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A Decision Framework for Solar PV Panels Supply Chain in Context of Sustainable Supplier Selection and Order Allocation

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Abstract: Sustainable supplier selection and order allocation (SSSOA) is paramount to sustainable supply chain management. It is a complex multi-dimensional decision-making process augmented with the triple bottom line of sustainability. This research presents a multi-phase decision framework to address a SSSOA problem for the multi-echelon renewable energy equipment (Solar PV Panels) supply chain. The framework comprises of fuzzy Multi-Criteria Decision-Making techniques augmented with fuzzy multi-objective mixed-integer non-linear programming mathematical model. The various economic, environmental, and social objectives were optimized for a multi-period, multi-modal transportation network of the supply chain. The results show that among the various sustainable criteria selected in this study, product cost, environmental management system, and health and safety rights of employees are the most important for decision-makers. The results of the mathematical model highlighted the impact of multimodal transportation on overall cost, time, and environmental impact for all periods. An analysis of results revealed that transfer cost and customer clearance cost contribute significantly towards overall cost. Furthermore, defect rate was also observed to play a critical role in supplier selection and order allocation.

Keywords: renewable energy supply chain; sustainable supplier selection; multi-objective optimization; order allocation; fuzzy multi-criteria decision making

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1. Introduction

Supply Chain Management (SCM) comprises of operations related to the flow of merchandise from supplier to the end customer [1]. It helps in the overall planning, controlling, and implementation of the organization's activities [2]. Over the years, organizations have shifted from conventional SCM to sustainable supply chain management (SSCM) to achieve high operational performance and business competitiveness [3]. Sustainability in SCM refers to a set of scales between economic benefits, environmental protection, and social improvements [4]. Its goal is to obtain an optimal compromise amongst the three diverging pillars (economic, environmental and social) by managing the resources, data, assets, and merchandise amongst the entities of the supply chain [5]. The concerns over ozone depletion, exhaustion of natural resources, and employees' social rights, etc. pried the enterprises to address the concerns of environmental pollution and social structure in their supply chains [6].

There has been a growing trend among organization to adopt sustainable supply chain practices [7]. An important aspect of sustainable supply chains is devising of purchasing strategies [8]. This poses a challenge for supply chain managers in the form of sustainable purchasing and vendor selection. This also motivates them to improve their supply chain activities for sustainable development of organization. Therefore, a concept of sustainable supplier selection and order allocation (SSSOA) has been introduced. It is an important aspect of SSCM [9]. SSSOA is a complex multi-criteria decision-making (MCDM) process augmented with order allocation techniques and various tangible and intangible criteria to assess the suppliers for optimal order allocation [10].

Fundamentally, SSSOA problems consist of two phases: (1) sustainable supplier selection, (2) optimal order allocation. Sustainable supplier selection can be further divided into two parts: (1) single souring, where one supplier can fulfill the total demand of the customer, and (2) multiple sourcing, where multiple suppliers need to be selected to fulfill the customer's demand. Generally, enterprises prefer multiple sourcing for more diverse, timely, and flexible order delivery [11–13]. However, due to several uncontrollable and unpredictable factors, it is challenging for decision-makers to select appropriate suppliers [14]. After the selection of the best suppliers under the triple bottom line of sustainability, another important question arises about "what amount to order?" The order allocation comprises a mathematical model consisting of single or multiple objectives that need to be optimized while ordering from suppliers and meeting customer's demands [15]. Researchers integrated the order allocation problem with supplier selection to reduce the cost and other parameters to enhance the performance of the supply chain, see for instance ([16–21]).

The quest of sustainability has also motivated the energy sector over the globe to adopt sustainable practices in production and delivery [22]. Therefore, global energy outlook is rapidly shifting towards renewable energy sources [23]. Of various types of renewable energy sources, Solar Photovoltaic (PV) Panels dominate the energy production both at domestic and commercial level [24]. Different reports suggest that China, Canada, USA, Japan, and Germany dominate the global production of Solar PV Panels [25]. According to the international trade data, these countries are also the major exporters of Solar PV Panels to the world. Although Solar PV Panels present a sustainable mean of energy production, their supply chain is still an unexplored area for application of sustainable practices. Therefore, implementation of SSSOA problem on the supply chains of solar PV Panel would intensify the deployment of overall sustainable objectives [26].

Despite several research studies conducted to address the aspect of sustainability in the SSSOA problem for various industries, the emphasis on sustainability concerns in the solar PV panels supply chains is still at an early stage. To the best of the authors' knowledge, no study has been conducted so far that evaluates the supply chain in the context of SSSOA of the Solar PV Panels industry. Therefore, the objective of this research is to develop a comprehensive fuzzified decision framework for solving the SSSOA problem in renewable energy supply chain networks (with emphasis on the Solar PV Panels industry). The originality of the study is to presents the novel fuzzified decision framework implemented on the solar PV panels supply chain. A numerical case study with real time data was used to examine the efficacy of the developed decision framework. The developed framework provides an insight to supply chain managers, particularly in the Solar PV Panels industry.

The remaining of this paper is organized as follows: Section 2 presents an overview of the existing literature on the SSSOA problem. Section 3 briefly describes the problem that is addressed in this study. Section 4 presents the decision framework, the development of the Fuzzy Multi-Objective Mixed Integer Non-Linear Programming (FMOMINLP) optimization model, and the solution approach used to solve FMOMINLP. Section 5 presents an application of the developed integrated approach to a case study. Section 6 presents conclusions and recommends avenues for future studies.

2. Relevant Literature

Over the years, extensive research has been carried out by the research community to address the augmentation of sustainability in supply chains. For instance, Cheraghalipour and Farsad [20] provided a decision-making tool of purchasing and ordering for the plastic industry while considering three pillars of sustainability. Zimon and Domingues [27] highlighted the potential factors that would influence the sustainable management of textile supply chains. Tseng et al. [28] developed a comprehensive mathematical model to feature the role of Big Data for minimizing uncertainties and achieving sustainable development in supply chains. With growing concerns about the sustainability in supply chains, researchers have analyzed supply chains in the context of supplier selection and order allocation (individually and integrally). MCDM techniques have been used along with multi-objective optimization to assess SSSOA problems [29–32]. The literature related to the SSSOA problem can be broadly divided into two categories, namely: Sustainable Supplier Selection (SSS) and Order Allocation (OA). The following section briefly presents an overview of some of the key studies in these two categories.

2.1. Sustainable Supplier Selection

Sustainable purchasing has a strategic relevance in SSCM [33]. It is a complex multi-variate decision-making problem that simultaneously evaluates the conflicting criteria and objectives along with uncertainties in human decision-making [34,35]. Traditionally, suppliers were assessed conflicting criteria like total cost, product quality, service level, and delivery time [36]. However, with growing awareness about sustainability, government regulations, and responsible purchasing practices, sustainable criteria are used for supplier selection [37]. For instance, Buyukzkan and Cifci [38] used five sustainable criteria for evaluating the sustainable performance of suppliers. Luthra et al. [39] argued that environmental costs and competencies, quality, and product price, occupational health, and safety systems are the main factors that influence sustainable purchasing decisions. Memari et al. [40] used 30 sustainable criteria for supplier evaluation of automotive spare parts manufacturers. Zhang et al. [41] used 15 sustainable criteria that can effectively improve enterprise supply chain performance. Once the sustainable criteria for supplier selection have been identified, the next step is evaluating the suppliers based on these criteria. Traditionally, MCDM techniques were developed to determine the optimal alternative among multiple, conflicting, and interactive criteria. However, due to the uncertain nature of human decision-making, researchers have integrated Fuzzy Set Theory (FST) with traditional MCDM techniques. FST is used along with MCDM techniques to transform crisp numeric values for more precise judgment of real-world systems [42]. A wealth of literature elucidates the importance of fuzzy logic in MCDM problems [33,40,43–46]. Table 1 presents some recent studies conducted on SSS with the help of fuzzy MCDM techniques.

Table 1. Relevant Studies of Criteria and Solving Techniques used for Sustainable Supplier Selection.

Study	Criteria Used	Fuzzy MCDM Technique
Alavi et al. [47]	Costs Quality Responsiveness Delivery Risk Technology Capability Waste Management Environmental Management System Human Rights Product Responsibility Health and Safety Management Ethical Issues Information disclosure	Fuzzy Best Worst Method

Table 1. *Cont.*

Study	Criteria Used	Fuzzy MCDM Technique
Orji and Ojadi [48]	Product price/cost Financial capability Quality Environmental competence Green product design Regular environmental audits Presence of training facilities Work safety procedures Compliance with regulations Information disclosure Social responsibility Use of personal protective equipment Presence of information technologies Adherence to policy changes Economic recovery programs	Fuzzy Analytical Hierarchy Process (FAHP)
Wang and Tsai [32]	Cost Quality Capacity Flexibility Technological Capability Environmental/Economic Management System Social responsibility Delay Reputation Customer Complaints Defect Rate	FAHP Data Envelopment Analysis
Wang et al. [49]	Transportation Cost Product Price Financial Ability Pollutant Discharge Resource Consumption Recycle System Flexibility Rights of Stakeholders Employee right and welfare Information Disclosure	VIKOR FAHP
Ecer and Pamucar [50]	Delivery (lead) time Transportation cost Service Price of product Quality of product Pollution control EMS Environmental competencies Green management Environmental cost Staff training Health and safety Information Disclosure The rights of stakeholders The interests and rights of the employee	Fuzzy Best Worst Method Bonferroni Combined Compromise Solution

VIKOR: VIseKriterijumska Optimizacija I Kompromisno Resenje.

2.2. Sustainable Order Allocation

Notably, optimal order allocation is paramount to SSSOA problems [51]. Extensive research has been done to allocate an order to potential customers while considering the three pillars of sustainability. Order allocation is a multi-objective process considering conflicting objectives that need to be simultaneously optimized for sustainable purchasing from potential suppliers [52–54]. A mathematical model containing conflicting objectives needs to be developed for optimum allocation of orders. Mohammed [55] developed a mixed-integer non-linear programming (MINLP) model containing cost, time, environmental and social impact as objectives to allocate orders to selected suppliers. The authors used a technique for multi-objective optimization of the mathematical model. Goren [56] developed the MILP model consisting of cost and value of purchasing as objectives for sustainable distribution of orders to the suppliers. Furthermore, to incorporate the aspect of uncertainty in input parameters, researchers shifted from conventional MILP/MINLP to fuzzified MILP/MINLP, see for instance, [37,57–60]. Various solution approaches have been used to solve the mathematical models developed for order allocation. Table 2 presents an overview of studies containing the type of mathematical model, objectives, and solution approaches to solve the mathematical modal.

Table 2. Classification of Studies w.r.t Mathematical Model, Objectives, and Solving Techniques for Order Allocation.

Study	Type of Mathematical Model	Objectives	Solution Approach
Bektur [51]	FMILP	Total Cost Value of Purchasing	Augmented Epsilon-Constraint
Kumar et al. [57]	FMILP	Carbon emission Energy use per product Waste generated per product % Profit to social and community welfare Order cost % Rejection on quality issues % Late delivery of items	Weighted Additive Method
Mohammed et al. [61]	FMILP	Total Cost Total Time Environmental Impact Social Impact Total Value of Purchasing	Epsilon-Constraint LP Metric
Beiki [62]	FMINLP	Total Cost Total Emissions Total purchase value	Genetic Algorithm
Nasr et al. [63]	FMINLP	Total costs Environmental effects Employment Lost sales Procurement value from sustainable suppliers	Fuzzy Goal Programming Approach

2.3. Decision Framework for SSSOA Problems

In recent years, researchers have developed a decision framework to address the SSSOA problem. Such frameworks comprise MCDM techniques with multi-objective programming models. For instance, Liaqait et al. [9] developed a decision support framework for the air condition industry. In their study, the multi-modal MINLP model integrated with noise pollution and demand uncertainty was developed. Mohammed et al. [61] proposed a decision framework for a two-stage SSSOA problem for the food industry. In their study, the FMILP model was developed to cope with the dynamic nature of the input parameters. Sodenkamp [64] presented a multi-level group decision framework augmented with a mathematical model for dynamic monitoring of strategic and tactical purchasing decisions on different organizational layers. Vahidi et al. [65] proposed a novel bi-objective two-stage mixed possibilistic-stochastic programming decision framework to address the SSSOA problem under operational and disruption risks. Omair et al. [66] proposed a decision support framework for the selection of sustainable suppliers of gloves manufacturing firm using Fuzzy Inference System (FIS) and AHP. Table 3 presents the decision framework developed by the researchers to address the SSSOA problem. It also provides deep insight into used criteria, mathematical models, case studies, and solving techniques. Furthermore, it highlights the novel establishment of decision framework and its application on solar PV panels industry.

Table 3. Literature Review of Established Decision Framework for SSSOA problem.

Study	Decision Framework for SSSOA	Sustainable Supplier Selection Criteria			Order Allocation	Information		Time Period		Product Type		Solving Techniques	Case Study
		Environmental	Economic	Social		Certain	Uncertain	Single	Multiple	Single	Multiple		
Khoshfetrat et al. [67]	✓	✓	✓	✓	✓		✓		✓		✓	AHP, Linear Solver	Automotive Industry
Bektu [51]	✓	✓	✓	✓	✓		✓		✓		✓	FAHP, FPROMETHEE AUGMECON, LP-metrics	Medical Equipment Industry
Goren [56]	✓	✓	✓	✓	✓	✓			✓		✓	DEMATEL, Taguchi loss functions	Construction Industry
Tayyab & Sarkar [68]	✓	✓	✓	✓	✓		✓		✓		✓	Weighted F-Goal programming	Textile Industry
Liaqait et al. [9]	✓	✓	✓	✓	✓	✓		✓		✓		FAHP, FTOPSIS, CRITIC Augmented ε-constraint 2	Air Conditioning Industry
Vahidi et al. [65]	✓	✓	✓	✓	✓		✓	✓			✓	SWOT-QFD, weighted Augmented ε-constraint	N/A Benchmark Solutions
Jia et al. [69]	✓	✓	✓	✓	✓	✓		✓		✓		Goal Programming	Steel Industry
Nasr et al. [63]	✓	✓	✓	✓	✓		✓		✓		✓	Goal Programming	Textile Industry
Cheraghalipour & Farsad [20]	✓	✓	✓	✓	✓		✓		✓		✓	Best Worst Method, Multi-Choice Goal Programming	Plastics Industry
Tirkolaee et al. [70]	✓	✓	✓	✓	✓		✓		✓		✓	FANP, FDEMATEL, FTOPSIS, Goal programming	Electronics Industry
Mohammed et al. [61]	✓	✓	✓	✓	✓		✓	✓		✓		FAHP, FTOPSIS, ε-constraint, LP Metric	Meat Industry
Mohammed et al. [71]	✓	✓	✓	✓	✓		✓	✓		✓		FAHP, FTOPSIS, ε-constraint, LP Metric	Meat Industry
Mohammed et al. [72]	✓	✓	✓	✓	✓		✓	✓		✓		FAHP, FTOPSIS, ε-constraint, LP Metric	Metal Industry
This Study	✓	✓	✓	✓	✓		✓		✓	✓		FAHP, FTOPSIS, Augmented ε-constraint 2, Delphi Technique	Solar PV Panels Industry

FPROMETHEE: Fuzzy Preference Ranking Organization Method for Enrichment Evaluation. AUGMECON: Augmented Epsilon Constraint. FDEMATEL: Fuzzy Decision-Making Trial and Evaluation Laboratory. FTOPSIS: Fuzzy Technique for Order of Preference by Similarity to Ideal Solution. CRITIC: Criteria Importance Through Intercriteria Correlation. SWOT-QFD: Strengths, Weaknesses, Opportunities, and Threats—Quality Function Deployment. FANP: Fuzzy Analytic Network Process.

To summarize, the literature, the SSSOA problem is a multi-dimensional comparative analysis process. Supplier evaluation criteria are the most important factor in supplier selection problems. Therefore, researchers have conducted extensive and wide-ranged surveys with managers and decision-makers for the selection of appropriate criteria. Furthermore, various stand-alone and hybrid MCDM techniques have been used for sustainable supplier selection. Amongst these techniques, AHP augmented with TOPSIS has been reported to be most useful. Furthermore, various bi and multi-objective mathematical models have been developed for optimum order allocation. The integration of FST in MCDM techniques and mathematical models has often been used to address the vagueness and uncertainty of the decision-making process. Although several decision frameworks have been developed to solve the SSSOA problem for various industries, no study exists in the literature that has aimed to solve the SSSOA problem for the Solar PV Panels industry. Therefore, a real time case of Solar PV Panels is presented to solve the SSSOA problem.

3. Problem Description

Figure 1 illustrates the multi-modal, multi-echelon supply chain network of Solar Panels examined in this study. The network consists of suppliers "*i*", seaport "*j*", warehouse "*k*", and customer "*m*". Supplier "*i*" ship the quantity X_{ijnt} through port "*j*" to the warehouse "*k*" which is then transported to the customer "*m*" using various transportation modes "*n*" at time period "*t*". The supply chain network is evaluated under the demand and capacity uncertainties of suppliers and warehouses. Moreover, a fuzzified MINLP mathematical model is developed to obtain an optimum quantity from the potential suppliers that are selected based on sustainable criteria to meet the customers' demands for each time period.

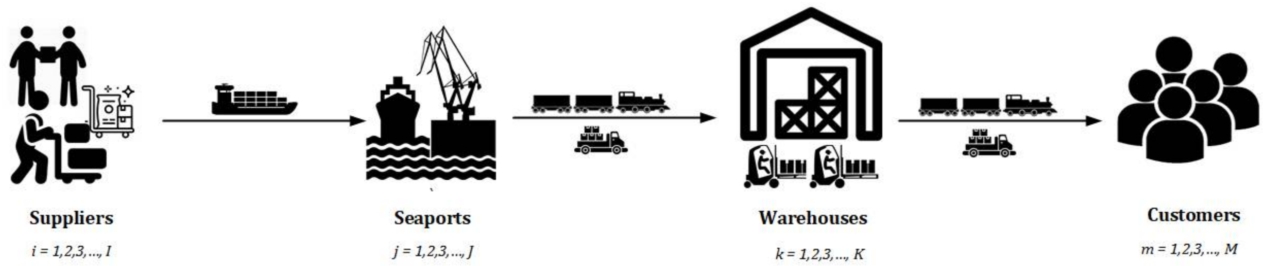

Figure 1. A Multi-Echelon Supply Chain Network Under Study.

4. Sustainability Assessment Framework for the Solar PV Panels Supply Chain

A three-phase decision framework is proposed for sustainable performance evaluation of the solar panel supply chain network as shown in Figure 2. In the first phase, MCDM techniques were used to evaluate the suppliers in the context of sustainable criteria. In the second phase, FMOMINLP mathematical model was developed for sustainable order allocation and is solved using Augmented Epsilon Constraint 2 (AUGMECON2) for the optimized solutions. In the third phase, MCDM techniques were used to analyze the results of the mathematical model to obtain the final solution. A brief overview of the steps involved in each phase is presented below:

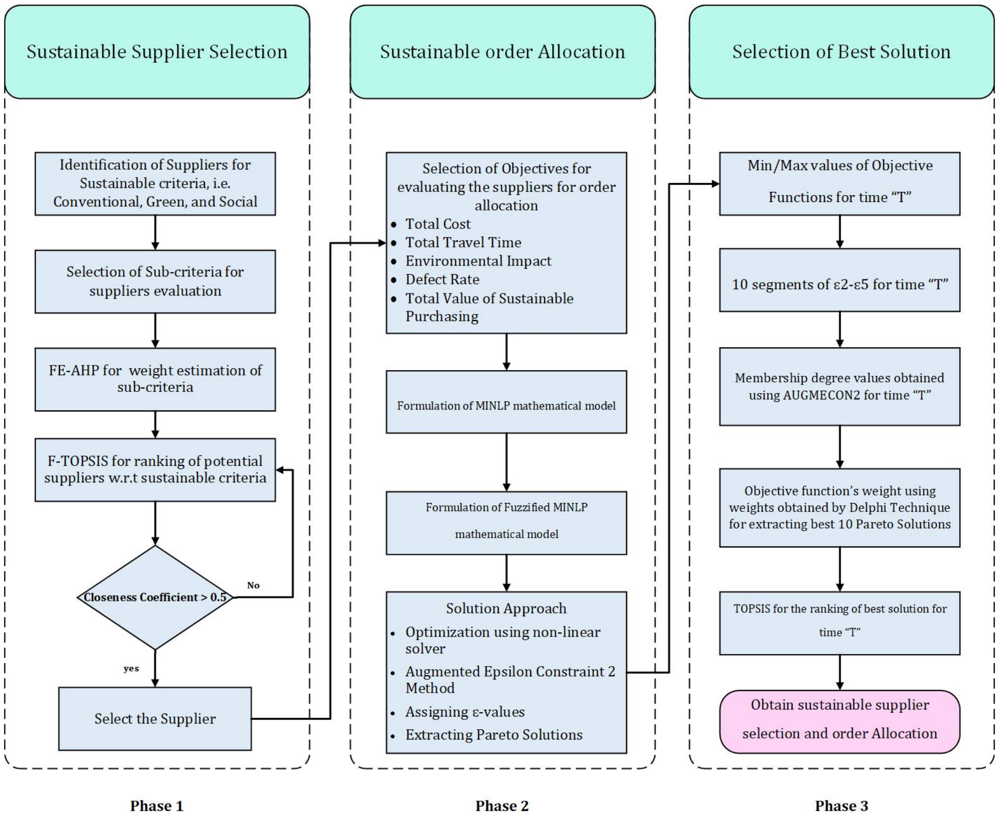

Figure 2. Generic Framework of Proposed Methodology.

4.1. Sustainable Supplier Selection

FEAHP is applied to evaluate the relative weights of each sustainable supplier selection criterion using the methodology described by Wang et al. [73]. The sub-criteria for each major sustainable criterion are presented in Table 4. The weights of each sustainable criterion and sub-criterion are incorporated in FTOPSIS to rank the supplier using the methodology described by Mohammed et al. [61]. The linguistic variables used to estimate the criteria weights and ranking of the suppliers are presented in Table 5. In the end, the best suppliers were selected based on a defined threshold of Closeness Coefficient (CC) having a value greater than 0.5 (i.e., CC $\geq$ 0.50).

Table 4. Criteria and Sub-criteria for sustainable supplier ranking.

Sustainable Criteria	Sub-Criteria
Economic	Cost (C1) Volume Flexibility (C2) Payment Terms (C3) Use of Technology (C4) Delivery Reliability (C5) Vendors Market reputation (C6) Defect Rate (C7) Quality (C8)
Environmental	Environment Management System (C1) Resource Consumption (C2) Pollution Production (C3)
Social	Information Disclosure (C1) Rights and Health of Employees (C2) Staff Personal and Technical Development (C3)

Table 5. Linguistic variables used of FTOPSIS and FEAHP.

Performance Ranking of Alternatives		Importance of Criteria	
Linguistic Variable	**Fuzzy Number**	**Linguistic Variable**	**Fuzzy Number**
Very low (VL)	(1, 1, 3)	Weakly Important (WI)	(0.1, 0.1, 0.3)
Low (L)	(1, 3, 5)	Moderately Important (MI)	(0.1, 0.3, 0.5)
Medium (M)	(3, 5, 7)	Important (I)	(0.3, 0.5, 0.7)
High (H)	(5, 7, 9)	Strongly Important (SI)	(0.5, 0.7, 0.9)
Very high (VH)	(7, 9, 9)	Extremely Important (WI)	(0.7, 0.9, 0.9)

4.2. Sustainable Order Allocation

Firstly, FMOMINLP mathematical model is developed using fuzzified demand, supply, capacity, and resource constraints. The objective functions of models are Total Cost (TC), Total Travel Time (TTT), Environmental Impact (EI), Defect Rate (DR), and Total Value of Sustainable Purchasing (TVSP). Secondly, the exact solution for each objective is estimated using a non-linear mixed-integer programming solver. Thirdly, the AUGMECON2 algorithm is used to simultaneously minimize TC, TTT, EI, and DR while maximizing TVSP.

4.3. Selection of Best Solution

After the estimation of min/max values of objective functions, the values were divided into 10 segments corresponding to φ-levels for time "t". Once the Pareto solutions were extracted for time t, TOPSIS augmented with weights assigned to each objective function using the Delphi technique was applied. 10 best optimal solutions were obtained using AUGMECON2 corresponding to φ-levels. TOPSIS was again applied to the selected Pareto solution to select the best optimal solution for t_1–t_4.

4.4. Development of Fuzzified Mathematical Model for Sustainable Order Allocation

This section presents the development of FMINLP mathematical model for Solar PV Panels supply chain. Several parameters are subject to uncertainty in the real world. Therefore, to cope with the dynamic nature of the input data in costs, capacity levels, demands, and defect rates, FST is applied in the mathematical model for more realistic scenarios. The multi-objective optimization model is presented below.

Assumptions

The assumptions of the mathematical model are as follows:

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

Sets

$i = 1, 2, 3, \ldots, I$ set of Suppliers

$j = 1, 2, 3, \ldots, J$ set of Port

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

$m = 1, 2, 3, \ldots, M$ set of Customers

$n = 1, 2, 3, \ldots, N$ *set of Transportation Modes*

$o = 1, 2, 3, \ldots, O$ *set of Transportation Modes*

(n and o: for interchangeable mode transfer decisions)

$t = 1, 2, 3, \ldots, T$ set of Time Period

Parameters

$C_{it}^{p} =$ Purchasing cos t per unit from supplier i at time "t"
$O_{it} =$ Ordering cost incurred by customer for i^{th} supplier at time "t"
$H_{ot} =$ Inventory Holding cost per unit incurred by customer at time "t"
$TC_{nt} =$ Transportation cost per kilometre for mode "n" at time "t"
$TrC_{not} =$ Transfer cost from mode "n" to mode "o" at time "t"
$CC_{ijt} =$ Custom clearence cost while moving from supplier "i" to port "j" at time "t"
$TrT_{not} =$ Transfer Time from mode "n" to mode "o" at time "t"
$CCT_{ijt} =$ Custom Clearence Time from supplier "i" to port "j" at time "t"
$d_{ijn} =$ Distance from supplier "i" to port "j" via mode "n"
$d_{jkn} =$ Distance from port "j" to warehouse "k" via mode "n"
$d_{kmn} =$ Distance from warehouse "k" to customer "m" via mode "n"
$w_i^{eco} =$ Weights of *economic* criteria obtained from FEAHP
$w_i^{e} =$ Weights of *environmental* criteria obtained from FEAHP
$w_i^{s} =$ Weights of *social* criteria obtained from FEAHP
$W_i^{economic} =$ Weights of supplier "i" from FTOPSIS w.r.t *economic* criteria
$W_i^{environmental} =$ Weights of supplier "i" from FTOPSIS w.r.t *environmental* criteria
$W_i^{social} =$ Weights of supplier "i" from FTOPSIS w.r.t *social* criteria
$CO_{2ijn} =$ Carbon dioxide emission in *gram per km* while travelling
from supplier "i" to port "j" via mode "n"

$CO_{2jkn} =$ Carbon dioxide emission in *gram per km* while travelling
from port "j" to warehouse "k" via mode "n"
$CO_{2klm} =$ Carbon dioxide emission in *gram per km* while travelling
from warehouse "k" to cutomer "l" via mode "m"
$S_{it} =$ Maximum capacity of i^{th} supplier at time "t"
$D_{mt} =$ Demand of m^{th} customer at time "t"
$\xi_{it} =$ Average Defect Rate of Suppiler "i" at time "t"
$CAPw_{kt} =$ Capacity of k^{th} warehouse at time "t"
$v_n =$ Velocity of mode "n"
$CAP_n =$ Capacity of vehicle used while moving through mode "n"

Integer Variables

$x_{ijnt} =$ Quantity shipped from supplier i to port j via mode n at time t
$x_{jknt} =$ Quantity shipped from port j to warehouse k via mode n at time t
$x_{kmnt} =$ Quantity shipped from warehouse k to to customer m via mode n at time t

Binary Variables

$$\alpha_{it} = \begin{cases} 1 & if \text{ supplier } i \text{ } is \text{ } selected \text{ } at \text{ } time \text{ } t, \\ 0 & otherwise \end{cases}$$

$$\beta jt = \begin{cases} 1 & if \text{ } tranfer \text{ } from \text{ mode } n \text{ } to \text{ } o \text{ } at \text{ } node \text{ } j \text{ } at \text{ } time \text{ } t \\ 0 & otherwise \end{cases}$$

$$\beta kt = \begin{cases} 1 & if \text{ } tranfer \text{ } from \text{ mode } n \text{ } to \text{ } o \text{ } at \text{ } node \text{ } k \text{ } at \text{ } time \text{ } t \\ 0 & otherwise \end{cases}$$

$$\phi_{kt} = \begin{cases} 1 & if \text{ } warehouse \text{ } k \text{ } is \text{ } selected \text{ } at \text{ } time \text{ } t, \\ 0 & otherwise \end{cases}$$

Objective Function 1: Total Cost (TC)

This objective function aims to minimize the sum of purchasing cost, ordering cost, inventory holding cost, transportation cost, transfer cost, and customs clearance cost. The equation below presents the minimization of total costs that occurred throughout the supply chain network.

$$
\begin{aligned}
&Min \quad \mathrm{TC} = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{n=1}^{N}\sum_{t=1}^{T}\left(\frac{C_{it}^{p\ pes}+C_{it}^{p\ mos}+C_{it}^{p\ opt}}{4}\right)x_{ijnt} + \sum_{i=1}^{I}\sum_{t=1}^{T}\left(\frac{O_{it}{}^{pes}+O_{it}{}^{mos}+O_{it}{}^{opt}}{4}\right)\alpha_{it}+ \\
&\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{n=1}^{N}\sum_{t=1}^{T}\frac{x_{ijnt}}{2}\left(\frac{H_{ot}{}^{pes}+H_{ot}{}^{mos}+H_{ot}{}^{opt}}{4}\right)+ \\
&\left(\begin{array}{l}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{n=1}^{N}\sum_{t=1}^{T}\left(\frac{TC_{nt}{}^{pes}+TC_{nt}{}^{mos}+TC_{nt}{}^{opt}}{4}\right)d_{ijn}\frac{x_{ijnt}}{Capn} + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{n=1}^{N}\sum_{t=1}^{T}\left(\frac{TC_{nt}{}^{pes}+TC_{nt}{}^{mos}+TC_{nt}{}^{opt}}{4}\right)d_{jkn}\frac{x_{jknt}}{Capn}+ \\ \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{t=1}^{T}\left(\frac{TC_{nt}{}^{pes}+TC_{nt}{}^{mos}+TC_{nt}{}^{opt}}{4}\right)d_{kmn}\frac{x_{kmnt}}{Capn}\end{array}\right) \\
&+\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{n=1}^{N}\sum_{o=1}^{O}\sum_{t=1}^{T}TrC_{not}\beta_{jt}x_{ijnt} + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{n=1}^{N}\sum_{o=1}^{O}\sum_{t=1}^{T}TrC_{not}\beta_{kt}x_{jknt}\right) + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{n=1}^{N}\sum_{t=1}^{T}\left(\frac{CC_{ijt}{}^{pes}+CC_{ijt}{}^{mos}+CC_{ijt}{}^{opt}}{4}\right)x_{ijnt}\alpha_{it}
\end{aligned} \tag{1}
$$

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 customs clearance time. The minimization of total travel time is expressed as follows.

$$
\begin{aligned}
&Min \quad \mathrm{TTT} = \left(\begin{array}{l}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{n=1}^{N}\sum_{t=1}^{T}\frac{d_{ijn}x_{ijnt}}{v_nCAP_n} + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{n=1}^{N}\sum_{t=1}^{T}\frac{d_{jkn}x_{jkmt}\phi_{kt}}{v_nCAP_n} \\ +\sum_{k=1}^{k}\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{t=1}^{T}\frac{d_{kmn}x_{kmnt}\phi_{kt}}{v_nCAP_n}\end{array}\right) \\
&+\left(\sum_{j=1}^{J}\sum_{n=1}^{N}\sum_{o=1}^{O}\sum_{t=1}^{T}TrT_{not}\frac{x_{jknt}\beta jt}{CAP_n} + \sum_{k=1}^{K}\sum_{n=1}^{N}\sum_{o=1}^{O}\sum_{t=1}^{T}TrT_{not}\frac{x_{kmnt}\beta kt}{CAP_n}\right) \\
&+\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{n=1}^{N}\sum_{t=1}^{T}\frac{CCT_{ijt}x_{ijnt}\alpha_{it}}{CAP_n}\right)
\end{aligned} \tag{2}
$$

Objective Function 3: Environmental Impact (EI)

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

$$
\begin{aligned}
&Min \quad \mathrm{EI} = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{n=1}^{N}\sum_{t=1}^{T}CO_{2ijn}\left[\frac{x_{ijnt}}{Cap_n}\right]d_{ijn} + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{n=1}^{N}\sum_{t=1}^{T}CO_{2jkn}\left[\frac{x_{jknt}}{Cap_n}\right]d_{jkn}\ \phi_{kt} \\
&+\sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{t=1}^{T}CO_{2kmn}\left[\frac{x_{kmnt}}{Cap_n}\right]d_{kmn}\ \phi_{kt}
\end{aligned} \tag{3}
$$

Objective Function 4: Defect Rate (DR)

This objective function aims to minimize the average defect rate of the selected suppliers.

$$
Min \quad DR = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{n=1}^{N}\sum_{t=1}^{T}\left(\frac{\xi_{it}{}^{pes}+\xi_{it}{}^{mos}+\xi_{it}{}^{opt}}{4}\right)x_{ijnt}\alpha_{it} \tag{4}
$$

Objective Function 5: Total Value of Sustainable Purchasing (TVSP)

This objective function aims to maximize the total value of purchased goods by maximizing the economic, social, and environmental criteria weights. The criteria weights obtained from fuzzy E-AHP are multiplied by supplier's weights obtained from fuzzy TOPSIS and the quantity ordered from the supplier. The equation below presents the maximization of the total value of sustainable purchasing as follows.

$$Max \quad \text{TVSP} = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{n=1}^{N}\sum_{t=1}^{T}\left(W_i^{enonomic} w_i^{eco} + W_i^{environmental} w_i^{e} + W_i^{social} w_i^{s}\right) x_{ijnt}\alpha_{it} \tag{5}$$

Constraints

$$\sum_{j=1}^{J}\sum_{n=1}^{N} x_{ijnt} \le \left[\frac{\varphi}{2}\frac{{S_{it}}^1 + {S_{it}}^2}{2} + \left(1-\frac{\varphi}{2}\right)\frac{{S_{it}}^3 + {S_{it}}^4}{2}\right]\alpha_{it} \qquad \forall i \in I, t \in T \tag{6}$$

$$\sum_{m=1}^{M}\sum_{n=1}^{N} x_{lmt} = \left[\frac{\varphi}{2}\frac{{D_{mt}}^1 + {D_{mt}}^2}{2} + \left(1-\frac{\varphi}{2}\right)\frac{{D_{mt}}^3 + {D_{mt}}^4}{2}\right] \qquad \forall l \in L, t \in T \tag{7}$$

$$\sum_{i=1}^{I}\sum_{n=1}^{N} x_{ijnt} = \sum_{k=1}^{K}\sum_{n=1}^{N} x_{jknt} \qquad \forall j \in J,\ \ t \in T \tag{8}$$

$$\sum_{j=1}^{J}\sum_{n=1}^{N} x_{jknt} = \sum_{m=1}^{M}\sum_{n=1}^{N} x_{kmnt} \qquad \forall k \in K,\ \ t \in T \tag{9}$$

$$\sum_{k=1}^{K}\sum_{n=1}^{N} x_{jknt} \le \left[\frac{\varphi}{2}\frac{{CAPw_{kt}}^1 + {CAPw_{kt}}^2}{2} + \left(1-\frac{\varphi}{2}\right)\frac{{CAPw_{kt}}^3 + {CAPw_{kt}}^4}{2}\right]\beta_{kt} \quad \forall j \in J,\ \ t \in T \tag{10}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} X_{ijnt} \le Cap_{nt} \qquad \forall n \in N, t \in T \tag{11}$$

$$\sum_{j=1}^{J}\sum_{m=1}^{K} X_{jknt} \le Cap_{nt} \qquad \forall n \in N, t \in T \tag{12}$$

$$\sum_{k=1}^{K}\sum_{m=1}^{M} X_{kmnt} \le Cap_{nt} \qquad \forall n \in N, t \in T \tag{13}$$

$$x_{ijnt}, x_{jknt}, x_{kmnt} \ge 0 \qquad \forall i, j, k, m, n, t \tag{14}$$

$$\alpha_{jt}, \beta_{jt}, \beta_{kt}, \phi_{kt} \ \in \{0, 1\} \qquad \forall i, j, k, l, t \tag{15}$$

Based on fuzzy formulation, the constraints of the FMINLP model should be satisfied with a confidence value that is denoted as φ and is determined by decision-makers. Furthermore, mos, pes, and opt are the three prominent points (the most likely, most pessimistic, and most optimistic values), respectively. Each objective function corresponds to an equivalent linear membership function, which can be determined using Equation (16). Figure 3 further illustrates the membership functions for each objective.

$$\mu_b = \begin{cases} 1 & if\ Z_b \le Max_b \\ \frac{Max_b - Z_b}{Max_b - Min_b} & if\ Min_b \le Z_b \le Max_b \\ 0 & if\ Z_b \ge Min_b \end{cases} \tag{16}$$

where Z_b represents the value of the b^{th} objective function and Max_b and Min_b represent the maximum and minimum values of b^{th} objective function, respectively.

The maximum and minimum values of each objective function are obtained using the above equations for the evaluation of membership degree.

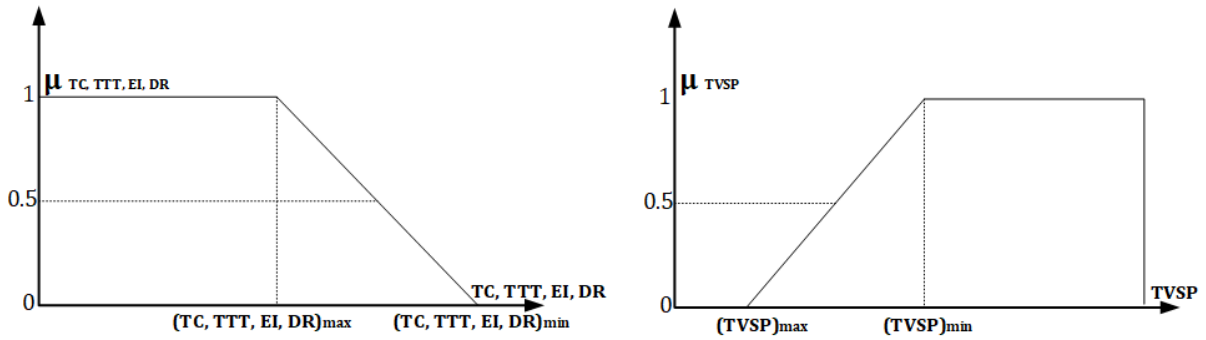

Figure 3. Membership Function for TC, TTT, EI, DR, TVSP.

4.5. Solving Algorithm: Augmented Epsilon Constraint 2 (AUGMECON2)

AUGMECON2 is an improved model of the AUGMECON generation method developed by Mavrotas and Florios [74]. It considers 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 a mono objective by considering one of the objectives as the main objective function and shifting other objectives as a constraint subject to some ε values. The stepwise approach of the algorithm is presented in Figure 4 and the model is presented as follows:

$$\begin{array}{l} max\left(f_1(x) + eps\left(\frac{S_2}{r_2} + \left((10-1)\frac{S_3}{r_3}\right) + \ldots + \left(10-(n-2)\frac{S_n}{r_n}\right)\right)\right) \\ \text{subject to} \\ f_2(x)\ ?\ S_2 = \varepsilon_2 \\ f_3(x)\ ?\ S_3 = \varepsilon_3 \\ \ldots \\ f_n(x)\ ?\ S_n = \varepsilon_n \end{array} \quad (17)$$

where $\varepsilon_2, \varepsilon_3, \ldots, \varepsilon_n$ are the RHS values for each objective function, $S_2, S_3, \ldots, S_n$ are the slack variables, $r_2, r_3, \ldots, r_n$ are the ranges of n objective functions and $eps \in \left[10^{-6}, 10^{-3}\right]$.

The modification in the model helps to perform the lexicographic optimization (i.e., sequentially optimizing $f_2, f_3, \ldots, f_n$) to generate the exact Pareto sets. For Pareto solutions, the mathematical model is transformed as presented in Equation (17). In this study, the minimization of TC is considered as the main objective function and other objective functions are considered as constraints.

$$\begin{array}{l} Min\ Z = Min \quad \text{TC} \\ \text{Subject to Equations (6)–(15) and :} \\ Min \quad TTT \le \varepsilon_2 \\ [Min \quad TTT]^{\min} \le \varepsilon_2 \le [Min \quad TTT]^{\max} \\ Min \quad EI \le \varepsilon_3 \\ [Min \quad EI]^{\min} \le \varepsilon_3 \le [Min \quad EI]^{\max} \\ Min \quad DR \le \varepsilon_4 \\ [Min \quad DR]^{\min} \le \varepsilon_4 \le [Max \quad DR]^{\max} \\ Max \quad TVSP \le \varepsilon_5 \\ [Max \quad TVSP]^{\min} \le \varepsilon_5 \le [Max \quad TVSP]^{\max} \end{array}$$

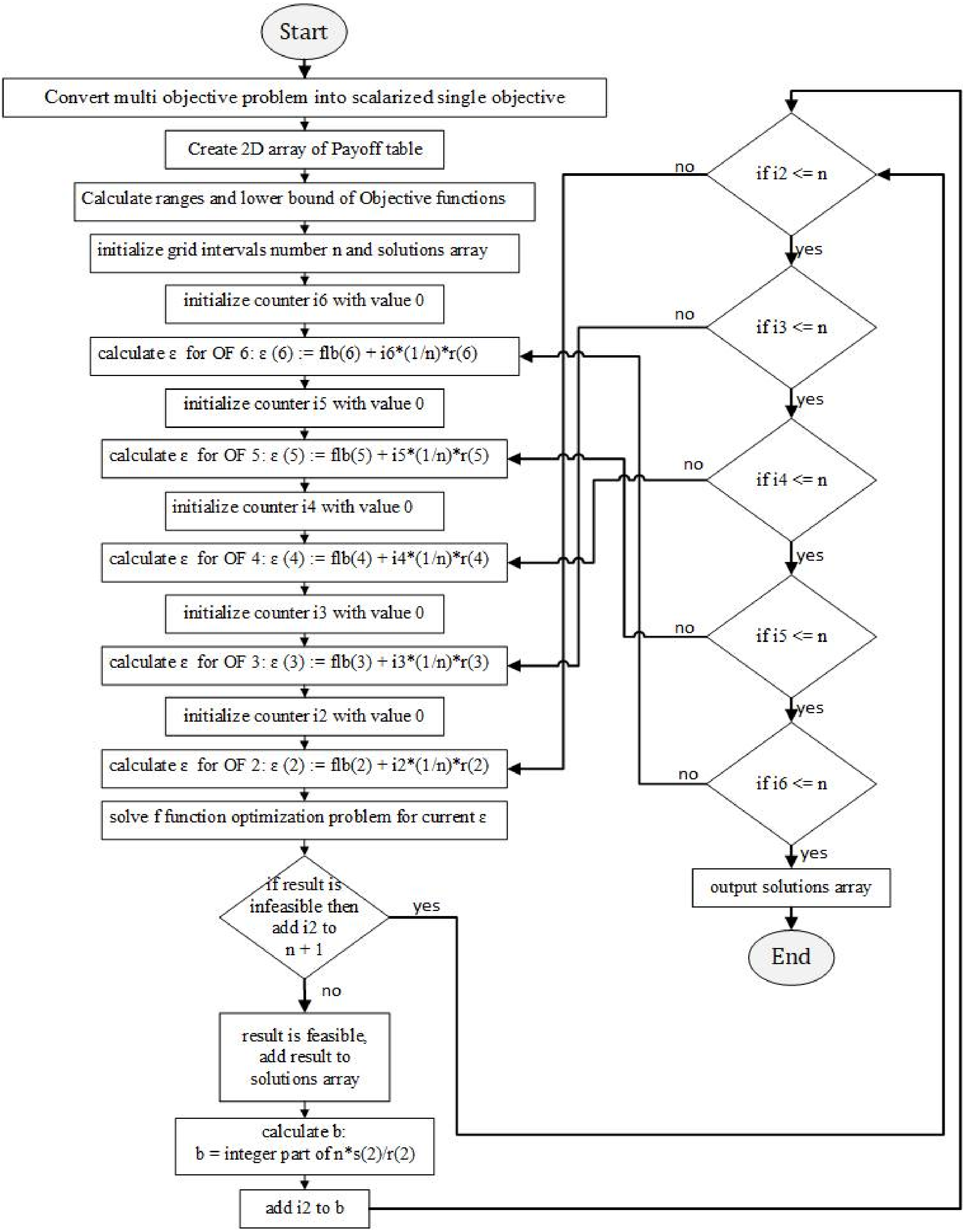

Figure 4. Steps of AUGMECON2.

4.6. Selection of Best Pareto Solution

TOPSIS incorporated with the weights obtained by the decision-makers to select the top 10 Pareto solutions of AUGMECON2. Later on, the four best solutions for each φ-level were selected. TOPSIS along with weights obtained by the Delphi technique for each objective function is applied to get the best Pareto optimal solution for each time period.

5. Application and Evaluation: Case Study

This section evaluates the developed methodology using a real-time solar panel supply chain network in Pakistan as a case study. Pakistan is adversely affected by global climate change and is in desperate need of sustainable development [75]. One such avenue for sustainable development is the energy production through renewable energy sources. Past researches and surveys suggest that Pakistan has tremendous potential for solar energy [76]. According to a World Bank report [77], Pakistan's current electricity demand can be met by utilizing just 0.071% of the country's area for solar photovoltaic (solar PV). Furthermore, by 2025, Pakistan plans to increase its renewable resources to 8–9 gigawatts [78]. Therefore, supply chain of solar PV Panels in Pakistan presents an interesting area for application of SSSOA problem.

The parameters related to the number of suppliers, number of warehouses, the capacity of suppliers and warehouses, types of transportation modes, and quarterly demand were provided by a leading solar energy solution providing organizations in Pakistan and is presented in Supplementary data S1. The supply chain of the organization comprises of five potential suppliers, three warehouses, three transportation modes, and two customers. The MCDM techniques were implemented using the Microsoft Excel (2016) software. The FMOMINLP model is solved using Python 3.7 software on a personal computer of Intel Core i5 2.5 GHz processor with 8 GB RAM. To solve the SSSOA problem for the solar panel supply chain under study, the developed fuzzy multi-objective optimization approach was applied as illustrated in the following two sub-sections.

5.1. Sustainable Criteria Weighting

Weights of criteria and sub-criteria were evaluated using FEAHP based on the preferences set by decision-makers while simultaneously assess the consistency ratio (CR) of the decision-making process. The final weights of each criterion are presented in Table 6.

Table 6. FEAHP Weights for Sustainable Criteria and Sub-Criteria.

Criteria	Global Weights	Sub-Criteria	Local Weights	Ranking
Economic	0.37	Cost	0.18	1
		Volume Flexibility	0.02	5
		Payment Terms	0.01	6
		Use of Technology	0.04	4
		Delivery Reliability	0.04	4
		Vendors Market reputation	0.02	5
		Defect Rate	0.08	2
		Quality	0.06	3
Environmental	0.34	Environment Management System	0.14	1
		Resource Consumption	0.04	3
		Pollution Production	0.09	2
Social	0.29	Information Disclosure	0.03	3
		Rights and Health of Employees	0.16	1
		Staff Personal and Technical Development	0.09	2

The ranking for the sustainable criteria is presented as economic > environmental > social for decision-makers assessing the suppliers. According to decision-makers, economic criteria ranked highest followed by environmental and social criteria. "Cost" is the most significant sub-criteria amongst eight sets of economic sub-criteria. Similarly, for environmental and social criteria, decision-makers considered "Environment Management System" and "Rights and Health of Employees" as significant sub-criterion for the sustainable supplier selection. These results provide clear insight for the decision-makers to take necessary actions to provide better product quality while minimizing cost and incorporating the environmental management system and rights and health of employees for sustainable performance.

5.2. Sustainable Supplier Ranking

After evaluating the weights for sustainable criteria through FEAHP, the next step was to rate the potential suppliers based on these criteria. FTOPSIS was used to determine the weights of each supplier for sustainable criteria. Three decision-makers were involved in this process to rate the potential suppliers based on specified criteria. Firstly, the relative closeness matrix for each supplier for sustainable criteria is evaluated using FTOPSIS and is presented in Table 7. The threshold of the closeness coefficient defined for the selection of the best supplier is 0.50. Therefore, supplier 1, supplier 2, and supplier 5 were selected for the allocation of optimum order.

Table 7. Suppliers ranking using FTOPSIS.

Supplier	Economic Criteria	Environmental Criteria	Social Criteria	Overall Closeness Coefficient	Ranking
Supplier 1	0.59	0.36	0.52	0.86	1
Supplier 2	0.42	0.29	0.47	0.38	3
Supplier 3	0.28	0.66	0.58	0.25	4
Supplier 4	0.34	0.64	0.42	0.22	5
Supplier 5	0.54	0.78	0.31	0.48	2

5.3. Sustainable Order Allocation

The proposed fuzzy mathematical model was initially solved by considering each objective separately. A on-linear solver is used to estimate the ideal solution for each objective function and is presented in Table 8.

Table 8. Ideal Solutions of OFs for Time Period “t” using Non-Linear Solver.

Time Period	Objective Function	Ideal Solution
t_1	TC	$86,010,537.27
	TTT	1969.20 h.
	EI	2,301,287.01 g
	DR	209,713,055.23
	TVSP	106,890.00
t_2	TC	$84,570,031.00
	TTT	1947.06 h.
	EI	2,266,699.06 g
	DR	179,724,063.56
	TVSP	104,624.00
t_3	TC	$88,714,382.25
	TTT	2063.38 h.
	EI	2,387,750.89 g
	DR	223,618,022.12
	TVSP	109,202.00
t_4	TC	$86,549,371.88
	TTT	2011.55 h.
	EI	2,330,471.34 g
	DR	214,302,000.10
	TVSP	106,720.00

In the second phase, AUGMECON2 was used to simultaneously solve the objectives. Pareto solutions were generated for each time period to find the optimal order quantity from the potential suppliers under fuzzified input parameters. TOPSIS augmented with CRITIC weight method was used to further evaluate the Pareto solution for the final solution.

5.4. Optimal Order Using AUGMECON2

For solving FMINLP mathematical model presented in Section 4.1, a payoff for objective functions was created for time period t. The min/max values of each objective function were evaluated using Equations (1)–(15) and presented in Table 9.

Table 9. Payoff Table using AUGMECON2 for Time Period "t".

Time Period	Objective Function	TC	TTT	EI	DR	TVSP
t_1	TC	86,120,647	2415	4,457,128	220,569,451	105,916
	TTT	86,328,159	1994	2,306,374	232,145,513	105,552
	EI	86,328,158	1994	2,306,373	232,145,513	105,552
	DR	86,328,169	1994	2,306,405	232,145,513	105,552
	TVSP	86,206,133	1994	2,306,523	209,790,035	106,032
t_2	TC	84,570,424	2407	4,543,832	232,005,750	103,943
	TTT	84,945,807	1958	2,270,702	232,005,750	103,382
	EI	84,948,076	1964	2,277,245	232,005,750	103,382
	DR	84,884,556	1964	2,277,302	232,005,750	103,504
	TVSP	84,662,709	1964	2,277,337	179,734,575	104,504
t_3	TC	88,801,958	2760	5,655,112	228,278,750	109,050
	TTT	88,908,452	2088	2,402,851	228,278,750	109,000
	EI	88,908,452	2088	2,402,851	228,278,750	109,000
	DR	88,908,452	2088	2,402,851	228,278,750	109,000
	TVSP	88,883,017	2088	2,402,855	223,620,000	109,100
t_4	TC	86,702,906	2472	4,643,109	216,530,314	106,626
	TTT	86,814,342	2018	2,331,549	218,961,250	106,550
	EI	86,810,794	2018	2,330,471	218,961,250	106,550
	DR	86,810,748	2019	2,330,815	218,961,250	106,550
	TVSP	86,785,145	2019	2,330,824	214,302,500	106,650

Table 10. Minimum and Maximum Value of Objective functions for t_1–t_4.

OFs	t_1		t_2		t_3		t_4	
	Max	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**
TC	86,328,169	86,120,647	84,948,075	84,570,424	88,908,452	88,801,957	86,814,342	86,702,905
TTT	2414	1994	2406	1958	2760	2087	2472	2018
EI	4,457,128	2,306,373	4,543,832	2,270,701	5,655,112	2,402,850	4,643,109	2,330,471
DR	232,145,512	209,790,034	232,005,750	179,734,575	228,278,750	223,620,000	218,961,250	214,302,500
TVSP	106,032	105,552	104,504	103,382	109,100	109,000	106,650	106,550

Once the min/max values of OFs were evaluated, the next step is the division of values into 10 segments between the minimum and maximum values. The 10 segments were assigned individually to ϵ_2, ϵ_3, ϵ_4 and ϵ_5 with the step interval of 2 using Equation (17). The combinations of ϵ-values are presented in Table 11.

Table 11. ε-values of TTT, EI, DR, and TVSP.

	Time Period	ε-Values			
		ε_2	ε_3	ε_4	ε_5
1	t_1	1994	2,306,373	209,790,035	105,552
	t_2	1958	3,407,267	179,734,575	104,504
	t_3	2088	2,402,851	223,620,000	109,000
	t_4	2018	4,643,109	214,302,500	106,550
2	t_1	1994	3,381,751	220,967,774	105,552
	t_2	2182	3,407,267	205,870,162	103,943
	t_3	2088	2,402,851	223,620,000	109,050
	t_4	2018	4,643,109	214,302,500	106,600
3	t_1	2415	2,306,373	209,790,035	105,792
	t_2	1958	4,543,832	179,734,575	104,504
	t_3	2088	2,402,851	223,620,000	109,100
	t_4	2018	2,330,471	214,302,500	106,650
4	t_1	2415	3,381,751	209,790,035	105,792
	t_2	2407	4,543,832	179,734,575	104,504
	t_3	2088	5,655,112	223,620,000	109,100
	t_4	2245	2,330,471	214,302,500	106,650
5	t_1	1994	2,306,373	220,967,774	105,792
	t_2	1958	3,407,267	205,870,162	103,943
	t_3	2088	4,028,981	223,620,000	109,100
	t_4	2018	3,486,790	214,302,500	106,650
6	t_1	1994	2,306,373	209,790,035	106,032
	t_2	1958	4,543,832	179,734,575	103,943
	t_3	2424	4,028,981	223,620,000	109,100
	t_4	2245	3,486,790	214,302,500	106,650
7	t_1	2206	2,306,373	209,790,035	106,032
	t_2	2407	4,543,832	23,200,5750	104,504
	t_3	2088	5,655,112	223,620,000	109,100
	t_4	2018	3,486,790	214,302,500	106,650
8	t_1	1994	3,381,751	209,790,035	106,032
	t_2	1958	3,407,267	179,734,575	104,504
	t_3	2088	4,028,981	223,620,000	109,100
	t_4	2245	3,486,790	214,302,500	106,650
9	t_1	1994	3,381,751	209,790,035	106,032
	t_2	1958	4,543,832	232,005,750	104,504
	t_3	2424	4,028,981	223,620,000	109,100
	t_4	2018	3,486,790	214,302,500	106,650
10	t_1	1994	3,381,751	209,790,035	106,032
	t_2	2407	4,543,832	179,734,575	104,504
	t_3	2088	5,655,112	223,620,000	109,100
	t_4	2245	3,486,790	214,302,500	106,650

Table 12 shows the values for the five objectives for each φ-level based on ε-iteration obtained in Table 11 for each time period. For instance, Solution 3 in Table 12 for t_4 shows TC of $86,703,205, TTT of 2472 h. EI of 4,643,103 g, a DR of 214,302,500, and TVSP of 106,650. The ε values corresponding to this solution are as follows: $\varepsilon_1 = 2245$, $\varepsilon_2 = 3,486,790, \varepsilon_3 = 214,302,500$ *and* $\varepsilon_4 = 106,650$. The iteration runs for each combination of ε-values corresponding to each φ-level to extract the Pareto optimal solution. The maximum number of iterations was set as 65,000.

Table 12. Values of TC, TTT, EI, DR, and TVSP using AUGMECON2 at φ-levels.

Time Period	φ	Min TC	Min TTT	Min EI	Min DR	Max TVSP	Run Time (min)
t_1	0.25	86,120,635	2311	3,976,972	220,684,988	105,915	0.50
	0.50	86,120,712	2416	4,458,428	220,684,056	105,915	0.75
	0.75	86,121,592	2415	4,457,128	213,537,533	105,992	0.78
	1.0	86,117,429	2419	4,466,736	209,790,035	106,031	0.67
t_2	0.25	84,577,452	2406	4,543,712	179,734,575	104,504	0.34
	0.50	84,577,449	2406	4,543,668	179,734,575	104504	0.52
	0.75	84,579,934	2406	4,544,632	179,734,575	104,504	0.67
	1.0	84,577,470	2407	4,546,570	179,734,575	104,504	0.55
t_3	0.25	88,802,287	2300	3,537,737	225,937,262	109,075	0.38
	0.50	88,802,298	2300	3,537,920	225,937,262	109,075	0.41
	0.75	88,802,598	2300	3,537,732	223,620,000	109,100	0.34
	1.0	88,802,584	2760	5,655,121	223,620,000	109,100	0.66
t_4	0.25	86,702,931	2473	4,643,708	216,619,762	106,625	0.82
	0.50	86,702,931	2473	4,643,708	216,619,762	106,625	0.37
	0.75	86,703,205	2472	4,643,104	214,302,500	106,650	0.71
	1.0	86,703,205	2472	4,643,104	214,302,500	106,650	0.64

It is worth mentioning that four φ-levels (0.25, 0.50, 0.75, and 1) with an incremental step of 0.25 were assigned by the decision makers for each solution. Finally, Equation (16) was used to determine the respective membership degrees (μ_b) based on the objective values obtained through the AUGMECON2 as shown in Table 13.

Table 13. Membership Degree Values of OFs using AUGMECON2.

	t_1				t_2				t_3				t_4			
μ (TC)	0.86	0.54	0.97	0.49	0.51	0.41	0.74	0.44	0.93	0.12	0.74	0.17	0.63	0.35	0.61	0.19
μ (TTT)	0.74	0.67	0.45	0.37	0.88	0.68	0.25	0.86	0.42	0.16	0.71	0.64	0.18	0.33	0.54	0.17
μ (EI)	0.36	0.18	0.33	0.84	0.64	0.94	0.38	0.17	0.37	0.17	0.54	0.27	0.18	0.57	0.17	0.54
μ (DR)	0.57	0.08	0.28	0.51	0.09	0.46	0.94	0.94	0.81	0.84	0.69	0.49	0.24	0.48	0.88	0.78
μ (TVSP)	0.41	0.74	0.22	0.76	0.54	0.49	0.18	0.04	0.14	0.46	0.81	0.37	0.74	0.54	0.84	0.37

5.5. Selection of Best Solution

To obtain the best result from the above Pareto solutions of AUGMECON2, TOPSIS augmented with OFs weights was applied. The weights of the functions were assigned by the DM's using Delphi's technique and are presented in Table 14. DMs should select one solution to allocate the order for each time period. The selection of the final solution following DM's preferences is a challenge due to the little difference found among the values of the five objectives revealed. Therefore, after extracting the top 10 Pareto optimal solutions at 4—levels for t_1–t_4, TOPSIS is applied to calculate the closeness coefficient (CC) matrix is presented in Table 15.

Table 14. DM's Assigned weights for each OF.

Objective Functions	TC	TTT	EI	DR	TVSP
Weights	0.24	0.19	0.16	0.21	0.20

Table 15. Relative Closeness Coefficient (CC) Matrix for Pareto solutions of AUGMECON2 for t_1–t_4.

		Time Period			
		t_1	t_2	t_3	t_4
CC	1	0.991	0.214	0.583	0.475
	2	0.374	0.134	0.797	0.436
	3	0.286	0.982	0.614	0.256
	4	0.369	0.074	0.579	0.841

Table 16 presents the finalized results for each objective function depending upon the results obtained from Table 15.

Table 16. Best optimal solution of each objective for t_1–t_4.

	CC	TC	TTT	EI	DR	TVSP
t_1	0.991	$86,120,635	2310	3,976,971	220,684,987	105,915
t_2	0.982	$84,577,448	2406	4,543,668	179,734,575	104,504
t_3	0.797	$88,802,598	2300	3,537,732	223,620,000	109,100
t_4	0.841	$86,703,205	2472	4,643,103	214,302,500	106,650

Figure 5 presents the optimal order allocation to suppliers to meet the demand for time period t_1 to time period t_4. Considering the aspect of sustainability in the SSSOA problem, the results obtained from AUGMECON2 yield a higher transportation cost for the enterprise. However, showed a reasonable performance by revealing Pareto solutions that were close enough to the ideal solutions. Moreover, the computational complexity of the FMOOM is linked with the time (e.g., CPUs) required to solve a problem within resources (e.g., computer specifications). Table 8 presents the run time required to reveal the solutions for the AUGMECON2 algorithm. Due to the complex and large-scale network problem, its runtime is considerably low, which shows the developed FMOOM is a tractable time-wise model.

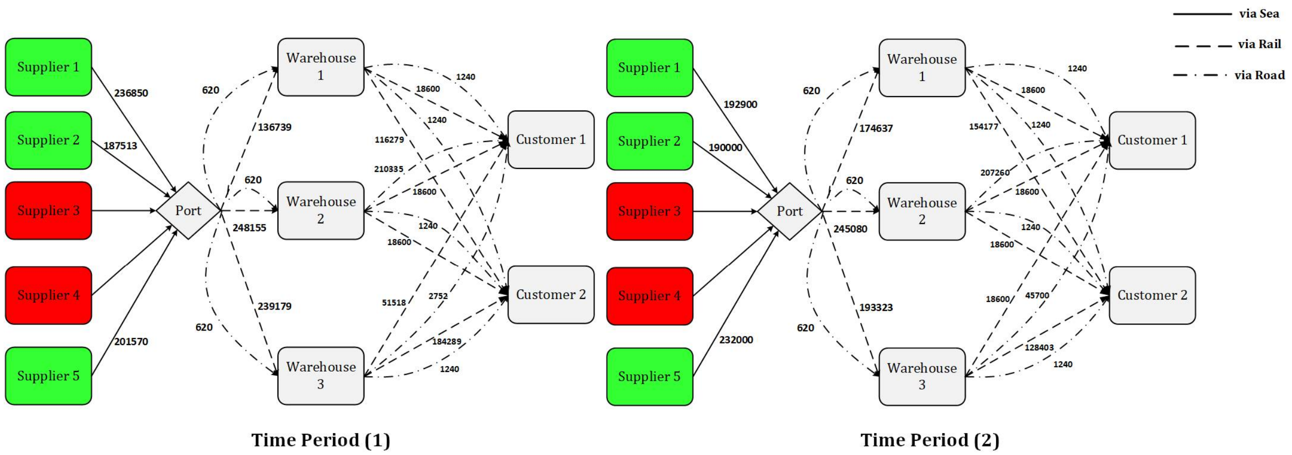

Figure 5. *Cont.*

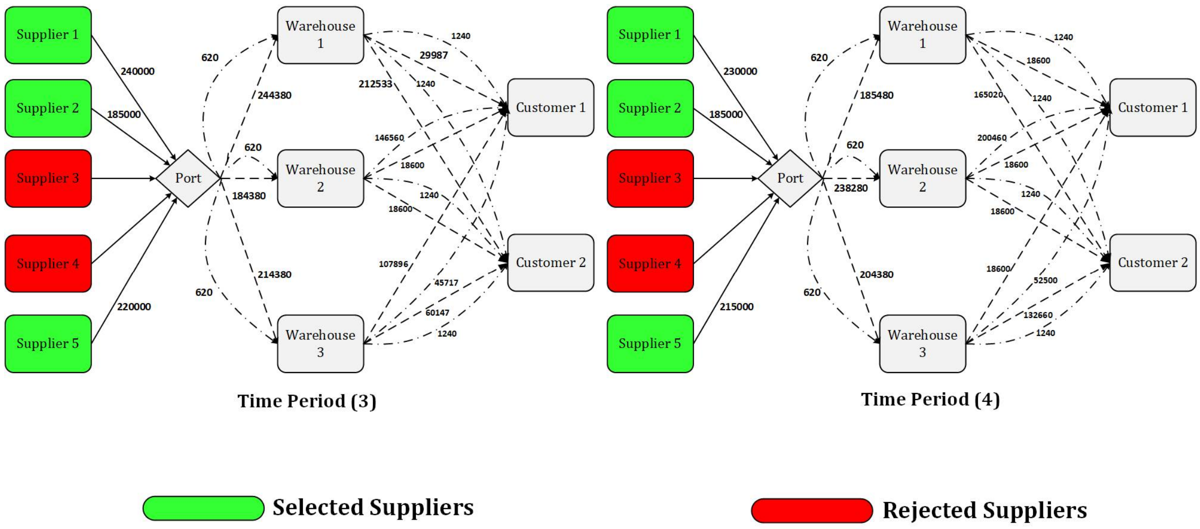

Figure 5. Best Optimal Solution for t_1, t_2, t_3, and t_4.

6. Managerial Insight

The implications of the 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. The sustainability-based analysis of the solar panels' supply chain has been conducted for the first time to provide an insight for the managers.
3. The comprehensive fuzzified model along with a multi-modal transportation network is developed to address the uncertainties encountered in demand, capacity, cost, and defect rate. Thus, making the decision framework more flexible for the managers.

7. Conclusions and Future Recommendations

Supplier selection and order allocation are the two main decisions in supply chain management.

In recent years, the complexity of these decisions has increased with the augmentation of sustainability in the processes. It is a multi-criteria decision-making approach that helps enterprises lead towards sustainable performance. Its core concept is to select the suppliers that meet the sustainable criteria (i.e., economic, environmental, and social) and allocate orders to enhance the overall sustainable performance of an enterprise. This study aims to explore the supply chain of Solar PV Panels in context of SSSOA problem. It is worth mentioning here that no study in literature has attempted to solve SSSOA for Solar PV Panels. Accordingly, this study presents a comprehensive three-phase decision framework for the Solar PV Panels supply chain. In the first step, criteria and sub-criteria were identified for supplier selection and solved using FEAHP and FTOPSIS. In the second phase, a fuzzy multi-objective mixed-integer non-linear programming mathematical model was developed that incorporated the uncertainties of demand, suppliers and warehouses capacity levels, and input parameters (e.g., purchasing cost, transportation cost, defect rate, etc.). The following main conclusions can be drawn from this work:

1. The result revealed that amongst the sustainable criteria, cost, environmental management system, and rights and health of employees ranked highest.
2. Out of five potential suppliers of solar panels located in various parts of the world, three of them met the decision makers' criteria.
3. Transfer cost and custom clearance cost contributed 54% towards the overall cost of the supply chain network.

4. Transfer time and custom clearance time contributed 13% to the overall travel time of the supply chain network.
5. Of the three modes of transportation (i.e., sea, rail, road), the shipment from rail dominated the overall transportation process with a share of 53%.
6. The defect rate of the suppliers played a critical role in the selection and allocation of orders.

The integration of FST with various real-time parameters (multi-modal, multi-period, customer clearance cost/time, and transfer cost/time) exemplifies the superiority of this study over similar SSSOA methodologies. Future studies can implement the proposed framework to various industries and supply chains. The decision framework can be improved by integrating multi-product, suppliers' resilience, and robustness by incorporating the effects of disruptions due to geographic proximity. The inclusion of more environmental and social aspects in the order allocation can further strengthen the decision framework.

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Abbreviations

AUGMECON2	Augmented Epsilon Constraint 2
CRITIC	Criteria Importance Through Intercriteria Correlation
CC	Closeness Coefficient
EI	Environmental Impact
FMILP	Fuzzy Mixed-Integer Linear Programming
FEAHP	Fuzzy Extended Analytical Hierarchy Process
FMINLP	Fuzzy Mixed-Integer Non-Linear Programming
FMOMINLP	Fuzzy Multi-Objective Mixed-Integer Non-Linear Programming
FST	Fuzzy Set Theory
FTOPSIS	Fuzzy Technique for Order of Preference by Similarity to Ideal Solution
MCDM	Multi Criteria Decision Making
MINLP	Mixed Integer Non-Linear Programming
MINLP	Mixed Integer Linear Programming
PV	Photovoltaic
SCM	Supply Chain Management
SSCM	Sustainable Supply Chain Management
SSS	Sustainable Supplier Selection
SSSOA	Sustainable Supplier Selection and Order Allocation
TC	Total Cost
TTT	Total travel Time

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