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Sustainable Supplier Selection and Order Allocation Using Fuzzy Multicriteria Decision Making and Multi Objective Optimization

by

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This thesis is dedicated to my late mother, father and friends for their continuous support, guidance and advise.

CERTIFICATE OF APPROVAL

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Abstract

For sustainable supply chain management, selection of an appropriate supplier based on sustainable criteria (conventional, environmental, and social) is the main concern of enterprises over the globe. Over the years, suppliers were evaluated on the basis of conventional criteria. However, with the growing concerns social and environmental aspects of sustainability are also under the evaluation. This research presents a holistic multi-phase framework to solve Sustainable Supplier Selection and Order Allocation (SSSOA) problem. In the first phase, sub-criteria were selected with the consultation of decision makers for evaluating sustainable supplier selection. The fuzzy extended analytical hierarchy process (fuzzy E-AHP) was applied to evaluate the relative weights of each sub-criteria. The fuzzy Technique for Order of Preference by Similarity to Ideal Solution (fuzzy TOPSIS) was applied to evaluate the conventional, environmental and social performance of potential suppliers. In second phase, consumer's demand was forecasted on the basis of month wise eight years demand data of case company. Moving Average (MA), Weighted Moving Average (WMA), Simple Exponential Smoothing (SES), Least Square Method (LSM), and Seasonal Auto Regressive Integrated Moving Average (SARIMA) techniques were used for the demand forecasting. The results of forecasting techniques were compared on the basis of least mean square error. In third phase, multiobjective Mixed Integer Nonlinear Programming (MOMINLP) mathematical model was developed. The model simultaneously optimizes the total cost, total travel time, environmental impact, total equivalent sound level, social impact, and total value of sustainable purchasing under conventional, environmental and social pillars of sustainability. The mathematical model was then solved using Augmented Epsilon Constraint 2 (AUGMECON2) and Weighted Metric Method (WMM) to find the pareto optimal solutions. In fourth phase, TOPSIS augmented with Criteria Importance Through Inter-criteria Correlation (CRITIC) weight method were used to select final pareto optimal solution obtained by comparing the results of two algorithms. A real time case study of air conditioning industry was used to assess the proposed framework. The results obtained from fuzzy E-AHP indicated that product quality, innovation capability, and staff personal and technical development ranked highest among three pillars of sustainability. The results also indicated that the decision makers preferred conventional, social and environmental criteria sequentially. It is also revealed that AUGMECON2 outperformed WMM. Finally, managerial implications of proposed methodology along with future recommendations are discussed for further research.

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Abbreviations

ACF	Auto Correlation Function
ADF	Augmented Dickey-Fuller
AHP	Analytic hierarchy process
AIC	Akaike's Information Criteria
AUGMECON2	Augmented Epsilon Constraint 2
CC	Closeness Coefficient
CI	Consistency Index
CR	Consistency Ratio
CRITIC	Criteria Importance Through Intercriteria Correlation
E-AHP	Extended Analytic Hierarchy Process
EI	Environmental Impact
EOQ	Economic Order Quantity
ERP	Enterprise Resource Planning
ESL	Equivalent Sound Level
FMOLP	Fuzzy Multi Objective Linear Programming
FST	Fuzzy Set Theory
MA	Moving Average
MCDM	Multi Criteria Decision Making
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non-Linear Programming
MOMINLP	Multi Objective Mixed Integer Non-Linear Programming
MSE	Mean Square Error
NDM	Normalized Decision Matrix
PACF	Partial Auto Correlation Function

RC	Relative Closeness
SARIMA	Seasonal Auto Regressive Integrated Moving Average
SCM	Supply Chain Management
SI	Social Impact
SSCM	Sustainable Supply Chain Management
SSOA	Supplier Selection and Order Allocation
SSSOA	Sustainable Supplier Selection and Order Allocation
TC	Total Cost
TOPSIS	Technique of Order Preference Similarity to the Ideal Solution
TT	Total Time
TVSP	Total Value of Sustainable Purchasing
WMA	Weighted Moving Average
WMM	Weighted Metric Method
WNDM	Weighted Normalized Decision Matrix

Chapter 1

Introduction

Supply chain management (SCM) is an interconnected framework of organizations involved in the provision of product and services to the end customers [1]. It plays pivotal role in organizations performance and has been studied in different aspects by the research community. Over the years, great public concern is drawn due to violation of corporate ethical codes by the organizations caused by the lack of environmental and social responsibility in supply chain operations [2, 3]. Therefore, both researchers and practitioners studied the prominent aspect of sustainable supply chain management (SSCM) [4, 5]. SSCM enables the organizations to achieve high logistics performance and resource utilization while pursing social, economic, and environmental goals of sustainability [6]. Nowadays, environmental and social impacts of supply chain is becoming an increasing concern for organizations over the globe [7, 8]. Therefore, enterprises are changing their policies and practices and have recognized the environmental and social protection of communities [9, 10].

SSCM is the integration of environmental and social issues in conventional SCM. Its objective is to gain the optimal compromise of three pillars of sustainability by managing the resources, data, assets, and merchandise amongst the entities of the supply chain. Previously, organizations developed their supply chains by only considering their conventional economic benefits. However, the concerns over depletion of ozone layer and natural resources, occupational and human safety, product safety, and child labor forced the global enterprises to incorporate the impact of environmental pollution and social security in their supply chains [11].

Mostly organizations focus on low production and transportation costs while compromising on environmental and social aspect of supply chains [12]. According to Harms et al. [13] cost reduction strategies adopted by managers tends to increase the risks at the production sites of the suppliers due to inadequate working or environmental conditions. Therefore, with growing concern related to these issues, sustainability is becoming an aspect on which the performance of an industry is judged [14]. SSCM allows the organizations to incorporate Corporate Social Responsibility (CSR) practices for achieving high efficiency in logistic performance and resource usage while reducing the social and environmental issues with in the supply chain.

Challenges like chemical content, labor practices, or impact on communities and habitats are originated in the operating practices of subcontractors and suppliers in the supply chains [15]. Preventive approach is adopted by the organizations by building sustainability criteria into its purchasing practices. This tends to increase the operational efficiency, low risks and innovative product development [16, 17].

Supplier selection can be classified into two groups: single sourcing and multiple sourcing. Single sourcing refers as the selection of best supplier by the decision makers to fulfill the entire customer/enterprise demand. On the other hand, multiple sourcing is the selection of more than one supplier as no single supplier can fulfill the customer/enterprise demand. Therefore, best suppliers should be selected by supply chain managers and decision makers for stabilized competitive environment [18]. However, extensive research suggested that multiple sourcing is preferred because of robust delivery and order flexibility by the both ends of supply chain (i.e. supplier and customer) [19].

Supplier selection is a complex MCDM process blended with various tangible and intangible criteria in order to assess the consistent suppliers. Several studies assessed the suppliers on the basis of uncertain and conflicting criteria like total cost, product quality, service level, and delivery time, [20–23]. With the growing concern regarding the environmental and social performance of supply chains, some new criteria have been evolved by stakeholders and academics over the years. This includes greenhouse emissions, waste management, recycling, disposal, and environmental quality controls etc. while evaluating environmental aspect. Whereas, social aspect includes, labor safety, employment index, cost effective community development, and staff personal and professional training etc. In recent years, many developing countries set their focus on social impact while evaluating their supply chains [24, 25]. In todays globalized businesses, sustainability is considered as the competitive advantage among organizations. Therefore, supplier selection and order allocation problem incorporate sustainable performance evaluation criteria thus aiming to increase the efficiency of supply chain for set of suppliers in order to purchase the right quantity from right supplier.

In multi variate problems, uncertainty in human decision making is fairly noticeable [26, 27]. Input parameters like costs, delivery time, and customer demand varies with respect to industries and coerce the decision makers to incorporate the aspect of uncertainty in activities [28]. A wealth of literature elucidated the importance of fuzzy logic in MCDM problems, see for instance, [29–32]. Zadeh [33] first proposed the Fuzzy Set Theory (FST) in MCDM to transform crisp numeric values for more precise judgement of real-world systems. FST is used to model the uncertainty of human judgements while performance rating and weights in the fuzzy MCDM [34]. In FST uncertainty of fuzzy sets is characterized through membership function. Therefore, this study used fuzzy MCDM techniques for the weight estimation of sustainable supplier selection criteria.

Supplier selection and order allocation problem is studied for very limited industries. Majority of the literature focused towards electronics, food, and agriculture industries. A very few studies analysed the suppliers for automotive industry. For instance, Hsu and Hu [35] evaluated the suppliers of an electronic company by incorporating the hazardous substance management (HSM) into supplier selection. Ninlawan et al. [36] evaluated green suppliers for computer parts manufacturers in Thailand. Lin et al. [37] analysed the effectiveness of enterprise resource planning (ERP) system in supplier selection for PC board suppliers. Banaeian et al. [38] studied the effect of green criteria while supplier selection in food industry. Amorim et al. [39] assessed the potential suppliers of food industry with uncertain demand. Jain et al. [40] evaluated the suppliers for Indian automobile industry using conventional MCDM techniques. Air conditioning industry is one of the fastest growing industry with market worth of $24.28 Billion [41, 42]. However, to the best of author knowledge no empirical study is available that evaluated the suppliers for air conditioning industry. Therefore, this study tried to evaluate the suppliers of an air conditioning company on the basis of sustainable performance indicators to meet the forecasted demand of a company.

Majority of the literature focused on economic and environmental aspects while investigating the supplier selection and order allocation problem [43–49]. Very few studies simultaneously investigated the three pillars of sustainability in supplier selection and order allocation problem. Furthermore, no study has simultaneously investigated the type of costs, times and equivalent sound level (i.e. noise pollution) as an objective function while considering economic, environmental and social aspect. In context of air conditioning industry, this is the first study to address the Sustainable Supplier Selection and Order Allocation (SSSOA) problem in addition with transfer cost, transfer time, custom clearance cost, custom clearance time, and equivalent sound level. Moreover, this is the first study that analyzed the supply chain with multi model transportation (i.e. sea, rail, and road) network in context of SSSOA problem.

1.1 Motivation

From the above discussion it can be concluded that SSSOA problem is multi criteria, multi objective complex decision-making problem. Sustainability in supply chain management is an emerging research area. Researchers and practitioners agreed to the fact that the goal of pursuing minimal total cost and maximal return on investment is interlinked with minimum delivery time, environmental impact and maximum purchasing value and social impact. Integration of sustainable practices while evaluating the suppliers will lead to competitive advantage. In today's global environment, complexity in supply chains is increasing with the involvement of multiple stakeholders. Efforts have been made to simultaneously analyse the economic and environmental performances of supply chains. However, studies that endeavor to optimize economic returns, environment concerns, and the social performance altogether for supply chains are rare. To the best of authors knowledge, no study was conducted until now that evaluates the suppliers of an air conditioning industry with respect to sustainable performance indicators. Keeping in view the above-mentioned facts, this study tends to provide a holistic framework that can provide an insight to decision makers and managers about SSSOA in air conditioning industry.

1.2 Scope of the Work

This study contributes to the body of knowledge by providing a holistic multi-phase framework for solving SSSOA problem for an air conditioning industry with multiple variable costs, times, emissions, and demand. It includes (1) criteria ranking using fuzzy E-AHP; (2) suppliers' ranking using fuzzy TOPSIS; (3) next period demand using established forecasting techniques; (4) MINLP mathematical modeling of multi echelon and multi- transportation mode supply chain of a case company was developed with respect to Total cost (includes purchasing cost, transportation cost, ordering cost, holding cost, transfer cost, and custom clearance cost), Total travel Time (includes transportation time, transfer time, and custom clearance time), Environmental Impact (particularly CO2 emissions), Total Equivalent Sound Level (i.e. measure of noise pollution), Social Impact, and Total Value Of Sustainable Purchasing as an objective functions to evaluate the sustainable performance of suppliers; (5) Mathematical model was analysed using Augmented Epsilon Constraint 2 (AUGMECON2) and Weighted Metric Method (WMM) algorithms to find the pareto optimal solutions; and finally (6) selection of best pareto optimal solution using TOPSIS augmented with CRITIC weight method.

1.3 Thesis Outline

The rest of the thesis is organized as follows:

Chapter 2

In this chapter, detailed literature on sustainable supplier selection criteria and techniques along with solving methods used for optimum order allocation is presented.

Chapter 3

This chapter firstly describes the proposed methodological framework and MCDM techniques. Secondly MINLP model for optimization of objective functions is presented. In the third phase, solution methods for solving the mathematical model are articulated. Lastly, forecasting techniques used for next period demand are described.

Chapter 4

This chapter presents the detailed analysis of the results obtained by applying the proposed framework on the case study

Chapter 5

This chapter concludes the preceding work along with managerial implications and suggests the avenues for future research.

Chapter 2

Literature Review

Managing the supply chain in sustainable manner turned out to be an increasing concern of organizations over the globe. SSCM comprises of economic, environmental, and social impact [50]. According to Pagell and Wu [51], the practices of SSCM are value driven fueled with desired environmental and social performance. It is a process of purchasing, producing, packaging, and transporting the goods while considering the ecological and social balance [52]. The sustainable performance of the supply chain can be reached by meeting the minimum threshold of environmental and social standards at various stages of supply chain [53]. According to Sheu et al. [54], SSCM is the integration of environmental and social issues in organizations buying decisions while encouraging companies to maintain steady relationship with green suppliers. The extensive literature is available to highlight the pivotal role of suppliers in SSCM.

Over the last decade, an extensive research is conducted on the role of suppliers and supplier selection techniques in context of SSCM. According to Jayaraman et al. [55], supplier selection is considered to be the most important strategic decision in SCM. Selecting the most appropriate suppliers impacts the supply chain at each level. Wolf [56] provided a framework in order to investigate the characteristics of suppliers in context of internal and external stakeholders needs to reduce risk in supply chain. Seuring and Gold [57] argued that organizations are shifted focus of social responsibility from firms to the supply chains by introducing more stakeholders in the supplier selection process.

2.1 Supplier Selection Criteria

In the decision-making process of supplier selection, the foremost question arises is which supplier and what quantity? This question also highlights the significance of purchasing from single or multiple sources/suppliers. To answer these questions, it is important to highlight the criteria on which the suppliers are evaluated.

Dickson [58] identified 23 different criteria for the evaluation of suppliers by distributing 273 questionnaires to managers and purchasing agents of United States and Canada. His study highlighted that product price, quality, on-time delivery, and supplier's effectiveness to meet the demand are the important factors for single supplier selection. Wilson [59] evaluated the relative preference of each supplier selection criteria and argued that product price, product quality, product delivery, and supplier service are the critical factors for single source supplier selection. Swift [60] determined the supplier evaluation criteria by conducting a survey of approximately 2000 purchasing managers affiliated with chemical and allied products, electronic equipment, and transportation equipment industries. His study concluded that product price, product availability, product design, supplier market reputation, and product reliability are the critical factors to evaluate the single and multiple suppliers. Vonderembse and Tracey [61] conducted a survey of 2000 purchasing managers affiliated with manufacturing industries of Midwest Region in order to identify their relative preferences for supplier selection criteria. According to them, product quality, product availability, product reliability, and product performance are the key factors to evaluate the suppliers. Lin et al. [62] evaluated four PC board suppliers with the help of customized enterprise resource planning (ERP) system. The study highlighted that time, cost and quality are the key factors for the success of ERP system. The suppliers were evaluated on the basis of product price, quality, delivery, service, and trust.

For multiple suppliers, Hong and Hayya [63] conducted an empirical research and concluded that multiple suppliers reduces the overall purchasing and inventory cost in a just-in-time environment. Their study highlighted that supplier's capacity, product quality, product on-time delivery, and product price are the important suppliers' evaluation criteria. Ghodsypour and O'Brien [64] highlighted the importance of single and multiple sourcing by considering total cost of purchasing and product quality as an evaluation criterion. Economic Order Quantities (EOQ) for both single and multiple sourcing was compared with and without constraints. Minner [65] did comprehensive review on multiple sourcing and argued that it can potentially increase the negotiation power of the buyer. In contrast to single supplier, multiple suppliers allow the buyer to mitigate risks under uncertain environment and create competitive advantages between potential suppliers.

2.2 Sustainable Supplier Selection Criteria

As discussed earlier, sustainability is a tri pillar approach with the combination of conventional, environmental and social aspect. Several studies highlighted the significance of sustainability in managing supply chain, see for instance [53, 75–78].

With the growing impact of sustainability in supply chain, various studies highlighted the importance of environmental and social pillars of sustainability. For example, Lu et al. [9] presented an approach for the evaluation of green supply chain. The multi criteria decision making (MCDM) techniques are used to evaluate the various links within the supply chain. The environment conscious product and supply chain design is constructed to enable the decision makers for better supply chain performance. Green et al. [43] did empirical research on green SCM in order to investigate the practices and performance models in manufacturing industry. The authors argued that while the majority of the organizations focused on economic aspects, they should adopt the environmental sustainability as a strategic imperative. The study further emphasized on including the environmental sustainability as an essential part of organization's mission. The organizations should develop manufacturing processes, delivery operations, and services in eco-friendly environment throughout the supply chain which would lead to better supply chain performance.

Zhang [49] developed a mathematical framework for designing supply chain networks by considering conventional, environmental and social objectives. In the first phase, customers' general and technical requirements are identified. Secondly, the relationship between the requirements are evaluated using established analytical approaches. Lastly, an integer linear programming model is developed with priority weights of requirements and system parameters for designing the supply chain network. Hutchins and Sutherland [79] studied corporate social responsibility in context of SCM. The study investigated the social sustainability measures and their implications on supply chain decision making. The study established a link between business monetary activities and social sustainability in order to demonstrate the impact of corporate decisions on national social sustainability measures. McCarthy et al. [80] studied the impacts of sustainability on various organizations. The study emphasized on incorporating the social pillar in organization's supply chain in order to provide an insight for supply chain managers about their social responsibilities. Mota et al. [81] studied the social impact of organizations supply chain by analyzing the facility location decisions along with their societal and economic performance. The developed mathematical model incorporated the job creation index along with population density of the region. The study concluded that better social contribution can be achieved with small compromise on economic performance for a small time period and would lead to long term financial benefits. However, Gallego-Álvarez et al. [7] and Mani et al. [8] highlighted that academics and practitioners least focused on social pillar of sustainability.

Walton et al. [82] did pioneer work by integrating environmental aspect with supply chain. Their study evaluated five furniture companies based equipped with ERP systems. Lee et al. [83] proposed a framework for the selection of green suppliers. Their study used MCDM technique for supplier evaluation on the basis of product quality, supplier technical capability, product life cycle cost, carbon foot print, supplier environment management system, supplier recycling capability, supplier green competencies as major criteria. The study emphasized that green production and environment protection are the critical part of social responsibility of supplier and supply chain. Govindan and Sivakumar [84] proposed a two-phase hybrid model for the selection of green supplier. The potential suppliers were evaluated on the basis of product cost, product quality, supplier on-time delivery, supplier's recycling capacity, and greenhouse gasses emission control. Mohammed et al. [85] highlighted the importance of sustainable livestock supplier selection by providing a framework for evaluating the suppliers on the basis of cost, supplier's technical capability, delivery reliability, enviro-waste management system, pollution production, supplier safety and staff development policies as sustainable criteria and sub-criteria. Lo et al. [86] used combination of 10 qualitative and quantitative economic, environmental and social criteria to evaluate the supplier performance. The study highlighted the relative preferences of criteria for various departments in an organization. Goren [87] used 13 sub-criteria for the evaluation of potential supplier with respect to economic, environmental and social aspect. The criteria were evaluated using MCDM techniques in order to obtain the relative preferences of decision makers. Table 2.1 presents the literature related to supplier selection criteria used by the researchers and practitioners.

2.3 Sustainable Supplier Selection Techniques

Researchers used various mathematical approaches and MCDM techniques (for instance, TOPSIS, AHP, analytic network process (ANP), quality function deployment (QFD), data envelopment analysis (DEA), and decision making trial and evaluation laboratory (DEMATEL) etc.) for the evaluation of sustainable suppliers see for instance [21, 56, 62, 77, 85, 90, 95–100]. However, Govindan et al. [23] and Chai et al. [100] highlighted that TOPSIS, AHP, VIKOR along with mixed integer mathematical programming are most widely used techniques for sustainable supplier selection problem.

Table 2.1: Summarized Literature Review for Sustainable Supplier Selection Criteria.

Authors	**Major Criteria**	**Sub Criteria**
Kannan et al. [22]	1. Cost 2. Quality 3. Delivery Reliability 4. Technology Capability 5. Environmental Metrix	N/A
Govindan and Sivakumar [84]	1. Cost 2. Quality 3. Delivery 4. Recycle capability 5. GHG emissions	1. Purchasing price 2. Order/setup cost 3. Control measures for GHG emissions 4. Inventory holding & Transportation cost 5. Quality systems 6. Product recycle and reuse
Mohammed et al. [85]	1. Conventional 2. Environmental 3. Social	1. Costs 2. Livestock healthiness or meat freshness 3. Delivery reliability 4. Environment management system 5. Technology capability 6. Waste management 7. Pollution production 8. Information disclosure 9. Safety, rights and health of employees 10. Staff development
Lo et al. [86]	1. Supplier Performance 2. Environmental Protection 3. Supplier Risk	1. Product quality 2. Green manufacturing 3. Service flexibility 4. Environmental performance 5. Innovation capability 6. Green logistic 7. Labour intensive 8. Financial stability 9. Supplier reputation 10. Information safety

Goren [87]	1. Economic 2. Social 3. Environmental	1. Price 2. Productivity 3. Capacity of the supplier 4. Long-term relationship – Continuity 5. Lead time 6. Production technology 7. Resource consumption 8. SMS 9. EMS
Mafakheri et al. [88]	1. Price Performance 2. Delivery Performance 3. Environmental Performance 4. Quality	1. Price increasing trend 2. Pay time 3. Penalty for delayed payment 4. Financial stability 5. Order fill rate 6. Flexibility in meeting customer needs 7. Perfect delivery rate 8. Green image 9. EMS
Vahidi et al. [89]	1. Economic 2. Environmental 3. Social	1. Transportation cost 2. Defective rate 3. Delivery lead time 4. Energy consumption 5. Capability of using green technologies 6. Technology level 7. Worker safety and labour health 8. Employee satisfaction 9. Job opportunity 10. Funding special projects (school, hospital, etc.) 11. Job security
Hamdan and Cheaitou [90]	1. Green 2. Traditional	1. Use of toxic substances 2. Use of resources 3. Green technology 4. Environmental management system 5. Staff training 6. Green market share

Ghadimi et al. [91]	7. Green image 2. Pollution control 3. Green competencies 4. Quality 5. Delivery/Service 6. Cost 7. Technical Capability 8. Health and Safety 9. Employment practises	1. Market reputation 2. Environmental management system 3. Safety audit and assessment 4. Internal Quality Audit 5. Production and transportation cost 6. Standardize health and safety conditions 7. Employee training and assessment

For example, Noci [101] evaluated the environmental efficiency of the suppliers using AHP. The case study of automotive industry is used to calculate the relative score of environmental performance for each supplier. Awasthi et al. [102] used a multi-stage framework of fuzzy TOPSIS for the selection of suppliers on the basis of eco-enviro aspect. Grisi et al. [45] evaluated the green supplier selection problem using fuzzy AHP. Büyüközkan and Çifçi [103] used hybrid framework augmented with fuzzy DEMATEL, fuzzy ANP, and fuzzy TOPSIS to evaluate the suppliers. Kannan et al. [104] used fuzzy TOPSIS augment with ad hoc weights to solve green supplier selection problem. Freeman and Chen [44] applied TOPSIS augmented with entropy and AHP method to evaluate the relative importance of sustainable suppliers. Table 2.2 summarize the literature related to solving techniques for sustainable supplier selection.

Table 2.2: Summarized Literature Review for Solving Techniques.

Research Studies	**Approaches**
Kannan et al. [22]	Fuzzy AHP-TOPSIS
Demirtas and Üstün [66]	ANP-AHP- MOMILP
Shankar and Yadav [67]	Fuzzy QFD
Hassanzadeh et al. [68]	SWOT
Songhori et al. [69]	Data Evaluation Analysis

Jadidi et al. [70]	TOPSIS
Kazemi et al. [71]	Interval based TOPSIS
Li et al. [72]	Fuzzy extended AHP
Ghorbani et al. [73]	SWOT and Entropy Weight Method
Zouggari and Benyoucef [74]	Fuzzy TOPSIS & CRITIC weight method
Govindan and Sivakumar [84]	Fuzzy TOPSIS
Mohammed et al. [85]	Fuzzy AHP-TOPSIS
Lo et al. [86]	Best-Worst Method & Fuzzy TOPSIS
Goren [87]	Fuzzy DEMATEL
Mafakheri et al. [88]	AHP-Dynamic Programming Approach
Vahidi et al. [89]	SWOT-QFD-DEMATEL
Scott et al. [95]	AHP-QFD
Hamdan and Cheaitou [90]	Fuzzy TOPSIS
Razmi and Rafiei [105]	ANP
Ghadimi et al. [91]	Multi-Agent Systems (MASs) approach
Gupta and Barua [99]	Best worst method & Fuzzy TOPSIS
Guo and Li [106]	Analytical (Q, R) Policy based analysis
Lin et al. [107]	ANP-TOPSIS

2.4 Order Allocation

Allocating optimum quantities to the potential suppliers is a complex decision problem [108]. Various mathematical models have been developed and optimized using different optimization algorithms by the researchers for the aid of decision makers and practitioners. Nazari-shirkouhi et al. [98] developed fuzzy MILP model under multi price and product uncertainty and used a novel exact algorithm for optimizing the quantity to be ordered by suppliers. Faez et al. [109] used scenario based MILP model for optimum quantity to solve using LP-LINGO optimization tool. Torabi et al. [110] modeled uncertainties and disruption risks using MILP and analyzed using augmented ϵ-constraint and differential evolution algorithm. Çebi and Otay [111] used MILP model with multi product uncertainties along with quantity discounts and analysed using augmented max-min and fuzzy goal programming algorithms to obtain optimum quantity for suppliers.

2.5 Sustainable Order Allocation

Previous studies included in Section 2.2 indicated that sustainable order allocation is done on the basis of set objectives which mainly includes cost, environmental and social impact that needs to be optimized. For evaluating optimum order quantity, single and multi-objective optimization models have been developed [46, 55, 85]. Jadidi et al. [70] compared crisp and fuzzy multi objective optimization model that tends to minimize total cost, defect rate, and late product delivery using normalized goal programming (NGP) method. Govindan and Sivakumar [84] used fuzzy TOPSIS and linear programming model to minimize total cost, quality rejection, late delivery, recycle waste, and greenhouse gases emissions. Goren [87] used fuzzy DEMATEL to calculate the weights of sustainable criteria considered in order to minimize total cost and maximize total value of purchasing. Hamdan and Cheaitou [90] developed a framework using mixed integer nonlinear programming model for analyzing green supply chain while maximizing total value and minimizing total cost of purchasing. Nazari-shirkouhi et al. [98] formulated two phased fuzzy multi objective linear programming (FMOLP) model to minimize total purchasing and ordering costs, the net number of rejected items from the suppliers, and the net number of late delivered items. The proposed model tends to incorporate uncertainty in information (incompleteness) and several conflicting criteria under conditions of multiple product and discount (multi-price level) environment and multiple sourcing. Table 2.3 summarizes the sustainable objectives and types of mathematical models used by the researchers and practitioners for optimum order allocation.

TABLE 2.3: Summarized literature of Sustainable Objective Functions and Model Type for Optimum Order Allocation.

Author s	**Objectives**	**Type of Mathematical Model**
Govindan and Sivakumar [84]	1. Total cost. 2. Quality rejection. 3. Late delivery. 4. Recycle waste. 5. Greenhouse gases emission.	MILP Model
Mohammed, et al. [85]	1. Total Cost 2. Travel time. 3. Environmental Impact. 4. Social Impact of Suppliers. 5. Total Purchasing Value.	Fuzzy- MILP Model
Vahidi et al. [89]	1. Total sustainability and resilience scores. 2. Total expected cost.	Two-Stage Mixed Possibilistic-Stochastic Programming Model.
Hamdan and Cheaitou [90]	1. Total green value of purchasing. 2. Total traditional value of purchasing. 3. Total cost of purchasing.	MILP Model

Ghadimi et al. [91]	1. Sustainability performance value. 2. Total purchasing cost.	MILP Model
Azadnia et al. [93]	Total Cost Social Impact Environmental Impact Total Value of Purchasing	MILP Model

2.6 Sustainable Order Allocation Techniques

Recently, incorporating the factors of sustainability in order allocation decisions has attracted considerable attention among scholars and industrialists [117]. Researchers used various exact, heuristics, and meta heuristics problem-solving algorithms (for instance, Epsilon Constraint Method, Weighted Sum Method, Goal Programming, and Genetic Algorithm etc.) for solving the objective functions [3, 21, 23, 85, 88, 93]. Table 2.4 presents the literature related to solving techniques for sustainable order allocation.

Table 2.4: Summarized Literature for Solving Algorithms used for Sustainable Order Allocation.

Research Studies	**Solving Algorithms**
Govindan and Sivakumar [84]	Weighted Additive Model (WAM)
Mafakheri et al. [88]	Dynamic Programming
Mohammed et al. [85]	Augmented ϵ-constraint method, WMM
Azadnia et al. [93]	Augmented ϵ-constraint method, WMM
Kumar et al. [118]	WMM
Vahidi et al. [119]	Weighted augmented ϵ-constraint method, Differential Evolution (DE) algorithm

2.7 Summary

To summarize, the literature reports extensive research has been done on the SSOA problem. It is a multi-dimensional comparative analysis process. With the growing interest of sustainability in the supply chains by the organizations, researcher shifted their focus to SSSOA.The researchers conducted extensive and wide-ranged surveys with managers and decision makers for the selection of appropriate criteria. Various stand-alone and hybrid MCDM techniques have been used for sustainable supplier selection out of which AHP augmented with TOPSIS used the most. Various single, bi, and multi objective models have been developed and solved using exact optimization algorithms for optimum order allocation. In recent years, researchers also included fuzzy set theory to incorporate the vagueness and uncertainty of decision-making process. Majority of the literature focused on conventional and green supplier selection and order allocation with the objectives of total cost, purchasing value, and environmental impact while determining the optimum order for suppliers with least focus on social impact. Furthermore, efforts are also underway to augment the appropriate sustainable criteria and objectives for supplier selection and optimum order allocation. However, there is still room to study the problem with more holistic approach by providing a concrete framework that incorporate multiple aspects of supply chain management. Moreover, the use of metaheuristics and hybrid exact optimization solving methods for allocation of the supplier's order is also very limited. Therefore, this study tries to provide a holistic approach that considers conventional, environmental, and social criteria listed in literature to evaluate the sustainable suppliers using fuzzy E-AHP and fuzzy TOPSIS. The forecasting techniques were used to determine the demand of the customer on the basis of eight-year month demand data. Total cost, total time, environmental impact, total value of sustainable purchasing, social impact, and total equivalent sound level (i.e. to incorporate noise pollution) are considered as the objectives to optimize using two solving algorithms. The pareto results of the both techniques are then compared to obtain final solution by applying TOPSIS along with CRITIC weight method.

Chapter 3

Methodology

3.1 Introduction

This chapter presents the methodology used to evaluate SSSOA problem. Sustainable supplier selection consists of multiple MCDM techniques for the evaluation of criteria and suppliers' relative weights. Once the suppliers are ranked, mathematical model consists of objective functions and constraints is developed for the optimal order allocation by augmenting the weights of suppliers in the objective functions. The mathematical model was solved using optimization algorithms for the optimized solution.

Figure 3.1 presents the multi echelon supply chain network problem. It consists of multiple suppliers, multiple ports, multiple warehouses, multiple customers, and multiple transportation modes. The supply chain network was evaluated in order to obtain an optimum sustainable quantity from the potential suppliers to meet the demand of the customers. Supplier i ship the quantity X_{ij} through port j to the warehouse k and then transported to the customer l using various modes m of transportation.

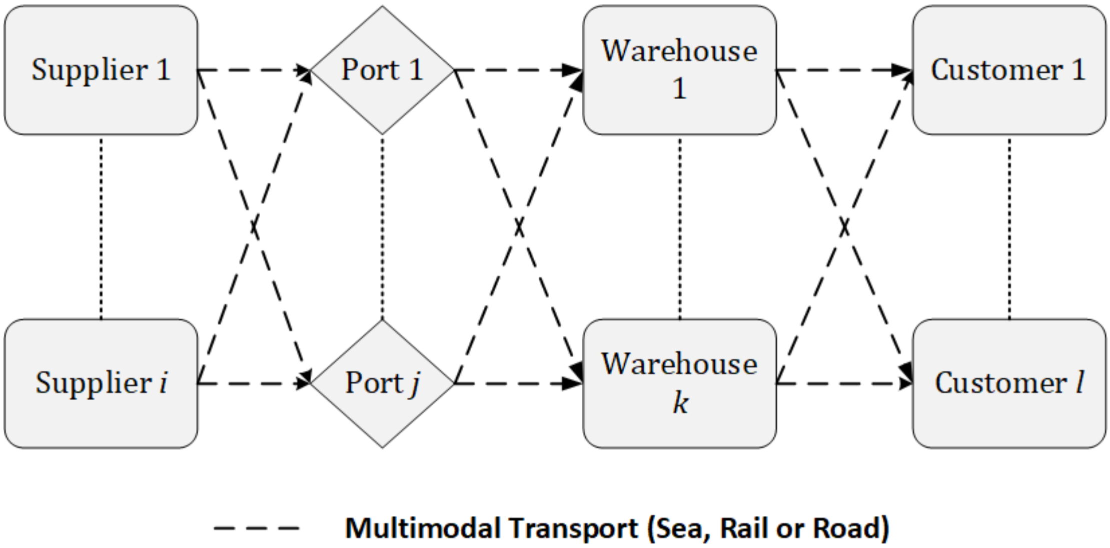

FIGURE 3.1: Multi Echelon Supply Chain Network.

3.2 Proposed Methodological Framework

This section comprises of comprehensive methodological framework used to solve the multi echelon supply chain networks shown in Figure 3.1. The proposed framework consists of four phases. In the first phase MCDM techniques were included in order to evaluate the suppliers in context of sustainable criteria. Second phase consists of customers demand estimation using conventional forecasting techniques. Third phase includes the mixed integer non-linear programming (MINLP) mathematical model to determine the sustainable optimum quantity for order allocation to each potential supplier. In the fourth phase, MCDM techniques are used to analyze the results obtained in previous phase in order to obtain the final results. The steps for each phase are given hereafter:

Phase 1

Step 1: Potential suppliers were identified. Selection of suppliers on the basis of three sustainable criteria (i.e. conventional, environmental and social).

Step 2: Selection of sub-criteria for each sustainable criterion after reviewing the literature (Table 1.2). Sixteen sub-criteria were selected corresponding to three

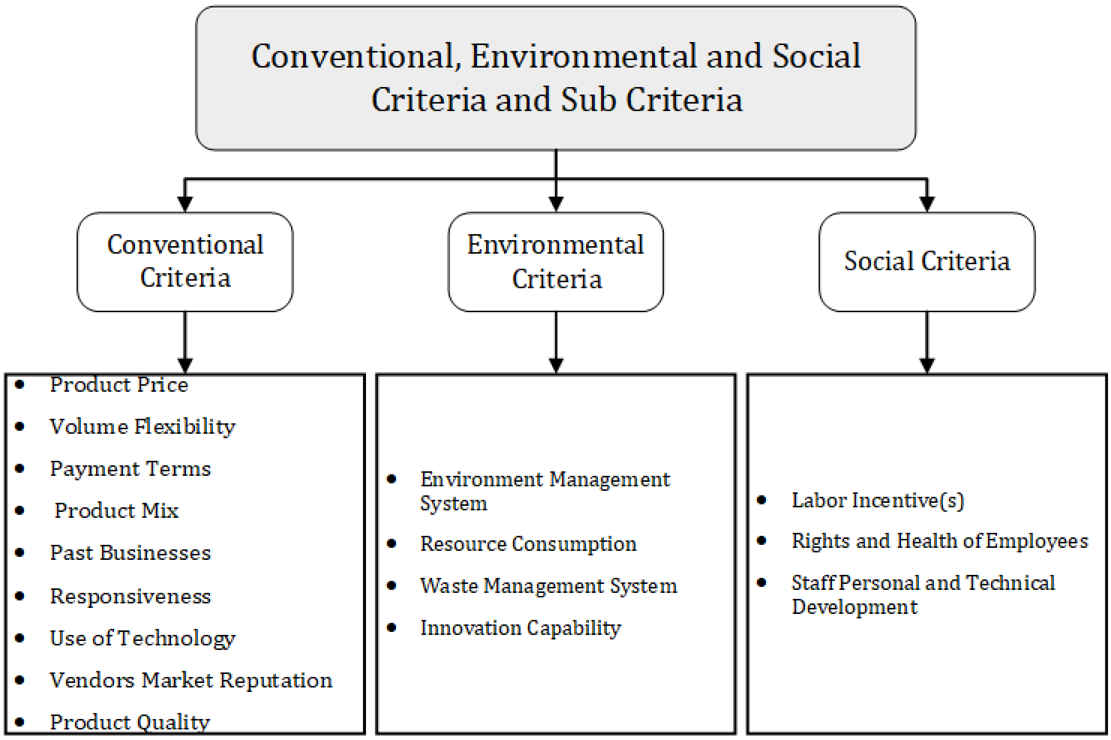

FIGURE 3.2: Criteria and Sub Criteria for Sustainable Supplier Selection.

major criteria i.e. conventional, environmental and social. Figure 3.2 presents the sub division of three major criteria. Conventional criterion was divided into nine sub-criteria, environmental criterion was divided into four sub-criteria and social criterion was divided into three sub-criteria.

Table 3.1 presents the description of each criterion along with respective studies from literature for more clear understanding.

TABLE 3.1: Description of Sub Criteria.

Major Criteria	**Sub Criteria**	**Description**	**Studies**
Conventional Criteria	Product Price	The minimum bid price that the consumer receives from the supplier.	[72, 87, 107, 120]
	Volume Flexibility	The capability of supplier to cope up with fluctuating demand by the customer in short period of time.	[98, 112, 120–122]

	Payment Terms	The terms and conditions regarding credit letters, invoices, payment schedule, etc.	[90, 112, 120, 123]
	Product Mix	The ability of a supplier to supply the multiple products to the customer.	[124]
	Past Businesses	The scale and total cost of projects that the vendor did in the past.	[120, 125]
	Responsiveness	The definite and purposeful response of the supplier against customer's demand in the specific time period.	[72, 87, 107, 120]
	Use of Technology	Technology solutions provided by the supplier for meeting customer satisfaction.	[85, 107, 126, 127]
	Vendors Market reputation	The perception of the supplier in the market and its rank amongst its competitors. Suppliers attitude and relationship with other customers.	[72, 120]
	Product Quality	The ability of the product to meet customer demand. The integral part of product for which the customer is paying for.	[72, 86, 87, 120]

Environmental Criteria	Environment Management System	The supplier holds EMS certification (ISO14001) or Eco-Management and Audit Scheme (EMAS). Continuous monitoring and documentation of internal and green process planning to identify the pollution prevention processes.	[21, 35, 83, 85, 128, 129]
	Resource Consumption	The type of raw material and energy resources (i.e. conventional or renewable) use by the supplier in its production facility.	[21, 22, 85, 87, 130, 131]
	Waste Management System	Deals with supplier's waste handling procedures (i.e. waste collection, segregation, transportation and disposal) and waste treatment procedures while minimizing the pollution effect.	[23, 36, 85, 132]
	Innovation Capability	Deals with innovative product design strategies to integrate green design (i.e. product's disassembly, recyclability and sustainability) and procurement processes.	[86, 107, 133]

Social Criteria	Labor Incentives	Deals with number and type of bonuses that the supplier offers to their employees for increasing their productivity turnover rate. The employees usually receive at the completion of the project.	[86, 134, 135]
	Rights and Health of Employees	This includes health allowances offers by the supplier to their employees. Includes the safety procedures and standards that the supplier applies in its facility.	[85, 87]
	Staff Personal and Technical Development	This includes the technical and personal development courses and trainings that the supplier offers to their employees.	[85, 87]

Step 3: Fuzzy E-AHP was applied to evaluate the relative weights of each supplier selection criteria.

Step 4: Fuzzy TOPSIS was applied to evaluate the weights of the supplier for conventional, environmental and social criteria.

Step 5: TOPSIS is applied on overall Closeness Coefficient matrix obtained from conventional, environmental and social criteria.

Step 6: Best suppliers were selected on the basis of defined threshold of the Closeness Coefficient.

Phase 2

Step 7: Demand data was plugged in in the network forecasted on the basis of previous five-year monthly data using conventional forecasting techniques i.e. moving average (MA), weighted moving average (WMA), exponential smoothing, least square fit and seasonal auto regressive integrated moving average (SARIMA) model. The techniques were compared on the basis of least mean square error (MSE).

Phase 3

Step 8: Selection of objectives while allocating optimal quantity to the potential suppliers. This includes Total Cost (TC), Total Travel Time (TTT), Environmental Impact (EI), Equivalent Sound Level (ESL), Social Impact (SI) and Total Value of Sustainable Purchasing (TVSP).

Step 9: Formulation of multi objective mixed integer nonlinear mathematical model along with demand, resource and capacity constraints to evaluate the sustainable suppliers on the basis of forecasted demand. The model simultaneously minimizes TC, TTT, EI and ESL while maximizes SI and TVP using AUGMECON2 and WMM algorithm.

Phase 4

Step 10: TOPSIS along with Equal Weight Method was applied on the Pareto solution obtained from AUGMECON2 and WMM to obtain the best 20 optimal solution.

Step 11: CRITIC Weight Method was applied on the selected Pareto solution obtained for AUGMECON2 and WMM.

Step 12: TOPSIS was applied on the selected Pareto solution obtained for AUGMECON2 and WMM to select the best optimal solution.

Figure 3.3 presents the flow chart for the proposed methodology developed on the basis of steps discussed above.

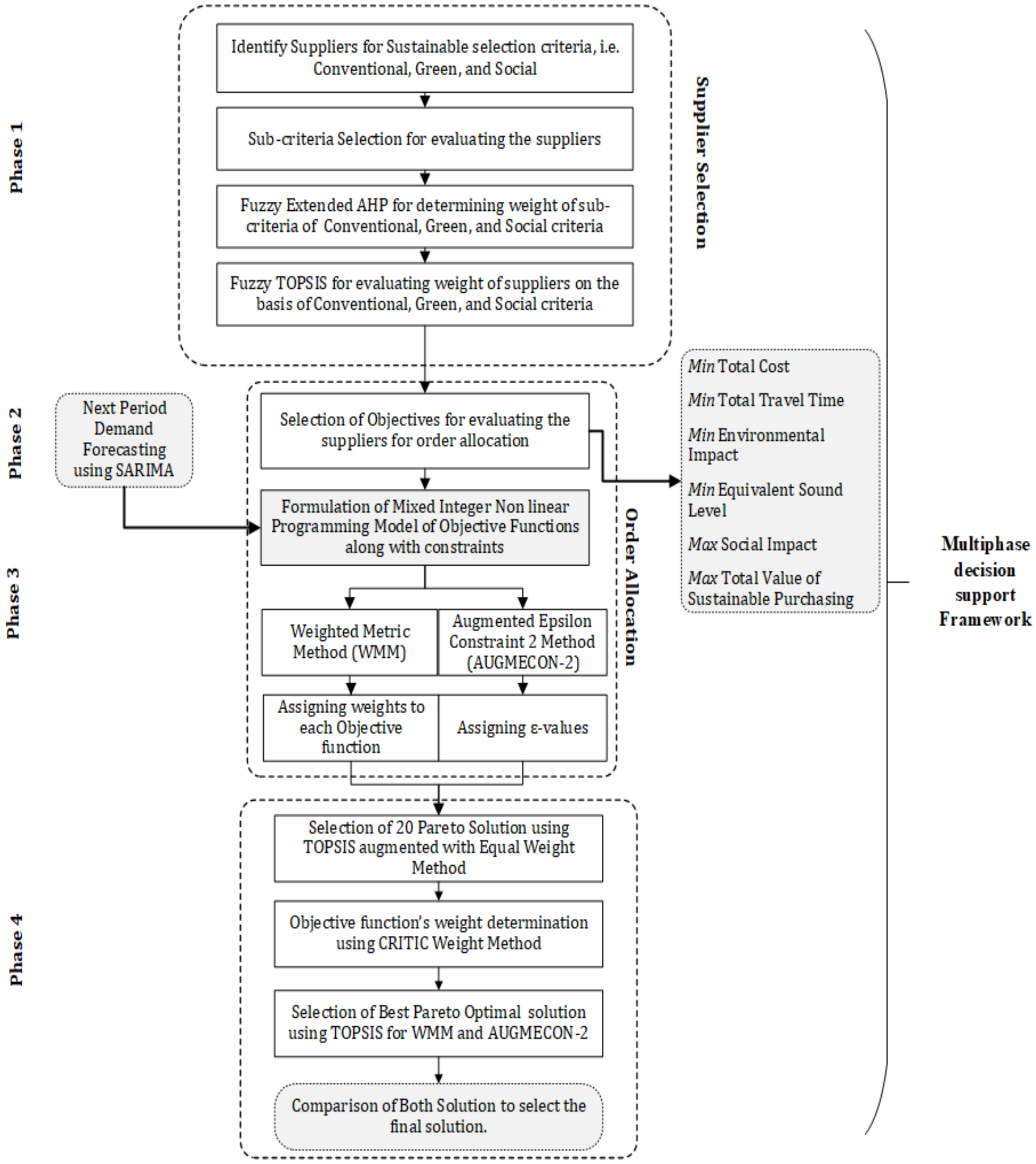

Figure 3.3: Flow Chart of Proposed Methodology.

3.3 Supplier Selection Techniques (Phase 1)

The supplier selection procedure basically comprises of two steps: criteria ranking and suppliers/alternative ranking. For suppliers' selection, firstly the criteria are ranked on the basis of weights calculated in context of their relative significance.

Criteria rankings refer as the key factors that are used to rank the suppliers. Suppliers ranking consists of group of suppliers that need to be rated for optimal order allocation. For criteria ranking Extended Fuzzy AHP (fuzzy E-AHP) was used in to order to find the relative weights. The weights obtained from Fuzzy E-AHP are then incorporated in fuzzy TOPSIS for the ranking of potential suppliers. In this study, linguistic variables are used to incorporate the incoherence in the decision-making process. For the transformation of linguistic variable into numeric form (i.e. x (a, n, m)), the direction highlighted by Dubios and Prade [136] were followed. Where, a is the most likely point, n refers the most pessimistic and m refers for the most optimistic point. For instance, in quantitative terms ≈75 can be defined as (60, 75, 90). The detailed steps of techniques used for suppliers' selection are presented in the subsequent sections.

3.3.1 Fuzzy Set Theory

In order to overcome vagueness in the decision-making process, Zadeh [33] proposed fuzzy set theory (FST) in MCDM to transform crisp numeric values for more precise judgement of real-world systems [137, 138]. FST was used to model the uncertainty of human judgements while performance rating and weights in the fuzzy MCDM [34]. Various studies argued that the comprehensiveness of decision-making process is strengthen by fuzzy MCDM see for instance, [23, 74, 104]. Triangular fuzzy numbers (TFNs) a, n, and m are used in this dissertation to access the preferences because of their simplicity [86, 99, 102, 103]. Where, a, n, and m present the least, average, and maximum value. The membership function used for the analysis was adopted from the study of Chang [139] and is a follows.

$$M_1 = (a_1, n_1, m_1), M_2 = (a_2, n_2, m_2)$$

$$Membership\ Function : V(\tilde{M}_i \geq \tilde{M}_j) = \begin{cases} 1 & , if\, n_2 \geq n_1 \\ \dfrac{a_1 - m_2}{(n_2 - m_2) - (n_1 - a_1)} & , otherwise \\ 0 & , a_1 \geq m_2 \end{cases} \tag{3.1}$$

3.3.2 Fuzzy E-AHP

AHP is a decision-making process which is first developed by Saaty [140] in 1990. According to Ayag [141], AHP is most widely used method for determining the weights of criteria. Fuzzy E-AHP is used in this study to evaluate the weights of sub-criteria for conventional, environmental and social criteria. It is a decision-making algorithm that incorporates Saaty's [142] AHP method with fuzzy set theory [143]. In this method, fuzzy numbers are presented by a membership function that is a real number between 0 and 1. Table 3.2 represents the linguistics variables used for weighing the criteria. Each decision maker needs to allocate weights to the sets of conventional, environmental and social criteria. This study followed the methodology used by Wang et al. [144]. Figure 3.4 presents the flow chart of the fuzzy E-AHP. The steps of implementation are as follows:

Step 1: The responses of all the decision makers are gathered to construct the combined fuzzified pair wise comparison matrix.

Step 2: Fuzzified pair wise comparison matrix was converted into crisp matrix.

$$\tilde{C}_{crisp} = \frac{(4 \otimes a + n + m)}{6} \tag{3.2}$$

Step 3: Normalize the combined fuzzified pair wise comparison matrix.

$$\tilde{C}_{ij} = \left(\frac{\sum_{i=1}^{I} a_{ij}}{\sum_{i=1}^{I} a_{ij} + \sum_{i=1}^{I} \sum_{j=1}^{J} m_{ij}}, \frac{\sum_{i=1}^{I} n_{ij}}{\sum_{i=1}^{I} \sum_{j=1}^{J} n_{ij}}, \frac{\sum_{i=1}^{I} m_{ij}}{\sum_{i=1}^{I} m_{ij} + \sum_{i=1}^{I} \sum_{j=1}^{J} a_{ij}} \right) \tag{3.3}$$

Step 4: The crisp AHP was used to determine the consistency index.

Step 5: Calculate the degree of possibility using the membership function presented in Eq. (3.1).

Step 6: Calculate the weights or priority vector W= $(w_1, w_2, \ldots, w_I)^T$ using the fuzzy comparison matrix.

$$w_i = \frac{\min V(M_i \geq M_k)}{\sum_{i=1}^{J} \min V(M_i \geq M_k)} \tag{3.4}$$

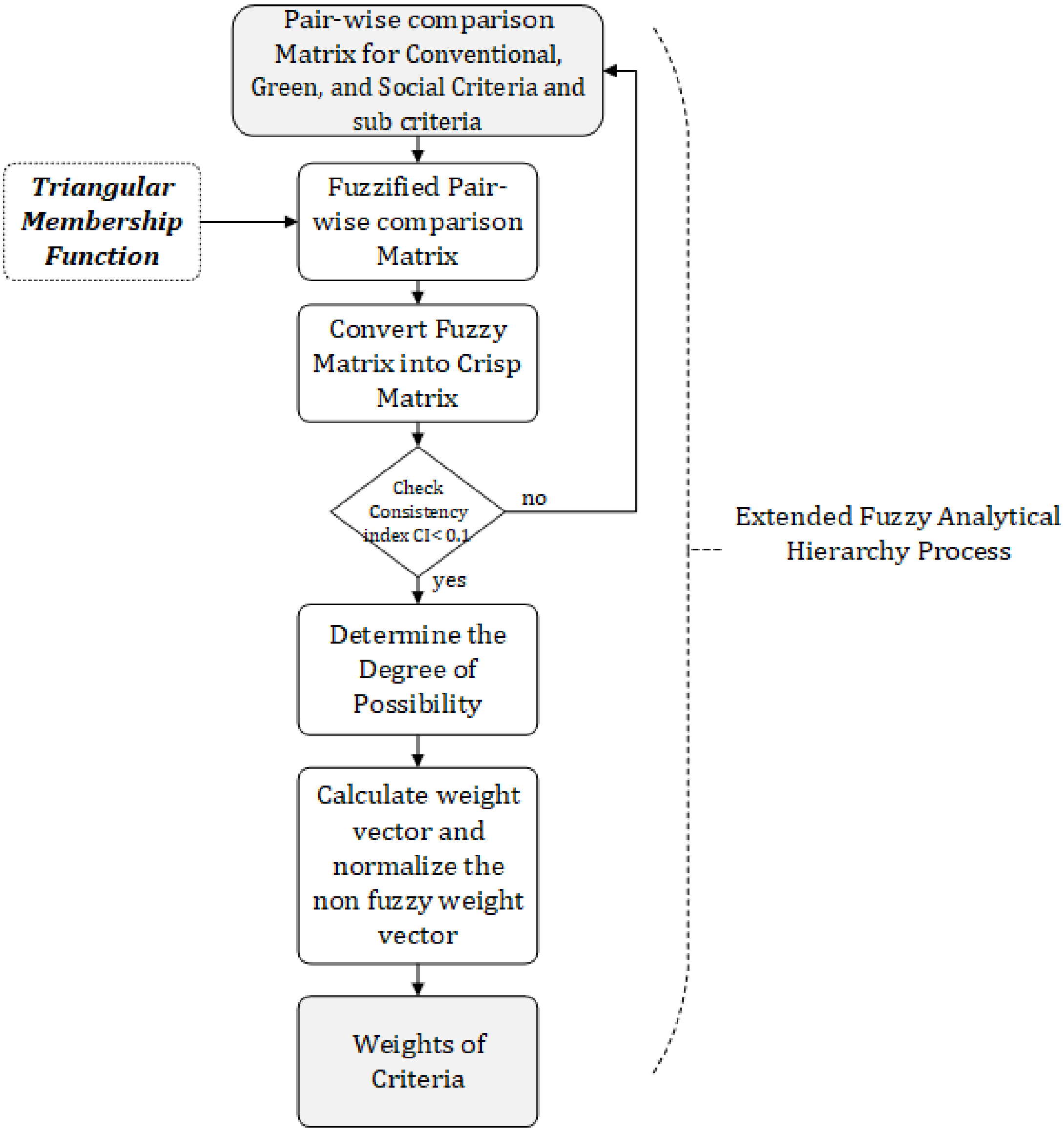

FIGURE 3.4: Flow Chart of Fuzzy E-AHP.

3.3.3 Fuzzy TOPSIS

This study used fuzzy TOPSIS to rank the supplier on the basis of three sustainable criteria i.e. conventional, environmental and social. In this study triangular fuzzy number rather than trapezoidal for simplicity. Table 3.2 shows the linguistic variables that are used to rank the alternatives on the basis of three criteria. The linguistic rating variables assigned to each of these fuzzy sets are low, medium and high as shown in Figure 3.5. The representation of fuzzy number into crisp number was adopted from the study of Chen [145]. For instance, the linguistic term low

"L" can be represented as (1, 3, 5). For the implementation of fuzzy TOPSIS, decision makers need to assign weights (i.e., linguistic variables) to each alternative for above mentioned criteria. The flow chart for implementation of fuzzy TOPSIS was shown in Figure 3.6. The steps of implementation are as follows [99, 146, 147]:

TABLE 3.2: Linguistic Variables used of Fuzzy TOPSIS and Fuzzy E-AHP.

Linguistic Variable	**Crisp Number**	**Fuzzy Number for TOPSIS**	**Fuzzy Number for E-AHP**
Very low (VL)	1	(0, 1, 3)	(0, 0.1, 0.3)
Low (L)	3	(1, 3, 5)	(0.1, 0.3, 0.5)
Medium (M)	5	(3, 5, 7)	(0.3, 0.5, 0.7)
High (H)	7	(5, 7, 9)	(0.5, 0.7, 0.9)
Very high (VH)	9	(7, 9, 10)	(0.7, 0.9, 1.0)
Intermediate Values	2, 4, 6, 8	–	–

Step 1: The responses of all the decision makers are gathered to construct the combined decision matrix.

$$a_{ij} = \min\left[{a_{ij}}^k\right] \ , n_{ij} = \frac{1}{K} \sum_{k=1}^{K} {n_{ij}}^k, \ m_{ij} = \max\left[{m_{ij}}^k\right] \tag{3.5}$$

Where, i represent the suppliers and j represents the criteria. Here, a, n, and m are the fuzzy numbers as highlighted in Table 3.2.

Step 2: The normalized decision matrix was constructed by normalizing the fuzzy decision matrix using expression given below.

$$\tilde{\mathrm{c}}_{\mathrm{ij}} = \left(\frac{a_{ij}}{\sqrt{\sum_i {m_{ij}}^2}}, \frac{n_{ij}}{\sqrt{\sum_i {m_{ij}}^2}}, \frac{m_{ij}}{\sqrt{\sum_i {m_{ij}}^2}}\right) \tag{3.6}$$

Step 3: The weighted normalized decision matrix was obtained by multiplying the matrix with the corresponding weight of each criteria.

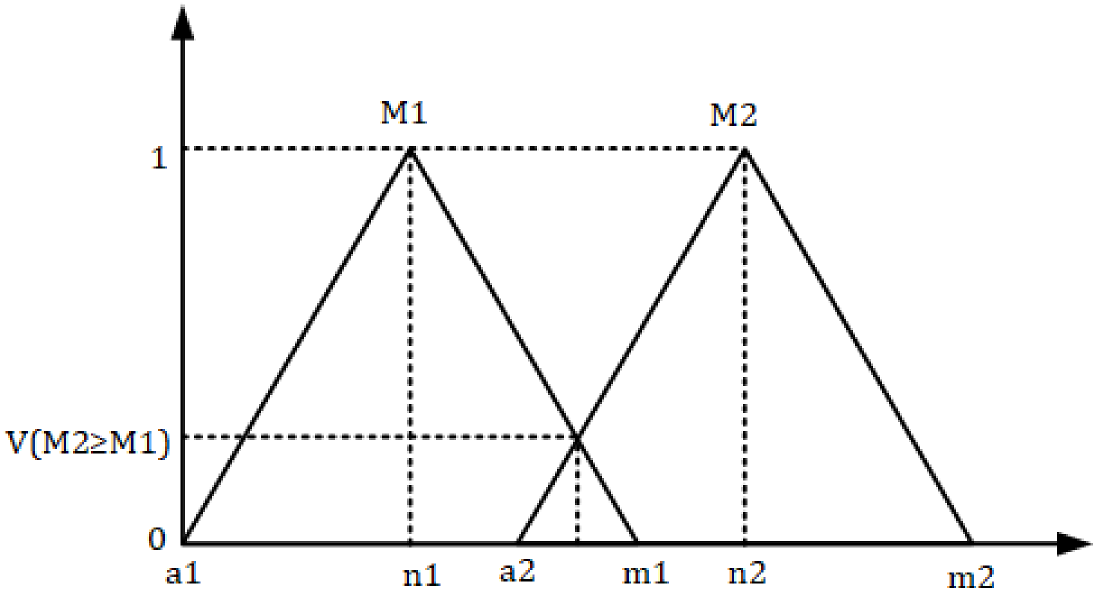

FIGURE 3.5: Membership Function for Criteria.

$$\tilde{v}_{ij} = [\tilde{c}ij * w_j] \tag{3.7}$$

Step 4: Positive ideal (best) and negative ideal (worst) solution was then obtained with the given expressions.

$$\tilde{Z}_j^+ = \{best(\tilde{Z}_{ij})\}_{i=1}^n, \tilde{Z}^+ = \{\tilde{Z}_1^+, \tilde{Z}_2^+, \tilde{Z}_3^+, ..., \tilde{Z}_m^+\} \tag{3.8}$$

$$\tilde{Z}_{j'}^- = \{worst(\tilde{Z}_{ij'})\}_{i=1}^n, \tilde{Z}^- = \{\tilde{Z}_1^-, \tilde{Z}_2^-, \tilde{Z}_3^-, ..., \tilde{Z}_m^-\} \tag{3.9}$$

Step 5: Calculate the Euclidean distance from fuzzy positive ideal solution and fuzzy negative ideal solution using the expression given below.

$$Sep^+ = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}^+{}_j), Sep^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}^-{}_j) \tag{3.10}$$

Where, $\tilde{v}^+{}_j$and $\tilde{v}^-$ are the fuzzy positive and negative points for criteria "j".

Step 6: Finally, the relative closeness RC_i of the alternatives from the ideal solution was obtained on which the alternatives are ranked from 0 to 1. The alternative with the value closer to 1 was considered as the best alternative.

$$RC_i = \frac{Sep_i^-}{Sep_i^- + Sep_i^+} \tag{3.11}$$

3.4 Forecasting Techniques (Phase 2)

In today's competitive environment, businesses shifted their focus on supply chain integration [148]. It plays a pivotal role in increasing revenues and profit margin [149, 150]. Such integration majorly relies on sharing information between the supply chain partners [96, 151]. Majority supply chains are demand driven and demand was mostly forecasted [152]. Therefore, the information sharing between echelons of supply chain can reduce the forecast error [153]. In this study, supply chain model was integrated with forecasted demand to evaluate the performance of supply chain on the basis of examining its impact on above defined objectives.

To forecast the demand, we used five conventional forecasting techniques on five years monthly data. The results obtained from each technique are compared on the basis of mean square error (MSE) (see Appendix C1-C4). The mathematical model was then evaluated on the next period forecasted demand obtained from technique having least MSE.

The brief of forecasting techniques are as follows.

3.4.1 Moving Average (MA)

Moving Average (MA) is the simplest model for extrapolative forecasting. This model uses the number of periods as a parameter for the computation of MA [154]. The formula for forecasting using MA is as follows:

$$F_t = \frac{\sum_{i=1}^{n} D_{t-i}}{n_i} \tag{3.12}$$

where, F_t is the forecast for time period t, $D_{t-i}$is the actual demand for previous time periods i and $n_i$is the total number of previous time periods.

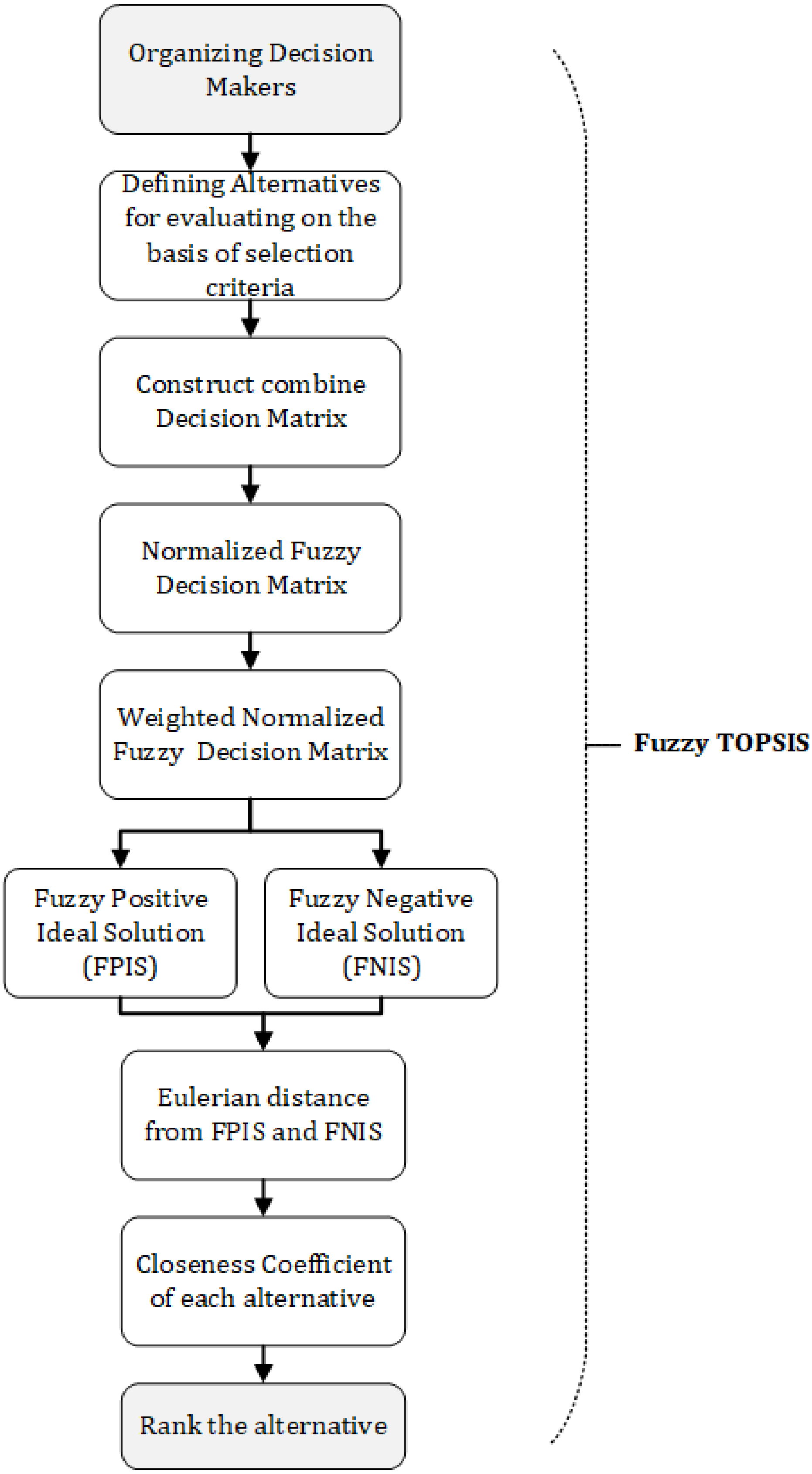

Figure 3.6: Flow Chart of Fuzzy TOPSIS.

3.4.2 Weighted Moving Average (WMA)

Weighted Moving Average (WMA) uses weights to the most recent demand in order to forecast the next period forecast [155]. The formula for forecasting using WMA is as follows:

$$F_t = \frac{W_{t-i} \sum_{i=1}^{n} D_{t-i}}{n_i} \tag{3.13}$$

where, $W_{t-i}$is the weights of previous time period used to forecast the next period demand.

3.4.3 Simple Exponential Smoothing (SES)

Exponential Smoothing is the simplest time series forecasting technique that uses the exponentially decreasing weights from nearest to the oldest observations [156]. It is extensively used for short-term forecast. The general formula for forecasting using SES is as follows:

$$F_t = \alpha D_{t-1} + (1-\alpha)F_{t-1} \tag{3.14}$$

where, $\alpha$is the smoothing constant and can have a value between 0 and 1. $D_{t-1}$is the actual demand of previous time period and $F_{t-1}$is the forecasted demand of previous time period. In order to initiate the process, actual demand of first period will be used as the forecasted demand of second period.

3.4.4 Least Square Method (LSM)

Least Square method (LSM) is used in time series analysis to estimate the values of parameters in regression equation [157]. This method uses the observed data to find the best fit [158]. The expressions used for estimating the next period forecast are as follows.

$$Y = ax + b \tag{3.15}$$

where, Y represents demand and x represents the time. a represents the slope and b represents the y-intercept and are calculated as follows:

$$a = \frac{n\Sigma\,(xy)\ -\ \Sigma x\,\Sigma y}{n\Sigma\,(x)^2\ -\ (\Sigma x)^2} \tag{3.16}$$

$$b = \frac{\Sigma y\ -\ a}{n} \tag{3.17}$$

3.4.5 Seasonal Auto Regressive Integrated Moving Average (SARIMA)

Effective forecasting is one of the major pillars of supply chain to meet customer demand. For reducing the forecast error, several time series analysis techniques have been developed over the years. The seasonal time series ARIMA model is developed by Box–Jenkins [159] and was used by various authors' for predicting the futuristic demand. It tries to explore the patterns in the past data by decomposing long term trends and seasonal patterns in order to predict the future trends and patterns [160]. Several studies argued the better performance of SARIMA by investigating it in comparison with other forecasting techniques (i.e. random walk, linear regression, support vector regression (SVR), historical average, simple ARIMA, and K-NN forecast models) [161–163]. Therefore, this study used SARIMA to predict next periods demand by adopting the methodology of Chang et al. [164]. The general formulation of SARIMA (p, d, q) (P, D, Q) s is as follows:

$$\Phi_{\mathrm{P}}(\mathrm{B}^{\mathrm{s}})\phi(\mathrm{B})\nabla_{\mathrm{s}}{}^{\mathrm{D}}\nabla^{\mathrm{d}}\mathrm{x}_{\mathrm{t}} = \Theta_{\mathrm{Q}}(\mathrm{B}^{\mathrm{s}})\theta(\mathrm{B})\mathrm{w}_{\mathrm{t}} \tag{3.18}$$

where, p is autoregressive polynomial order, d is normal differencing parameter, q is moving average polynomial order, P is seasonal autoregressive polynomial order, D is seasonal differencing parameter, Q is seasonal moving average polynomial order, s represents the seasonal period, $\Phi_{\mathrm{P}}(\mathrm{B}^{\mathrm{s}})$ is the seasonal autoregressive term, $\Theta_{\mathrm{Q}}(\mathrm{B}^{\mathrm{s}})$ is the seasonal moving average component, w_{t} is non stationary time series,

∇^d and $\nabla_s{}^D$ is the ordinary and seasonal differencing component, and B is the backshift operator.

Figure 3.7 presents the flowchart of SARIMA model. The steps for implementation are as follows:

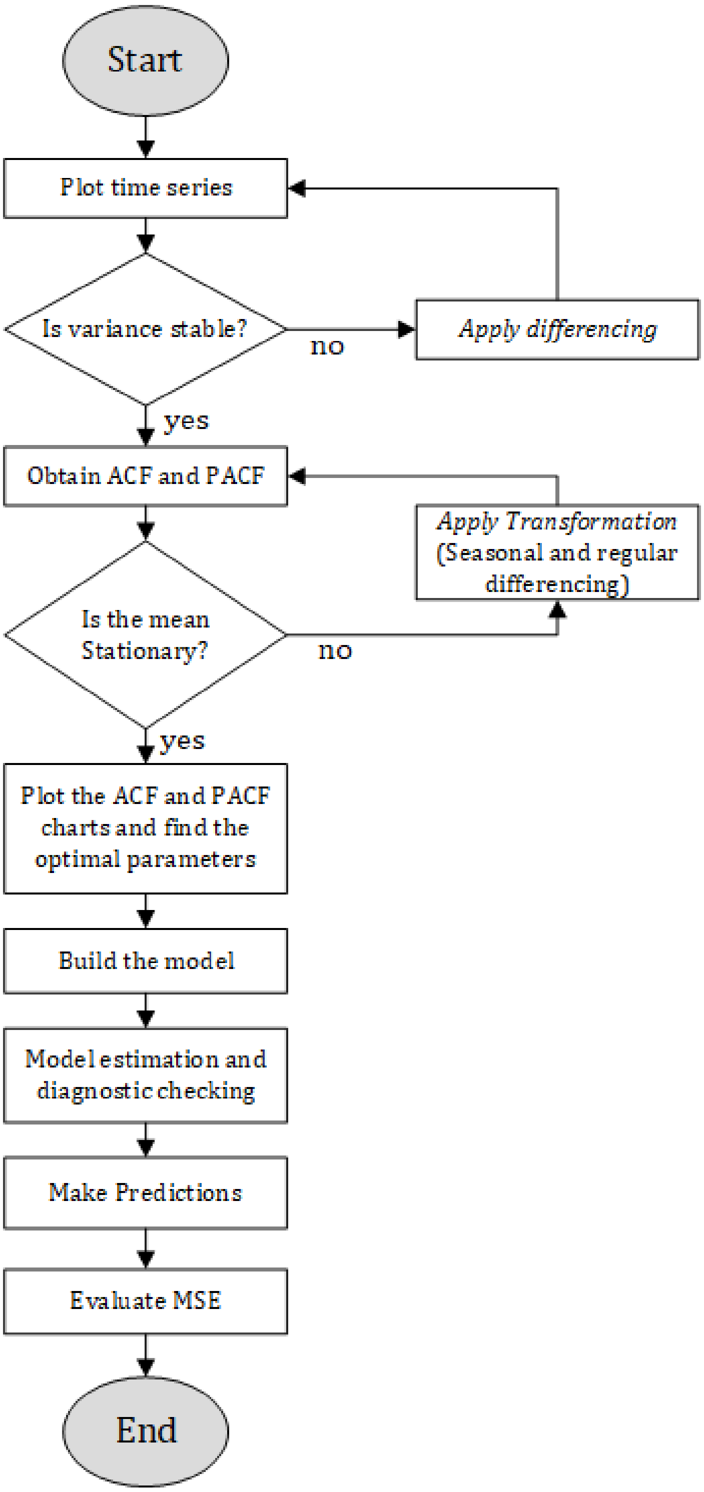

FIGURE 3.7: Flow Chart of SARIMA.

Step 1: First step is to plot the time series data in order to identify the key features of the plot for instance, seasonality and trend.

Step 2: If there is only trend then first differencing can be applied. If there is trend and seasonality then both non-seasonal and seasonal differencing will be applied as two successive operation to make the time series data stationary.

Step 3: Next step is to plot the auto correlation function (ACF) and partial auto correlation function (PACF) in order to estimate the auto correlation values, lagged value, correlation of residuals and their lagged values that will result in the combination of (p, d, q)(P, D, Q)s values.

Step 4: For estimating and diagnostic checking this study used Akaike's Information Criteria (AIC) [165] to select the best model. The model with least AIC is selected.

Step 5: Using the best values obtained from AIC diagnostic test, the time series is predicted for the next season forecast.

Step 6: The last step is to evaluate MSE.

The results for n periods obtained from all the techniques listed above are then compare on the basis of MSE. The forecasted demand obtained from the technique having least MSE is used in the mathematical model as a customers' demand.

3.5 Development of Mathematical Model for Order Allocation (Phase 3)

In this section the development of multi objective optimization model of multi echelon supply chain network for SSSOA problem is discussed. This model aims to evaluate the optimum quantity of AC units that needs to be allocated to each supplier. It includes minimization of Total Cost (TC), Total Travel Time (TTT), Environmental Impact (EI), Equivalent Sound Level (ESL) and maximization of

Social Impact (SI) and Total Value of Sustainable Purchasing (TVSP). The multi objective optimization model was developed on the basis of assumptions, sets, parameters and variables given below.

3.5.1 Assumptions

The assumptions of the mathematical model are as follows:

1. The model is a single period model.
2. The shipments are considered as less than a container load (LCL) shipment.
3. The transfer cost and transfer time can only be applied at the nodes.
4. The custom clearance cost and time can only be applied while moving through port.

3.5.2 Sets

$i = 1, 2, 3, \cdots, I$ set of Suppiers

$j = 1, 2, 3, \cdots, J$ set of Port (Transfer Point)

$k = 1, 2, 3, \cdots, K$ set of Warehouses

$l = 1, 2, 3, \cdots, L$ set of Customers

$$\left.\begin{array}{ll} m = 1, 2, 3, ..., M & \text{set of Transportation Modes} \\ n = 1, 2, 3, ..., N & \text{set of Transportation Modes} \end{array}\right\} \begin{array}{l} \text{used for interchangeable} \\ \text{transport transfer decisions} \end{array}$$

3.5.3 Parameters

C_i^P = Per Unit Purchasing Cost from Supplier i.

O_i = Ordering cost incurred by the customer from i^{th} supplier.

H_0 = Inventory Holding cost per unit incurred by the customer.

TC_m = Transportation cost per kilometre for mode "m".

TrC_{mn} = Transfer cost while shifting from mode "m" to "n".

CC_{ij} = Custom Clearance Cost while moving from supplier "i" to port "j".

TrT_{mn} = Transfer time while shifting from mode "m" to "n".

CCT_{ij} = Custom Clearance Time while moving from supplier "i" to port "j".

d_{ijm} = Distance from supplier "i" to port "j" via mode "m".

d_{jkm} = Distance from port "j" to warehouse "k" via mode "m".

d_{klm} = Distance from warehouse "k" to customer "l" via mode "m".

w_i^c = Weight of conventional criteria obtained from fuzzy E-AHP.

w_i^e = Weight of environmental criteria obtained from fuzzy E-AHP.

w_i^s = Weight of social criteria obtained from fuzzy E-AHP.

$W_i^{conventional}$ = Weight of supplier "i" obtained from fuzzy TOPSIS w.r.t. conventional criteria.

$W_i^{environmental}$ = Weight of supplier "i" obtained from fuzzy TOPSIS w.r.t. environmental criteria.

W_i^{social} = Weight of supplier "i" obtained from fuzzy TOPSIS w.r.t. social criteria.

CO_{2ijm} = Carbon dioxide emission in gram per kilometre while travelling from supplier "i" to port "j" via mode "m".

CO_{2jkm} = Carbon dioxide emission in gram per kilometre while travelling from port "j" to warehouse "k" via mode "m".

CO_{2klm} = Carbon dioxide emission in gram per kilometre while travelling from warehouse "k" to customer "l" via mode "m".

S_i = Maximum Capacity of i^{th} supplier.

D_l = Demand of l^{th} customer.

$CAPw_k$ = Capacity of k^{th} warehouse.

V_m = Velocity of mode "m".

CAP_m = Capacity of vehicle used while moving through mode "m".

$Cap_{m=2}$ = Maximum capacity of mode 2.

$Cap_{m=3}$ = Maximum capacity of mode 3.

3.5.4 Variables

X_{ijm} = Quantity shipped from supplier i to port j via mode m

X_{jkm} = Quantity shipped from port j to warehouse k via mode m

X_{klm} = Quantity shipped from warehouse k to customer l via mode m

Binary Variables :

$$Y_i = \begin{cases} 1 & \text{if supplier } i \text{ is selected,} \\ 0 & \text{otherwise} \end{cases}$$

$$a_j = \begin{cases} 1 & \text{if tranfer from mode } m \text{ to } n \text{ at node } j \\ 0 & \text{otherwise} \end{cases}$$

$$ak = \begin{cases} 1 & \text{if tranfer from mode } m \text{ to } n \text{ at node } k \\ 0 & \text{otherwise} \end{cases}$$

$$Z_k = \begin{cases} 1 & \text{if warehouse k is selected,} \\ 0 & \text{otherwise} \end{cases}$$

3.5.5 Objective Function 1: Total Cost (TC)

This objective function aims to minimize the sum of purchasing cost, ordering cost, inventory holding cost, transportation cost[1], custom clearance cost[2] and transfer

[1]The transfer cost comprises of the labor cost occurs during the transfer of goods from one mode of transportation to another mode of transportation. For instance, the labor cost occurs during the transfer of goods from ship to rail and vice versa.

[2]The custom clearance cost incorporates the cost of process of preparing and submitting Customs Entry documentation on the port. It is important to highlight that this cost only occur via moving through the sea port. Our model does not incorporate the dry port or custom clearance through borders at this moment.

cost. Equation below presents the minimization of total costs occurred throughout the supply chain network.

$$Min\quad \mathrm{TC} = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1}^{M} C_i^p X_{ijm} + \sum_{i=1}^{I} O_i Y_i + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1}^{M} \frac{X_{ijm}}{2}$$
$$\times H_0 + \Bigg(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1}^{M} TC_m d_{ijm} \frac{X_{ijm}}{Cap_m} + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{m=1}^{M} TC_m d_{jkm} \frac{X_{jkm}}{Cap_m}$$
$$+ \sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{m=1}^{M} TC_m d_{klm} \frac{X_{klm}}{Cap_m} Z_k \Bigg) + \Bigg(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{n=1}^{N} TrC_{mn} a_j X_{ijm}$$
$$+ \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=1}^{N} TrC_{mn} a_k Z_k X_{jkm} \Bigg) + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1}^{M} CC_{ij} X_{ijm} Y_i \tag{3.19}$$

3.5.6 Objective Function 2: Total Travel Time (TTT)

This objective function tends to minimize the total travel time from supplier to customer. It includes transportation time, transfer time and custom clearance time. The minimization of total travel time is expressed as follows.

$$Min\quad \mathrm{TTT} = \Bigg(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1}^{M} \frac{d_{ijm} X_{ijm}}{v_m CAP_m} + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{m=1}^{M} \frac{d_{jkm} X_{jkm}}{v_m CAP_m}$$
$$+ \sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{m=1}^{M} \frac{d_{klm} X_{klm} Z_k}{v_m CAP_m} \Bigg) + \Bigg(\sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{n=1}^{N} TrT_{mn} \frac{X_{jkm}}{CAP_m}$$
$$+ \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=1}^{N} TrT_{mn} \frac{X_{klm}}{CAP_m} \Bigg) + \left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1}^{M} \frac{CCT_{ij} X_{ijm} Y_i}{CAP_m} \right) \tag{3.20}$$

3.5.7 Objective Function 3: Environmental Impact (EI)

This objective function aims to minimize the total carbon dioxide (CO_2) emissions throughout the transportation process. The equation below presents the minimization of the carbon dioxide emissions for all the three transportation modes (i.e. sea, rail and road).

$$Min\quad \mathrm{EI} = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1}^{M} CO_{2ijm} \left[\frac{X_{ijm}}{CAP_m} \right] d_{ijm} + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{m=1}^{M}$$
$$CO_{2jkm} \left[\frac{X_{jkm}}{CAP_m} \right] Z_k d_{jkm} + \sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{m=1}^{M} CO_{2klm} \left[\frac{X_{klm}}{CAP_m} \right] Z_k d_{klm} \tag{3.21}$$

3.5.8 Objective Function 4: Equivalent Sound Level (ESL)

For SSSOA it is important to analyze the impact of supply chain on the ecosystem [166]. While analyzing the environmental impact of the supply, it is important for the managers to study the impact of supply chain in context of noise pollution [167]. Therefore, this objective function aims to minimize the total equivalent sound level produced by three transportation mode (i.e. sea, rail, and road). It includes the overall summation of equivalent sound level produced by ships, trains and heavy vehicles. The objective function is constructed on the basis of following assumptions [168]:

1. Panamax vessels are used for the transportation of goods from suppliers to port.
2. Diesel locomotives under full power of Class 20 along with slab track is considered for calculating the equivalent sound level of train.
3. Dense-Graded Asphaltic Concrete (DGAC) is considered for calculating the equivalent sound level of road traffic.
4. Heavy duty trucks with gross vehicle weight of *12,000 kg*.
5. The distance between source and receiver is considered to be *30m*.

The general equation of total equivalent sound level is as follows:

$$Min\ \ \text{ESL} = Leq_{ship} + Leq_{rail} + Leq_{road} \tag{3.22}$$

1. **Equivalent Sound Level for Ship (Leq_{ship}):**

Human maritime activities have increased over the past 50 years [169]. The massive exploration of oil and gas industries and global marine traffic are the main sources acoustic pollution in oceans [96]. According to Rolland et al. [170], propellers and engines of commercial shipping vessels are the dominant sources of human generated noise. The continuous acoustic noise severely effects the marine life and disturbed the ocean eco-system [171].

For calculating the equivalent sound level of ships, this study adopted the model developed by Environmental Protection Department (EPD), Hongkong [172] and is given as follows:

$$Leq_{ship} = L_{\max} + 10\log\left(\frac{kd}{v_{m=1}}\right) + 10\log T + 10\log N + \Delta F \tag{3.23}$$

where, $L_{\max}$is measured vessel pass by noise level in dB(A) and depends on sound pressure level $\mathrm{L_{max1}}$, distance between source and receiver $\mathrm{R_1}$, slant distance $\mathrm{R_2}$, and ΔF is a façade effect and is calculated with the help of expression given below:

$$L_{\max} = \mathrm{L_{max1}} + 20\ \log\left(\frac{\mathrm{R_1}}{\mathrm{R_2}}\right) \tag{3.24}$$

In this study the values of $\mathrm{R_1}$ andΔF are taken as 30m and 3dB(A). $\mathrm{R_2}$ is calculated using the height of 1.5 meter. k is the empirical noise constant (i.e., 2), d is the perpendicular distance between source and measurement point (i.e., 30m), $v_{m=1}$is the velocity of ships/vessels. T is the total time period and N is the number of ships/ vessels and are calculated as follows:

$$T = \left(\frac{\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1} d_{ijm}Y_i + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{m=1} d_{jkm}Z_k + \sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{m=1} d_{klm}Z_k}{v_{m=1}}\right) \tag{3.25}$$

$$N = \left(\frac{\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1} X_{ijm} + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{m=1} X_{jkm} + \sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{m=1} X_{klm}}{CAP_{m=1}}\right) \tag{3.26}$$

1. **Equivalent Sound Level for Rail (Leq_{rail}):**

Rail is considered as the most eco-friendly mode of transportation. However, it is one of the most excessive noise producing source. According to European Commission Report [173], in Europe during the night time, approximately 9 million people are exposed to the sound level of 50 dB(A) [174]. Due to low transportation cost, the vast network of railways is most suitable for low carbon economies which would result in large noise disturbance in rural and urban areas [175]. However, as compared to road traffic and ships, rail noise is less annoying and ISO 1996-1 (2003) recommends a railway noise bonus of between 3 and 6 dB(A) in railway noise assessments.

There are three main sources of railway noise: rolling, engine and aerodynamic noise dependent on rail speed [176]. Rolling noise is due to the vibration–excitation between wheels and track and this vibration excitation is due to the combined roughness level of the wheels and track [177]. According to Watson et al. [178], rolling noise is the most dominating factor while traveling between 30 to 200 km/h. Engine noise includes exhaust noise, fan noise, power transmission and cooling system noise [179]. Moreover, it also includes idling and accelerating noise when travelling at the speed less than 60 km/h. Aerodynamic noise dominantly contributes to high speed train. However, this study focused on cargo trains only.

For calculating the equivalent sound level of train, the United Kingdom (UK) model of Calculation of Railway Noise (CRN) [180] is adopted along with the corrections recommended by the Department for Environment, Food and Rural Affairs (DEFRA) [181]. The Leq_{rail} is calculated as follows:

$$Leq_{rail} = (SEL - 43.3 + 10\log_{10} \times \left(\frac{\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=2} d_{ijm}Y_i + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{m=2} d_{jkm}Z_k + \sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{m=2} d_{klm}Z_k}{v_{m=2}}\right)\Bigg) \times \tilde{\mathrm{V}} \tag{3.27}$$

where, SEL is the sound exposure level [182] for flat and continuously welded track on concrete sleepers laid, $v_{m=2}$is the velocity of transportation mode and $\tilde{\mathrm{V}}$ is the total number of ships/vessels travels and is calculated using equations as follows:

$$SEL = 48.1 - 10\log_{10}(v_{m=2}) \tag{3.28}$$

$$\tilde{V} = \left(\frac{\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=2} X_{ijm} + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{m=2} X_{jkm} + \sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{m=2} X_{klm}}{CAP_{m=2}}\right) \tag{3.29}$$

Corrections in the model are applied for slab track (i.e. +2 dB(A)) and for Diesel locomotives under full power Class 20 (i.e. +0 dB(A)) and are adapted from [180].

1. **Equivalent Sound Level for Road (Leq_{road}):**

The maximum population of the globe is exposed to road traffic as compared to rail or aircraft. According to Li [183], the primary reasons for road traffic noise are rolling noise (i.e. the interaction between tyres and road) and engine noise (i.e. propulsion system of the vehicle). The vehicle noise is dependent on the speed it travels [184]. At low speed, engine noise dominates while at high speed rolling noise is most dominating [185]. The factors that influence the rolling noise emissions includes, irregularities on road surface, friction between tyre and road surface, and aerodynamic noise [186]. The engine noise comprises of all contributory mechanisms and horns.

For calculating the equivalent sound level of road, this study adopted the traffic noise model developed by Blokland and Peters [187].

The Leq_{road} is calculated as follows:

$$Leq_{road} = (Leq_{rolling} + Leq_{propulsion}) \times (T \times N) \tag{3.30}$$

where, $Leq_{rolling}$ is the noise emission level produced by the interaction of the rolling tyre with the road and $Leq_{propulsion}$ is the noise emission level due to the propulsion system of the vehicle, generated by components such as engine, gearbox, cooling system, exhaust, etc. The distance between the source and receiver is assumed to be 30 m. For rolling noise a logarithmic relation with vehicle speed is generally considered as the best fit and is as follows:

$$Leq_{rolling} = A_{rolling} + B_{rolling} \times \log\left(\frac{v}{v_{ref}}\right) \tag{3.31}$$

$$Leq_{propulsion} = A_{propulsion} + B_{propulsion} \times \left(\frac{v - v_{ref}}{v_{ref}}\right) + C_{propulsion} \times a \tag{3.32}$$

Where, $A_{rolling}$, $B_{rolling}$, $A_{propulsion}$, $B_{propulsion}$, $C_{propulsion}$, and a the coefficients for the heavy duty truck and are adopted from European Union Commission [188]. v is the velocity of the vehicle, T is the total time the truck travels, N is the number of vehicles, and v_{ref} is the reference velocity and is taken as 70 km/hrs.

3.5.9 Objective Function 5: Social Impact (SI)

The overall social impact of the potential supplier is maximize using the objective function given below. This analysis includes the supplier's social weight that is evaluated using fuzzy TOPSIS in the supplier selection section. The maximization of social impact of supplier is given below.

$$Max \quad \text{SI} = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1}^{M} W_i^{social} X_{ijm} \tag{3.33}$$

3.5.10 Objective Function 6: Total Value of Sustainable Purchasing (TVSP)

Value is used to describe for any financial benefit (i.e. increase in revenues, total cost or price reduction etc.) that a company gets while purchasing from a specific supplier [19]. According to Kuzgun and Asugman [188], total customer value includes the low price, credit services, product acquisition services, and risk reduction services. This objective function aims to maximize the total value of purchased goods by maximizing the conventional, social and environmental criteria weights. The criteria weights obtained from fuzzy E-AHP is multiplied with supplier's weights obtained from fuzzy TOPSIS and the quantity ordered form the supplier. Equation below presents the maximization of total value of sustainable purchasing as follows.

$$\begin{aligned} Max \quad \text{TVSP} \; &= \textstyle\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1}^{M} W_i^{conventional} w_i^c X_{ijm} \\ s + &\textstyle\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1}^{M} W_i^{environmental} w_i^e X_{ijm} + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1}^{M} W_i^{social} w_i^s X_{ijm} \end{aligned} \tag{3.34}$$

3.5.11 Constraints

Supply Constraint:

This constraint ensures that the total quantity obtained from all suppliers using any transportation mode should be less than or equals to the total capacity of the supplier. The constraint is expressed as follows:

$$\sum_{j=1}^{J}\sum_{m=1}^{M} X_{ijm} \leq S_i Y_i \qquad \forall i \in I \tag{3.35}$$

Warehouse Constraint:

These constraints ensure that the total quantity enters from port to the warehouse should be less than or equals to the overall storage capacity of the warehouse. Moreover, the total quantity shipped from the warehouse should be less than or equals to the capacity of the warehouse. It is presented in equation as follows:

$$\sum_{j=1}^{J}\sum_{m=1}^{M} X_{jkm} \leq CAPw_k Z_k \qquad \forall k \in K \tag{3.36}$$

$$\sum_{l=1}^{L}\sum_{m=1}^{M} X_{klm} \leq CAPw_k Z_k \qquad \forall k \in K \tag{3.37}$$

Demand Constraint:

This constraint ensures that the total quantity shipped to the customer from the warehouses should be equals to the forecasted demand of the customer. It is presented as follows:

$$\sum_{l=1}^{L}\sum_{m=1}^{M} X_{klm} = D_l \qquad \forall k \in K \tag{3.38}$$

Equality Constraint:

This constraint ensures that the total quantity shipped from the supplier to port should be equals to the total quantity shipped from port to the warehouse. It is presented as follows:

$$\sum_{i=1}^{I}\sum_{m=1}^{M} X_{ijm} = \sum_{k=1}^{K}\sum_{m=1}^{M} X_{jkm} \qquad \forall j \in J \tag{3.39}$$

Mode Capacity Constraint:

The constraint is to ensure that the quantity shipped from port to warehouse, and from warehouse to customer should be greater than or equals to the minimum capacity of the mode. It is presented as follows:

$$\sum_{i=1}^{I}\sum_{j=1}^{J} X_{ijm=1} \geq Cap_{m=1} \tag{3.40}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} X_{ijm=2} \geq Cap_{m=2} \tag{3.41}$$

$$\sum_{j=1}^{J}\sum_{k=1}^{K} X_{jkm=2} \geq Cap_{m=2} \tag{3.42}$$

$$\sum_{j=1}^{J}\sum_{k=1}^{K} X_{jkm=3} \geq Cap_{m=3} \tag{3.43}$$

$$\sum_{k=1}^{J}\sum_{l=1}^{K} X_{klm=2} \geq Cap_{m=2} \tag{3.44}$$

$$\sum_{k=1}^{J}\sum_{l=1}^{K} X_{klm=3} \geq Cap_{m=3} \tag{3.45}$$

Non Negativity and Binary Constraint:

These constraints ensure that the total quantity shipped from supplier to port, from port to warehouse and from warehouse to customer should be greater than zero. The decision variables Y_i and Z_k are binary. It is presented as follows:

$$\begin{aligned} &X_{ijm}, X_{jkm}, X_{klm} \geq 0 && \forall i, j, k, l, m \\ &Y_i\,, Z_k\, \in \{0, 1\} && \forall i, k \end{aligned} \tag{3.46}$$

3.6 Solution Methods

3.6.1 Augmented Epsilon Constraint 2 (AUGMECON2)

For solving the proposed MINLP model, AUGMECON2 algorithm has been used. AUGMECON2, developed by Mavrotas and Florios [189], is an improved model of AUGMECON generation method. It takes into account the complexities of discrete variables and non-convex problems by introducing the slack variable at each iteration. This technique transforms the multi objective optimization problem into mono-objective by considering one of the objectives as main objective function and shifting other objectives as a constraint subject to some ε values. The generic model is presented as follows:

$$max\ \left(f_1\left(x\right)\ +\ eps\ \left(\frac{S_2}{r_2}\ +\ \left((10-1)\frac{S_3}{r_3}\right) + \ldots + \ \left(10-(n-2)\ \frac{S_n}{r_n}\right)\right)\right) \tag{3.47}$$

subject to

$$\begin{aligned} f_2\left(x\right)\ &-\ S_2\ =\ \varepsilon_2 \\ f_3\left(x\right)\ &-\ S_3\ =\ \varepsilon_3 \\ \ldots & \\ f_n\left(x\right)\ &-\ S_n\ =\ \varepsilon_n \end{aligned}$$

where, ε_2, ε_3,..., ε_n are the RHS values for each objective function, S_2, S_3,..., S_n are the slack variables,r_2, r_3,..., r_n are the ranges of $n$objective functions and $eps\ \in [10^{-6}\ ,\ 10^{-3}\ ]$.

The modification in the model helps to perform the lexicographic optimization (i.e. sequentially optimizing f_2, f_3, ..., f_n) to generate the exact pareto sets. Figure 3.8 presents the flowchart of AUGMECON2 method. The steps of implementation are as follows:

Step 1: Transforming multi objective into single objective optimization problem.

Step 2: Create payoff table with the help of steps given below:

1. create p_t as payoff table 2D array;

2. initialize counter i with value 1 (i is payoff table row);

3. solve $f(i)$ optimization problem (minimize for i_4);

4. save result to payoff table: p_t $(i, j) = f(j)$ where j = 1,..,6

5. add i to 1;

6. if i <= 6 then go to step 3 else go to step 7;

7. end.

Step 3: Calculate ranges of objective functions with the help of steps given below:

1. create r array (it stores ranges of the OFs) and f_{lb} array (it stores lower bounds of OFs);

2. initialize counter i with value 2 (i is OF number);

3. calculate min and max values for OF_i using payoff table (min_i = min (p_t (j, i)), max_i = max (p_t (j, i)), where j = 1,..,6);

4. save min value to f_{lb} array ($f_{lb}(i) = min_i$), save difference to r array ($r(i) = max_i$ - min_i)

5. increase i to 1;

6. if $i \leq 6$ then go to step 10 else go to step 14;

7. end.

Step 4: calculate ε values for each objective function on the basis of steps given below.

1. initialize grid intervals number n and solutions array;

2. initialize counter i_6 with value 0;

3. calculate ε for oF 6: ε (6) = f_{lb} (6) + i_6*(1/n) *r (6);

4. initialize counter i_5 with value 0;

5. calculate ε for OF 5: $\varepsilon(5) = f_{lb}$ (5) + i_5*(1/n) *r ((5);

6. initialize counter i_4 with value 0;

7. calculate ε for OF 4: $\varepsilon(4) = f_{lb}$ (4) + i_4*(1/n) *r (4);

8. initialize counter i_3 with value 0;

9. calculate ε for OF 3: $\varepsilon(3) = f_{lb}$ (3) + i_3*(1/n) *r (3);

10. initialize counter i_2 with value 0;

11. calculate ε for OF 2: $\varepsilon(2) = f_{lb}$ (2) + i_2*(1/n) *r (2);

Step 5: Solve the problem for current ε values of each objective function and if result is feasible then add result to solutions array.

Step 6: If the result is infeasible the run the iterations to find the feasible solution on the basis of steps given below:

1. if result is infeasible then increase i_2 to $n + 1$ and go to step 29;

2. calculate bypass coefficient: b = integer part of n*s (2)/r (2), if $b = 0$ then $b = 1$;

3. increase i_2 to b;

4. if $i_2 \leq n$ then go to step 25;

5. increase i_3 to 1;

6. if $i_3 \leq n$ then go to step 23;

7. increase i_4 to 1;

8. if $i_4 \leq n$ then go to step 21;

9. increase i_5 to 1;

10. if $i_5 \leq n$ then go to step 19;

11. increase i_6 to 1;

12. if $i_6 \leq n$ then go to step 17;

13. output solutions array;

14. end.

For Pareto solutions the mathematical model is transformed as presented in Equations (3.46)-(3.51). In this study minimization of Total Cost is considered as the main objective function and other objective functions are considered as constraints.

$$Min\,Z = Min \quad \text{TC} \tag{3.48}$$

Subject to Eq. (3.35)-(3.44)

$$\begin{gathered} Min \quad TTT \leq \varepsilon_1 \\ [Min \quad TTT]^{\min} \leq \varepsilon_1 \leq [Min \quad TTT]^{\max} \end{gathered} \tag{3.49}$$

$$\begin{gathered} Min \quad EI \leq \varepsilon_2 \\ [Min \quad EI]^{\min} \leq \varepsilon_2 \leq [Min \quad EI]^{\max} \end{gathered} \tag{3.50}$$

$$\begin{gathered} Max \quad ESL \leq \varepsilon_3 \\ [Max \quad ESL]^{\min} \leq \varepsilon_3 \leq [Max \quad ESL]^{\max} \end{gathered} \tag{3.51}$$

$$\begin{gathered} Max \quad SI \leq \varepsilon_4 \\ [Max \quad SI]^{\min} \leq \varepsilon_4 \leq [Max \quad SI] \end{gathered} \tag{3.52}$$

$$\begin{gathered} Min \;\; TVSP \leq \varepsilon_5 \\ [Min \;\; TVSP]^{\min} \leq \varepsilon_5 \leq [Min \;\; TVSP]^{\max} \end{gathered} \tag{3.53}$$

3.6.2 Weighted Metric Method

For evaluating the model using weight sum method, the multiobjective optimization problem is transformed into mono-objective with the help of expression used

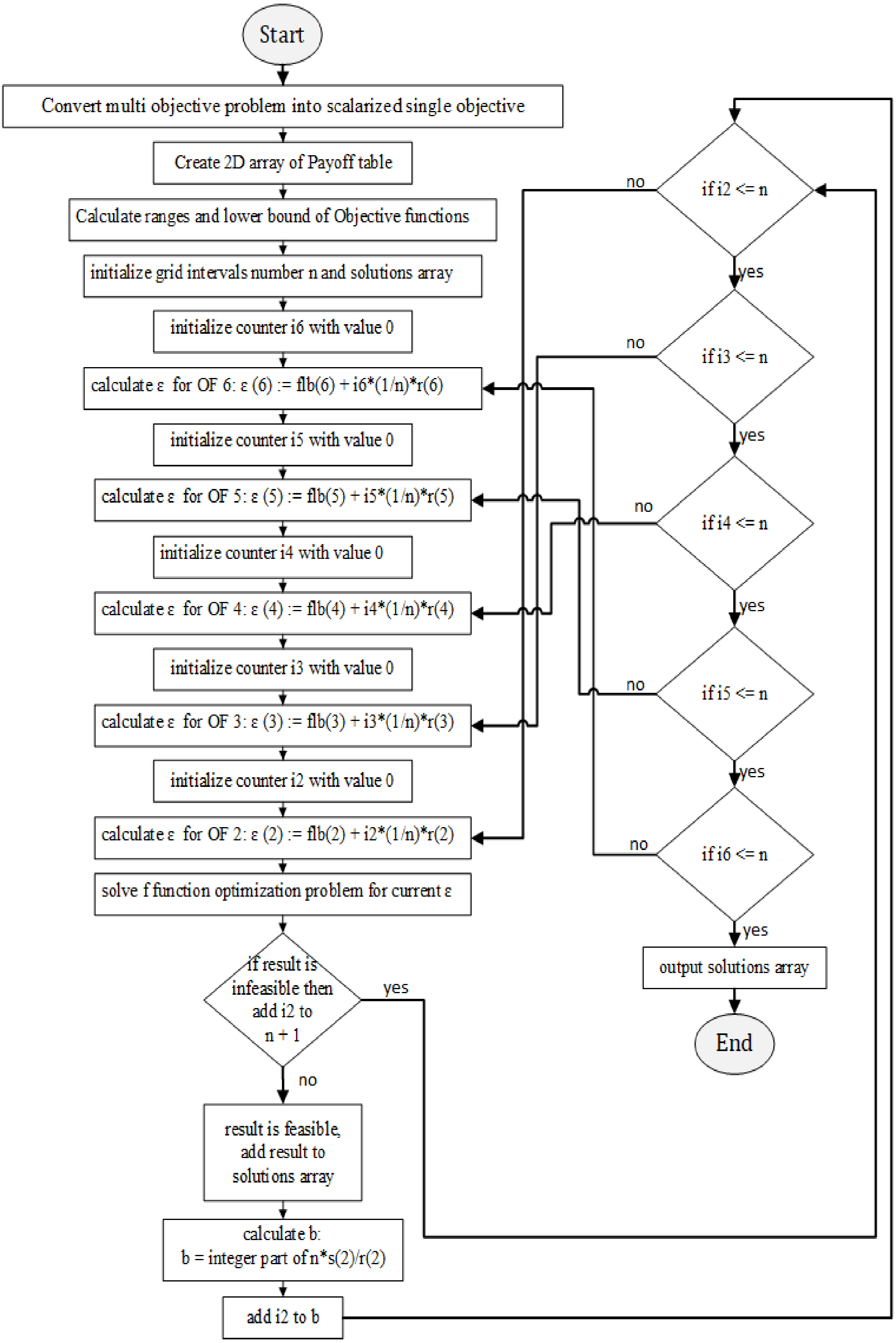

Figure 3.8: Flow Chart of AUGMECON2.

by Kim and De Weck [190]. Figure 3-9 presents the flowchart of WMM.

$$F(i) = \frac{f_i - f_i^{utopia}}{f_i^{\max} - f_i^{\min}} \tag{3.54}$$

The transformation of mathematical model is as follows:

$$Min\, Z = \begin{bmatrix} w_1 \frac{\mathrm{TC} - \mathrm{TC}^{utopia}}{\mathrm{TC}^{\max} - \mathrm{TC}^{\min}} + w_2 \frac{TTT - TTT^{utopia}}{TTT^{\max} - TTT^{\min}} \\ + w_3 \frac{EI - EI^{utopia}}{EI^{\max} - EI^{\min}} + w_4 \frac{ESL - ESL^{utopia}}{ESL^{\max} - ESL^{\min}} \\ + w_5 \frac{SI - SI^{utopia}}{SI^{\max} - SI^{\min}} + w_6 \frac{TVP - TVP^{utopia}}{TVP^{\max} - TVP^{\min}} \end{bmatrix} \tag{3.55}$$

where, utopia point (ideal point) refers to the point that optimizes all objective functions [191].

Subject to Equations (3.35)-(3.44).

The steps of implementation are as follows:

Step 1: Convert multi objective optimization problem into single objective problem.

Step 2: Create payoff table with the help of steps given below:

f_{min}, f_{max}, f, (f^{utopia}) calculation:

1. (a) *initialize i with 1, f_{min} array, f_{max} array, f array;*
   (b) *calculate f_{min}: $f_{min}(i)$ = min (pt (j, i)) where j = 1,...,6;*
   (c) *calculate fmax: fmax(i) = max (pt (j, i)) where j = 1,...,6;*
   (d) *calculate f: f(i) = pt (i, i);*
   (e) *increase i to 1;*
   (f) *if i <= 6 then go to step 2;*
   (g) *end.*

Step 3: Define combination of weights for each objective function. The total sum of weights should be equals to 1.

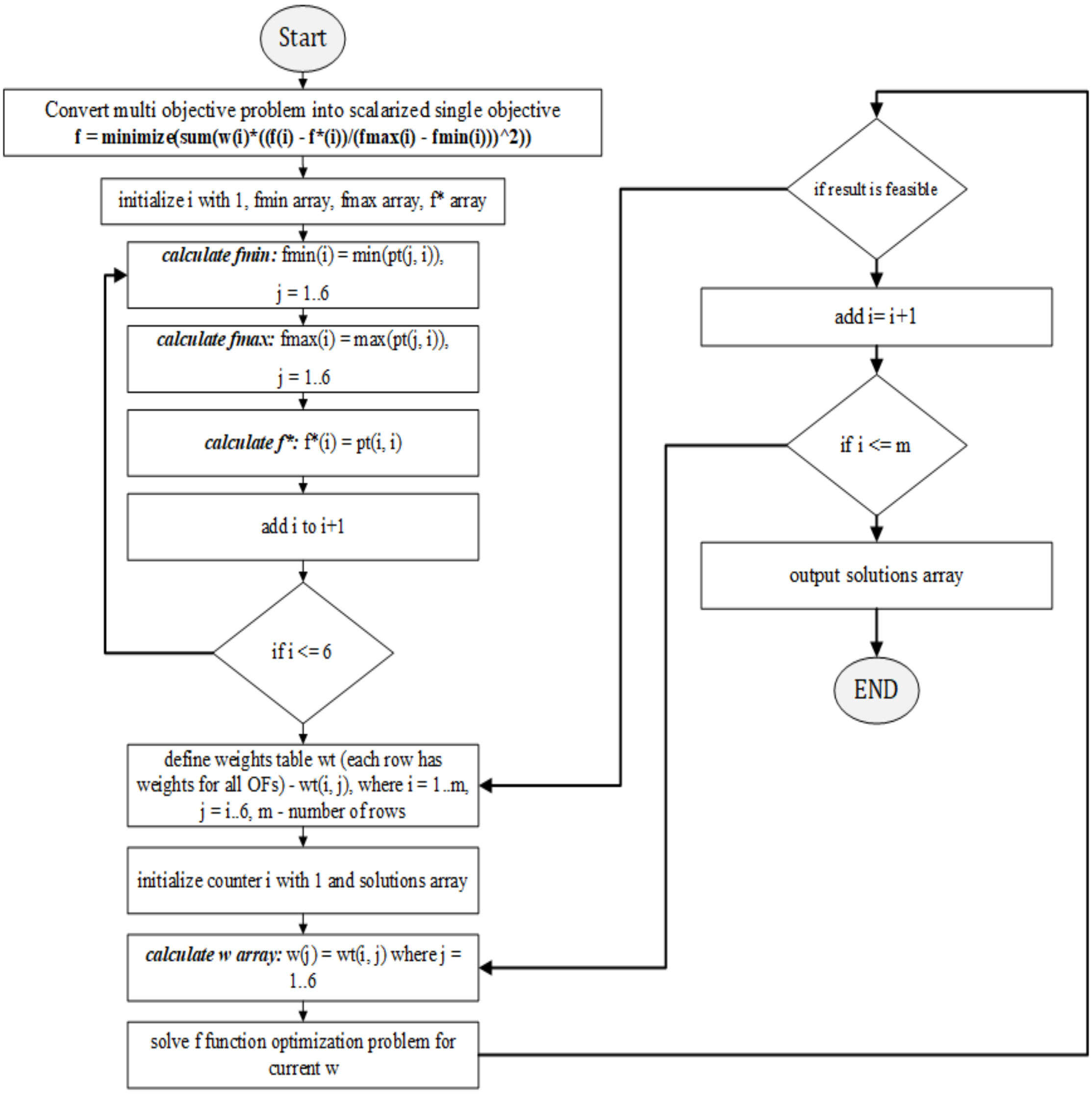

FIGURE 3.9: Flow Chart of WMM.

Step 4: Calculate the feasible solution for objective functions with the help of steps given below:

1. solve function f optimization problem for current w;
2. if result is feasible then add result to solutions array;
3. increase i to 1;
4. if $i <= 6$ then go to step 3;
5. output solutions array;
6. end.

3.7 Selection of Best Pareto Solution (Phase 4)

This section presents the techniques used for the selection of best pareto solutions obtained from solving algorithms in the previous section. MCDM techniques are used for the analysis of the pareto solutions. The purpose of using these techniques are to assist the decision makers to implement the analytical approach rather than the intuition for the selection of best solution.

3.7.1 CRITIC Weight Method

CRITIC Weight Method is used to assign weights to the pareto solution relative to each objective function. It is firstly developed by Diakoulaki et al. [194] which tends to determine the relative weights for MCDM problems. This method incorporates contrast intensity and conflict between attributes that occurred in the structure of decision-making process [193]. This study used CRITIC weight method to estimate the weights of the criteria (i.e. Objective Functions) used to evaluate the final pareto solution. It is worth mentioning here that this method does not need the independence of attributes and can transform qualitative attributes into quantitative [94]. The attributes considered in this study while applying the CRITIC method are the objective functions whose pareto optimal results are extracted by applying multi objective optimization algorithms. The implementation of this technique is as follows:

Step 1: Decision matrix was constructed on the basis of obtained pareto optimal results by optimizing multiobjective model.

Step 2: A normalized decision matrix was derived to transforms dimensional attributes into non-dimensional attributes.

$$\bar{\mathrm{X}}_{\mathrm{ij}} = \left[\frac{X_{ij} - X_j{}^{worst}}{X_j{}^{best} - X_j{}^{worst}}\right] \tag{3.56}$$

Step 3: Standard deviation of each criteria is then calculated using normalized decision matrix.

$$\sigma_j = \sqrt{\frac{\sum(X_i - \mu)^2}{N}} \tag{3.57}$$

Step 4: The linear correlation coefficient between attributes were calculated with the help of expression used by Whang and Zhang [194].

$$Correl(Xij) = \frac{n\left(\sum X_{ij}\right) - \left(\sum X_i\right)\left(\sum X_j\right)}{\sqrt{\left[n\sum X_i{}^2 - \left(\sum X_i\right)^2\right]\left[n\sum X_j{}^2 - \left(\sum X_j\right)^2\right]}} \tag{3.58}$$

Step 5: The relative index C for each attribute is calculated by the given expression.

$$C_j = \sigma_j \times \sum_{k=1}^{m}(1 - r_{jk}) \tag{3.59}$$

where, r_{jk} is the correlation matrix obtained from *Step 4*.

Step 6: Finally, the attribute weights was determined as follows.

$$w_j = \frac{C_j}{\sum_{j=1}^{n} C_j} \tag{3.60}$$

3.7.2 TOPSIS

Several techniques have been established with the sophisticated algorithms and propositions in order to analyse the MCDM problems. In this study, we have used TOPSIS model which was firstly developed by Hwang and Yoon [195]. The underlying concept in TOPSIS is that the most preferred alternative should not only have the shortest distance from "positive ideal solution", but also the longest distance from "negative-ideal solution" [62]. "Positive ideal solution" refers to the most effective or least costly value among a set of feasible solutions [196]. Conversely, a negative ideal solution refers to the least effectiveness and highest costly value among a set of feasible solutions [197]. In this study TOPSIS was used to find the final optimal solution form set of pareto optimal solutions obtained by optimizing the multiobjective model. Figure 3.10 presents the flowchart of TOPSIS augmented with CRITIC weight method used for the determination of final pareto solution which was constructed as follows [118, 198].

Step 1: Decision matrix was created on the basis of obtained pareto optimal results by optimizing multiobjective model.

Step 2: A normalized decision matrix was derived to transforms dimensional attributes into non-dimensional attributes.

$$NDM_{\mathrm{ij}} = \left[\frac{q_{ij}}{\left[\sum_{i=1}^{n} q_{ij}^{2}\right]^{1/2}} \right] \tag{3.61}$$

Step 3: Weighted normalized decision matrix was created.

$$WNDM = [W_j * NDM_{ij}] \tag{3.62}$$

Step 4: The next step was evaluating the Positive ideal (best) and negative ideal (worst) solutions.

$$Z_j^{+} = \{best(Z_{ij})\}_{i=1}^{n}, Z^{+} = \ \{Z_1^{+}, Z_2^{+}, Z_3^{+}, ..., Z_m^{+})\} \tag{3.63}$$

$$Z_{j'}^{-} = \ \{worst(Z_{ij'})\}_{i=1}^{n}, Z^{-} = \{Z_1^{-}, Z_2^{-}, Z_3^{-}, ..., Z_m^{-})\} \tag{3.64}$$

Where, j= {1, 2, ... , m} are associated with beneficial attributes and j'= {1, 2, ..., m'} are associated with non-beneficial attributes. It is the maximum or minimum value for the particular attribute out of all the values of the specific attribute.

Step 6: The separation measure between alternatives was calculated by Euclidean distances (i.e. Sep_i^{+} and Sep_i^{-}.

$$Sep_i^{+} = \sqrt{\sum_{j=1}^{m} \left(Zij - \ Z_j^{+}\right)^2} \tag{3.65}$$

$$Sep_i^{-} = \sqrt{\sum_{j=1}^{m} \left(Zij - \ Z_j^{-}\right)^2} \tag{3.66}$$

Step 7: Finally, the relative closeness RC_i of the alternatives from the ideal solution was obtained on which the alternatives are ranked.

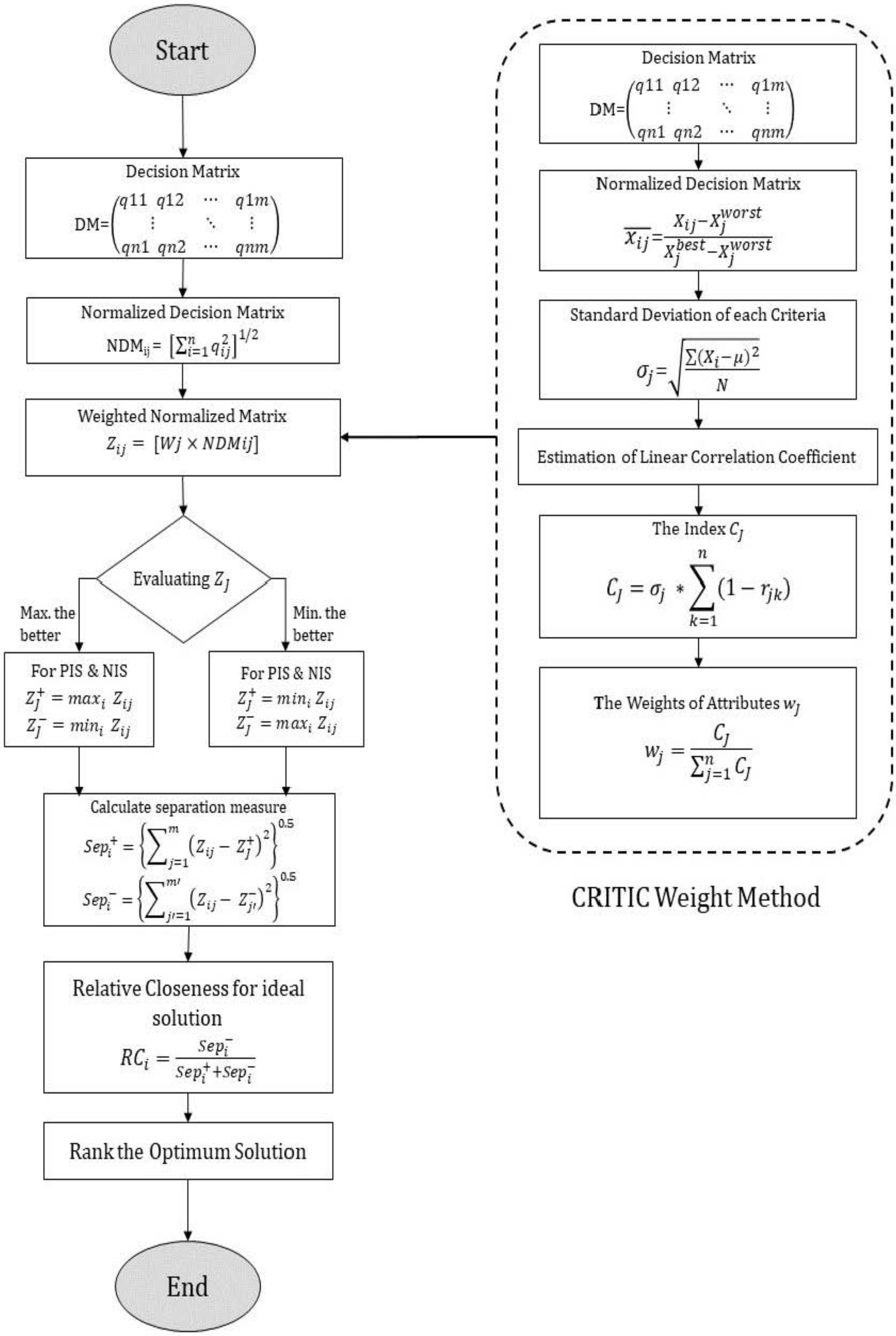

FIGURE 3.10: Flow Chart of TOPSIS Augmented CRITIC Weight Method.

$$RC_i = \frac{Sep_i^-}{Sep_i^- + Sep_i^+} \tag{3.67}$$

3.8 Software Requirements

For applying various techniques highlighted above following software are used.

1. The fuzzy E-AHP and Fuzzy TOPSIS is done using the Microsoft Excel (2016) software.
2. The Forecasting techniques are applied using Python 3.7 (Jupyter Notebook) software.
3. For solving MINLP model, Python 3.7 (Jupyter Notebook) software is used with the help of GEKKO library that ran on personal computer of Core i5 2.5 GHz processor with 8 GB of RAM.

Chapter 4

Results and Analysis

In this chapter, the proposed methodology was applied and evaluated using real-time supply chain network of an organization that sells split and centralized air conditioning units. Appendix D.1 presents the input data used for this case study. The parameters related to number of suppliers, number of number of warehouses, capacity of suppliers and warehouses, types of transportation modes and monthly demand were provided by the organization. The supply chain of the organization comprises of three suppliers, three warehouses, three transportation modes, and one customer as shown in Figure 4.1. Supplier i can supply the number of units to any warehouse k via port j. Moreover, any potential warehouse can meet the forecasted demand of customer through available transportation modes.

4.1 Sustainable Supplier Selection

4.1.1 Sustainable Criteria Weighting

In the first step, weights of each sustainable criteria (i.e. conventional, social and environmental) was evaluated using Fuzzy E-AHP based on the preferences set by decision makers. Then, the weights of each sub-criteria were calculated. Table 4-1

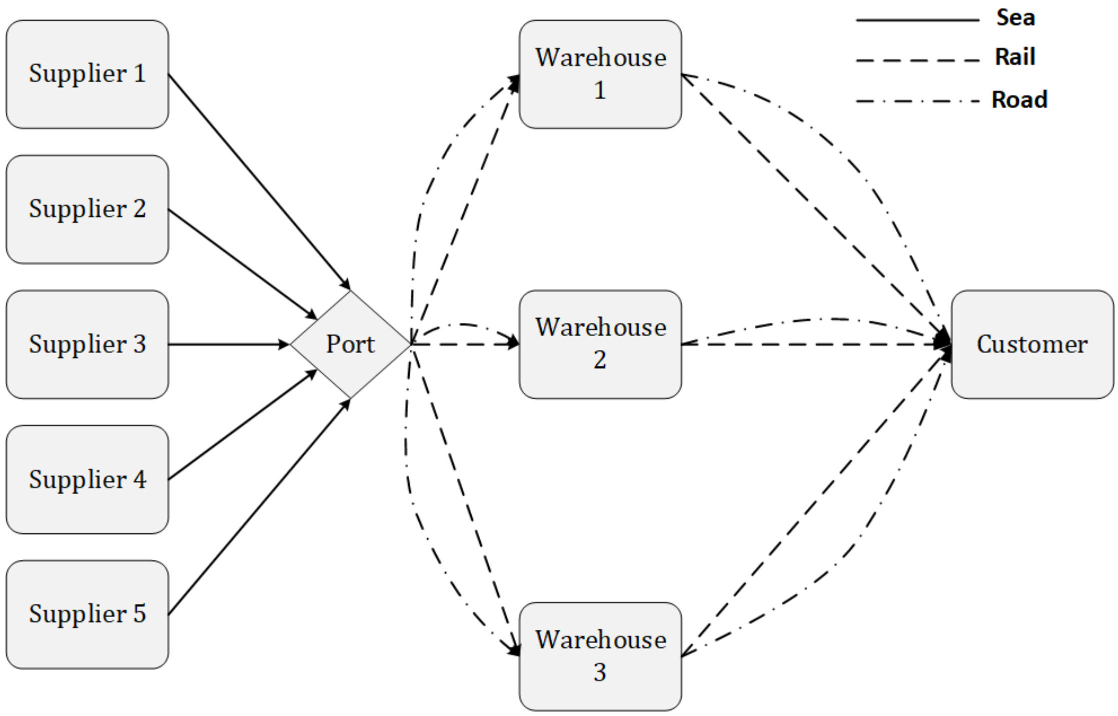

FIGURE 4.1: Multi Echelon Supply Chain Network of Case Company.

presents the final weights of each criteria. The ranking for the sustainable criteria was presented as *conventional* > *social* > *environmental* for decision makers accessing the suppliers.

For evaluating the weights of the sustainable criteria using fuzzy E-AHP, first step is to check the consistency ratio (CR) of the decision-making process using the expression given below [199].

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{4.1}$$

$$CR = \frac{CI}{RI} \tag{4.2}$$

where, $\lambda_{\max}$ is the maximum eigen value, n is the number of criteria (dimension of matrix), RI is the random consistency index, and CI is the closeness index used to calculate CR. The threshold of CR is 10% [142]. The steps for the calculation of CR are listed in Appendix A.1. After checking the consistency of the decision matrices, fuzzy E-AHP is applied to evaluate the weights of the sustainable criteria with the steps presented in Appendix A.2.

According to decision makers, conventional criteria ranked highest followed by social and environmental criteria. Product quality is the most significant sub-criteria amongst nine set of conventional sub-criteria. Similarly, for environmental and social criteria, decision makers considered innovation capability and staff personal and technical development as a significant sub-criterion for sustainable supplier selection. These results provide insight for the decision makers to take necessary actions in order to provide better product quality while increasing innovation capability of the product with staff personal and technical development. The step-wise calculations are presented in Appendix A.2.1 and A.2.2.

TABLE 4.1: Fuzzy E-AHP Weights for Sustainable Criteria and Sub Criteria.

Criteria	**Global Weights**	**Sub-Criteria**	**Local Weights**	**Ranking**
		Product Price	0.06	3
		Volume Flexibility	0.01	6
		Payment Terms	0.01	6
		Product Mix	0.07	2
Conventional	0.41	Past Businesses	0.01	6
		Responsiveness	0.03	5
		Use of Technology	0.04	4
		Vendors Market reputation	0.06	3
		Product Quality	**0.12**	1
		Environment Management System	0.04	4
Environmental	0.29	Resource Consumption	0.07	3
		Waste Management System	0.08	2

		Innovation Capability	**0.10**	1
Social	0.30	Labor Incentives	0.02	3
		Rights and Health of Employees	0.03	2
		Staff Personal and Technical Development	**0.25**	1

4.1.2 Sustainable Supplier Ranking

After evaluating the weights for sustainable criteria, next step is to rate the potential suppliers on the basis of conventional, environmental and social criteria. For rating the suppliers, fuzzy TOPSIS was used to determine the weights of each supplier with respect to sustainable criteria. Four decision makers were involved in this process to rate the potential suppliers on the basis of specified criteria. Firstly, the relative closeness matrix for each supplier with respect to sustainable criteria was evaluated using fuzzy TOPSIS. Afterwards, TOPSIS was applied to obtain overall supplier ranking and are presented in Table 4.2. The step-wise calculations are presented in Appendix B.1.

TABLE 4.2: Closeness Coefficient for Sustainable Supplier Selection using TOPSIS.

Supplier	**Conventional Criteria**	**Environmental Criteria**	**Social Criteria**	**Overall Closeness Coefficient**	**Rank**
Supplier 1	0.33	0.24	0.30	0.17	3
Supplier 2	0.50	0.68	0.17	0.42	2
Supplier 3	**0.63**	**0.62**	**0.73**	**0.94**	1
Supplier 4	0.32	0.23	0.53	0.230	5
Supplier 5	**0.70**	0.48	0.45	0.612	2

Table 4.2 illustrates the suppliers' rating based on sustainable performance criteria is as follows:

For Conventional Criteria:

Supplier 5 > Supplier 2 > Supplier 1 > Supplier 3 > Supplier 4

For Environmental Criteria:

Supplier 3 > Supplier 2 > Supplier 5 > Supplier 1 > Supplier 4

For Social Criteria:

Supplier 3 > Supplier 2 > Supplier 4 > Supplier 5 > Supplier 1

The threshold of the closeness coefficient defined for the selection of best supplier is 0.50. Therefore, **Supplier 2, Supplier 3, and Supplier 5** were selected for the allocation of optimum order.

4.2 Demand Forecasting

Once the supplier rating is done on the basis of fuzzy E-AHP and Fuzzy TOPSIS, the next step is to forecast the next period demand using the techniques enlisted in Section 3.4. Before apply any of the technique, first step is to plot the actual data in order to check the trend and seasonality of the data. Figure 4.2 presents the actual demand data of AC from year 2012 to 2020. The initial demand data shows increasing trend and seasonality over the years.

The next period demand is forecasted using MA, WMA, SES, LSM, and SARIMA using Equation (3.12)-(3.18). The detail calculations of first four techniques are presented in Appendix C.1-C.4. Whereas, the results of SARIMA forecasting are presented hereafter.

Step 1: In order to identify the model use for demand forecasting, first step is to visualize the time series data to detect the existence of seasonality and/or trend as shown in Figure 4.2.

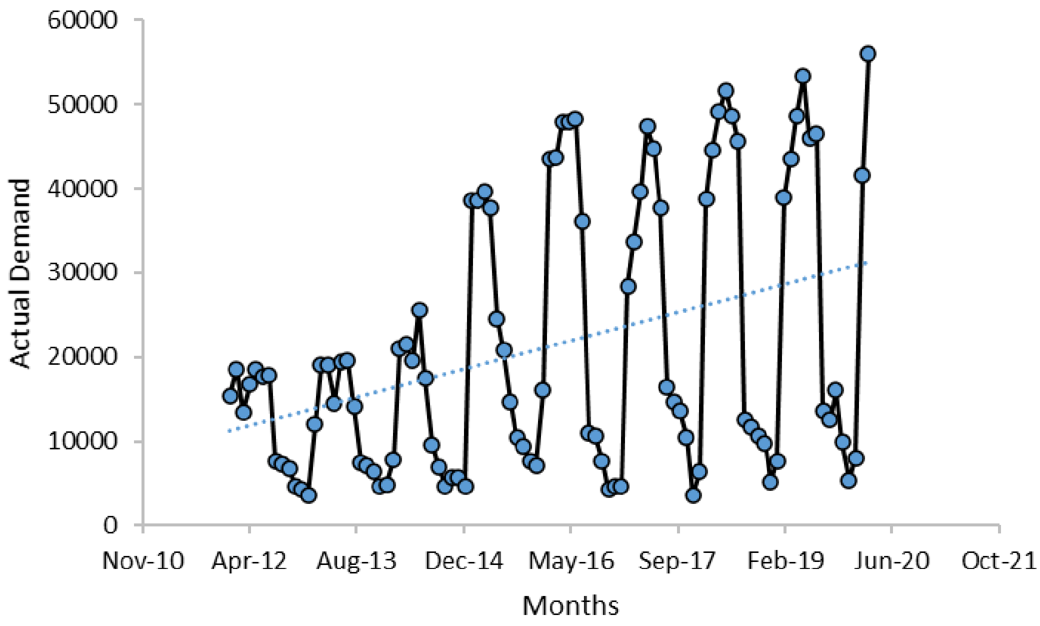

FIGURE 4.2: Actual Monthly Demand Data from Jan-2012 to Mar-2020.

Step 2: After visualizing the time series, next step is to identify the stationarity of the data. For precise assessment of stationarity or non-stationary Augmented Dickey-Fuller (ADF) test (Agiakloglou and Newbold, 1992) is used and the results are presented in Table 4.3.

The null-hypothesis of ADF test is that the data is non-stationary. In ADF test, if p-value is less than 0.05, null hypothesis can be rejected. However, the p-value is greater than 0.05, null hypothesis cannot be rejected. We can conclude than the mean is not stationary so differencing needs to be applied for making the data stationary.

TABLE 4.3: Model Diagnosis.

Test Statistics	-1.078823
p-value	0.723443
#Lags Used	12.000000
No. of Observations Used	86.000000
Critical Value (1%)	-3.508783
Critical Value (5%)	–2.895784
Critical Value (10%)	-2.585038

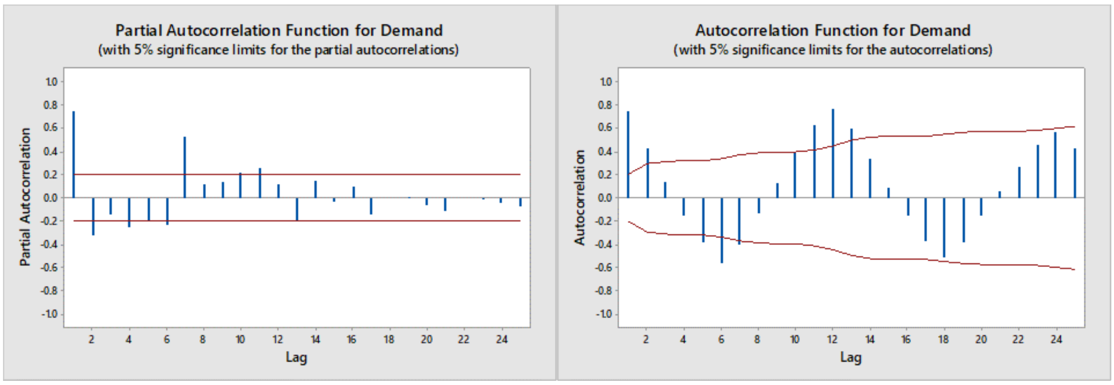

FIGURE 4.3: PACF and ACF of Monthly Demand.

Step 3: The partial auto correlation function (PACF) and auto correlation function (ACF) of the data is plotted in order to estimate the auto correlation values, lagged value, correlation of residuals and their lagged values that will result in the combination of (p, d, q)(P, D, Q)s values and are presented in Figure 4.3.

Step 4: In order to select the model, Akaike's Information Criteria (AIC) is used. The AIC measures how well a model fits the data while taking into account the overall complexity of the model. The objective is to find the model that yields the lowest AIC value. The AIC values of suggested models are presented in Appendix C5.

The results show that the minimum AIC value is *1457.5969711484167* and suggest that (p, d, q) *(P, D, Q) s = **(1, 1, 1) (0, 1, 1, 12)12**. The model is further diagnosed using the data analytics plots (i.e. Standardize Residual, Histogram, Normal Distribution, QQ-plot, Correlogram) as presented in Figure 4.4.

Standardize residual is use to identify the outliers in the data set. For calculating standardize residuals, firstly mean residual is obtained and then divide each residual with the standard deviation of the residuals. The top left plot shows that, the specified model does not display any obvious seasonality and appears to be a white noise (i.e. sequence of random numbers and cannot be predicted). In the top right plot, N (0,1) presents the standard normal distribution and KDE line presents the Leptokurtic distribution (i.e. greater fluctuations in the data set and having the potential of high and low returns.). The QQ-plot on the bottom left shows that the ordered distribution of residuals (blue dots) follows the linear trend of the samples

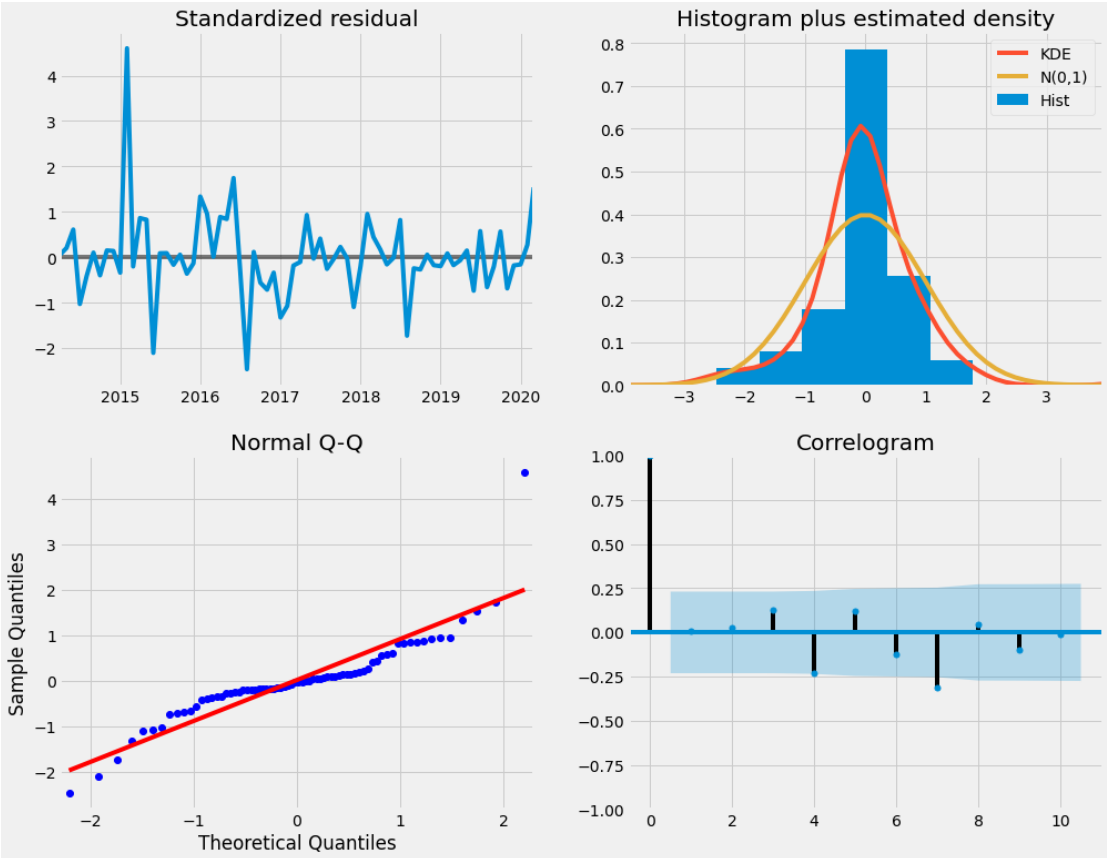

FIGURE 4.4: Model Diagnosis.

taken from a standard normal distribution with N (0, 1). The Correlogram in the bottom right is the plot between auto correlation and lags. The graph only signifies the single high positive correlation at zero lag and have minor negative correlation at lag 4 and 7 which indicates the absence of any specific pattern. For the selection of next period demand, the MSE of all the techniques are compared and the forecasted demand of the techniques with least MSE is used as an input for MINLP model. Table 4.4 presents the MSE of forecasting techniques. It can be seen that SARIMA has least MSE error while Exponential Smoothing has a highest value. Therefore, the demand used for next period obtained by SARIMA is **57746** units. The actual and forecasted demand is presented in Figure 4.5.

TABLE 4.4: Mean Square Error (MSE) Comparison of Forecasting Techniques.

Forecasting Techniques	**MSE**
MA	73579035.100
WMA	150565240.568

Forecasting Techniques	MSE
ES	230019461.907
LSM	217310120.891
SARIMA	30458660.510
Min	30458660.510
Max	230019461.907

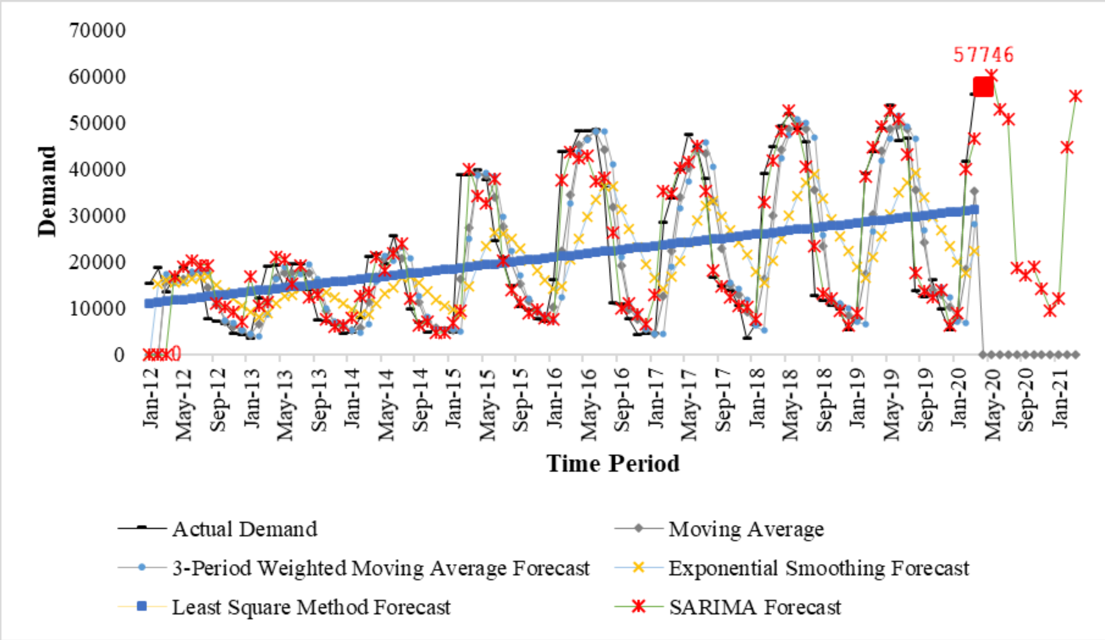

FIGURE 4.5: Actual vs Forecasted Demand.

4.3 Optimal Order Allocation

The mathematical model was initially solved by considering each objective separately. Non-linear solver is used to estimate the optimum solution for each objective function. Table 4.5 presents the solution for each objective function obtained from exact non-linear solver.

In the next step, all the objectives were simultaneously solved using AUGMECON2 and WMM algorithms. The Pareto solutions were generated using these techniques in order to find the optimal order quantity from the potential suppliers

TABLE 4.5: Optimum Solution of each Objective Function using Non-linear Solver.

Objective Function	**Ideal Solution Breakdown**	
Total Cost	\$ 18,215,455.20	Purchasing cost = \$ 8459740 Ordering cost = \$ 10.8 Holding cost = \$ 115,528 Transportation cost = \$ 224,878.50 Transfer cost = \$ 109,583.90 Custom Clearance cost = \$ 9,305,714.00
Total Travel Time	2,517.36 hrs.	Transportation Time = 2,341.25 hrs. Transfer Time = 175.72 hrs. Custom Clearance time = 0.38 hrs.
Environmental Impact	4,133,135.87 grams	EI for Ship = 5,758.35 grams EI for Rail = 2,469,227.52 grams EI for Road = 1,658,150.00 grams
Equivalent Sound Level	509,799.37 dB (A)	ESL for Ship = 103,590.87 dB (A) ESL for Rail = 8,184.76 (A) ESL for Road = 398,023.74 dB (A)
Social Impact	8,053.88	N/A
Total Value of Sustainable Purchasing	10,023.24	N/A

under forecasted demand obtained from Section 4.1 and 4.2. The Pareto solution obtained from both techniques are further evaluated using TOPSIS augmented with CRITIC weight method to obtain the final solution. The closeness coefficient matrix obtained from both techniques are compared in order to extract the final results based on higher closeness coefficient value as done by [85].

4.3.1 Evaluation of Optimal Order Using AUGMECON2

For solving six objectives MINLP mathematical model, firstly minimum and maximum values of each objective function are evaluated using Equations (3.46)-(3.51). The maximum and minimum values presented in Table 4.6.

Table 4.6: Payoff Table for Minimum and Maximum Values of Objective Functions.

Objective Function	**TC**	**TTT**	**EI**	**ESL**	**SI**	**TVSP**
TC	18,215,455.20	2,874.90	4,133,686.17	509,799.37	8,764.04	9,904.88
TTT	18,836,772.31	2,872.30	4,133,135.87	509,799.37	8,053.88	9,786.52
EI	18,836,772.31	2,872.30	4,133,135.87	509,799.37	8,053.88	9,786.52
ESL	18,466,445.39	2,907.36	4,167,999.43	509,799.37	8,369.48	9,904.87
SI	18,217,887.14	2,908.35	4,167,504.17	509,799.04	8,764.04	9,904.88
TVSP	18,342,121.70	2,906.94	4,167,866.36	509,799.37	8,290.60	10,023.24

The (max, min) values of each objective function are:

{(18,836,772.31, 18,217,887.14)};
{(2,908.35, 2,872.30)};
{(4,167,999.43, 4,133,135.87)};
{(509,799.37, 509,799.04)};
{(8,764.04, 8,053.88)};
and {(10,023.24, 9,786.52)}.

The ideal solutions are: TC = \$ 18,217,887.14, TTT = 2,872.30 hrs., EI = 4,133,135.87 grams, ESL = 509,799.04 dB (A), SI = 8,764.04 and TVSP = 10,023.24. Once the minimum and maximum values are evaluated, the next step is to assign the epsilon values (ε_2, ε_3, ε_4, ε_5) with the step interval of 2 using Equations (3.46)-(3.51) The combinations of ε-values are presented in Table 4.7.

Table 4.7: ϵ-values of TTT, EI, ESL, SI, TVSP.

	ϵ-values				
	ϵ_2	ϵ_3	ϵ_4	ϵ_5	ϵ_6
1	2,872.30	4,133,135.87	509,799.04	8,053.88	9,786.52
2	2,890.32	4,133,135.87	509,799.04	8,053.88	9,786.52
3	2,908.35	4,133,135.87	509,799.04	8,053.88	9,786.52
4	2,872.30	4,150,567.65	509,799.04	8,053.88	9,786.52
5	2,872.30	4,133,135.87	509,799.37	8,053.88	9,786.52
6	2,890.32	4,133,135.87	509,799.37	8,053.88	9,786.52

	ϵ-values				
	ϵ_2	ϵ_3	ϵ_4	ϵ_5	ϵ_6
7	2,872.30	4,133,135.87	509,799.20	8,764.04	9,786.52
8	2,872.30	4,133,135.87	509,799.04	8,053.88	10,023.24
9	2,890.32	4,133,135.87	509,799.04	8,053.88	10,023.24
10	2,908.35	4,133,135.87	509,799.04	8,053.88	10,023.24
11	2,908.35	4,133,135.87	509,799.20	8,053.88	10,023.24
12	2,872.30	4,150,567.65	509,799.20	8,053.88	10,023.24
13	2,890.32	4,150,567.65	509,799.37	8,053.88	10,023.24
14	2,908.35	4,150,567.65	509,799.37	8,053.88	10,023.24
15	2,872.30	4,150,567.65	509,799.20	8,053.88	10,023.24
16	2,872.30	4,150,567.65	509,799.37	8,053.88	10,023.24
17	2,890.32	4,150,567.65	509,799.37	8,053.88	10,023.24
18	2,908.35	4,150,567.65	509,799.37	8,053.88	10,023.24
19	2,890.32	4,167,999.43	509,799.37	8,053.88	10,023.24
20	2,908.35	4,167,999.43	509,799.37	8,053.88	10,023.24

The iteration runs for each combination of ϵ-values to extract the pareto optimal solution. The maximum number of iterations were set as 50,000. The pareto solutions obtained using these ε-values are presented in the Table 4.8.

Table 4.8: Pareto Solutions of Six Objective Functions using AUGMCON2.

S. No.	TC	TTT	EI	ESL	SI	TVSP
1	18,256,398.81	2,875.81	4,138,228.87	519,333.78	8,608.64	9,943.73
2	18,216,706.60	2,891.75	4,152,996.44	516,249.13	8,764.04	9,904.88
3	18,217,973.54	2,910.20	4,169,698.74	509,799.04	8,764.04	9,904.88
4	18,216,312.83	2,881.02	4,163,274.65	521,296.75	8,764.04	9,904.88
5	18,215,505.59	2,874.73	4,133,135.87	510,079.26	8,764.04	9,904.88
6	18,216,592.76	2,890.32	4,149,102.06	510,079.25	8,764.04	9,904.88
7	18,215,442.42	2,874.55	4,133,135.87	509,799.20	8,764.04	9,904.88
8	18,339,677.66	2,872.94	4,133,135.87	509,799.26	8,290.60	10,023.24
9	18,340,925.07	2,890.32	4,150,913.95	509,799.37	8,290.60	10,023.24

S. No.	TC	TTT	EI	ESL	SI	TVSP
10	18,342,222.89	2,908.35	4,169,299.87	509,799.37	8,290.60	10,023.24
11	18,342,222.89	2,908.35	4,169,299.87	509,799.37	8,290.60	10,023.24
12	18,339,583.17	2,876.06	4,150,562.92	552,967.43	8,290.72	10,023.24
13	18,340,924.98	2,890.32	4,150,912.98	509,799.37	8,290.60	10,023.24
14	18,342,222.65	2,908.34	4,169,296.44	509,799.37	8,290.60	10,023.24
15	18,339,583.17	2,876.06	4,150,562.92	552,967.43	8,290.72	10,023.24
16	18,339,964.24	2,876.06	4,150,567.65	552,983.56	8,290.64	10,023.24
17	18,340,924.98	2,890.32	4,150,912.98	509,799.37	8,290.60	10,023.24
18	18,342,222.65	2,908.34	4,169,296.44	509,799.37	8,290.60	10,023.24
19	18,341,227.18	2,890.32	4,168,180.62	517,931.65	8,290.60	10,023.24
20	18,342,222.65	2,908.35	4,169,296.44	509,799.37	8,290.60	10,023.24

The obtain best result from the above pareto solutions of AUGMECON2, TOPSIS augmented with CRITIC weight method is used as discussed in Section 3.7. The criteria weight calculations are presented in Appendix E.1. The weights of the functions are calculated using Equation (3.65) and are presented in the Table 4.9.

Table 4.9: CRITIC weights of Six Objective Functions for AUGMECON2.

Objective Functions	Weights
TC	0.16
TTT	0.13
EI	0.11
ESL	0.15
SI	0.16
TVSP	0.29

After calculating the weights of criteria, next step is to apply TOPSIS in order to calculate the closeness coefficient (CC) matrix. The calculations for TOPSIS augmented with CRITIC weights are presented in Appendix E.2. The results for CC matrix are presented in Table 4.10.

Table 4.10: Relative Closeness Coefficient (CC) Matrix for Pareto Solutions of AUGMECON2.

S. No.	**CC**
1	0.716
2	0.777
3	0.798
4	0.726
5	0.820
6	0.815
7	**0.821**
8	0.600
9	0.596
10	0.592
11	0.592
12	0.196
13	0.596
14	0.592
15	0.196
16	0.196
17	0.596
18	0.592
19	0.540
20	0.592

It can be seen that solution at point 7 has highest closeness coefficient values amongst all 20 solutions. Therefore, it will be considered as the best optimal solution using AUGMECON2 having TC = $18,215,442.42, TTT = 2,874.55 hrs., EI = 4,133,135.87 grams, ESL = 509,799.20 dB(A), SI = 8,764.04, and TVSP = 9,904.88.

4.3.2 Evaluation of Optimal Order Using WMM

For simultaneously solving the six objectives of mathematical model using WMM, the minimum and maximum values of each objective function were determined. Next, 25 different combinations of weights are allocated to six objective functions. The weight combinations of six objectives are presented in Table 4.11.

TABLE 4.11: Weights for TC, TTT, EI, ESL, SI, TVSP.

S. No.	$\mathbf{w}_1$	$\mathbf{w}_2$	$\mathbf{w}_3$	$\mathbf{w}_4$	$\mathbf{w}_5$	$\mathbf{w}_6$
1.	0.20	0.20	0.20	0.20	0.10	0.10
2.	0.30	0.10	0.20	0.10	0.20	0.10
3.	0.40	0.10	0.20	0.10	0.10	0.10
4.	0.40	0.20	0.20	0.05	0.10	0.05
5.	0.40	0.10	0.30	0.05	0.10	0.05
6.	0.40	0.20	0.30	0.05	0.05	0.00
7.	0.40	0.20	0.05	0.05	0.20	0.10
8.	0.40	0.10	0.10	0.20	0.10	0.10
9.	0.50	0.10	0.20	0.05	0.10	0.05
10.	0.50	0.10	0.10	0.10	0.10	0.10
11.	0.50	0.20	0.05	0.05	0.10	0.10
12.	0.50	0.30	0.05	0.05	0.05	0.05
13.	0.60	0.05	0.20	0.05	0.05	0.05
14.	0.20	0.10	0.10	0.50	0.05	0.05
15.	0.20	0.10	0.20	0.40	0.05	0.05
16.	0.20	0.10	0.40	0.20	0.05	0.05
17.	0.20	0.10	0.30	0.20	0.10	0.10
18.	0.20	0.10	0.10	0.05	0.50	0.05
19.	0.20	0.10	0.05	0.05	0.40	0.20
20.	0.20	0.20	0.05	0.05	0.30	0.20

After assigning weights to each objective, Equation (3.53) is used to solve the objective functions and generate the pareto solutions for the combinations of weights listed above. The pareto solutions for WMM are presented in Table 4.12.

Table 4.12: Pareto Solutions of Six Objective Functions using WMM.

Sr. No.	TC	TTT	EI	ESL	SI	TVSP
1	18,260,179.84	2,874.27	4,133,585.06	509,799.37	8,593.60	9,947.49
2	18,255,982.23	2,874.42	4,133,584.52	509,799.37	8,640.26	9,930.35
3	18,260,064.08	2,874.31	4,133,565.19	509,799.37	8,612.94	9,939.28
4	18,243,699.36	2,874.63	4,133,752.17	509,799.37	8,656.44	9,931.78
5	18,245,493.77	2,874.60	4,133,739.89	509,799.36	8,649.60	9,933.49
6	18,245,901.59	2,874.77	4,133,657.43	509,799.36	8,729.24	9,899.08
7	18,247,940.91	2,875.30	4,136,948.70	510,353.76	8,659.26	9,927.45
8	18,264,952.57	2,875.59	4,134,834.69	509,799.37	8,621.68	9,932.27
9	18,258,607.83	2,874.44	4,133,588.35	509,799.37	8,645.52	9,926.31
10	18,275,883.65	2,874.18	4,133,534.59	509,799.37	8,579.82	9,942.71
11	18,265,446.72	2,874.35	4,133,678.46	509,799.37	8,588.96	9,945.90
12	18,265,719.66	2,875.77	4,135,172.62	509,799.36	8,572.92	9,952.66
13	18,252,981.12	2,874.54	4,133,771.46	509,799.36	8,621.08	9,940.62
14	18,259,076.71	2,874.31	4,133,561.69	509,799.37	8,613.06	9,939.90
15	18,254,757.33	2,874.70	4,133,952.30	509,799.37	8,614.36	9,942.30
16	18,276,167.02	2,874.18	4,133,533.62	509,799.37	8,578.60	9,943.04
17	18,260,193.01	2,874.45	4,133,771.62	509,799.37	8,593.60	9,947.49
18	18,228,101.81	2,874.88	4,133,771.36	509,799.36	8,731.14	9,910.38
19	18,252,098.63	2,875.20	4,134,335.74	509,799.36	8,655.26	9,926.60
20	18,263,795.28	2,874.54	4,133,756.48	509,799.36	8,625.80	9,931.24

The obtain best result from the above pareto solutions of WMM, TOPSIS augmented with CRITIC weight method is used as discussed in Section 3.7. The weight calculations are presented in Appendix F.1. The weights of the functions are calculated using Equation (3.59) and are presented in the Table 4.13.

Table 4.13: CRITIC weights of Six Objective Functions for WMM.

Objective Functions	Weights
TC	0.17
TTT	0.17
EI	0.12
ESL	0.12
SI	0.21
TVSP	0.21

Once the weights for objective functions are calculated, next step is to apply TOPSIS in order to calculate the closeness coefficient (CC) matrix. The calculations for TOPSIS augmented with CRITIC Method are presented in Appendix F.2. The results for CC matrix are presented in Table 4.14.

TABLE 4.14: Relative Closeness Coefficient (CC) Matrix for Pareto Solutions of WMM.

S. No.	CC
1	0.254
2	0.439
3	0.310
4	0.537
5	0.499
6	0.773
7	0.544
8	0.337
9	0.463
10	0.202
11	0.235
12	0.225
13	0.354
14	0.312
15	0.324
16	0.201
17	0.254
18	**0.816**
19	0.520
20	0.358

It can be seen that solution at point 18 has highest closeness coefficient values amongst all 20 solutions. Therefore, it will be considered as the best optimal solution using WMM having TC = \$18,228,101.81, TTT = 2,874.88 hrs., EI

= 4,133,771.36 grams, ESL = 509,799.36 dB(A), SI = 8,731.14, and TVSP = 9,910.38.

4.4 Final Solution Selection

The selection of final solution from both techniques is a challenging task for decision makers because of little difference in the among the values of six objective functions Therefore, the CC matrix obtained by applying TOPSIS augmented with CRITIC weight method is compared. The Ideal solution of AUGMECON2 is 0.848 and of WMM is 0.816. The ideal values obtained from AUGMECON 2 algorithm are obtained with ε-value assignment of ε_2 = 2,872.30, ε_3 = 4,133,135.87, ε_4 = 509,799.20, ε_5 = 8,764.04, and ε_6 = 9,786.52. While the ideal values obtained by WMM are obtained with weights assignment of $w_1 = 0.20$, $w_2 = 0.10$, $w_3 = 0.10$, $w_4 = 0.05$, $w_5 = 0.50$, and $w_6 = 0.05$. Table 4.15 presents the CC matrix obtained by apply TOPSIS augmented with CRITIC weight method on the Pareto solutions of both algorithms.

TABLE 4.15: Comparison of CC Matrix for AUGMECON2 and WMM.

CC Matrix		
S. No.	**AUGMECON 2**	**WMM**
1	0.716	0.254
2	0.777	0.439
3	0.798	0.310
4	0.726	0.537
5	0.820	0.499
6	0.815	0.773
7	0.821	0.544
8	0.600	0.337
9	0.596	0.463
10	0.592	0.202
11	0.592	0.235

CC Matrix		
S. No.	**AUGMECON 2**	**WMM**
12	0.196	0.225
13	0.596	0.354
14	0.592	0.312
15	0.196	0.324
16	0.196	0.201
17	0.596	0.254
18	0.592	0.816
19	0.540	0.520
20	0.592	0.358

As the CC matrix of AUGMECON 2 contains the highest value of 0.821, which leads to the Total cost of $18,215,442.42, Total Travel Time of 2,874.55 hrs., Total Environmental impact of 4,133,135.87 grams, Equivalent Sound level of 509,799.20 dB(A), Social Impact of 8,764.04, and Total Value of Sustainable Purchasing of 9,904.88. Figure 4.6 presents the optimal order allocation to suppliers in order to meet the demand.

4.5 Managerial Implications

The implications of above demonstrated results from the managerial perspective are as follows:

1. The comprehensive sustainability-based analysis has been presented using the proposed multi-phase holistic framework for solving the SSSOA problem.
2. Proposed decision support framework can be used for the selection of suppliers based on economic, environmental and social criteria of sustainability.
3. The sustainability-based analysis has been augmented for the first time with forecasting technique for companies to manage the uncertain demand.

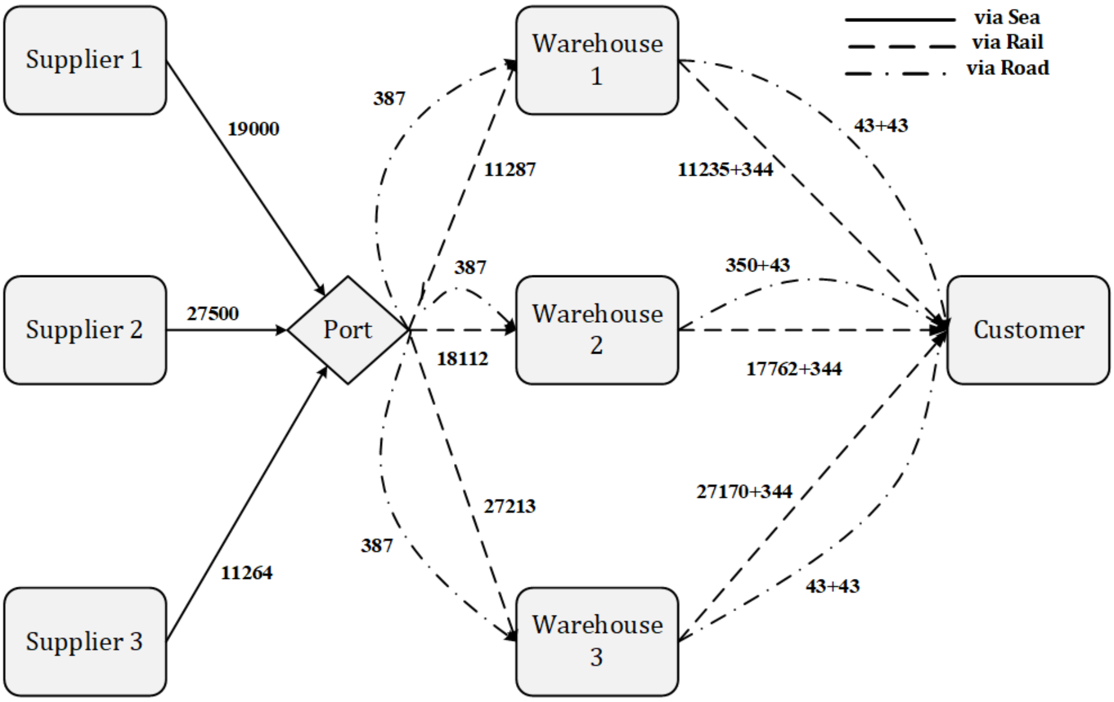

Figure 4.6: Optimal Order Allocation to Potential Supplier.

4. The integration of multi-modal transportation network in the proposed framework provides more flexibility to the decision makers.

5. Carbon emissions and noise pollution have been integrated in mathematical model to provide a broader impact of supply chains on environment.

6. The developed mathematical model consists of several real time variables that effects the overall performance of supply chains.

Chapter 5

Conclusion and Future Recommendations

Sustainable Supplier Selection and Order Allocation helps organizations to move towards sustainable development. This study presents a comprehensive multi-phase decision support framework for SSSOA problem. A real time case study of air conditioning industry is used to assess the proposed framework. Following main conclusions can be drawn:

1. The result showed that amongst the sustainable criteria, product quality, staff personal and technical development and innovation capability ranked highest.
2. The transfer cost and custom clearance cost contributes 51.7% to the total cost of the supply chain network.
3. Similarly, transfer time and custom clearance time contributes 7.0% to the total travel time of the supply chain network.
4. The transportation via ship contributes 1.0%, via rail contributes 59.7%, and via truck contributes 40.1% to total overall environmental impact of supply chain.

5. The transportation via ship contributes 20.3%, via rail contributes 1.6%, and via truck contributes 78.1% to total equivalent sound level of supply chain.

6. The results revealed that AUGMECON2 outperformed WMM because it obtained the highest closeness coefficient of 0.821/1.0.

5.1 Future Recommendations

Following are the recommendations for future research:

1. Future studies can implement the proposed multi-stage methodological framework in a closed loop supply chain while solving supplier selection and order allocation problem.

2. The proposed methodology can be improved by integrating multi product and multi period supply chains for a large size case study.

3. Solving the multi-objectives using more sophisticated algorithms (for instance AUGMECON-R) for more optimized solutions.

4. The proposed framework can be improved by transforming the multi objective mathematical model in to fuzzy multi objective mathematical model to handle the uncertainty and dynamic nature of input parameters.

5. Integration of supply chain robustness analysis by incorporating the effects of disruptions due to geographic proximity (i.e. what if scenarios') in the proposed framework can be an interesting research direction for future studies.

6. Incorporation of quantity discounts and inventory control with multi period horizon can be an interesting avenue to proceed.

7. Analysing the current supply chain and comparing it with newly proposed supply chain network integrated with facility allocation problem is another un explored research domain.

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Appendix

A.1: Consistency Index Calculation

Combined Decision Matrix

Sustainable Criteria	Conventional	Environmental	Social
Conventional	1.00	0.20	7.00
Environmental	5.00	1.00	0.14
Social	0.14	7.00	1.00

Normalized Decision Matrix

$$\text{NDM} = \frac{\sum_{j=1}^{n} x_{ij}}{n}$$

Where, i represents rows and j represents column.

Sustainable Criteria	Conventional	Environmental	Social
Conventional	0.16	0.02	0.86
Environmental	0.81	0.12	0.02
Social	0.02	0.85	0.12

Weight Matrix

$$\text{Weight} = \frac{\sum_{i=1}^{n} x_{ij}}{n}$$

Sustainable Criteria	Weight
Conventional	0.35
Environmental	0.32
Social	0.33

Weight Normalized Matrix

Sustainable Criteria	Conventional	Environmental	Social
Conventional	0.35	0.06	2.33
Environmental	1.74	0.32	0.05
Social	0.05	2.22	0.33

Eigen Value

$$\lambda_{max} = 7.74$$

Consistency Index and Consistency Ratio

CI = 0.05, CR = 0.09

A.2: Calculations for Fuzzy E-AHP

A.2.1: Weights Calculation for Sustainable Criteria

Combined Decision Matrix

Sustainable Criteria	Conventional	Environmental	Social
Conventional	7.25	8.20	9.17
Environmental	5.17	6.14	7.13
Social	7.17	8.14	9.13

Extended Fuzzy Normalized Decision Matrix

Sustainable Criteria	a	n	m
Conventional (S1)	0.29	0.36	0.47
Environmental (S2)	0.20	0.27	0.36
Social (S3)	0.28	0.36	0.47

Degree of Possibility for a Convex Fuzzy Number to be greater than Convex Fuzzy Number

S1>S2	0.462
S1>S3	1.000
S2>S1	1.000
S2>S3	1.000
S3>S1	1.00
S3>S2	0.48

Weight Vector

Conventional (S1)	0.462
Environmental (S2)	1.000
Social (S3)	0.48

Normalized Weight Vector

Conventional (S1)	0.41
Environmental (S2)	0.29
Social (S3)	0.30

A.2.2: Weights Calculation for Sustainable Sub-Criteria

A.2.2.1: For Conventional Sub-Criteria

Weight Matrix

Sub-Criteria	Weights
Product Price	0.274
Volume Flexibility	0.175
Payment Terms	0.147
Product Mix	0.104
Past Businesses	0.105
Responsiveness	0.071
Use of Technology	0.049
Vendors Market reputation	0.044
Product Quality	0.031

Extended Fuzzy Normalized Decision Matrix

Sub Criteria	a	n	m
Product Price	0.04	0.23	0.82
Volume Flexibility	0.03	0.17	0.67
Payment Terms	0.03	0.16	0.64
Product Mix	0.03	0.12	0.47
Past Businesses	0.04	0.13	0.48
Responsiveness	0.03	0.08	0.30
Use of Technology	0.02	0.06	0.22
Vendors Market reputation	0.03	0.04	0.12
Product Quality	0.02	0.01	0.05

Weight Vector

Product Price	0.511
Volume Flexibility	0.102
Payment Terms	0.102
Product Mix	0.549
Past Businesses	0.082
Responsiveness	0.259
Use of Technology	0.377
Vendors Market reputation	0.458
Product Quality	1.000

Normalized Weight Vector

Product Price	0.15
Volume Flexibility	0.03
Payment Terms	0.03
Product Mix	0.16
Past Businesses	0.02
Responsiveness	0.08
Use of Technology	0.11
Vendors Market reputation	0.13
Product Quality	0.29

A.2.2.2: For Environmental Sub-Criteria

Weight Matrix

Sub-Criteria	**Weights**
Environment Management System	0.426
Resource Consumption	0.206
Waste Management System	0.148
Innovation Capability	0.219

Extended Fuzzy Normalized Decision Matrix

Sub Criteria	a	n	m
Environment Management System	0.11	0.50	0.93
Resource Consumption	0.07	0.29	0.60
Waste Management System	0.10	0.17	0.33
Innovation Capability	0.24	0.04	0.73

Degree of Possibility

S1>S2	0.70
S1>S3	0.40
S1>S4	0.57
S2>S1	1.00
S2>S3	0.68
S2>S4	0.72
S3>S1	1.00
S3>S2	1.00
S3>S4	0.83
S4>S1	1.00
S4>S2	1.00
S4>S3	1.00

Weight Vector

Environment Management System	0.399
Resource Consumption	0.678
Waste Management System	0.826
Innovation Capability	1.000

Normalized Weight Vector

Environment Management System	0.14
Resource Consumption	0.23
Waste Management System	0.28
Innovation Capability	0.34

A.2.2.3: For Social Sub-Criteria

Weight Matrix

Sub-Criteria	**Weights**
Labour Incentives	0.597
Rights and Health of Employees	0.281
Staff Personal and Technical Development	0.122

Weighted Normalized Pair-wise Non-Fuzzified Decision Matrix

	Labour Incentives	**Rights and Health of Employees**	**Staff Personal and Technical Development**
Labour Incentives	1.19	3.56	1.30
Rights and Health of Employees	0.49	0.56	1.49
Staff Personal and Technical Development	0.51	0.23	0.24

Extended Fuzzy Normalized Decision Matrix

Sub Criteria	**a**	**n**	**m**
Labour Incentives	0.09	0.61	2.22
Rights and Health of Employees	0.09	0.34	1.23
Staff Personal and Technical Development	0.09	0.05	0.13

Degree of Possibility

S1>S2	0.81
S1>S3	0.07
S2>S1	1.00
S2>S3	0.13
S3>S1	1.00
S3>S2	1.00

Weight Vector

Labour Incentives	0.070
Rights and Health of Employees	0.126
Staff Personal and Technical Development	1.000

Normalized Weight Vector

Labour Incentives	0.06
Rights and Health of Employees	0.11
Staff Personal and Technical Development	0.84

B.1: Calculations for Fuzzy TOPSIS

B.2.1: Relative Closeness Matrix Calculation for Conventional Criteria

Euclidean Distances

	Product Price	Volume Flexibility	Payment Terms	Product Mix	Past Businesses	Responsiveness	Use of Technology	Vendors Market reputation	Product Quality	Sep+
S 1	0.047	0.012	0.007	0.017	0.006	0.006	0.003	0.002	0.001	0.101
S 2	0.046	0.010	0.011	0.008	0.007	0.005	0.008	0.002	0.001	0.098
S 3	0.054	0.011	0.014	0.008	0.005	0.009	0.006	0.004	0.001	0.111
S 4	0.058	0.012	0.039	0.000	0.001	0.000	0.007	0.009	0.001	0.127
S 5	0.000	0.002	0.001	0.032	0.013	0.007	0.000	0.000	0.004	0.059

	Product Price	Volume Flexibility	Payment Terms	Product Mix	Past Businesses	Responsiveness	Use of Technology	Vendors Market reputation	Product Quality	Sep-
S 1	0.011	0.004	0.032	0.015	0.008	0.006	0.005	0.007	0.003	0.092
S 2	0.012	0.006	0.032	0.025	0.006	0.005	0.001	0.007	0.003	0.097
S 3	0.006	0.006	0.025	0.029	0.010	0.009	0.002	0.005	0.003	0.096
S 4	0.000	0.008	0.002	0.032	0.013	0.000	0.002	0.000	0.003	0.060
S 5	0.058	0.014	0.039	0.001	0.000	0.007	0.008	0.009	0.000	0.136

B.2.2: Relative Closeness Matrix Calculation for Environmental Criteria

Gather Responses

Decision Maker 1

	Environment Management System			Resource Consumption			Waste Management System			Innovation Capability		
S 1	5	7	9	1	3	5	3	5	7	3	5	7
S 2	7	9	10	5	7	9	3	5	7	5	7	9
S 3	5	7	9	5	7	9	3	5	7	5	7	9
S 4	1	3	5	3	5	7	5	7	9	7	9	10
S 5	5	7	9	7	9	10	1	3	5	3	5	7

Decision Maker 2

	Environment Management System			Resource Consumption			Waste Management System			Innovation Capability		
S 1	1	1	3	7	9	10	1	1	3	5	7	9
S 2	1	3	5	5	7	9	1	3	5	3	5	7
S 3	1	3	5	3	5	7	1	1	3	5	7	9
S 4	5	7	9	5	7	9	7	9	10	1	1	3
S 5	7	9	10	1	1	3	5	7	9	5	7	9

Decision Maker 3

	Environment Management System			Resource Consumption			Waste Management System			Innovation Capability		
S 1	3	5	7	5	7	9	1	3	5	7	9	10
S 2	1	3	5	3	5	7	1	3	5	5	7	9
S 3	7	9	10	5	7	9	1	1	3	3	5	7
S 4	1	3	5	7	9	10	3	5	7	7	9	10
S 5	3	5	7	5	7	9	7	9	10	1	1	3

Decision Maker 4

	Environment Management System			Resource Consumption			Waste Management System			Innovation Capability		
S 1	7	9	10	7	9	10	3	5	7	7	9	10
S 2	3	5	7	3	5	7	3	5	7	3	5	7
S 3	1	3	5	3	5	7	5	7	9	1	1	3
S 4	5	7	9	1	1	3	5	7	9	7	9	10
S 5	3	5	7	5	7	9	3	5	7	5	7	9

Combined Fuzzified Decision Matrix

	Environment Management System			Resource Consumption			Waste Management System			Innovation Capability		
S 1	1	5.5	10	1	7	10	1	3.5	7	3	7.5	10
S 2	1	5	10	3	6	9	1	4	7	3	6	9
S 3	1	5.5	10	3	6	9	1	3.5	9	1	5	9
S 4	1	5	9	1	5.5	10	3	7	10	1	7	10
S 5	3	6.5	10	1	6	10	1	6	10	1	5	9

Normalized Combined Fuzzified Decision Matrix

	Environment Management System			Resource Consumption			Waste Management System			Innovation Capability		
S 1	0.082	0.452	0.823	0.082	0.576	0.823	0.082	0.288	0.576	0.247	0.617	0.823
S 2	0.094	0.470	0.941	0.282	0.564	0.847	0.094	0.376	0.659	0.282	0.564	0.847
S 3	0.098	0.541	0.983	0.295	0.590	0.885	0.098	0.344	0.885	0.098	0.491	0.885
S 4	0.081	0.404	0.727	0.081	0.444	0.808	0.242	0.565	0.808	0.081	0.565	0.808
S 5	0.254	0.551	0.847	0.085	0.508	0.847	0.085	0.508	0.847	0.085	0.424	0.763

Weighted Normalized Combined Fuzzified Decision Matrix

	Environment Management System			Resource Consumption			Waste Management System			Innovation Capability		
S 1	0.009	0.227	0.762	0.006	0.169	0.494	0.008	0.048	0.193	0.059	0.022	0.601
S 2	0.011	0.236	0.871	0.020	0.166	0.508	0.010	0.063	0.220	0.068	0.020	0.618
S 3	0.011	0.272	0.910	0.021	0.173	0.531	0.010	0.058	0.296	0.024	0.017	0.646
S 4	0.009	0.203	0.673	0.006	0.130	0.485	0.025	0.095	0.270	0.019	0.020	0.590
S 5	0.029	0.277	0.785	0.006	0.149	0.509	0.009	0.086	0.284	0.020	0.015	0.557

Positive Ideal (best) and Negative Ideal (worst) Solution

	Environment Management System			Resource Consumption			Waste Management System			Innovation Capability		
Z+	0.029	0.277	0.910	0.021	0.173	0.531	0.025	0.095	0.296	0.068	0.022	0.646
Z-	0.009	0.203	0.673	0.006	0.130	0.485	0.008	0.048	0.193	0.019	0.015	0.557

Euclidean Distances

	Environment Management System	Resource Consumption	Waste Management System	Innovation Capability	Sep+
S 1	0.091	0.023	0.066	0.027	0.207
S 2	0.034	0.014	0.048	0.016	0.112
S 3	0.011	0.000	0.023	0.026	0.059
S 4	0.144	0.037	0.015	0.043	0.239
S 5	0.072	0.021	0.013	0.058	0.165

	Environment Management System	**Resource Consumption**	**Waste Management System**	**Innovation Capability**	**Sep-**
S 1	0.053	0.023	0.000	0.0345	0.110
S 2	0.116	0.026	0.018	0.0452	0.205
S 3	0.142	0.037	0.060	0.0515	0.291
S 4	0.000	0.000	0.053	0.0192	0.072
S 5	0.078	0.018	0.057	0.0006	0.153

B.2.3: Relative Closeness Matrix Calculation for Social Criteria

Gather Responses

Decision Maker 1

	Labour Incentives			Rights and Health of Employees			Staff Personal and Technical Development		
S 1	5	7	9	3	5	7	3	5	7
S 2	3	5	7	5	7	9	5	7	9
S 3	5	7	9	3	5	7	3	5	7
S 4	1	3	5	7	9	10	1	3	5
S 5	3	5	7	1	3	5	3	5	7

Decision Maker 2

	Labour Incentives			Rights and Health of Employees			Staff Personal and Technical Development		
S 1	1	1	3	1	1	3	5	7	9
S 2	1	3	5	1	3	5	1	3	5
S 3	1	3	5	1	3	5	5	7	9
S 4	5	7	9	3	5	7	7	9	10
S 5	7	9	10	3	5	7	5	7	9

Decision Maker 3

	Labour Incentives			Rights and Health of Employees			Staff Personal and Technical Development		
S 1	3	5	7	7	9	10	7	9	10
S 2	1	3	5	5	7	9	5	7	9
S 3	5	7	9	3	5	7	3	5	7
S 4	5	7	9	1	3	5	7	9	10
S 5	7	9	10	5	7	9	1	3	5

Decision Maker 4

	Labour Incentives			Rights and Health of Employees			Staff Personal and Technical Development		
S 1	3	5	7	7	9	10	7	9	10
S 2	5	7	9	5	7	9	5	7	9
S 3	1	3	5	3	5	7	3	5	7
S 4	7	9	10	1	3	5	5	7	9
S 5	5	7	9	7	9	10	5	7	9

Combined Fuzzified Decision Matrix

	Labour Incentives			Rights and Health of Employees			Staff Personal and Technical Development		
S 1	1	4.5	9	1	6	10	3	7.5	10
S 2	1	4.5	9	1	6	9	1	6	9
S 3	1	5	9	1	4.5	7	3	5.5	9
S 4	1	6.5	10	1	5	10	1	7	10
S 5	3	7.5	10	1	6	10	1	5.5	9

Step 3: Normalized Combined Fuzzified Decision Matrix

	Labour Incentives			Rights and Health of Employees			Staff Personal and Technical Development		
S 1	0.094	0.424	0.849	0.094	0.566	0.943	0.283	0.707	0.943
S 2	0.104	0.469	0.937	0.104	0.625	0.937	0.104	0.625	0.937
S 3	0.115	0.575	1.036	0.115	0.518	0.806	0.345	0.633	1.036
S 4	0.093	0.603	0.927	0.093	0.464	0.927	0.093	0.649	0.927
S 5	0.271	0.678	0.904	0.090	0.542	0.904	0.090	0.497	0.813

Weighted Normalized Combined Fuzzified Decision Matrix

	Labour Incentives			Rights and Health of Employees			Staff Personal and Technical Development		
S 1	0.009	0.257	1.886	0.009	0.193	1.163	0.026	0.037	0.127
S 2	0.010	0.284	2.082	0.010	0.213	1.156	0.010	0.033	0.126
S 3	0.011	0.349	2.302	0.011	0.177	0.994	0.032	0.033	0.139
S 4	0.009	0.365	2.061	0.009	0.158	1.144	0.009	0.034	0.125
S 5	0.025	0.410	2.008	0.008	0.185	1.114	0.008	0.026	0.109

Positive Ideal (best) and Negative Ideal (worst) Solution

	Labour Incentives			Rights and Health of Employees			Staff Personal and Technical Development		
Z+	0.025	0.410	2.302	0.011	0.213	1.163	0.032	0.037	0.139
Z-	0.009	0.257	1.886	0.008	0.158	0.994	0.008	0.026	0.109

Euclidean Distances

	Labour Incentives	Rights and Health of Employees	Staff Personal and Technical Development	Sep+
S 1	0.256	0.012	0.008	0.276
S 2	0.147	0.004	0.015	0.166
S 3	0.037	0.100	0.002	0.139
S 4	0.142	0.034	0.016	0.191
S 5	0.170	0.032	0.023	0.225

	Labour Incentives	Rights and Health of Employees	Staff Personal and Technical Development	Sep-
S 1	0.000	0.100	0.016	0.116
S 2	0.115	0.099	0.010	0.224
S 3	0.246	0.011	0.022	0.279
S 4	0.119	0.087	0.010	0.216
S 5	0.114	0.071	0.000	0.185

B.2.4: Overall Relative Closeness Matrix Calculation for Sustainable Criteria

Combined Decision Matrix

	RC (Conventional)	RC (Environmental)	RC (Social)
S 1	0.48	0.35	0.30
S 2	0.50	0.65	0.57
S 3	0.46	0.83	0.67
S 4	0.32	0.23	0.53
S 5	0.70	0.48	0.45

Normalized Combined Decision Matrix

	RC (Conventional)	RC (Environmental)	RC (Social)
S 1	0.42	0.28	0.25
S 2	0.44	0.53	0.49
S 3	0.41	0.67	0.58
S 4	0.28	0.19	0.46
S 5	0.62	0.39	0.39

Weighted Normalized Combined Decision Matrix

	RC (Conventional)	RC (Environmental)	RC (Social)
S 1	0.18	0.08	0.08
S 2	0.18	0.15	0.15
S 3	0.17	0.19	0.17
S 4	0.12	0.05	0.13
S 5	0.26	0.11	0.11

Positive Ideal (best) and Negative Ideal (worst) Solution

	RC (Conventional)	RC (Environmental)	RC (Social)
Z+	0.26	0.19	0.17
Z-	0.12	0.05	0.08

Euclidean Distances

	Sep+	Sep-
S 1	0.168	0.063
S 2	0.088	0.136
S 3	0.087	0.177
S 4	0.200	0.060
S 5	0.099	0.155

C.1: Calculations for Moving Average Forecast

Month-Year	Actual Demand	Forecasted Demand	Actual - Forecast	(Actual - Forecast)2	(Actual - Forecast)/Actual
Jan-12	15300				
Feb-12	18600				
Mar-12	13450	15783	2333	5444444	0.173482032
Apr-12	16750	16267	483	233611	0.028855721
May-12	18600	16267	2333	5444444	0.125448029
Jun-12	17670	17673	3	11	0.000188644
Jul-12	17869	18046	177	31447	0.009924077
Aug-12	7690	14410	6720	45153920	0.873818812
Sep-12	7210	10923	3713	13786369	0.514979196
Oct-12	6689	7196	507	257387	0.075845916
Nov-12	4550	6150	1600	2558933	0.351575092
Dec-12	4355	5198	843	710649	0.193570608
Jan-13	3561	4155	594	353232	0.166900683
Feb-13	12000	6639	5361	28743895	0.446777778
Mar-13	18996	11519	7477	55905529	0.393609181

Apr-13	19101	16699	2402	5769604	0.125752578
May-13	14506	17534	3028	9170803	0.20876419
Jun-13	19414	17674	1740	3028760	0.089643213
Jul-13	19531	17817	1714	2937796	0.087757923
Aug-13	14056	17667	3611	13039321	0.256900968
Sep-13	7421	13669	6248	39041669	0.841979967
Oct-13	7101	9526	2425	5880625	0.341501197
Nov-13	6350	6957	607	368854	0.095643045
Dec-13	4560	6004	1444	2084173	0.316593567
Jan-14	4863	5258	395	155762	0.081157036
Feb-14	7886	5770	2116	4478867	0.26836588
Mar-14	21056	11268	9788	95798419	0.464839792
Apr-14	21487	16810	4677	21877447	0.217682009
May-14	19560	20701	1141	1301881	0.058333333
Jun-14	25600	22216	3384	11453712	0.132200521
Jul-14	17439	20866	3427	11746614	0.196532676
Aug-14	9630	17556	7926	62826760	0.823087574
Sep-14	6988	11352	4364	19047405	0.624546842

Oct-14	4650	7089	2439	5950347	0.524587814
Nov-14	5660	5766	106	11236	0.018727915
Dec-14	5670	5327	343	117878	0.060552616
Jan-15	4667	5332	665	442668	0.142561246
Feb-15	38560	16299	22261	495552121	0.577308091
Mar-15	38677	27301	11376	129405792	0.294119675
Apr-15	39600	38946	654	428152	0.016523569
May-15	37664	38647	983	966289	0.026099193
Jun-15	24560	33941	9381	88009415	0.381976113
Jul-15	20764	27663	6899	47591602	0.3322417
Aug-15	14604	19976	5372	28858384	0.367844426
Sep-15	10364	15244	4880	23814400	0.470860672
Oct-15	9436	11468	2032	4129024	0.215345485
Nov-15	7605	9135	1530	2340900	0.201183432
Dec-15	7144	8062	918	842112	0.128452781
Jan-16	16052	10267	5785	33466225	0.360391229
Feb-16	43560	22252	21308	454030864	0.489164371
Mar-16	43774	34462	9312	86713344	0.212729017

Apr-16	47952	45095	2857	8160544	0.059573462
May-16	48003	46576	1427	2035378	0.029720365
Jun-16	48266	48074	192	36992	0.003984862
Jul-16	36210	44160	7950	63197200	0.219543404
Aug-16	11008	31828	20820	433472400	1.891351744
Sep-16	10689	19302	8613	74189511	0.805812829
Oct-16	7630	9776	2146	4603885	0.281214504
Nov-16	4261	7527	3266	10664579	0.766408511
Dec-16	4566	5486	920	845787	0.201416265
Jan-17	4583	4470	113	12769	0.024656339
Feb-17	28455	12535	15920	253457013	0.559491595
Mar-17	33665	22234	11431	130660140	0.339541561
Apr-17	39650	33923	5727	32794711	0.144430433
May-17	47341	40219	7122	50727632	0.150447463
Jun-17	44691	43894	797	635209	0.017833568
Jul-17	37760	43264	5504	30294016	0.145762712
Aug-17	16500	32984	16484	271711267	0.999010101
Sep-17	14662	22974	8312	69089344	0.566907652

Oct-17	13694	14952	1258	1582564	0.09186505
Nov-17	10495	12950	2455	6028662	0.233952676
Dec-17	3487	9225	5738	32928469	1.645636172
Jan-18	6374	6785	411	169195	0.064532999
Feb-18	38744	16202	22542	508156792	0.581827724
Mar-18	44561	29893	14668	215150224	0.32916676
Apr-18	49136	44147	4989	24890121	0.101534516
May-18	51660	48452	3208	10289125	0.062091883
Jun-18	48600	49799	1199	1436802	0.024663923
Jul-18	45600	48620	3020	9120400	0.06622807
Aug-18	12566	35589	23023	530043180	1.832139636
Sep-18	11664	23277	11613	134854027	0.995598994
Oct-18	10554	11595	1041	1082987	0.098604005
Nov-18	9788	10669	881	775574	0.089974118
Dec-18	5224	8522	3298	10876804	0.631316998
Jan-19	7661	7558	103	10678	0.01348823
Feb-19	38997	17294	21703	471020209	0.556529989
Mar-19	43601	30086	13515	182646215	0.30996231

Apr-19	48614	43737	4877	23781878	0.100314038
May-19	53442	48552	4890	23908840	0.091494829
Jun-19	46086	49381	3295	10854828	0.071489534
Jul-19	46596	48708	2112	4460544	0.045325779
Aug-19	13667	35450	21783	474484567	1.593814785
Sep-19	12482	24248	11766	138446600	0.942664103
Oct-19	16005	14051	1954	3816813	0.122066021
Nov-19	9835	12774	2939	8637721	0.298830707
Dec-19	5344	10395	5051	25509234	0.94510978
Jan-20	7995	7725	270	73080	0.0338128
Feb-20	41556	18298	23258	540919059	0.559670485
Mar-20	56000	35184	20816	433319733	0.371720238
	Sum		**556103**	**7137166405**	**33.5195**

Mean Absolute Deviation	**Mean Square Error**	**Mean Absolute Percentage Error**
5733.024	73579035	34.55615

C.2: Calculations for Weighted Moving Average Forecast

Last Period Weight = 0.6, Second Last Period Weight = 0.4

Month-Year	Actual Demand	Forecasted Demand	Actual - Forecast	(Actual - Forecast)^2	(Actual - Forecast)/Actual
Jan-12	15300				
Feb-12	18600				
Mar-12	13450	17280	-3830	3830	14668900
Apr-12	16750	15510	1240	1240	1537600
May-12	18600	15430	3170	3170	10048900
Jun-12	17670	17860	-190	190	36100
Jul-12	17869	18042	-173	173	29929
Aug-12	7690	17789	-10099	10099	101997880
Sep-12	7210	11762	-4552	4552	20717063
Oct-12	6689	7402	-713	713	508369
Nov-12	4550	6897	-2347	2347	5510287
Dec-12	4355	5406	-1051	1051	1103760
Jan-13	3561	4433	-872	872	760384
Feb-13	12000	3879	8121	8121	65957138

Mar-13	18996	8624	10372	10372	107570087
Apr-13	19101	16198	2903	2903	8429732
May-13	14506	19059	-4553	4553	20729809
Jun-13	19414	16344	3070	3070	9424900
Jul-13	19531	17451	2080	2080	4327232
Aug-13	14056	19484	-5428	5428	29465355
Sep-13	7421	16246	-8825	8825	77880625
Oct-13	7101	10075	-2974	2974	8844676
Nov-13	6350	7229	-879	879	772641
Dec-13	4560	6650	-2090	2090	4369772
Jan-14	4863	5276	-413	413	170569
Feb-14	7886	4742	3144	3144	9885994
Mar-14	21056	6677	14379	14379	206761393
Apr-14	21487	15788	5699	5699	32478601
May-14	19560	21315	-1755	1755	3078621
Jun-14	25600	20331	5269	5269	27764469
Jul-14	17439	23184	-5745	5745	33005025
Aug-14	9630	20703	-11073	11073	122620188

Sep-14	6988	12754	-5766	5766	33242143
Oct-14	4650	8045	-3395	3395	11524667
Nov-14	5660	5585	75	75	5595
Dec-14	5670	5256	414	414	171396
Jan-15	4667	5666	-999	999	998001
Feb-15	38560	5068	33492	33492	1121700667
Mar-15	38677	25003	13674	13674	186983746
Apr-15	39600	38630	970	970	940512
May-15	37664	39231	-1567	1567	2454862
Jun-15	24560	38438	-13878	13878	192609987
Jul-15	20764	29802	-9038	9038	81678214
Aug-15	14604	22282	-7678	7678	58957827
Sep-15	10364	17068	-6704	6704	44943616
Oct-15	9436	12060	-2624	2624	6885376
Nov-15	7605	9807	-2202	2202	4849685
Dec-15	7144	8337	-1193	1193	1424204
Jan-16	16052	7328	8724	8724	76101197
Feb-16	43560	12489	31071	31071	965419469

Mar-16	43774	32557	11217	11217	125825576
Apr-16	47952	43688	4264	4264	18178285
May-16	48003	46281	1722	1722	2965973
Jun-16	48266	47983	283	283	80316
Jul-16	36210	48161	-11951	11951	142821621
Aug-16	11008	41032	-30024	30024	901464595
Sep-16	10689	21089	-10400	10400	108155840
Oct-16	7630	10817	-3187	3187	10154420
Nov-16	4261	8854	-4593	4593	21091975
Dec-16	4566	5609	-1043	1043	1087015
Jan-17	4583	4444	139	139	19321
Feb-17	28455	4576	23879	23879	570197089
Mar-17	33665	18906	14759	14759	217822177
Apr-17	39650	31581	8069	8069	65108761
May-17	47341	37256	10085	10085	101707225
Jun-17	44691	44265	426	426	181817
Jul-17	37760	45751	-7991	7991	63856081
Aug-17	16500	40532	-24032	24032	577556250

Sep-17	14662	25004	-10342	10342	106956964
Oct-17	13694	15397	-1703	1703	2900890
Nov-17	10495	14081	-3586	3586	12860830
Dec-17	3487	11775	-8288	8288	68684314
Jan-18	6374	6290	84	84	7022
Feb-18	38744	5219	33525	33525	1123912215
Mar-18	44561	25796	18765	18765	352125225
Apr-18	49136	42234	6902	6902	47634843
May-18	51660	47306	4354	4354	18957316
Jun-18	48600	50650	-2050	2050	4204140
Jul-18	45600	49824	-4224	4224	17842176
Aug-18	12566	46800	-34234	34234	1171966756
Sep-18	11664	25780	-14116	14116	199250163
Oct-18	10554	12025	-1471	1471	2163253
Nov-18	9788	10998	-1210	1210	1464100
Dec-18	5224	10094	-4870	4870	23720796
Jan-19	7661	7050	611	611	373810
Feb-19	38997	6686	32311	32311	1043987797

Mar-19	43601	26463	17138	17138	293724755
Apr-19	48614	41759	6855	6855	46985541
May-19	53442	46609	6833	6833	46692622
Jun-19	46086	51511	-5425	5425	29428455
Jul-19	46596	49028	-2432	2432	5916570
Aug-19	13667	46392	-32725	32725	1070925625
Sep-19	12482	26839	-14357	14357	206111964
Oct-19	16005	12956	3049	3049	9296401
Nov-19	9835	14596	-4761	4761	22665217
Dec-19	5344	12303	-6959	6959	48427681
Jan-20	7995	7140	855	855	730341
Feb-20	41556	6935	34621	34621	1198641338
Mar-20	56000	28132	27868	27868	776647719
Sum		**47902**	**785062**	**14604828335**	**47**

Mean Absolute Deviation	**Mean Square Error**	**Mean Absolute Percentage Error**
8093.42	150565240.57	48.70

C.3: Calculations for Exponential Smoothing Forecast

$\alpha = 0.6$

Month-Year	**Actual Demand**	**Forecasted Demand**	**Actual - Forecast**	**(Actual - Forecast)^2**	**(Actual - Forecast)/Actual**
Jan-12	15300				
Feb-12	18600	15300	3300	10890000	0.177419
Mar-12	13450	15960	2510	6300100	0.186617
Apr-12	16750	15458	1292	1669264	0.077134
May-12	18600	15716	2884	8315148.96	0.155032
Jun-12	17670	16293	1377	1895798.534	0.077922
Jul-12	17869	16568	1301	1691310.654	0.07278
Aug-12	7690	16829	9139	83513951.47	1.188374
Sep-12	7210	15001	7791	60697771.29	1.080566
Oct-12	6689	13443	6754	45612490.06	1.009673
Nov-12	4550	12092	7542	56881184.2	1.657574
Dec-12	4355	10584	6229	38795074.89	1.430211
Jan-13	3561	9338	5777	33372058.31	1.622257
Feb-13	12000	8182	3818	14573425.97	0.318126

Mar-13	18996	8946	10050	101002752.1	0.529059
Apr-13	19101	10956	8145	66341188.48	0.426418
May-13	14506	12585	1921	3690271.845	0.132429
Jun-13	19414	12969	6445	41535529.83	0.331967
Jul-13	19531	14258	5273	27802895.85	0.269973
Aug-13	14056	15313	1257	1579354.934	0.089408
Sep-13	7421	15061	7640	58375392.97	1.029562
Oct-13	7101	13533	6432	41374525.6	0.905831
Nov-13	6350	12247	5897	34772753.02	0.928637
Dec-13	4560	11067	6507	42347219.23	1.427078
Jan-14	4863	9766	4903	24039205.86	1.008221
Feb-14	7886	8785	899	808890.5493	0.114048
Mar-14	21056	8606	12450	155014782.4	0.591304
Apr-14	21487	11096	10391	107981081.9	0.483613
May-14	19560	13174	6386	40782473.55	0.326489
Jun-14	25600	14451	11149	124297805.1	0.435504
Jul-14	17439	16681	758	574736.8954	0.043472
Aug-14	9630	16833	7203	51876132.57	0.747924

Sep-14	6988	15392	8404	70627333.91	1.202634
Oct-14	4650	13711	9061	82105447.15	1.948646
Nov-14	5660	11899	6239	38924677.91	1.102291
Dec-14	5670	10651	4981	24812070.43	0.878514
Jan-15	4667	9655	4988	24879518.24	1.068767
Feb-15	38560	8657	29903	894168487.9	0.775484
Mar-15	38677	14638	24039	577879297.3	0.621535
Apr-15	39600	19446	20154	406195651.9	0.508947
May-15	37664	23477	14187	201283365.6	0.376684
Jun-15	24560	26314	1754	3076693.107	0.071419
Jul-15	20764	25963	5199	27032100.62	0.250397
Aug-15	14604	24923	10319	106489857.7	0.706614
Sep-15	10364	22860	12496	156137866.3	1.205665
Oct-15	9436	20360	10924	119342757.4	1.157738
Nov-15	7605	18176	10571	111736080.4	1.389945
Dec-15	7144	16061	8917	79520434.58	1.24824
Jan-16	16052	14278	1774	3147294.304	0.11052
Feb-16	43560	14633	28927	836785747.6	0.664078

Mar-16	43774	20418	23356	545493364.6	0.533554
Apr-16	47952	25089	22863	522700285	0.476782
May-16	48003	29662	18341	336396374.8	0.382083
Jun-16	48266	33330	14936	223080788.6	0.309449
Jul-16	36210	36317	107	11510.83831	0.002963
Aug-16	11008	36296	25288	639474389.6	2.297223
Sep-16	10689	31238	20549	422272279.2	1.922468
Oct-16	7630	27128	19498	380188060.8	2.555493
Nov-16	4261	23229	18968	359774758.6	4.451474
Dec-16	4566	19435	14869	221092618.6	3.256501
Jan-17	4583	16461	11878	141095123.1	2.591828
Feb-17	28455	14086	14369	206477430.5	0.504984
Mar-17	33665	16960	16705	279072328.2	0.496226
Apr-17	39650	20301	19349	374397981.2	0.488004
May-17	47341	24171	23170	536871752.5	0.489438
Jun-17	44691	28805	15886	252377530.7	0.355472
Jul-17	37760	31982	5778	33386620.03	0.153022
Aug-17	16500	33138	16638	276806656.2	1.008334

Sep-17	14662	29810	15148	229462086	1.033147
Oct-17	13694	26780	13086	171253990.8	0.955631
Nov-17	10495	24163	13668	186817609.4	1.302346
Dec-17	3487	21429	17942	321933273.1	5.14554
Jan-18	6374	17841	11467	131492072.1	1.799027
Feb-18	38744	15548	23196	538073000.4	0.598709
Mar-18	44561	20187	24374	594097748.8	0.546983
Apr-18	49136	25062	24074	579571746.1	0.489952
May-18	51660	29877	21783	474518132	0.421669
Jun-18	48600	34233	14367	206403496.4	0.295612
Jul-18	45600	37107	8493	72137839.24	0.186259
Aug-18	12566	38805	26239	688499825.6	2.088117
Sep-18	11664	33557	21893	479322021.6	1.877008
Oct-18	10554	29179	18625	346880915.1	1.764709
Nov-18	9788	25454	15666	245417022.2	1.60051
Dec-18	5224	22321	17097	292294865.8	3.272709
Jan-19	7661	18901	11240	126344491	1.467211
Feb-19	38997	16653	22344	499243377.2	0.572961

Mar-19	43601	21122	22479	505305612.6	0.515562
Apr-19	48614	25618	22996	528825354.9	0.473037
May-19	53442	30217	23225	539398880.5	0.434583
Jun-19	46086	34862	11224	125977501.5	0.243544
Jul-19	46596	37107	9489	90044460.46	0.203648
Aug-19	13667	39005	25338	641996975.2	1.85393
Sep-19	12482	33937	21455	460322491	1.718885
Oct-19	16005	29646	13641	186079661.2	0.852303
Nov-19	9835	26918	17083	291824841.2	1.736948
Dec-19	5344	23501	18157	329687732.9	3.397699
Jan-20	7995	19870	11875	141011924.2	1.485284
Feb-20	41556	17495	24061	578937719.9	0.579005
Mar-20	56000	22307	33693	1135211492	0.601659
Sum			**1264228**	**22541907267**	**96**

Mean Absolute Deviation	**Mean Square Error**	**Mean Absolute Percentage Error**
12900	230019462	97.91043

C.4: Calculations for Least Square Method Forecast

a = 205.05 b = 10947.10

t	Month-Year	Actual Demand	y(t)*t	t^2	Forecasted Demand	Actual - Forecast	(Actual - Forecast)^2	(Actual - Forecast)/Actual
1	Jan-12	15300	1	11152	11152	4147.851515	17204672.191745	0.271101
2	Feb-12	18600	4	11357	11357	7242.799505	52458144.673346	0.389398
3	Mar-12	13450	9	11562	11562	1887.747495	3563590.606245	0.140353
4	Apr-12	16750	16	11767	11767	4982.695485	24827254.300892	0.297474
5	May-12	18600	25	11972	11972	6627.643476	43925658.039293	0.356325
6	Jun-12	17670	36	12177	12177	5492.591466	30168561.008830	0.310843
7	Jul-12	17869	49	12382	12382	5486.539456	30102115.199856	0.307042
8	Aug-12	7690	64	12588	12588	4897.512554	23985629.217690	0.636868
9	Sep-12	7210	81	12793	12793	5582.564564	31165027.111311	0.774281
10	Oct-12	6689	100	12998	12998	6308.616574	39798643.076515	0.943133
11	Nov-12	4550	121	13203	13203	8652.668584	74868673.621030	1.901685
12	Dec-12	4355	144	13408	13408	9052.720594	81951750.147456	2.078696
13	Jan-13	3561	169	13613	13613	10051.7726	101038132.474220	2.822739
14	Feb-13	12000	196	13818	13818	1817.824613	3304486.325380	0.151485
15	Mar-13	18996	225	14023	14023	4973.123377	24731956.119118	0.261798
16	Apr-13	19101	256	14228	14228	4873.071367	23746824.545229	0.255121
17	May-13	14506	289	14433	14433	73.01935683	5331.826472	0.005034

18	Jun-13	19414	324	14638	14638	4775.967347	22809864.099025	0.246006
19	Jul-13	19531	361	14843	14843	4687.915337	21976550.207292	0.240024
20	Aug-13	14056	400	15048	15048	992.1366729	984335.177616	0.070585
21	Sep-13	7421	441	15253	15253	7832.188683	61343179.562132	1.055409
22	Oct-13	7101	484	15458	15458	8357.240693	69843471.994730	1.17691
23	Nov-13	6350	529	15663	15663	9313.292703	86737420.963102	1.46666
24	Dec-13	4560	576	15868	15868	11308.34471	127878660.135153	2.4799
25	Jan-14	4863	625	16073	16073	11210.39672	125672994.671922	2.305243
26	Feb-14	7886	676	16278	16278	8392.448732	70433195.722944	1.064221
27	Mar-14	21056	729	16484	16484	4572.499258	20907749.463359	0.217159
28	Apr-14	21487	784	16689	16689	4798.447248	23025095.991744	0.223319
29	May-14	19560	841	16894	16894	2666.395238	7109663.565737	0.136319
30	Jun-14	25600	900	17099	17099	8501.343228	72272836.683668	0.332084
31	Jul-14	17439	961	17304	17304	135.2912183	18303.713751	0.007758
32	Aug-14	9630	1024	17509	17509	7878.760792	62074871.611086	0.818148
33	Sep-14	6988	1089	17714	17714	10725.8128	115043060.252483	1.53489
34	Oct-14	4650	1156	17919	17919	13268.86481	176062773.382654	2.853519
35	Nov-14	5660	1225	18124	18124	12463.91682	155349222.527636	2.202105
36	Dec-14	5670	1296	18329	18329	12658.96883	160249491.868504	2.232622
37	Jan-15	4667	1369	18534	18534	13867.02084	192294267.006495	2.971292
38	Feb-15	38560	1444	18739	18739	19820.92715	392869153.047608	0.514028
39	Mar-15	38677	1521	18944	18944	19732.87514	389386361.257149	0.510197

40	Apr-15	39600	1600	19149	19149	20450.82313	418236166.663936	0.516435
41	May-15	37664	1681	19354	19354	18309.77112	335247718.443234	0.486135
42	Jun-15	24560	1764	19559	19559	5000.719109	25007191.611738	0.203612
43	Jul-15	20764	1849	19764	19764	999.6670996	999334.309957	0.048144
44	Aug-15	14604	1936	19969	19969	5365.38491	28787355.235973	0.367391
45	Sep-15	10364	2025	20174	20174	9810.43692	96244672.565667	0.946588
46	Oct-15	9436	2116	20379	20379	10943.48893	119759949.963604	1.159759
47	Nov-15	7605	2209	20585	20585	12979.54094	168468483.013457	1.706711
48	Dec-15	7144	2304	20790	20790	13645.59295	186202206.954558	1.910077
49	Jan-16	16052	2401	20995	20995	4942.64496	24429739.198657	0.307915
50	Feb-16	43560	2500	21200	21200	22360.30303	499983151.606979	0.513322
51	Mar-16	43774	2601	21405	21405	22369.25102	500383391.214032	0.511017
52	Apr-16	47952	2704	21610	21610	26342.19901	693911448.709488	0.549345
53	May-16	48003	2809	21815	21815	26188.147	685819043.326000	0.545552
54	Jun-16	48266	2916	22020	22020	26246.09499	688857502.262084	0.54378
55	Jul-16	36210	3025	22225	22225	13985.04298	195581427.175626	0.38622
56	Aug-16	11008	3136	22430	22430	11422.00903	130462290.260069	1.03761
57	Sep-16	10689	3249	22635	22635	11946.06104	142708374.346583	1.117603
58	Oct-16	7630	3364	22840	22840	15210.11305	231347538.958977	1.993462
59	Nov-16	4261	3481	23045	23045	18784.16506	352844856.954393	4.408394
60	Dec-16	4566	3600	23250	23250	18684.21707	349099967.468269	4.092032
61	Jan-17	4583	3721	23455	23455	18872.26908	356162540.172836	4.117885

62	Feb-17	28455	3844	23660	23660	4794.678912	22988945.865003	0.1685
63	Mar-17	33665	3969	23865	23865	9799.626902	96032687.411930	0.291092
64	Apr-17	39650	4096	24070	24070	15579.57489	242723153.808423	0.392927
65	May-17	47341	4225	24275	24275	23065.52288	532018345.814531	0.487221
66	Jun-17	44691	4356	24481	24481	20210.47087	408463132.867361	0.452227
67	Jul-17	37760	4489	24686	24686	13074.41886	170940428.581382	0.34625
68	Aug-17	16500	4624	24891	24891	8390.633148	70402724.621037	0.508523
69	Sep-17	14662	4761	25096	25096	10433.68516	108861785.969998	0.711614
70	Oct-17	13694	4900	25301	25301	11606.73717	134716347.677615	0.847578
71	Nov-17	10495	5041	25506	25506	15010.78918	225323791.731026	1.43028
72	Dec-17	3487	5184	25711	25711	22223.84119	493899117.122067	6.373341
73	Jan-18	6374	5329	25916	25916	19541.8932	381885589.733856	3.065876
74	Feb-18	38744	5476	26121	26121	12623.05479	159341512.302693	0.325807
75	Mar-18	44561	5625	26326	26326	18235.00278	332515326.493514	0.409214
76	Apr-18	49136	5776	26531	26531	22604.95077	510983799.451403	0.460049
77	May-18	51660	5929	26736	26736	24923.89876	621200729.555333	0.48246
78	Jun-18	48600	6084	26941	26941	21658.84675	469105642.680627	0.445655
79	Jul-18	45600	6241	27146	27146	18453.79474	340542540.429762	0.404688
80	Aug-18	12566	6400	27351	27351	14785.25727	218603832.437862	1.176608
81	Sep-18	11664	6561	27556	27556	15892.30928	252565494.137952	1.362509
82	Oct-18	10554	6724	27761	27761	17207.36129	296093282.438382	1.630411
83	Nov-18	9788	6889	27966	27966	18178.4133	330454709.968464	1.857214

84	Dec-18	5224	7056	28171	28171		22947.46531	526586163.975693	4.3927
85	Jan-19	7661	7225	28377	28377		20715.51732	429132657.670213	2.704023
86	Feb-19	38997	7396	28582	28582		10415.43067	108481196.126729	0.267083
87	Mar-19	43601	7569	28787	28787		14814.37866	219465815.206095	0.339772
88	Apr-19	48614	7744	28992	28992		19622.32665	385035703.327977	0.403635
89	May-19	53442	7921	29197	29197		24245.27464	587833342.582541	0.453675
90	Jun-19	46086	8100	29402	29402		16684.22263	278363284.917841	0.362024
91	Jul-19	46596	8281	29607	29607		16989.17062	288631918.512230	0.364606
92	Aug-19	13667	8464	29812	29812		16144.88139	260657194.944805	1.181304
93	Sep-19	12482	8649	30017	30017		17534.9334	307473889.173267	1.404818
94	Oct-19	16005	8836	30222	30222		14216.98541	202122674.008005	0.888284
95	Nov-19	9835	9025	30427	30427		20592.03741	424032004.899359	2.093751
96	Dec-19	5344	9216	30632	30632		25288.08942	639487466.759759	4.732053
97	Jan-20	7995	9409	30837	30837		22842.14143	521763425.325384	2.857053
98	Feb-20	41556	9604	31042	31042		10513.80656	110540128.283308	0.253003
99	Mar-20	56000	9801	31247	31247		24752.75455	612698857.587521	0.442013
						Sum	**1281583.938**	**21513701968**	**110.8006**

Mean Absolute Deviation	**Mean Square Error**	**Mean Absolute Percentage Error**
12945.29	217310120.9	111.9198

C.5: AIC Values

ARIMA	(0, 0, 0)x(0, 0, 0, 12)	AIC:2276.85435794071
ARIMA	(0, 0, 0)x(0, 0, 1, 12)	AIC:1968.5384123269605
ARIMA	(0, 0, 0)x(0, 1, 0, 12)	AIC:1779.598528239443
ARIMA	(0, 0, 0)x(0, 1, 1, 12)	AIC:1545.529334512792
ARIMA	(0, 0, 0)x(1, 0, 0, 12)	AIC:1798.2874649361447
ARIMA	(0, 0, 0)x(1, 0, 1, 12)	AIC:1773.6451451055354
ARIMA	(0, 0, 0)x(1, 1, 0, 12)	AIC:1561.7113293143607
ARIMA	(0, 0, 0)x(1, 1, 1, 12)	AIC:1542.5099239275717
ARIMA	(0, 0, 1)x(0, 0, 0, 12)	AIC:2182.404676434777
ARIMA	(0, 0, 1)x(0, 0, 1, 12)	AIC:1895.2011189434218
ARIMA	(0, 0, 1)x(0, 1, 0, 12)	AIC:1728.3436622487297
ARIMA	(0, 0, 1)x(0, 1, 1, 12)	AIC:1490.885497879504
ARIMA	(0, 0, 1)x(1, 0, 0, 12)	AIC:1927.6842801736773
ARIMA	(0, 0, 1)x(1, 0, 1, 12)	AIC:1884.7215653702847
ARIMA	(0, 0, 1)x(1, 1, 0, 12)	AIC:1529.563966825967
ARIMA	(0, 0, 1)x(1, 1, 1, 12)	AIC:1492.077206548442
ARIMA	(0, 1, 0)x(0, 0, 0, 12)	AIC:2075.7464947896797
ARIMA	(0, 1, 0)x(0, 0, 1, 12)	AIC:1800.0254360378187
ARIMA	(0, 1, 0)x(0, 1, 0, 12)	AIC:1734.6610236150225
ARIMA	(0, 1, 0)x(0, 1, 1, 12)	AIC:1489.2312031995368
ARIMA	(0, 1, 0)x(1, 0, 0, 12)	AIC:1755.7333915013464
ARIMA	(0, 1, 0)x(1, 0, 1, 12)	AIC:1719.5675711771935
ARIMA	(0, 1, 0)x(1, 1, 0, 12)	AIC:1504.6543632469131
ARIMA	(0, 1, 0)x(1, 1, 1, 12)	AIC:1486.6632888922811
ARIMA	(0, 1, 1)x(0, 0, 0, 12)	AIC:2052.3464023450833
ARIMA	(0, 1, 1)x(0, 0, 1, 12)	AIC:1772.8937960878193
ARIMA	(0, 1, 1)x(0, 1, 0, 12)	AIC:1707.0971830349827
ARIMA	(0, 1, 1)x(0, 1, 1, 12)	AIC:1463.5992467989126
ARIMA	(0, 1, 1)x(1, 0, 0, 12)	AIC:1786.6502907127044
ARIMA	(0, 1, 1)x(1, 0, 1, 12)	AIC:1741.3489821582623
ARIMA	(0, 1, 1)x(1, 1, 0, 12)	AIC:1504.1795617218022
ARIMA	(0, 1, 1)x(1, 1, 1, 12)	AIC:1464.4224325906011

ARIMA	(1, 0, 0)x(0, 0, 0, 12)	AIC:2095.988035816257
ARIMA	(1, 0, 0)x(0, 0, 1, 12)	AIC:1813.0965823079976
ARIMA	(1, 0, 0)x(0, 1, 0, 12)	AIC:1738.9602196870233
ARIMA	(1, 0, 0)x(0, 1, 1, 12)	AIC:1497.4930597614139
ARIMA	(1, 0, 0)x(1, 0, 0, 12)	AIC:1740.5188173772399
ARIMA	(1, 0, 0)x(1, 0, 1, 12)	AIC:1780.3216795721924
ARIMA	(1, 0, 0)x(1, 1, 0, 12)	AIC:1496.3669563176675
ARIMA	(1, 0, 0)x(1, 1, 1, 12)	AIC:1498.2728761518297
ARIMA	(1, 0, 1)x(0, 0, 0, 12)	AIC:2071.2047985614745
ARIMA	(1, 0, 1)x(0, 0, 1, 12)	AIC:1792.1937419049527
ARIMA	(1, 0, 1)x(0, 1, 0, 12)	AIC:1721.5902206652768
ARIMA	(1, 0, 1)x(0, 1, 1, 12)	AIC:1479.68812451092
ARIMA	(1, 0, 1)x(1, 0, 0, 12)	AIC:1782.0963138667162
ARIMA	(1, 0, 1)x(1, 0, 1, 12)	AIC:1710.45663511869
ARIMA	(1, 0, 1)x(1, 1, 0, 12)	AIC:1498.2636529401623
ARIMA	(1, 0, 1)x(1, 1, 1, 12)	AIC:1480.4428239335223
ARIMA	(1, 1, 0)x(0, 0, 0, 12)	AIC:2072.699763738772
ARIMA	(1, 1, 0)x(0, 0, 1, 12)	AIC:1793.4339469405083
ARIMA	(1, 1, 0)x(0, 1, 0, 12)	AIC:1732.8285009520628
ARIMA	(1, 1, 0)x(0, 1, 1, 12)	AIC:1485.6177805441862
ARIMA	(1, 1, 0)x(1, 0, 0, 12)	AIC:1734.539951978408
ARIMA	(1, 1, 0)x(1, 0, 1, 12)	AIC:1761.4969196288407
ARIMA	(1, 1, 0)x(1, 1, 0, 12)	AIC:1485.0711394203654
ARIMA	(1, 1, 0)x(1, 1, 1, 12)	AIC:1486.8545928049155
ARIMA	(1, 1, 1)x(0, 0, 0, 12)	AIC:2054.056848885755
ARIMA	(1, 1, 1)x(0, 0, 1, 12)	AIC:1770.2973770428384
ARIMA	(1, 1, 1)x(0, 1, 0, 12)	AIC:1701.6173504017565
ARIMA	**(1, 1, 1)x(0, 1, 1, 12)**	**AIC:1457.5969711484167**
ARIMA	(1, 1, 1)x(1, 0, 0, 12)	AIC:1764.5172763094524
ARIMA	(1, 1, 1)x(1, 0, 1, 12)	AIC:1741.6222458074196
ARIMA	(1, 1, 1)x(1, 1, 0, 12)	AIC:1477.4181349309501
ARIMA	(1, 1, 1) x (1, 1, 1,12)	AIC:1458.4771238132791

D.1: Input Data

Set of Supplier = 3

Set of port = 1

Set of warehouses = 3

Set of Customer = 1

Set of Transportation Mode = 3 (Sea, rail, road)

Purchasing Cost for Each Supplier (\$/unit)

$C_1^p = 155$, $C_2^p = 135$, $C_3^p = 160$

Ordering Cost for Each Supplier (\$)

$O_1 = 4.3$, $O_2 = 3.4$, $O_3 = 3.1$

Inventory Holding Cost (\$/unit)

$H_0 = 4$

Transportation Cost (\$/km)

$TC_{sea} = 0.8$, $TC_{rail} = 1.2$, $TC_{road} = 1.5$

Transfer Cost Matrix (\$/unit)

TrC_{mn} = Transfer cost from mode "m" to mode "n"

	Sea	**Rail**	**Road**
Sea	1.2	0.9	0.7
Rail	0.9	1.0	1.1
Road	0.7	1.1	0.6

Custom Clearance Cost (\$/unit)

CC_{ij} = Custom clearance cost while moving from supplier "i" to port "j"

$CC_{11} = 1.1{*}C_1^p$, $CC_{21} = 1.1{*}C_2^p$, $CC_{31} = 1.1{*}C_3^p$

Transfer Cost Matrix (\$/unit)

TrC_{mn} = Transfer cost from mode "m" to mode "n"

	Sea	**Rail**	**Road**
Sea	1.2	0.9	0.7
Rail	0.9	1.0	1.1
Road	0.7	1.1	0.6

Transfer Time Matrix (Hrs./container)

$TrTmn$ = Transfer time from mode "m" to mode "n"

	Sea	**Rail**	**Road**
Sea	0.7	0.17	0.17
Rail	0.17	0.4	0.12
Road	0.17	0.12	0.1

Custom Clearance Time (Hrs./container)

CCT_{ij} = Custom clearance time from supplier "i" to port "j"

CCT_{11} =4, $CCT_{21} = 4$, $CCT_{31} = 4$

Maximum Capacity of Supplier "i" (Units)

S_i = Maximum capacity of supplier "i"

$S_1 = 19000$, $S_2 = 27500$, $S_3 = 23100$

Capacity of Warehouse "k" (Units)

$CAPw_k$ = Capacity of k^{th} warehouse

$CAPw_1 = 23500$, $CAPw_2 = 18500$, $CAPw_3 = 27600$

Velocity of Mode "m": (Adapted from [201])

Mode	Velocity (km/hr)
Sea	35
Rail	60
Road	90

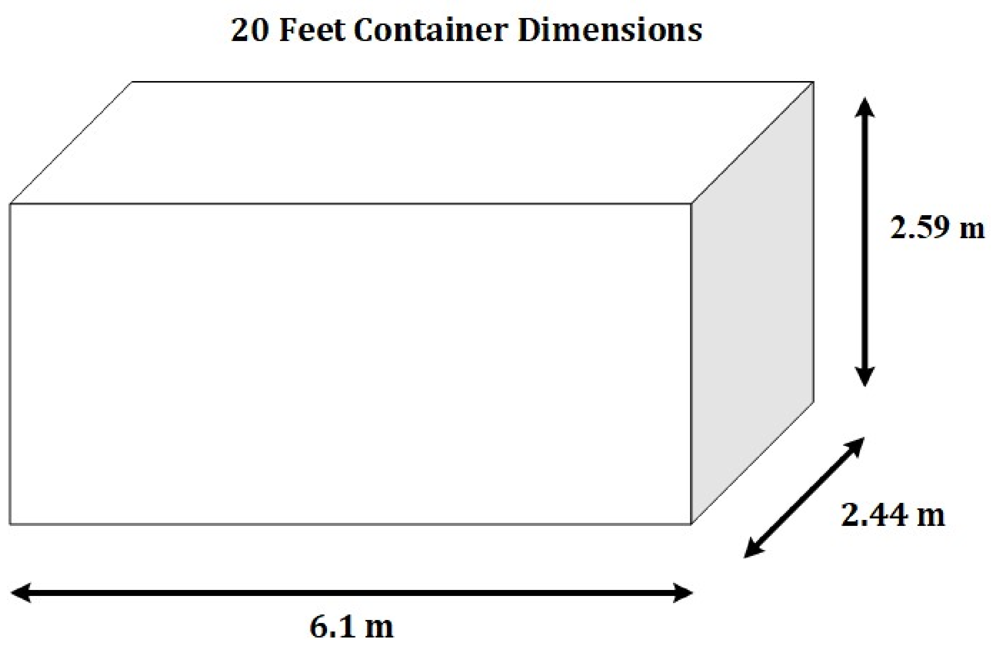
Capacity of Mode "m"

Mode	Capacity/Carrier
Sea	602000* units
Rail	645** units
Road	43 units

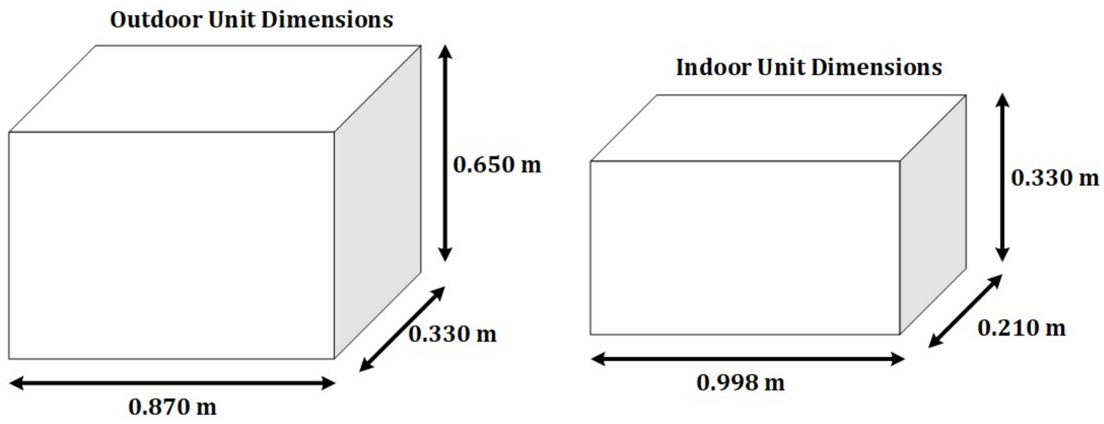
*Panamax ship having an average capacity of 15000 TEUs

**15 containers each having a capacity of 43 units per container are permissible per train

Dimensions of Container



Dimensions of 1 Unit



CO_2 Emissions (grams/km) (Adapted from [85])

For Sea: 6.04

For Rail: 17

For Road: 50

E.1: CRITIC Weight Calculations for AUGMECON2

Normalized Decision Matrix

f1	f2	f3	f4	f5	f6
0.68	0.92	0.86	0.78	0.67	0.33
0.99	0.50	0.46	0.85	1.00	0.00
0.98	0.00	0.00	1.00	1.00	0.00
0.99	0.78	0.18	0.73	1.00	0.00
1.00	0.95	1.00	0.99	1.00	0.00
0.99	0.53	0.56	0.99	1.00	0.00
1.00	0.96	1.00	1.00	1.00	0.00
0.02	1.00	1.00	1.00	0.00	1.00
0.01	0.53	0.51	1.00	0.00	1.00
0.00	0.05	0.01	1.00	0.00	1.00
0.00	0.05	0.01	1.00	0.00	1.00
0.02	0.92	0.52	0.00	0.00	1.00
0.01	0.53	0.51	1.00	0.00	1.00
0.00	0.05	0.01	1.00	0.00	1.00
0.02	0.92	0.52	0.00	0.00	1.00
0.02	0.92	0.52	0.00	0.00	1.00
0.01	0.53	0.51	1.00	0.00	1.00
0.00	0.05	0.01	1.00	0.00	1.00
0.01	0.53	0.04	0.81	0.00	1.00
0.00	0.05	0.01	1.00	0.00	1.00

Standard Deviation

	f1	f2	f3	f4	f5	f6
Std. Deviation	0.46	0.38	0.36	0.36	0.47	0.47

Symmetric Matrix

f	f1	f2	f3	f4	f5	f6
f1	1.00	0.24	0.33	0.21	1.00	-1.00
f2	0.24	1.00	0.85	-0.50	0.22	-0.22
f3	0.33	0.85	1.00	-0.12	0.31	-0.31
f4	0.21	-0.50	-0.12	1.00	0.22	-0.22
f5	1.00	0.22	0.31	0.22	1.00	-1.00
f6	-1.00	-0.22	-0.31	-0.22	-1.00	1.00

Conflict Measurement

f	f1	f2	f3	f4	f5	f6
f1	0.00	0.76	0.67	0.79	0.00	2.00
f2	0.76	0.00	0.15	1.50	0.78	1.22
f3	0.67	0.15	0.00	1.12	0.69	1.31
f4	0.79	1.50	1.12	0.00	0.78	1.22
f5	0.00	0.78	0.69	0.78	0.00	2.00
f6	2.00	1.22	1.31	1.22	2.00	0.00

Quality of Information

f1	1.96
f2	1.66
f3	1.43
f4	1.94
f5	2.00
f6	3.66

E.2: TOPSIS using CRITIC weights for AUGMECON2

Normalized Decision Matrix

f1	f2	f3	f4	f5	f6
0.223080	0.222497	0.222725	0.224051	0.227768	0.222707
0.222595	0.223730	0.223520	0.222720	0.231880	0.221837
0.222610	0.225158	0.224419	0.219938	0.231880	0.221837
0.222590	0.222900	0.224073	0.224898	0.231880	0.221837
0.222580	0.222413	0.222451	0.220059	0.231880	0.221837
0.222593	0.223619	0.223310	0.220059	0.231880	0.221837
0.222579	0.222399	0.222451	0.219938	0.231880	0.221837
0.224097	0.222275	0.222451	0.219938	0.219354	0.224488
0.224113	0.223619	0.223408	0.219938	0.219354	0.224488
0.224128	0.225014	0.224397	0.219938	0.219354	0.224488
0.224128	0.225014	0.224397	0.219938	0.219354	0.224488
0.224096	0.222516	0.223389	0.238562	0.219357	0.224488
0.224113	0.223619	0.223408	0.219938	0.219354	0.224488
0.224128	0.225014	0.224397	0.219938	0.219354	0.224488
0.224096	0.222516	0.223389	0.238562	0.219357	0.224488
0.224101	0.222516	0.223389	0.238568	0.219355	0.224488
0.224113	0.223619	0.223408	0.219938	0.219354	0.224488
0.224128	0.225014	0.224397	0.219938	0.219354	0.224488
0.224116	0.223619	0.224337	0.223446	0.219354	0.224488
0.224128	0.225014	0.224397	0.219938	0.219354	0.224488

Weighted Normalized Decision Matrix

f1	f2	f3	f4	f5	f6
0.034584	0.029146	0.025203	0.034374	0.036060	0.064379
0.034509	0.029307	0.025293	0.034170	0.036711	0.064128

0.034512	0.029494	0.025395	0.033743	0.036711	0.064128
0.034508	0.029199	0.025356	0.034504	0.036711	0.064128
0.034507	0.029135	0.025172	0.033761	0.036711	0.064128
0.034509	0.029293	0.025270	0.033761	0.036711	0.064128
0.034507	0.029133	0.025172	0.033743	0.036711	0.064128
0.034742	0.029117	0.025172	0.033743	0.034728	0.064894
0.034745	0.029293	0.025281	0.033743	0.034728	0.064894
0.034747	0.029475	0.025393	0.033743	0.034728	0.064894
0.034747	0.029475	0.025393	0.033743	0.034728	0.064894
0.034742	0.029148	0.025278	0.036600	0.034729	0.064894
0.034745	0.029293	0.025281	0.033743	0.034728	0.064894
0.034747	0.029475	0.025393	0.033743	0.034728	0.064894
0.034742	0.029148	0.025278	0.036600	0.034729	0.064894
0.034743	0.029148	0.025278	0.036601	0.034728	0.064894
0.034745	0.029293	0.025281	0.033743	0.034728	0.064894
0.034747	0.029475	0.025393	0.033743	0.034728	0.064894
0.034745	0.029293	0.025386	0.034281	0.034728	0.064894
0.034747	0.029475	0.025393	0.033743	0.034728	0.064894

Positive Ideal (best) and Negative Ideal (worst) Solution

	f1	**f2**	**f3**	**f4**	**f5**	**f6**
Z+	0.034507	0.029117	0.025172	0.033743	0.036711	0.064894
Z-	0.034747	0.029494	0.025395	0.036601	0.034728	0.064128

Euclidean Distances

	Sep+	**Sep-**
1	0.001046	0.002643
2	0.000906	0.003154
3	0.000883	0.003487
4	0.001099	0.002912

5	0.000767	0.003498
6	0.000792	0.003480
7	0.000766	0.003513
8	0.001997	0.002992
9	0.002008	0.002968
10	0.002042	0.002959
11	0.002042	0.002959
12	0.003487	0.000849
13	0.002008	0.002968
14	0.002042	0.002959
15	0.002042	0.002959
16	0.003487	0.000849
17	0.003489	0.000849
18	0.002008	0.002968
19	0.002042	0.002959
20	0.002087	0.002452

F.1: CRITIC Weight Calculations for WMM

Normalized Decision Matrix

f1	f2	f3	f4	f5	f6
0.33	0.94	0.98	1.00	0.13	0.90
0.42	0.85	0.99	1.00	0.43	0.58
0.34	0.91	0.99	1.00	0.25	0.75
0.68	0.72	0.94	1.00	0.53	0.61
0.64	0.74	0.94	1.00	0.48	0.64
0.63	0.63	0.96	1.00	0.99	0.00
0.59	0.29	0.00	0.00	0.55	0.53
0.23	0.11	0.62	1.00	0.31	0.62
0.37	0.84	0.98	1.00	0.46	0.51
0.01	1.00	1.00	1.00	0.04	0.81
0.22	0.89	0.96	1.00	0.10	0.87
0.22	0.00	0.52	1.00	0.00	1.00
0.48	0.77	0.93	1.00	0.30	0.78
0.36	0.92	0.99	1.00	0.25	0.76
0.45	0.67	0.88	1.00	0.26	0.81
0.00	1.00	1.00	1.00	0.04	0.82
0.33	0.83	0.93	1.00	0.13	0.90
1.00	0.56	0.93	1.00	1.00	0.21
0.50	0.36	0.77	1.00	0.52	0.51
0.26	0.77	0.93	1.00	0.33	0.60

Standard Deviation

	f1	f2	f3	f4	f5	f6
Std. Deviation	0.23	0.29	0.24	0.22	0.28	0.24

Symmetric Matrix

f	f1	f2	f3	f4	f5	f6
f1	1.00	-0.23	-0.12	-0.19	0.86	-0.66
f2	-0.23	1.00	0.76	0.32	-0.22	0.18
f3	-0.12	0.76	1.00	0.84	-0.06	0.03
f4	-0.19	0.32	0.84	1.00	-0.16	0.13
f5	0.86	-0.22	-0.06	-0.16	1.00	-0.95
f6	-0.66	0.18	0.03	0.13	-0.95	1.00

Conflict Measurement

f	f1	f2	f3	f4	f5	f6
f1	0.00	1.23	1.12	1.19	0.14	1.66
f2	1.23	0.00	0.24	0.68	1.22	0.82
f3	1.12	0.24	0.00	0.16	1.06	0.97
f4	1.19	0.68	0.16	0.00	1.16	0.87
f5	0.14	1.22	1.06	1.16	0.00	1.95
f6	1.66	0.82	0.97	0.87	1.95	0.00

Quality of Information

f1	1.25
f2	1.21
f3	0.85
f4	0.91
f5	1.54
f6	1.51

F.2: TOPSIS using CRITIC weights for WMM

Normalized Decision Matrix

f1	f2	f3	f4	f5	f6
0.223648	0.223576	0.223584	0.223595	0.222683	0.223899
0.223596	0.223587	0.223584	0.223595	0.223892	0.223513
0.223646	0.223579	0.223583	0.223595	0.223184	0.223714
0.223446	0.223604	0.223593	0.223595	0.224311	0.223545
0.223468	0.223601	0.223592	0.223595	0.224134	0.223584
0.223473	0.223614	0.223588	0.223595	0.226197	0.222809
0.223498	0.223656	0.223766	0.223838	0.224384	0.223448
0.223706	0.223678	0.223652	0.223595	0.223410	0.223556
0.223628	0.223589	0.223584	0.223595	0.224028	0.223422
0.223840	0.223569	0.223581	0.223595	0.222326	0.223791
0.223712	0.223582	0.223589	0.223595	0.222562	0.223863
0.223715	0.223692	0.223670	0.223595	0.222147	0.224015
0.223559	0.223597	0.223594	0.223595	0.223395	0.223744
0.223634	0.223579	0.223583	0.223595	0.223187	0.223728
0.223581	0.223609	0.223604	0.223595	0.223221	0.223782
0.223843	0.223568	0.223581	0.223595	0.222294	0.223798
0.223648	0.223590	0.223594	0.223595	0.222683	0.223899
0.223255	0.223623	0.223594	0.223595	0.226247	0.223063
0.223549	0.223648	0.223625	0.223595	0.224280	0.223428
0.223692	0.223597	0.223593	0.223595	0.223517	0.223533

Weighted Normalized Decision Matrix

f1	f2	f3	f4	f5	f6
0.038546	0.037206	0.026246	0.027854	0.047144	0.046473
0.038537	0.037208	0.026246	0.027854	0.047400	0.046393
0.038546	0.037207	0.026246	0.027854	0.047250	0.046435
0.038511	0.037211	0.026247	0.027854	0.047488	0.046400

0.038515	0.037211	0.026247	0.027854	0.047451	0.046408
0.038516	0.037213	0.026247	0.027854	0.047888	0.046247
0.038520	0.037220	0.026267	0.027885	0.047504	0.046380
0.038556	0.037223	0.026254	0.027854	0.047298	0.046402
0.038542	0.037209	0.026246	0.027854	0.047428	0.046374
0.038579	0.037205	0.026246	0.027854	0.047068	0.046451
0.038557	0.037207	0.026247	0.027854	0.047118	0.046466
0.038557	0.037226	0.026256	0.027854	0.047030	0.046498
0.038531	0.037210	0.026247	0.027854	0.047294	0.046441
0.038543	0.037207	0.026246	0.027854	0.047250	0.046438
0.038534	0.037212	0.026248	0.027854	0.047258	0.046449
0.038579	0.037205	0.026246	0.027854	0.047061	0.046453
0.038546	0.037209	0.026247	0.027854	0.047144	0.046473
0.038478	0.037214	0.026247	0.027854	0.047898	0.046300
0.038529	0.037218	0.026251	0.027854	0.047482	0.046376
0.038553	0.037210	0.026247	0.027854	0.047320	0.046397

Positive Ideal (best) and Negative Ideal (worst) Solution

	f1	**f2**	**f3**	**f4**	**f5**	**f6**
Z+	0.038478	0.037205	0.026246	0.027854	0.047898	0.046498
Z-	0.038579	0.037226	0.026267	0.027885	0.047030	0.046247

Euclidean Distances

	Sep+	**Sep-**
1	0.000758	0.000259
2	0.000513	0.000402
3	0.000655	0.000294
4	0.000423	0.000489
5	0.000458	0.000457
6	0.000253	0.000861

7	0.000416	0.000495
8	0.000613	0.000312
9	0.000490	0.000422
10	0.000838	0.000212
11	0.000785	0.000240
12	0.000872	0.000253
13	0.000609	0.000334
14	0.000654	0.000296
15	0.000645	0.000310
16	0.000844	0.000212
17	0.000758	0.000258
18	0.000198	0.000876
19	0.000437	0.000474
20	0.000591	0.000330