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○
30. *To what extent do you think factor* ***"Disability-Adjusted Life Years (DALY)"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○
31. *To what extent do you think factor* ***"Disease and Epidemiological Dynamics"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○
32. *To what extent do you think factor* ***"Equity of Humanitarian Logistics"*** *can*	○	○	○	○	○

be considered as a vaccine supply chain issue?					
33. To what extent do you think factor ***"Temperature and Exposure Control"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○
34. To what extent do you think factor ***"Yield Uncertainty"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○
35. To what extent do you think factor ***"Vaccination Schedule"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○
36. To what extent do you think factor ***"Lack of System Checks (for accuracy, properly prepared vaccine, uncompromised vaccine)"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○
37. To what extent do you think factor ***"Immunization Costs"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○
38. To what extent do you think factor ***"Inadequate or Lacking Safeguards"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○
39. To what extent do you think factor ***"Lack of Confidence in Vaccination Programs"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○
40. To what extent do you think factor ***"Monitoring of Vaccine Cold Chain"*** *can be considered as a vaccine supply chain issue?*	○	○	○	○	○

APPENDIX B: Questionnaire based on validation of 25 key issues by vaccine supply chain experts of developing countries.

Please rank, in order of importance from most important to least important, the following reasons for selecting as key issues of vaccine supply chain.

	Not Important	Slightly Important	Moderately Important	Important	Very Important
1. *How important is factor **"Demand Forecast"** to be considered as vaccine supply chain key issue?*	○	○	○	○	○
2. *How important is factor **"Vaccine Shortage"** to be considered as vaccine supply chain key issue?*	○	○	○	○	○
3. *How important is factor **"Proper Planning and Scheduling"** to be considered as vaccine supply chain key issue?*	○	○	○	○	○
4. *How important is factor **"Vaccine Wastage"** to be considered as vaccine supply chain key issue?*	○	○	○	○	○
5. *How important is factor **"Stock Management"** to be considered as vaccine supply chain key issue?*	○	○	○	○	○
6. *How important is factor **"Vaccine Advocacy and Education"** to be considered as vaccine supply chain key issue?*	○	○	○	○	○
7. *How important is factor **"Communication Between the Supply Chain Members"** to be considered as vaccine supply chain key issue?*	○	○	○	○	○
8. *How important is factor **"Coordination with Local Administration"** to be considered as*	○	○	○	○	○

vaccine supply chain key issue?					
9. *How important is factor **"Sustainable Financing"** to be considered as vaccine supply chain key issue?*	○	○	○	○	○
10. *How important is factor **"Availability of Human Resource"** to be considered as vaccine supply chain key issue?*	○	○	○	○	○
11. *How important is factor **"Geographical Barriers"** to be considered as vaccine supply chain key issue?*	○	○	○	○	○
12. *How important is factor **"Monitoring of Vaccinated Population"** to be considered as vaccine supply chain key issue?*	○	○	○	○	○
13. *How important is factor **"Transportation Disruptions"** to be considered as vaccine supply chain key issue?*	○	○	○	○	○
14. *How important is factor **"Procurement Lead-Time"** to be considered as vaccine supply chain key issue?*	○	○	○	○	○
15. *How important is factor **"Storage and Handling of Vaccines"** to be considered as vaccine supply chain key issue?*	○	○	○	○	○
16. *How important is factor **"Vaccine Regulatory Management"** to be considered as vaccine supply chain key issue?*	○	○	○	○	○
17. *How important is factor **"Risk of Natural/Unnatural Causes"** to be considered as vaccine supply chain key issue?*	○	○	○	○	○
18. *How important is factor **"Optimum Number of Cold Chain Vehicles"** to*	○	○	○	○	○

be considered as vaccine supply chain key issue?					
19. How important is factor ***"Vaccine Supply Quality"*** *to be considered as vaccine supply chain key issue?*	○	○	○	○	○
20. How important is factor ***"Location of Vaccine Storage and immunization camp"*** *to be considered as important vaccine supply chain key issue?*	○	○	○	○	○
21. How important is factor ***"Vaccine hesitancy"*** *to be considered as vaccine supply chain key issue?*	○	○	○	○	○
22. How important is factor ***"Responsiveness"*** *to be considered as vaccine supply chain key issue?*	○	○	○	○	○
23. How important is factor ***"Temperature and Exposure Control"*** *to be considered as vaccine supply chain key issue?*	○	○	○	○	○
24. How important is factor ***"Immunization Costs"*** *to be considered as vaccine supply chain key issue?*	○	○	○	○	○
25. How important is factor ***"Monitoring of Vaccine Cold Chain"*** *to be considered as vaccine supply chain key issue?*	○	○	○	○	○

APPENDIX C: Questionnaire based on distribution of 25 key issues into 5 main domains.

	Operational	Environmental	Economic	Social	Management
1. *According to you, factor **"Demand Forecast"** should belong to which domain/category of vaccine supply chain issue?*	○	○	○	○	○
2. *According to you, factor **"Vaccine Shortage"** should belong to which domain/category of vaccine supply chain issue?*	○	○	○	○	○
3. *According to you, factor **"Proper Planning and Scheduling"** should belong to which domain/category of vaccine supply chain issue?*	○	○	○	○	○
4. *According to you, factor **"Vaccine Wastage"** should belong to which domain/category of vaccine supply chain issue?*	○	○	○	○	○
5. *According to you, factor **"Stock Management"** should belong to which domain/category of vaccine supply chain issue?*	○	○	○	○	○
6. *According to you, factor **"Vaccine Advocacy and Education"** should belong to which domain/category of vaccine supply chain issue?*	○	○	○	○	○
7. *According to you, factor **"Communication Between the Supply Chain Members"** should belong to which*	○	○	○	○	○

domain/category of vaccine supply chain issue?					
8. *According to you, factor* ***"Coordination with Local Administration"*** *should belong to which domain/category of vaccine supply chain issue?*	○	○	○	○	○
9. *According to you, factor* ***"Sustainable Financing"*** *should belong to which domain/category of vaccine supply chain issue?*	○	○	○	○	○
10. *According to you, factor* ***"Availability of Human Resource"*** *should belong to which domain/category of vaccine supply chain issue?*	○	○	○	○	○
11. *According to you, factor* ***"Geographical Barriers"*** *should belong to which domain/category of vaccine supply chain issue?*	○	○	○	○	○
12. *According to you, factor* ***"Monitoring of Vaccinated Population"*** *should belong to which domain/category of vaccine supply chain issue?*	○	○	○	○	○
13. *According to you, factor* ***"Transportation Disruptions"*** *should belong to which domain/category of vaccine supply chain issue?*	○	○	○	○	○
14. *According to you, factor* ***"Procurement Lead-Time"*** *should belong to which domain/category of vaccine supply chain issue?*	○	○	○	○	○

15. According to you, factor ***“Storage and Handling of Vaccines”*** *should belong to which domain/category of vaccine supply chain issue?*	○	○	○	○	○
16. According to you, factor ***“Vaccine Regulatory Management”*** *should belong to which domain/category of vaccine supply chain issue?*	○	○	○	○	○
17. According to you, factor ***“Risk of Natural/Unnatural Causes”*** *should belong to which domain/category of vaccine supply chain issue?*	○	○	○	○	○
18. According to you, factor ***“Optimum Number of Cold Chain Vehicles”*** *should belong to which domain/category of vaccine supply chain issue?*	○	○	○	○	○
19. According to you, factor ***“Vaccine Supply Quality”*** *should belong to which domain/category of vaccine supply chain issue?*	○	○	○	○	○
20. According to you, factor ***“Location of Vaccine Storage and immunization camp”*** *should belong to which domain/category of vaccine supply chain issue?*	○	○	○	○	○
21. According to you, factor ***“Vaccine hesitancy”*** *should belong to which domain/category of vaccine supply chain issue?*	○	○	○	○	○
22. According to you, factor ***“Responsiveness”*** *should belong to which*	○	○	○	○	○

domain/category of vaccine supply chain issue?					
*23. According to you, factor **"Temperature and Exposure Control"** should belong to which domain/category of vaccine supply chain issue?*	○	○	○	○	○
*24. According to you, factor **"Immunization Costs"** should belong to which domain/category of vaccine supply chain issue?*	○	○	○	○	○
*25. According to you, factor **"Monitoring of Vaccine Cold Chain"** should belong to which domain/category of vaccine supply chain issue?*	○	○	○	○	○

APPENDIX D: Questionnaire based on prioritization of 25 key issues and 5 domains using FANP.

D.1. First part of the questionnaire for developing pairwise comparison matrix (outer dependencies) with respect to goal (Level 1) and criteria of Level 2.

Please read the following questions and put checkmarks on the pair-wise comparison matrices. The instruction for filling the questionnaire is given below:

- **i.** If two criteria x and y are considered to be equally important **(EI)**, then put a mark **~** in box below **EI.**
- **ii.** If criteria x is weakly more important **(WMI)** than criteria y, then put a mark ✓ in box below **WMI,** or if criteria y is weakly more important than criteria x, then put a mark ✕ below **WMI**.
- **iii.** If criteria x is strongly more important **(SMI)** than criteria y, then put a mark ✓ in box below **SMI**, or if criteria y is strongly more important than criteria x, then put a mark ✕ in box below **SMI**.
- **iv.** If criteria x is very strongly more important **(VSMI)** than criteria y, then put a mark ✓ in box below **VSMI**, or if criteria y is very strongly more important than criteria x, then put a mark ✕ in box below **VSMI**.
- **v.** If criteria x is absolutely more important **(AMI)** than criteria y, then put a mark ✓ in box below **AMI**, or if criteria y is very strongly more important than criteria x, then put a mark ✕ in box below **AMI**.

Goal → / **Questions ↓**	**With respect to 'prioritize (rank) the issues based on their relative importance in the vaccine supply chain to help decision-makers to drive their efforts and resources on eliminating the most important issues'**
Question 1	How important is proper management of **'Operational issues (F1)'** when compared with the **'Environmental issues (F2)'?**
Question 2	How important is proper management of **'Operational issues (F1)'** when compared with the **'Economical issues (F3)'?**
Question 3	How important is proper management of **'Operational issues (F1)'** when compared with the **'Social issues (F4)'?**
Question 4	How important is proper management of **'Operational issues (F1)'** when compared with the **'Organizational issues (F5)'?**
Question 5	How important is proper management of **'Environmental issues (F2)'** when compared with the **'Economical issues (F3)'?**
Question 6	How important is proper management of **'Environmental issues (F2)'** when compared with the **'Social issues (F4)'?**
Question 7	How important is proper management of **'Environmental issues (F2)'** when compared with the **'Organizational issues (F5)'?**
Question 8	How important is proper management of **'Economical issues (F3)'** when compared with the **'Social issues (F4)'?**

Question 9	How important is proper management of **'Economical issues (F3)'** when compared with the **'Organizational issues (F5)'?**
Question 10	How important is proper management of **'Social issues (F4)'** when compared with the **'Organizational issues (F5)'?**

Remark: Please answer to each of the question according to the instructions provided at the starting of the questionnaire, and then enter your answer or any opinion/suggestion if any provided in the table given below.

WITH RESPECT TO GOAL		**Response**				
QUESTIONS	**COMPARISON BETWEEN CRITERIA**	**EI**	**WMI**	**SMI**	**VSMI**	**AMI**
Question 1	F1 and F2					
Question 2	F1 and F3					
Question 3	F1 and F4					
Question 4	F1 and F5					
Question 5	F2 and F3					
Question 6	F2 and F4					
Question 7	F2 and F5					
Question 8	F3 and F4					
Question 9	F3 and F5					
Question 10	F4 and F5					
	Opinion/suggestion of expert:					

D.2. Second part of the questionnaire for developing pairwise comparison matrix with respect to criteria (Level 2) and sub-criteria of Level 3.

Criteria → / **Q.No. ↓**	**With respect to proper management of 'Operational issues (F1)' criteria's:**
Question 1	How important is **'Monitoring of vaccine cold chain (F1-1)'** when compared with the **'Inventory Management (F1-2)'?**
Question 2	How important is **'Monitoring of vaccine cold chain (F1-1)'** when compared with the **'Vaccine Stock-outs (F1-3)'?**
Question 3	How important is **'Monitoring of vaccine cold chain (F1-1)'** when compared with the **'Demand Forecast (F1-4)'?**
Question 4	How important is **'Monitoring of vaccine cold chain (F1-1)'** when compared with the **'Procurement Lead-Time (F1-5)'?**
Question 5	How important is **'Monitoring of vaccine cold chain (F1-1)'** when compared with the **'Quick responsiveness (F1-6)'?**
Question 6	How important is **'Monitoring of vaccine cold chain (F1-1)'** when compared with the **'Temperature and exposure control (F1-7)'?**

Question 7	How important is **'Monitoring of vaccine cold chain (F1-1)'** when compared with the **' Geographical Barriers (F1-8)'?**
Question 8	How important is **'Monitoring of vaccine cold chain (F1-1)'** when compared with the **'Storage and Handling of Vaccines (F1-9)'?**

WITH RESPECT TO CRITERIA 'OPERATIONAL ISSUES (F1)'		**Response**				
QUESTIONS	**COMPARISON BETWEEN SUB-CRITERIA**	**EI**	**WMI**	**SMI**	**VSMI**	**AMI**
Question 1	F1-1 and F1-2					
Question 2	F1-1 and F1-3					
Question 3	F1-1 and F1-4					
Question 4	F1-1 and F1-5					
Question 5	F1-1 and F1-6					
Question 6	F1-1 and F1-7					
Question 7	F1-1 and F1-8					
Question 8	F1-1 and F1-9					
	Opinion/suggestion of expert:					

Remark: Likewise, similar questions were designed for constructing pairwise comparison matrix between the rest of the criteria and sub-criteria (i.e. Level 2 and Level 3).

D.3. Third part of the questionnaire for developing pairwise comparison matrix (inner dependencies) between the criteria (Level 1).

Criteria → **Q.No. ↓**	**With respect to proper management of 'Operational issues (F1)' criteria's:**
Question 1	How important is proper management of **'Economical issues (F3)'** when compared with the **'Organizational issues (F5)'?**

WITH RESPECT TO CRITERIA 'OPERATIONAL ISSUES (F1)'		**Response**				
QUESTIONS	**COMPARISON BETWEEN CRITERIA**	**EI**	**WMI**	**SMI**	**VSMI**	**AMI**
Question 1	F3 and F5					
	Opinion/suggestion of expert:					

Criteria → **Q.No. ↓**	**With respect to proper management of 'Environmental issues (F1)' criteria's:**
Question 1	How important is proper management of **'Operational issues (F1)'** when compared with the **'Economical issues (F3)'?**

Question 2	How important is proper management of **‘Operational issues (F1)’** when compared with the **‘Organizational issues (F5)’?**
Question 3	How important is proper management of **‘Economical issues (F3)’** when compared with the **‘Organizational issues (F5)’?**

WITH RESPECT TO CRITERIA ‘ ENVIRONMENTAL ISSUES (F2)’		**Response**				
QUESTIONS	**COMPARISON BETWEEN CRITERIA**	**EI**	**WMI**	**SMI**	**VSMI**	**AMI**
Question 1	F1 and F3					
Question 2	F1 and F5					
Question 3	F3 and F5					
	Opinion/suggestion of expert:					

Remark: Likewise, similar questions were designed for constructing pairwise comparison matrix between the rest of the criteria (i.e. Level 2).

D.4. Fourth part of the questionnaire for developing pairwise comparison matrix (inner dependencies) between the sub-criteria (Level 3).

Sub-criteria → / **Q.No. ↓**	**With respect to better ‘Monitoring of vaccine cold chain (F1-1)’:**
Question 1	How important is **‘Sustainable financing (F3-2)’** when compared with the **‘Vaccine advocacy and education (F4-2)’?**
Question 2	How important is **‘Sustainable financing (F3-2)’** when compared with the **‘Availability of human resource (F5-1)’?**
Question 3	How important is **‘Sustainable financing (F3-2)’** when compared with the **‘Proper planning and scheduling (F5-2)’?**
Question 4	How important is **‘Vaccine advocacy and education (F4-2)’** when compared with the **‘Availability of human resource (F5-1)’?**
Question 5	How important is **‘Vaccine advocacy and education (F4-2)’** when compared with the **‘Proper planning and scheduling (F5-2)’?**
Question 6	How important is **‘Availability of human resource (F5-1)’** when compared with the **‘Proper planning and scheduling (F5-2)’?**

WITH RESPECT TO SUB-CRITERIA ‘MONITORING OF VACCINE COLD CHAIN (F1-1)’		Response				
QUESTIONS	**COMPARISON BETWEEN SUB-CRITERIA**	**EI**	**WMI**	**SMI**	**VSMI**	**AMI**
Question 1	F3-2 and F4-2					
Question 2	F3-2 and F5-1					
Question 3	F3-2 and F5-2					
Question 4	F4-2 and F5-1					
Question 5	F4-2 and F5-2					
Question 6	F5-1 and F5-2					
	Opinion/suggestion of expert:					

Remark: Likewise, similar questions were designed for constructing pairwise comparison matrix between the rest of the sub-criteria (i.e. Level 3).

Appendix E. Results of ISM-FANP calculations.

E.1. Contextual relationship matrix and reachability matrix

Table E.1
SSIM for main domain.

Factors	F5	F4	F3	F2
F1	A	O	X	V
F2	A	O	X	
F3	X	X		
F4	A			

Table E.2
SSIM for issues.

Sub-Criteria	F5-6	F5-5	F5-4	F5-3	F5-2	F5-1	F4-4	F4-3	F4-2	F4-1	F3-2	F3-1	F2-3	F2-2	F2-1	F1-10	F1-9	F1-8	F1-7	F1-6	F1-5	F1-4	F1-3	F1-2
F1-1	V	O	V	O	A	A	O	O	A	O	A	V	O	V	O	V	O	O	V	O	O	O	V	O
F1-2	O	O	O	A	A	O	O	O	A	O	O	V	V	V	O	V	V	O	O	O	A	A	V	
F1-3	V	O	A	O	A	O	O	O	O	O	A	V	X	A	A	A	O	O	A	V	A	A		
F1-4	V	O	O	A	A	O	O	O	O	O	O	O	O	V	O	O	O	O	O	O	O			
F1-5	V	O	O	O	A	O	O	O	O	O	O	O	O	O	A	A	O	A	O	A				
F1-6	V	O	O	A	A	A	O	O	O	O	A	V	O	V	A	V	O	A	O					
F1-7	O	O	O	O	A	O	O	O	A	O	A	V	O	V	O	O	O	O						
F1-8	V	O	O	O	A	O	V	O	O	O	O	V	O	V	X	V	O							
F1-9	V	O	O	O	A	A	O	O	A	O	A	O	O	V	O	O								
F1-10	V	A	O	A	A	O	O	A	O	O	A	O	O	V	A									
F2-1	V	O	O	O	O	O	O	O	O	O	O	V	O	V										
F2-2	A	A	O	A	A	O	A	O	A	A	O	V	A											
F2-3	V	O	A	A	A	O	O	O	O	O	O	O												
F3-1	A	A	O	O	O	A	O	O	O	O	X													
F3-2	V	V	O	V	O	V	V	V	V	O														
F4-1	V	O	O	O	O	O	O	A	A															
F4-2	V	O	O	O	O	O	O	V																
F4-3	V	O	V	O	A	A	V																	
F4-4	V	O	O	O	O	O																		
F5-1	V	O	O	O	V																			
F5-2	V	O	O	V																				
F5-3	V	O	O																					
F5-4	V	O																						
F5-5	V																							

Table E.3.
Initial reachability matrix for main domains.

	F1	F2	F3	F4	F5
F1	1	1	1	0	0
F2	0	1	1	0	0
F3	1	1	1	1	1
F4	0	0	1	1	0
F5	1	1	1	1	1

Table E.4.
Final reachability matrix for main domains.

	F1	F2	F3	F4	F5
F1	1	1	1	1	1
F2	1	1	1	1	1
F3	1	1	1	1	1
F4	1	1	1	1	1
F5	1	1	1	1	1

E.2. Pairwise comparison matrices and consistency ratio of the pairwise comparison matrix in case of triangular fuzzy numbers.

Table E.5
Linguistic scales for the level of importance [339]**.**

Linguistic variables	TFN	Reciprocal TFN	Fuzzy numbers
Just equal (JE)	(1,1,1)	(1,1,1)	1
Equally important (EI)	(1/2,1,3/2)	(2/3,1,2)	1
Weakly more important (WMI)	(1,3/2,2)	(1/2,2/3,1)	3
Strongly more important (SMI)	(3/2,2,5/2)	(2/5,1/2,2/3)	5
Very strongly more important (VSMI)	(2,5/2,3)	(1/3,2/5,1/2)	7
Absolutely more important (AMI)	(5/2,3/1,7/2)	(2/7,1/3,2/5)	9

Table E.6
The fuzzy pairwise comparison matrix of one expert with respect to goal (outer dependencies).

Goal	F1	F2	F3	F4	F5
F1	(1,1,1)	(3/2,2,5/2)	(3/2,2,5/2)	(3/2,2,5/2)	(1/2,1,3/2)
F2	(2/5,1/2,2/3)	(1,1,1)	(2/5,1/2,2/3)	(2,5/2,3)	(2/5,1/2,2/3)
F3	(2/5,1/2,2/3)	(3/2,2,5/2)	(1,1,1)	(2,5/2,3)	(1/2,1,3/2)
F4	(2/5,1/2,2/3)	(1/3,2/5,1/2)	(1/3,2/5,1/2)	(1,1,1)	(2/7,1/3,2/5)
F5	(2/3,1,2)	(3/2,2,5/2)	(2/3,1,2)	(5/2,3,7/2)	(1,1,1)
λmax = 5.1465, CI = 0.0367 , RI = 1.11, CR = 0.0333 $\leq$ 0.1 consistency					

Table E.7
The fuzzy pairwise comparison matrix of organizational factor of one expert (inner dependencies).

F1	F3	F5
F3	(1,1,1)	(3/2,2,5/2)
F5	(2/5,1/2,2/3)	(1,1,1)
λmax = 2.000, CI = 0.000 , RI = 0.000, CR = 0.000 ≤ 0.1 consistency		

In the context of fuzzy environment, [409] presented a method to check the consistency of a pairwise comparison matrix. Suppose, if $\tilde{A} = [\tilde{a}_{ij}]$, in which, $\tilde{a}_{ij} = (p_{ij}, q_{ij}, r_{ij})$ is a TFN judgement matrix. First, construct A, and calculate the consistency ratio using Eq. 3.3-3.4. If A is consistent, then Ã is consistent. For example, the middle numbers of the fuzzy matrix (See Table E.6) are taken for evaluation. Now, eigenvalue (λmax), is calculated for the matrix. Further, using Table E.8, random index (RI) is obtained. Then, consistency ratio is calculated as 0.0333, which is less than 0.1 and is acceptable. Hence, the matrix A is consistent which implies that fuzzy judgment matrix Ã is consistent. The same procedure is applied for each 16 experts separately.

Table E.8
Random index used to compute consistency ratio (CR) [391].

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59
n	16	17	18	19	20	21	22	23	24	25					
RI	1.60	1.61	1.62	1.63	1.63	1.64	1.65	1.65	1.66	1.66					

E.3. CFCS defuzzification method

Defuzzification is the method of converting fuzzy numbers into crisp numbers [410]. In this paper, Converting the fuzzy data into crisp scores (CFCS) method has been used for the defuzzification purpose [411]. The CFCS method steps are as follows:

Step 1: Normalization

If, $A_{ij}^{k} = (p_{ij}^{k}, q_{ij}^{k}, r_{ij}^{k})$ indicates the triangular fuzzy assessment of the kth expert then:

$$xp_{ij}^{k} = (p_{ij}^{k} - min\, p_{ij}^{k}) / \Delta_{\min}^{\max} \quad \text{(E.1)}$$

$$xq_{ij}^{k} = (q_{ij}^{k} - min\, p_{ij}^{k}) / \Delta_{\min}^{\max} \quad \text{(E.2)}$$

$$xr_{ij}^{k} = (r_{ij}^{k} - min\,p_{ij}^{k}) / \Delta_{\min}^{\max} \quad \text{(E.3)}$$

where

$$\Delta_{\min}^{\max} = \max r_{ij}^{k} - \min p_{ij}^{k} \quad \text{(E.4)}$$

Step 2: Computing the lower (Ls) and upper (Us) normalised value:

$$xps_{ij}^{k} = xq_{ij}^{k} / (1 + xq_{ij}^{k} - xp_{ij}^{k}) \quad \text{(E.5)}$$

$$xrs_{ij}^{k} = xr_{ij}^{k} / (1 + xr_{ij}^{k} - xq_{ij}^{k}) \quad \text{(E.6)}$$

Step 3: Calculating total normalised crisp value:

$$x_{ij}^{k} = [xps_{ij}^{k}(1 - xps_{ij}^{k}) + xrs_{ij}^{k} xrs_{ij}^{k}] / [1 - xps_{ij}^{k} + xrs_{ij}^{k}] \quad \text{(E.7)}$$

Step 4: Computing crisp value:

$$z_{ij}^{k} = \min p_{ij}^{k} + x_{ij}^{k} \Delta_{\min}^{\max} \quad \text{(E.8)}$$

E.4. Crisp values using defuzzification and calculation of final weights.

Table E.9 & E.10 shows crisp value (inner and outer dependency matrix) obtained after defuzzification for one expert regarding goal and organization. To aggregate the opinions of sixteen experts, Eq. 3.12-3.13 are used. Using Eq. 3.14, the final weights are then calculated using the geometric mean method. The final crisp values and outer and inner dependence weight (W_{21}) and (W_{22}) for the sixteen experts are shown in Table E.11 & E.12. Other calculations are populated in the same manner.

Table E.9
The final crisp value of one expert with respect to goal (outer dependency matrix).

Goal	F1	F2	F3	F4	F5
F1	1.000	1.967	1.967`	1.967	1.033
F2	0.510	1.000	0.510	2.464	0.510
F3	0.510	1.987	1.000	2.464	1.031
F4	0.518	0.410	0.410	1.000	0.338
F5	1.157	2.003	1.157	2.964	1.000

Table E.10
The final crisp value of one expert (inner dependency matrix).

F1	F3	F5
F3	1.000	1.975
F5	1.5	1.000

Table E.11
Integrated crisp values of 16 experts and final weights with respect to the goal.

Goal	F1	F2	F3	F4	F5	Weights (W_{21})
F1	1.000	1.935	1.996	1.953	1.126	**0.2813**
F2	0.468	1.000	0.474	2.482	0.442	**0.1382**
F3	0.496	1.977	1.000	2.441	0.989	**0.2178**
F4	0.457	0.407	0.410	1.000	0.350	**0.0889**
F5	1.137	1.980	1.127	2.928	1.000	**0.2738**

Table E.12
Integrated crisp values of 16 experts and final weights with respect to the organizational factor (F1).

F1	F3	F5	Weights (W_{22})
F3	**1.000**	**1.897**	**0.5364**
F5	**1.417**	**1.000**	**0.4636**

Appendix F. Questionnaire based on AHP and COPRAS-G.

F.1. AHP questionnaire for obtaining weights of 10 reasons/criteria's of vaccine shortages.

Goal → / **Q.No. ↓**	**With respect to weighting/ranking important reasons/criteria's for basic vaccine shortages:**
Question 1	How important is the criteria **'Production (C1)'** when it is compared with the criteria **'Regulation (C2)'?**
Question 2	How important is the criteria **'Production (C1)'** when it is compared with the criteria **'Procurement system (C3)'?**
Question 3	How important is the criteria **'Production (C1)'** when it is compared with the criteria **'Product and packaging requirements (C4)'?**
Question 4	How important is the criteria **'Production (C1)'** when it is compared with the criteria **'Uncertainty in demand (C5)'?**
Question 5	How important is the criteria **'Production (C1)'** when it is compared with the criteria **'Vaccine wastages (C6)'?**
Question 6	How important is the criteria **'Production (C1)'** when it is compared with the criteria **'Political commitment and financing (C7)'?**
Question 7	How important is the criteria **'Production (C1)'** when it is compared with the criteria **'Changes in immunization program schedules of countries (C8)'?**
Question 8	How important is the criteria **'Production (C1)'** when it is compared with the criteria **'Stock management and coordination in supply chain (C9)'?**
Question 9	How important is the criteria **'Production (C1)'** when it is compared with the criteria **'Global information available on current and future supply capacity and vaccines at risk of a shortage'?**

WITH RESPECT TO CRITERIA ' GOAL'		**Response**				
QUESTIONS	**COMPARISON BETWEEN CRITERIA**	**EI**	**MI**	**SI**	**EXI**	**EXMI**
Question 1	C1 and C2					
Question 2	C1 and C3					
Question 3	C1 and C4					
Question 4	C1 and C5					
Question 5	C1 and C6					
Question 6	C1 and C7					
Question 7	C1 and C8					
Question 8	C1 and C9					
Question 9	C1 and C10					
	Opinion/suggestion of expert:					

Remark: Likewise, similar questions were designed for constructing pairwise comparison matrix between the rest of the criteria of vaccine shortages.

F.2. COPRAS-G questionnaire for ranking 15 solutions/alternatives to overcome vaccine shortages.

G → / Q.No. ↓	**With respect to 'prioritizing/ranking important solutions that can help in overcoming basic vaccine shortages problems':**
Question 1	How important is the effect of the solution/alternative **'Better information system (A1)'** to overcome the vaccine shortage **issue/criteria 'Production (C1)'?**
Question 2	How important is the effect of the solution/alternative **'Better information system (A1)'** to overcome the vaccine shortage **issue/criteria 'Regulation (C2)'?**
Question 3	How important is the effect of the solution/alternative **'Better information system (A1)'** to overcome the vaccine shortage **issue/criteria 'Procurement system (C3)'?**
Question 4	How important is the effect of the solution/alternative **'Better information system (A1)'** to overcome the vaccine shortage **issue/criteria 'Product and packaging requirements (C4)'?**
Question 5	How important is the effect of the solution/alternative **'Better information system (A1)'** to overcome the vaccine shortage **issue/criteria 'Uncertainty in demand (C5)'?**
Question 6	How important is the effect of the solution/alternative **'Better information system (A1)'** to overcome the vaccine shortage **issue/criteria 'Vaccine wastages (C6)'?**
Question 7	How important is the effect of the solution/alternative **'Better information system (A1)'** to overcome the vaccine shortage **issue/criteria 'Political commitment and financing (C7)'?**
Question 8	How important is the effect of the solution/alternative **'Better information system (A1)'** to overcome the vaccine shortage **issue/criteria 'Changes in immunization program schedules of countries (C8)'?**
Question 9	How important is the effect of the solution/alternative **'Better information system (A1)'** to overcome the vaccine shortage **issue/criteria 'Stock management and coordination in supply chain (C9)'?**
Question 10	How important is the effect of the solution/alternative **'Better information system (A1)'** to overcome the vaccine shortage **issue/criteria 'Global information available on current and future supply capacity and vaccines at risk of a shortage'?**

WITH RESPECT TO CRITERIA ' GOAL'		**Response**				
QUESTIONS	**COMPARISON BETWEEN ALTERNATIVE AND CRITERIA**	**Very poor**	**Poor**	**Fair**	**Good**	**Very good**
Question 1	A1 and C1					
Question 2	A1 and C2					
Question 3	A1 and C3					
Question 4	A1 and C4					
Question 5	A1 and C5					
Question 6	A1 and C6					
Question 7	A1 and C7					
Question 8	A1 and C8					
Question 9	A1 and C9					
Question 10	A1 and C10					
	Opinion/suggestion of expert:					

Appendix G. Questionnaire based on FAHP and FMOORA.

G.1. FAHP questionnaire for obtaining weights of 10 barriers in NGVSCs design.

Goal → **Q.No. ↓**	**With respect to weighting/ranking barriers of NGVSCs:**
Question 1	How important is **'Improper monitoring of temperature-controlled supply chain (B1)'** when it is compared with **'Improper stock management (B2)'?**
Question 2	How important is **'Improper monitoring of temperature-controlled supply chain (B1)'** when it is compared with **'Unavailability of vaccines and equipment's (B3)?**
Question 3	How important is **'Improper monitoring of temperature-controlled supply chain (B1)'** when it is compared with **'Poor demand forecast (B4)'?**
Question 4	How important is **'Improper monitoring of temperature-controlled supply chain (B1)'** when it is compared with **'Higher lead-time gaps (B5)'?**
Question 5	How important is **'Improper monitoring of temperature-controlled supply chain (B1)'** when it is compared with **'Inadequate cool innovations for vaccine handling and storage (B6)'?**
Question 6	How important is **'Improper monitoring of temperature-controlled supply chain (B1)'** when it is compared with **'Environmental uncertainties (B7)'?**
Question 7	How important is **'Improper monitoring of temperature-controlled supply chain (B1)'** when it is compared with **'Improper transportation management (B8)'?**
Question 8	How important is **'Improper monitoring of temperature-controlled supply chain (B1)'** when it is compared with **'High vaccine wastage (B9)'?**
Question 9	How important is **'Improper monitoring of temperature-controlled supply chain (B1)'** when it is compared with **'Outdated methods of collecting and managing data and information on child vaccination (B10)'?**
Question 10	How important is **'Improper monitoring of temperature-controlled supply chain (B1)'** when it is compared with **'High rate of vaccine hesitancy (B11)'?**
Question 11	How important is **'Improper monitoring of temperature-controlled supply chain (B1)'** when it is compared with **'Inadequate training and programs for upgrading employee skills and education (B12)'?**
Question 12	How important is **'Improper monitoring of temperature-controlled supply chain (B1)'** when it is compared with **'Unavailability of healthcare workers (B13)'?**
Question 13	How important is **'Improper monitoring of temperature-controlled supply chain (B1)'** when it is compared with **'Vaccine regulatory complexities (B14)'?**
Question 14	How important is **'Improper monitoring of temperature-controlled supply chain (B1)'** when it is compared with **'Inadequate immunization surveillance, assessment and monitoring (B15)'?**

WITH RESPECT TO CRITERIA ‘ GOAL’		**Response**				
QUESTIONS	**COMPARISON BETWEEN BARRIERS**	**EI**	**WMI**	**SMI**	**VSMI**	**AMI**
Question 1	B1 and B2					
Question 2	B1 and B3					
Question 3	B1 and B4					
Question 4	B1 and B5					
Question 5	B1 and B6					
Question 6	B1 and B7					
Question 7	B1 and B8					
Question 8	B1 and B9					
Question 9	B1 and B10					
Question 10	B1 and B11					
Question 11	B1 and B12					
Question 12	B1 and B13					
Question 13	B1 and B14					
Question 14	B1 and B15					
	Opinion/suggestion of expert:					

Remark: Likewise, similar questions were designed for constructing pairwise comparison matrix between the rest of the barriers.

G.2. FMOORA questionnaire for prioritizing solutions to design NGVSCs.

Goal → **Q.No. ↓**	**With respect to prioritizing/ranking solutions to help design NGVSCs:**
Question 1	How important is solution **‘Improve communication between policy-makers and vaccine supply chain experts (S1)’** to remove/eliminate barrier **‘Improper monitoring of temperature-controlled supply chain (B1)’?**
Question 2	How important is **‘Improve communication between policy-makers and vaccine supply chain experts (S1)’** when it is compared with **‘Improper stock management (B2)’?**
Question 3	How important is **‘Improve communication between policy-makers and vaccine supply chain experts (S1)’** when it is compared with **‘Unavailability of vaccines and equipment’s (B3)’?**
Question 4	How important is **‘Improve communication between policy-makers and vaccine supply chain experts (S1)’** when it is compared with **‘Poor demand forecast (B4)’?**
Question 5	How important is **‘Improve communication between policy-makers and vaccine supply chain experts (S1)’** when it is compared with **‘Higher lead-time gaps (B5)’?**
Question 6	How important is **‘Improve communication between policy-makers and vaccine supply chain experts (S1)’** when it is compared with

	'Inadequate cool innovations for vaccine handling and storage (B6)'?
Question 7	How important is **'Improve communication between policy-makers and vaccine supply chain experts (S1)'** when it is compared with **'Environmental uncertainties (B7)'?**
Question 8	How important is **'Improve communication between policy-makers and vaccine supply chain experts (S1)'** when it is compared with **'Improper transportation management (B8)'?**
Question 9	How important is **'Improve communication between policy-makers and vaccine supply chain experts (S1)'** when it is compared with **'Outdated methods of collecting and managing data and information on child vaccination (B10)'?**
Question 10	How important is **'Improve communication between policy-makers and vaccine supply chain experts (S1)'** when it is compared with **'High rate of vaccine hesitancy (B11)'?**
Question 11	How important is **'Improve communication between policy-makers and vaccine supply chain experts (S1)'** when it is compared with **'Inadequate training and programs for upgrading employee skills and education (B12)'?**
Question 12	How important is **'Improve communication between policy-makers and vaccine supply chain experts (S1)'** when it is compared with **'Unavailability of healthcare workers (B13)'?**
Question 13	How important is **'Improve communication between policy-makers and vaccine supply chain experts (S1)'** when it is compared with **'Vaccine regulatory complexities (B14)'?**
Question 14	How important is **'Improve communication between policy-makers and vaccine supply chain experts (S1)'** when it is compared with **'Inadequate immunization surveillance, assessment and monitoring (B15)'?**

WITH RESPECT TO CRITERIA ' GOAL'		**Response**				
QUESTIONS	**COMPARISON BETWEEN SOLUTIONS AND BARRIERS**	**EI**	**WMI**	**SMI**	**VSMI**	**AMI**
Question 1	S1 and B2					
Question 2	S1 and B3					
Question 3	S1 and B4					
Question 4	S1 and B5					
Question 5	S1 and B6					
☐						
	Opinion/suggestion of expert:					

Remark: Likewise, similar questions were designed for constructing pairwise comparison matrix between the rest of the solutions and barriers.

Appendix H. Questionnaire based on EFA, Two-way assessment, and DEMATEL.

H.1. EFA questionnaire related to performance indicators of VSC.

Note: Sample questions of the questionnaire have been shown in this section because of the large size of the questionnaire items.

Please respond to each of the questions given below.

Question: According to you, "How important are the given performance indicators in measuring vaccine supply chain performance"?

H.1.1. Finance dimension of BSC

	Not Important	Slightly Important	Moderately Important	Important	Very Important
1. *Reduction in total supply chain costs*	○	○	○	○	○
2. *Vaccine procurement costs*	○	○	○	○	○
3. *Reduction in wastage costs*	○	○	○	○	○
4. *Reduction in inventory costs*	○	○	○	○	○
5. *Growth of earnings growth rate*	○	○	○	○	○

H.1.2. Customer dimension of BSC

	Not Important	Slightly Important	Moderately Important	Important	Very Important
6. *Less distance to travel to health centers for vaccination*	○	○	○	○	○
7. *Better vaccination services and proper attitude of health workers towards parents*	○	○	○	○	○
8. *Reduction in parents complaints*	○	○	○	○	○
9. *Enhancement to reply to parents problems*	○	○	○	○	○
10. *Provide better knowledge to parents to enhance their awareness regarding vaccination benefits*	○	○	○	○	○

H.1.2. Internal process dimension of BSC

	Not Important	Slightly Important	Moderately Important	Important	Very Important
11. *Enhancement of emergency supply chains*	◯	◯	◯	◯	◯
12. *Reduction in time through system*	◯	◯	◯	◯	◯
13. *Increase in annual number of inventory turns*	◯	◯	◯	◯	◯
14. *Increase in percentage personnel time dedicated to logistics*	◯	◯	◯	◯	◯
15. *Increase in transport capacity*	◯	◯	◯	◯	◯

H.1.1. Learning and growth dimension of BSC

	Not Important	Slightly Important	Moderately Important	Important	Very Important
1. *Enhancement of degree of employee work satisfaction*	◯	◯	◯	◯	◯
2. *Enhancement of employee motivation and empowerment*	◯	◯	◯	◯	◯
3. *Enhancement of employee productivity*	◯	◯	◯	◯	◯
4. *Reduction of employee turnover rate*	◯	◯	◯	◯	◯
5. *Assessing and improvement in data and internal and external information systems*	◯	◯	◯	◯	◯

H.2. EFA questionnaire related to sustainability practices criteria's in immunization programs.

Please respond to each of the questions given below.

Question: According to you, "How important are the given sustainability practice's criteria's for sustainable development of child immunization programs in India?

H.2.1. Social dimension of sustainable development

	Not Important	Slightly Important	Moderately Important	Important	Very Important
1. *Increase in number of employees*	○	○	○	○	○
2. *Enhancement of benefits provided to employees*	○	○	○	○	○
3. *Enhancement of benefits provided to full-time employees that are not provided to temporary or part-time employees*	○	○	○	○	○
4. *Reduce the incidence of health and safety problems*	○	○	○	○	○
5. *Workers representation in formal joint management-worker health and safety committees*	○	○	○	○	○

H.2.2. Economy dimension of sustainable development

	Not Important	Slightly Important	Moderately Important	Important	Very Important
6. *Reduce economic impacts of deteriorating social or environmental conditions*	○	○	○	○	○
7. *Maintain changes in the productivity of immunization programs*	○	○	○	○	○

8. *Reduce economic impacts from the use of products and services*	O	O	O	O	O
9. *Increase economic development in areas of high poverty for better immunization*	O	O	O	O	O
10. *Reduce economic impacts from a change in operation or activity location*	O	O	O	O	O

H.2.3. Environmental dimension of sustainable development

	Not Important	Slightly Important	Moderately Important	Important	Very Important
11. *Maximizing the reclaimed products and packaging material*	O	O	O	O	O
12. *Installing solar power and another energy forms*	O	O	O	O	O
13. *Minimizing vaccine travel distance or choosing eco-friendly or environmentally-friendly vehicles*	O	O	O	O	O
14. *Substituting old, inefficient kerosene and gas refrigerators by energy-efficient refrigeration system*	O	O	O	O	O
15. *Permitting transportation of certain thermostable vaccines in controlled temperature chains without the need for ice packs*	O	O	O	O	O

H.3. Two-way assessment related questionnaires to measure impact of KPIs.

H.3.1. AHP questionnaire for obtaining priority weights of IP and LAG dimensions of BSC, to be used for Two-way assessment.

Note: The objective of the questionnaire is to weight/rank the key performance indicators of vaccine supply chain based on their level of importance on vaccine supply chain performance improvement. The instruction to fill the questionnaire is given below:

<u>Instructions for filling the questionnaire:</u>

1. A list of items and their symbols are shown in Table H.1. These items are the key performance indicators of vaccine supply chain.

2. Each questionnaire item has to compared with each other. For example, if you are comparing item **'Improvement in delivery responsiveness (INP1)'** with item **'Increase in outreach centres (INP2)'** from the list of key performance indicators, then, based on your opinions you have to rate the importance of item INP1 when it is compared with the INP2. Likewise, compare all the items of Table H.1.
3. The scale for comparison of two items is **"Equally important (EI) -1 ", "Moderately important (MI) – 3", "Strongly important (SI) – 5", "Extremely important (EXI) – 7", "Extremely more important (EXMI) – 9"**.
4. You have to record your opinions in Table H.2, which you will find attached alongside the questionnaire.

Based on the given instructions, the expert's completed the questionnaire. Table H.1 is the Table containing KPIs with their denotation, and Table H.2 is an empty pairwise comparison matrix given to the experts for recording their responses.

H.3.2. Questionnaire for calculating current utility using Two-way assessment.

Note: The objective of the questionnaire is to measure the impact of the key performance indicators on vaccine supply chain performance improvement. The instruction to fill the questionnaire is given below:

Instructions for filling the questionnaire:

1. A list of items and their symbols are shown in Table H.3. These items are the key performance indicators of vaccine supply chain.
2. Based on your opinions, rate each of the items on how it will have an impact on improving vaccine supply chain performance. For example, how would you rate the item **'Increase in supply chain dashboards (LAH10)'** in improving vaccine supply chain performance.
3. You have to record your opinions with a tick mark ✓ in Table H.4, which you will find attached alongside the questionnaire.
4. The scale for rating the items is **"Very low impact – Rank 1", "Low impact – Rank 2", "Moderate impact – Rank 3", "High impact – Rank 4", "Very high impact – Rank 5"**.

Based on the given instructions, the expert's completed the questionnaire. Table H.3 is the Table containing KPIs with their denotation, and Table H.4 is response sheet to measure the impact, shown below.

Table H.4. Response sheet for calculating the impacts of KPIs.

	Very low impact	Low impact	Moderate impact	High impact	Very high impact
INP1					
INP2					
INP3					
INP4					
INP5					
□					

H.3.3. Questionnaire for DEMATEL to check the stability of results obtained from Two-way assessment.

H.3.3.1. DEMATEL

The DEMATEL is one the popular methods that uses expert's opinions to rank the items or dimension and to draw a causal relationship between the dimension of any system, process, or organization.

The steps used in the DEMATEL methodology are summarized as follows [412]:

Step 1: Construct an initial-direct relation matrix (A), which is a pairwise comparison matrix using expert' opinions. To incorporate all the responses from H respondent, the initial or average direct relation matrix $'a_{ij}'$ is developed by using Eq. (H.1) as follows:

$$a_{ij} = \frac{1}{H}\sum_{K=1}^{H} x_{ij}^{k} \qquad \text{(H.1)}$$

where K = number of respondents with $1 \le ij \le H$

k = number of factors

Step 2: Compose a normalized direct-relation matrix (D) using Eq. (2):

$$D = A\lambda$$

$$where, \lambda = Min\left[\frac{1}{\max\sum_{j=1}^{n} a_{ij}}, \frac{1}{\max\sum_{i=1}^{n} a_{ij}}\right] \qquad \text{(H.2)}$$

Step 3: Compute the total relation matrix (T) by using Eq. (3):

$$T = D(I - D)^{-1} \qquad \text{(H.3)}$$

where represents the identity matrix.

Step 4: Compute the prominence $(r + c)$ and relation $(r - c)$ value for each factor using Eqs. (4) and (5):

$$r_{sum} = \left[\sum_{b=1}^{n} t_{ab}\right]_{n\times 1} \qquad (H.4)$$

$$c_{sum} = \left[\sum_{a=1}^{n} t_{ab}\right]_{1\times n} \qquad (H.5)$$

Step 5: Rank the factors using prominence $(r + c)$ values. The vector $(r_i + c_i)$ named as 'Prominence" exhibits the overall effect contributed and experience by a factor i.

H.3.3.2. Questionnaire preparation

Note: The objective of the questionnaire is to rank the key performance indicators of vaccine supply chain based on their level of importance on vaccine supply chain performance improvement. The instruction to fill the questionnaire is given below:

<u>Instructions for filling the questionnaire:</u>

1. A list of items and their symbols are shown in Table H.5. These items are the key performance indicators of vaccine supply chain.
2. Each questionnaire item has to compared with each other. For example, if you are comparing item **'Improvement in delivery responsiveness (INP1)'** with item **'Increase in outreach centres (INP2)'** from the list of key performance indicators, then, based on your opinions you have to rate the influence of item INP1 when it is compared with the INP2. Likewise, compare all the items of Table H.5.
3. The scale for comparison of two items is **"No influence - 0 "**, **"Very low influence - 1", "Low influence - 2"**, **"High influence – 3"**, **"Very high influence - 4"**.
4. You have to record your opinions in Table H.6, which you will find attached alongside the questionnaire.

<u>Based on the given instructions, the expert's completed the questionnaire. Table H.5 is the Table containing KPIs with their denotation, and Table H.6 is an empty direct relationship matrix given to the experts for recording their responses.</u>

H.3.3.3. Initial direct-relationship matrix (A) and Total-relationship matrix (T)

Using expert's responses, initial direct-relationship matrix and total relationship matrix is calculated from Eq. H.1-H.3, and is shown in Table H.7 & H.8. Finally, using Eq. H.5-H.6, prominence and relation values are calculated, shown in Table 7.19.

Table H.7. Initial direct-relationship matrix (A).

	INP1	INP2	INP3	INP4	INP5	INP6	INP7	INP8	INP9	INP10	INP11	INP12	INP13	INP14	INP15	INP16	INP17	INP18	INP19	LAG1	LAG2	LAG3	LAG4	LAG5	LAG6	LAG7	LAG8	LAG9	LAG10	LAG11	LAG12	LAG13
INP1	0.000	2.125	1.750	2.000	1.625	2.500	2.750	2.125	2.000	1.625	2.750	2.375	1.625	1.125	2.000	1.250	2.125	2.625	2.375	0.625	1.375	2.875	1.625	2.250	1.750	2.625	1.750	1.500	1.875	2.125	1.875	0.875
INP2	2.500	0.000	2.375	1.875	1.250	1.250	1.500	1.750	1.750	1.125	1.500	2.125	2.000	1.875	1.750	2.000	2.000	1.500	2.000	2.250	2.375	2.250	1.875	2.500	2.000	1.875	1.750	1.875	2.250	2.000	1.500	1.125
INP3	1.625	1.500	0.000	1.750	1.500	1.875	1.250	2.375	2.000	1.500	1.500	1.875	2.000	1.125	2.250	2.125	2.625	1.625	1.500	2.500	2.250	2.375	1.875	1.750	1.375	1.625	1.750	1.500	2.625	2.375	2.375	1.000
INP4	2.500	1.750	2.250	0.000	1.625	1.750	1.750	2.000	1.750	0.875	1.750	0.625	1.625	2.125	2.750	2.250	2.000	1.750	2.750	2.375	1.250	1.125	2.375	2.750	2.125	2.000	1.375	1.875	1.250	1.750	2.750	2.000
INP5	1.625	1.625	1.000	2.375	0.000	1.875	2.375	2.000	2.250	1.375	2.500	2.625	1.125	1.750	2.000	1.625	2.750	1.750	1.250	1.125	2.625	2.375	2.750	1.500	2.625	2.375	1.125	2.500	2.125	1.625	1.750	2.000
INP6	2.125	2.125	1.750	2.750	1.750	0.000	2.125	1.625	1.625	1.750	2.000	2.375	1.500	2.125	2.000	1.875	1.625	1.125	1.000	2.125	2.125	2.750	2.500	2.500	2.125	1.625	2.250	1.875	1.250	1.500	1.375	1.875
INP7	2.250	2.625	1.250	2.500	1.625	2.375	0.000	1.750	2.375	2.375	2.125	2.125	1.875	2.125	0.625	1.500	1.875	1.750	2.625	2.750	2.125	1.750	1.625	2.000	2.875	1.375	1.750	2.750	2.750	2.250	2.000	2.125
INP8	2.000	1.250	2.250	1.375	2.625	1.750	1.750	0.000	1.500	2.375	2.500	1.875	1.625	1.375	2.250	1.125	1.875	1.875	1.875	1.250	1.875	1.875	2.375	2.375	1.625	1.750	2.000	2.375	2.250	1.750	2.500	1.875
INP9	1.500	2.750	1.750	0.750	1.625	1.250	2.250	2.125	0.000	1.875	1.750	2.375	1.750	1.875	2.125	2.500	2.625	1.125	2.375	3.250	1.750	2.125	1.875	2.250	2.000	2.625	2.625	1.375	2.375	1.875	2.625	1.625
INP10	1.125	1.250	1.625	2.125	2.250	1.250	2.125	1.500	2.250	0.000	2.375	2.250	2.250	1.875	2.375	1.750	2.375	1.875	2.875	1.875	2.125	1.875	1.875	3.000	1.250	2.500	1.750	2.000	1.625	2.625	2.250	3.125
INP11	2.500	2.125	1.500	1.250	1.250	2.125	1.625	2.375	2.375	1.750	0.000	2.625	1.000	1.875	1.125	2.125	1.625	1.875	1.875	2.750	2.625	2.000	2.250	2.625	1.500	3.375	1.625	2.250	1.625	1.250	2.000	1.375
INP12	2.000	2.375	2.500	2.250	1.875	2.250	1.875	2.000	2.250	1.750	1.750	0.000	2.250	2.375	1.875	1.625	2.250	2.375	2.000	2.750	2.500	2.625	1.250	1.750	2.625	2.625	1.500	1.375	2.125	2.375	1.375	1.750
INP13	1.500	1.625	2.375	2.000	1.000	2.000	2.125	1.875	1.625	1.625	1.625	1.750	0.000	2.750	2.000	0.625	1.500	1.625	1.250	2.500	3.000	2.125	2.750	3.500	1.500	2.750	1.500	1.750	2.500	1.500	2.625	2.375
INP14	1.375	1.250	1.375	2.750	1.625	1.500	1.750	1.000	1.625	2.125	2.250	1.250	1.875	0.000	2.000	2.000	2.750	1.375	1.750	1.875	1.125	2.500	2.125	2.500	1.875	3.000	2.000	2.625	2.125	1.625	1.625	2.125
INP15	1.500	2.125	1.625	3.000	1.625	2.125	1.625	2.375	2.375	1.750	1.750	1.500	2.875	1.750	0.000	2.625	1.000	1.875	1.125	2.125	1.625	1.875	1.875	2.750	2.625	2.000	2.250	2.625	1.500	3.375	1.625	2.250
INP16	2.875	2.250	2.250	3.000	2.375	2.250	1.500	2.875	1.625	1.625	2.250	2.000	1.625	1.125	2.125	0.000	1.625	2.750	1.125	2.375	2.125	1.625	2.000	2.250	1.750	2.750	2.250	2.125	1.875	2.375	2.250	1.625
INP17	1.375	1.625	2.250	1.625	2.500	2.375	2.500	2.500	2.125	2.250	2.125	2.000	2.375	1.750	1.875	2.125	0.000	1.375	1.125	2.875	2.375	1.375	0.875	3.000	2.000	2.000	1.750	1.125	1.625	2.125	1.625	1.750
INP18	2.000	1.250	1.750	2.000	1.875	1.000	2.375	2.000	2.000	1.500	2.250	1.750	1.875	1.875	2.625	2.125	1.625	0.000	2.000	2.000	2.625	1.250	1.625	2.375	1.750	2.375	2.875	2.375	1.625	1.875	2.625	2.000
INP19	1.125	0.750	1.250	2.000	2.500	1.250	1.750	2.125	1.500	1.875	1.250	2.125	2.250	1.750	2.625	1.750	2.250	1.125	0.000	2.000	2.125	2.750	1.750	1.875	2.125	1.625	2.250	1.750	2.250	2.125	1.125	1.625
LAG1	2.000	2.125	2.250	1.000	2.125	2.000	2.125	2.750	2.250	2.125	2.625	1.250	1.000	2.625	2.250	1.000	2.500	2.625	1.125	0.000	1.500	2.125	1.375	2.250	1.875	1.500	2.375	2.250	1.500	1.500	1.000	1.625
LAG2	1.625	2.875	2.250	2.375	2.125	1.625	2.250	2.750	2.000	2.750	1.750	2.500	2.375	2.375	2.875	2.500	2.000	1.625	2.250	1.875	0.000	2.625	1.875	1.750	3.125	1.750	1.375	2.625	1.125	1.375	1.250	1.750
LAG3	2.375	0.875	2.750	1.500	2.625	2.750	1.875	2.875	2.125	2.125	2.750	1.125	1.750	2.500	2.375	2.500	1.500	1.375	3.000	1.625	2.000	0.000	2.500	2.500	2.625	2.250	2.625	1.875	2.125	2.875	2.250	2.000
LAG4	2.500	2.375	1.625	2.125	3.000	1.750	2.500	1.750	1.375	2.250	2.000	2.750	2.375	1.500	2.375	2.000	2.000	1.625	1.125	2.375	2.000	1.625	0.000	1.250	2.375	1.625	2.125	3.000	2.750	1.500	1.875	2.250
LAG5	2.000	1.250	1.750	1.875	1.500	2.000	2.750	2.125	1.500	1.375	2.750	1.625	2.625	1.375	2.125	2.125	2.375	2.625	1.125	1.500	1.250	2.250	2.375	0.000	2.500	1.750	1.375	2.000	1.625	1.750	1.375	1.375
LAG6	2.125	1.500	2.125	1.500	2.750	2.250	2.625	1.875	1.125	1.750	2.250	1.500	2.000	2.000	2.125	2.500	1.875	3.125	2.250	2.500	2.250	2.500	1.875	1.750	0.000	1.875	1.625	1.625	1.875	2.125	2.750	2.125
LAG7	2.250	1.250	1.500	1.750	1.375	2.375	1.375	2.500	2.000	1.875	2.375	1.125	2.875	1.875	2.875	2.875	2.625	2.375	1.875	2.500	2.875	1.125	1.250	0.250	1.750	0.000	2.000	2.500	1.750	2.000	1.750	2.125
LAG8	2.000	2.625	3.000	2.000	2.375	1.250	1.875	2.250	1.125	2.500	2.375	1.875	1.625	2.750	2.625	1.875	1.875	1.500	1.875	1.875	1.875	2.125	1.250	1.625	2.250	1.000	0.000	2.125	1.625	2.500	2.125	2.625
LAG9	2.750	1.750	1.875	2.250	1.750	2.875	2.250	2.000	2.000	2.250	1.750	2.625	2.500	2.250	2.750	1.250	2.250	2.625	2.375	2.375	2.375	2.000	2.000	1.500	2.250	2.500	2.500	0.000	2.250	1.625	2.125	1.750
LAG10	2.250	1.625	1.375	2.250	2.750	1.375	2.750	2.250	1.500	2.125	2.250	1.000	2.250	2.375	1.750	1.875	1.625	3.000	2.500	2.375	2.375	2.750	2.625	2.000	2.125	1.750	1.250	1.750	0.000	2.750	1.875	2.125
LAG11	1.750	2.125	1.500	2.000	2.125	2.250	1.625	1.875	1.750	2.875	2.375	2.375	1.875	2.250	2.000	1.625	1.250	2.375	1.625	2.375	2.625	2.500	2.375	1.625	1.625	2.375	1.875	1.500	1.750	0.000	2.625	2.250
LAG12	2.375	2.375	1.250	2.250	2.500	2.250	1.875	1.625	1.875	1.250	0.875	2.500	1.625	1.750	2.125	2.500	2.625	2.250	2.000	1.625	2.875	1.375	1.500	1.750	2.375	2.375	2.500	2.250	2.875	2.750	0.000	1.250
LAG13	0.750	1.125	1.875	2.375	2.375	2.250	0.500	1.875	1.500	2.125	1.625	1.625	1.875	2.375	2.250	2.375	2.000	1.750	2.250	2.000	1.250	2.375	2.375	1.875	1.625	1.750	2.750	2.375	1.250	1.875	1.750	0.000

Table H.8. Total-relationship matrix (T).

	INP1	INP2	INP3	INP4	INP5	INP6	INP7	INP8	INP9	INP10	INP11	INP12	INP13	INP14	INP15	INP16	INP17	INP18	INP19	LAG1	LAG2	LAG3	LAG4	LAG5	LAG6	LAG7	LAG8	LAG9	LAG10	LAG11	LAG12	LAG13
INP1	0.2621	0.2743	0.2767	0.2990	0.2911	0.2958	0.3055	0.3119	0.2772	0.2775	0.3160	0.2911	0.2849	0.2791	0.3174	0.2788	0.3020	0.2990	0.2863	0.2961	0.3024	0.3204	0.2860	0.3154	0.3029	0.3198	0.2869	0.2969	0.2868	0.3036	0.2895	0.2636
INP2	0.2883	0.2357	0.2772	0.2878	0.2768	0.2694	0.2790	0.2972	0.2647	0.2619	0.2891	0.2782	0.2811	0.2804	0.3044	0.2796	0.2912	0.2750	0.2718	0.3083	0.3056	0.3025	0.2802	0.3089	0.2966	0.2993	0.2775	0.2923	0.2828	0.2921	0.2747	0.2580
INP3	0.2751	0.2566	0.2423	0.2850	0.2797	0.2770	0.2744	0.3049	0.2673	0.2663	0.2878	0.2739	0.2798	0.2691	0.3101	0.2804	0.2984	0.2754	0.2636	0.3108	0.3032	0.3027	0.2792	0.2977	0.2868	0.2947	0.2768	0.2861	0.2869	0.2965	0.2860	0.2556
INP4	0.2915	0.2637	0.2778	0.2649	0.2855	0.2798	0.2856	0.3039	0.2678	0.2613	0.2957	0.2610	0.2791	0.2866	0.3220	0.2867	0.2949	0.2817	0.2848	0.3135	0.2934	0.2900	0.2906	0.3160	0.3017	0.3046	0.2764	0.2965	0.2724	0.2921	0.2954	0.2732
INP5	0.2888	0.2709	0.2696	0.3079	0.2717	0.2908	0.3038	0.3137	0.2837	0.2777	0.3159	0.2978	0.2814	0.2914	0.3213	0.2875	0.3144	0.2906	0.2739	0.3070	0.3228	0.3169	0.3048	0.3081	0.3189	0.3200	0.2815	0.3146	0.2932	0.2996	0.2909	0.2826
INP6	0.2894	0.2719	0.2745	0.3065	0.2898	0.2574	0.2935	0.3016	0.2688	0.2763	0.3025	0.2877	0.2798	0.2902	0.3143	0.2842	0.2922	0.2754	0.2640	0.3132	0.3082	0.3156	0.2951	0.3156	0.3050	0.3023	0.2906	0.2992	0.2746	0.2913	0.2791	0.2747
INP7	0.3104	0.2968	0.2859	0.3230	0.3086	0.3102	0.2837	0.3241	0.2976	0.3043	0.3247	0.3039	0.3045	0.3103	0.3170	0.2980	0.3165	0.3042	0.3061	0.3437	0.3299	0.3234	0.3028	0.3301	0.3358	0.3203	0.3035	0.3315	0.3151	0.3219	0.3075	0.2969
INP8	0.2872	0.2594	0.2805	0.2876	0.3024	0.2824	0.2887	0.2782	0.2673	0.2852	0.3092	0.2817	0.2819	0.2796	0.3179	0.2738	0.2959	0.2860	0.2761	0.3009	0.3058	0.3036	0.2936	0.3136	0.2979	0.3044	0.2873	0.3063	0.2890	0.2951	0.2949	0.2748
INP9	0.2954	0.2946	0.2887	0.2940	0.3041	0.2902	0.3105	0.3251	0.2597	0.2931	0.3148	0.3026	0.2986	0.3019	0.3325	0.3077	0.3221	0.2909	0.2971	0.3456	0.3201	0.3231	0.3008	0.3281	0.3190	0.3322	0.3112	0.3080	0.3057	0.3129	0.3111	0.2856
INP10	0.2917	0.2753	0.2885	0.3159	0.3146	0.2927	0.3107	0.3186	0.2941	0.2684	0.3255	0.3033	0.3081	0.3043	0.3389	0.2999	0.3209	0.3030	0.3065	0.3291	0.3276	0.3218	0.3039	0.3410	0.3110	0.3335	0.3014	0.3193	0.2971	0.3251	0.3085	0.3089
INP11	0.2992	0.2761	0.2750	0.2899	0.2876	0.2920	0.2914	0.3172	0.2836	0.2810	0.2788	0.2961	0.2777	0.2909	0.3077	0.2921	0.2976	0.2908	0.2804	0.3268	0.3206	0.3100	0.2955	0.3214	0.3009	0.3317	0.2869	0.3092	0.2845	0.2923	0.2918	0.2716
INP12	0.3079	0.2943	0.3048	0.3208	0.3129	0.3099	0.3114	0.3295	0.2975	0.2968	0.3212	0.2741	0.3112	0.3149	0.3360	0.3016	0.3228	0.3137	0.2981	0.3451	0.3367	0.3365	0.2988	0.3280	0.3336	0.3389	0.3013	0.3139	0.3075	0.3253	0.3003	0.2930
INP13	0.2886	0.2724	0.2906	0.3049	0.2881	0.2941	0.3022	0.3140	0.2767	0.2831	0.3059	0.2870	0.2674	0.3075	0.3240	0.2755	0.2997	0.2909	0.2754	0.3276	0.3296	0.3159	0.3072	0.3381	0.3053	0.3267	0.2888	0.3069	0.3005	0.3000	0.3045	0.2897
INP14	0.2772	0.2574	0.2672	0.3048	0.2866	0.2777	0.2867	0.2914	0.2673	0.2801	0.3043	0.2701	0.2840	0.2584	0.3129	0.2846	0.3063	0.2775	0.2728	0.3085	0.2932	0.3097	0.2883	0.3137	0.2994	0.3200	0.2858	0.3079	0.2851	0.2916	0.2812	0.2771
INP15	0.2975	0.2874	0.2888	0.3273	0.3051	0.3043	0.3034	0.3299	0.2947	0.2927	0.3167	0.2920	0.3157	0.3020	0.3047	0.3109	0.3007	0.3032	0.2816	0.3319	0.3199	0.3213	0.3040	0.3373	0.3290	0.3260	0.3078	0.3271	0.2947	0.3346	0.3004	0.2963
INP16	0.3226	0.2947	0.3027	0.3331	0.3215	0.3116	0.3079	0.3434	0.2903	0.2963	0.3299	0.3049	0.3040	0.2986	0.3414	0.2796	0.3157	0.3211	0.2872	0.3409	0.3333	0.3237	0.3108	0.3361	0.3232	0.3424	0.3133	0.3264	0.3056	0.3269	0.3143	0.2925
INP17	0.2826	0.2689	0.2851	0.2951	0.3043	0.2952	0.3032	0.3185	0.2801	0.2876	0.3089	0.2869	0.2961	0.2893	0.3170	0.2915	0.2736	0.2834	0.2692	0.3285	0.3169	0.3013	0.2771	0.3275	0.3074	0.3123	0.2877	0.2932	0.2840	0.3043	0.2869	0.2771
INP18	0.2962	0.2683	0.2825	0.3056	0.3007	0.2808	0.3060	0.3166	0.2826	0.2819	0.3150	0.2882	0.2943	0.2957	0.3332	0.2966	0.3017	0.2683	0.2864	0.3213	0.3254	0.3041	0.2916	0.3231	0.3092	0.3225	0.3086	0.3159	0.2889	0.3061	0.3056	0.2850
INP19	0.2647	0.2429	0.2577	0.2859	0.2908	0.2656	0.2784	0.2981	0.2576	0.2690	0.2817	0.2742	0.2806	0.2754	0.3123	0.2723	0.2903	0.2655	0.2396	0.3006	0.2980	0.3051	0.2750	0.2962	0.2945	0.2915	0.2806	0.2869	0.2786	0.2901	0.2658	0.2625
LAG1	0.2841	0.2686	0.2781	0.2787	0.2919	0.2826	0.2908	0.3139	0.2750	0.2791	0.3084	0.2696	0.2699	0.2939	0.3143	0.2690	0.3015	0.2930	0.2628	0.2796	0.2967	0.3039	0.2764	0.3093	0.2979	0.2977	0.2899	0.3014	0.2753	0.2883	0.2712	0.2684
LAG2	0.3084	0.3063	0.3068	0.3287	0.3221	0.3069	0.3220	0.3456	0.2992	0.3158	0.3266	0.3155	0.3188	0.3200	0.3558	0.3189	0.3250	0.3088	0.3070	0.3390	0.3069	0.3421	0.3131	0.3344	0.3466	0.3330	0.3051	0.3373	0.2996	0.3175	0.3043	0.2985
LAG3	0.3292	0.2886	0.3228	0.3276	0.3405	0.3329	0.3276	0.3586	0.3105	0.3180	0.3520	0.3074	0.3202	0.3320	0.3606	0.3296	0.3290	0.3160	0.3269	0.3464	0.3469	0.3167	0.3327	0.3551	0.3506	0.3510	0.3331	0.3383	0.3238	0.3491	0.3287	0.3120
LAG4	0.3146	0.2943	0.2917	0.3191	0.3279	0.3026	0.3195	0.3249	0.2847	0.3029	0.3235	0.3131	0.3121	0.3020	0.3416	0.3052	0.3184	0.3032	0.2853	0.3388	0.3291	0.3217	0.2799	0.3201	0.3297	0.3243	0.3088	0.3360	0.3157	0.3125	0.3063	0.2994
LAG5	0.2832	0.2553	0.2696	0.2896	0.2817	0.2817	0.2980	0.3037	0.2629	0.2668	0.3082	0.2731	0.2910	0.2750	0.3106	0.2828	0.2974	0.2920	0.2610	0.3001	0.2922	0.3033	0.2890	0.2756	0.3049	0.2997	0.2742	0.2962	0.2757	0.2900	0.2753	0.2635
LAG6	0.3100	0.2824	0.2989	0.3113	0.3256	0.3102	0.3218	0.3277	0.2820	0.2968	0.3280	0.2966	0.3074	0.3094	0.3392	0.3136	0.3174	0.3243	0.3012	0.3410	0.3336	0.3345	0.3076	0.3278	0.2967	0.3287	0.3035	0.3182	0.3044	0.3220	0.3193	0.2982
LAG7	0.2983	0.2672	0.2783	0.3010	0.2927	0.2987	0.2909	0.3225	0.2816	0.2863	0.3155	0.2785	0.3067	0.2947	0.3356	0.3054	0.3138	0.3006	0.2832	0.3273	0.3280	0.3013	0.2855	0.2935	0.3073	0.2880	0.2957	0.3162	0.2890	0.3063	0.2925	0.2859
LAG8	0.2998	0.2903	0.3038	0.3098	0.3119	0.2883	0.3026	0.3240	0.2743	0.2994	0.3210	0.2938	0.2944	0.3117	0.3372	0.2969	0.3093	0.2936	0.2887	0.3237	0.3192	0.3212	0.2910	0.3179	0.3199	0.3081	0.2717	0.3162	0.2929	0.3192	0.3028	0.2975
LAG9	0.3320	0.2988	0.3091	0.3356	0.3253	0.3321	0.3308	0.3439	0.3070	0.3171	0.3353	0.3253	0.3286	0.3270	0.3633	0.3097	0.3369	0.3308	0.3165	0.3546	0.3497	0.3424	0.3226	0.3394	0.3433	0.3518	0.3290	0.3087	0.3229	0.3295	0.3242	0.3065
LAG10	0.3138	0.2858	0.2905	0.3235	0.3279	0.3000	0.3260	0.3350	0.2891	0.3044	0.3306	0.2916	0.3132	0.3169	0.3365	0.3068	0.3162	0.3247	0.3073	0.3416	0.3373	0.3402	0.3206	0.3338	0.3293	0.3294	0.3002	0.3224	0.2797	0.3326	0.3097	0.3007
LAG11	0.3006	0.2875	0.2867	0.3138	0.3126	0.3058	0.3036	0.3231	0.2868	0.3085	0.3253	0.3047	0.3019	0.3092	0.3334	0.2977	0.3048	0.3096	0.2892	0.3350	0.3342	0.3301	0.3104	0.3217	0.3157	0.3315	0.3028	0.3122	0.2984	0.2874	0.3134	0.2965
LAG12	0.3111	0.2928	0.2848	0.3192	0.3194	0.3074	0.3093	0.3215	0.2896	0.2875	0.3061	0.3078	0.3004	0.3036	0.3367	0.3111	0.3251	0.3100	0.2954	0.3265	0.3395	0.3164	0.2994	0.3246	0.3282	0.3326	0.3123	0.3234	0.3153	0.3282	0.2777	0.2837
LAG13	0.2651	0.2529	0.2715	0.2968	0.2943	0.2845	0.2659	0.3001	0.2624	0.2772	0.2922	0.2728	0.2805	0.2891	0.3135	0.2865	0.2927	0.2791	0.2762	0.3064	0.2916	0.3052	0.2890	0.3019	0.2927	0.2992	0.2935	0.3014	0.2700	0.2918	0.2799	0.2440