Complex & Intelligent Systems (2022) 8:4115–4143
https://doi.org/10.1007/s40747-022-00686-w

ORIGINAL ARTICLE

Carbon mechanism on sustainable multi-objective solid transportation problem for waste management in Pythagorean hesitant fuzzy environment

Shyamali Ghosh[1] · Karl-Heinz Küfer[2] · Sankar Kumar Roy[1] · Gerhard-Wilhelm Weber[3]

Received: 12 May 2021 / Accepted: 3 February 2022 / Published online: 18 March 2022

Abstract

Waste management involved in various fields of global ecosystem that provides several positive effects for green environment and sustainable development. We devise a multi-objective solid transportation model of waste management problem in agriculture field and forest department for urban or rural development. Starting to end point of the problem covered by considering the objective functions as transportation cost, job opportunity and carbon emission. Carbon emission is restricted by the combination of several policies of carbon mechanism (carbon tax, cap-and-trade and offset policy). Various critical sitchs appear in such realistic process and uncertainty attached with related data. Here we prefer Pythagorean hesitant fuzzy environment to overcome deep uncertainty rather than single uncertainty. After that, we initiate a ranking approach to convert uncertain data into crisp data. To justify the appropriateness of the formulated model and to select the best policy of carbon mechanism, we study two industrial applications with various cases of such mechanism. To derive the Pareto-optimal solution of the problems, two fuzzy techniques, namely, fuzzy programming and Pythagorean hesitant fuzzy programming, are utilized here. Comparative study, model validation, sensitivity analysis, managerial insights and conclusions with future research scopes are outlined at last.

Keywords Multi-objective decision making · Waste management · Solid transportation problem · Carbon tax, cap, trade and offset policy · Sustainability · Pythagorean hesitant fuzzy programming

Introduction

In this section we focus on solid waste management (SWM), sustainability with sustainable development (SD), extension and activities of transportation problem (TP) in various environments, and application of carbon mechanism in several cases.

Solid waste management

Solid waste management is a new concept in sustainability and transportation. This management relates with solid wastes which are irregular combinations of rejected and unwanted items that created bad smell, attracted to virus and bacteria, and pollute environment directly or indirectly. A part of solid wastes (e.g., paper, wood, cotton, vegetables, cardboard, leather, ash, crop, spoil fruit, etc.) finished their activities in first user or first time, but these may rework second time by proper way of recycling. After recycling process the generated items are resold in market, and SWM provides

✉ Sankar Kumar Roy
sankroy2006@gmail.com

Shyamali Ghosh
shyamalighosh1989@gmail.com

Karl-Heinz Küfer
karl-heinz.kuefer@itwm.fraunhofer.de

Gerhard-Wilhelm Weber
gerhard.weber@put.poznan.pl

1 Department of Applied Mathematics with Oceanology and Computer Programming, Vidyasagar University, Midnapore, West Bengal 721102, India

2 Department of Optimization and Operations Research, Fraunhofer-Institut für Techno- und Wirtschaftsmathematik ITWM, Fraunhofer-Platz 1, 67663 Kaiserslautern, Germany

3 Faculty of Engineering Management, Poznan University of Technology, Poznan, Poland

economical, environmental and social effect of sustainability. Starting process is to transport fresh items from agriculture field and forest department to cold storage for preservation and for future marketing. During this process, some waste items are found which are managed by decomposition, recycle (e.g., composting, vermi-composting, bio-methanation, pyrolysis processes) and reuse. In India, two creative mechanisms for recycling of solid wastes are approved to dispose the waste items that supply compost and waste to energy. The loop of SWM is completed by reaching all the recycled items to the customers or turns into biosphere in non-toxic way. Reuse of recycled waste items reduces environmental pollution and generates an income by trading these items. When woody biomass, fruit or vegetable wastes converts into bio-fuel [16] then that fulfil social satisfaction by increasing independency of fuel wood, improve environment and provide economical value, as bio-fuel is one type of renewable cleaner energy source used as alternative to fossil fuel. Compost used as organic substrates that protect plants, improve the soil with nutrient value and prevent water runoff by increasing plant cover.

There are several activities of SWM and some of them are provided from literature as: Abdullah and Gho [1] initiated an SWM problem by decision making process in Pythagorean fuzzy (PF) environment. A network for waste collection with sustainability and multiple objectives was designed by Asl et al. [5]. Mingaleva et al. [32] presented a case study from Russia on the base of waste management for green and smart cities. Recycle and cost reliability of SWM in uncertain situation were displayed by Muneeb et al. [33], and they proposed a decentralized decision making bi-level model. Nagarajan et al. [34] proved that vegetable wastes can be used as an alternative resource for bio-gas and bio-compost which are produced by lab scale process. Rabbani et al. [41] solved a multi-objective location-routing problem of industrial hazardous waste by metaheuristic algorithms. A case study of Bilaspur city (India) presented by Rathore and Sarmah [42] for the location of transfer station in urban area and to segregate the solid waste items. Use of vegetable wastes for bioenergy production was presented by Singh et al. [44]. Urban waste collection with robust bi-objective and arc routing problem performed in a multi-trip were presented by an invasive weed optimization by Tirkolaee et al. [46]. In [47] the authors Tirkolaee et al. provided a hybrid augmented ant colony optimization with multiple trip for SWM arc routing problem in urban area with fuzzy demand. In urban area, waste management was implemented by robust green location–allocation model with inventory in uncertain environment which was designed by Tirkolaee et al. [48]. Zaeimi and Rassafi [58] proposed municipal SWM using fuzzy chance-constrained programming in an uncertain environment for economical and environmental improvement.

Sustainability and sustainable development

Sustainability has a major area due to cooperate on environment, social and economical domain. Definition of "Sustainability" is that "Development which meets the demands of the present without compromising the capability of the future generations to meet their own demands" (Brundtland commission [8]). SD followed by sustainability and development which are concerned with three common parts as economical, social and environmental fact together. The three attributes of SD are fulfilled through transportation and SWM as follows.

Society: Social problem is created by the lack of job position when regional development is neglected. During SWM and transportation, social responsibility is completed by creating maximum number of job opportunities, satisfying public demand, human health, modern transportation planning, road management, pricing policies, improved vehicle technology, using clean fuels for minimum emissions, supplying recycled items, etc.

Economy: Economy and transportation are two sections of sustainable transportation that cannot be separated any time. Minimum transportation cost, carbon emission cost, and economical value from recycled items cause economic progression of sustainability.

Environment: Sustainable transportations have a responsibility on environment to reduce perilous carbon emissions and air pollution that can critically mutilate global health and disorder to urban ecosystem. It needs to promote a sustainable transportation system using green vehicles (e.g., electric vehicles, compressed air vehicles, hydrogen and fuel-cell vehicles, natural-gas vehicles, clean diesel vehicles, etc.). Minimum carbon emission from the recycle process of SWM can support towards an environment preservation.

Intersection of society, economy and environment: If optimum requirements of society, economy and environment factors are coincide, then SD and SWM provide green transportation by protecting environment, fulfilling social satisfaction and providing a highly growth economy.

A sustainable transportation with an integrated AHP–DEA multi-objective optimization model in mining industry was proposed by Gupta et al. [17]. A robust optimization model with resilient closed loop supply chain was designed by Lotfi et al. [27] for sustainability. Vafaei et al. [50] provided a case study for designing a distribution network on sustainable multi-channel supply chain. A green closed-loop supply chain network was designed by Zhen et al. [61] in an uncertain situation for sustainability.

Extension of TP with SWM and SD

TP is generated as linear programming problem initiated by Hitchcock [20] and it is renamed as Hitchcock–Koopmans TP. To transform the fresh items or waste items, closed type of vehicles are always used to prevent scattering or to control odour. The fresh items are transported from sources to destinations through several types of conveyances such as trucks, goods train, ships, etc. and dumper placer, hydraulic compactor vehicle, tripper, etc., are used for transporting waste items. Electric vehicles are suggested for sustainable transportation with economical and environmental improvement. Adding conveyance constraints on classical TP, the extended TP is called as solid transportation problem (STP), which was first defined by Haley [18]. Asim et al. [4] designed an integrated uncertain model on closed loop supply chain for transportation of production with cost reliability. An STP in fully intuitionistic fuzzy (IF) situation was initiated by Ghosh et al. [15], where the problem was expanded for multi-objective scenarios and fixed-charge.

Sustainable transportation on SWM includes transportation cost, job opportunity, carbon emission, etc., during shipment of items from distinct sources to several destinations by completing various steps. Traditional TP is not enough to control such situation that balance all the conflicting facts of sustainability. Therefore, a multi-objective transportation problem (MOTP) was initiated and extended as multi-objective solid transportation problem (MOSTP) by including conveyance constraint. TP with its several additions in various situations and different methodologies are incorporated from literature. Some related applications are selected here as: Dalman et al. [10] designed an MOSTP with multi-item and applied fuzzy approach in uncertain situation for finding a solution. An MOTP with truckload constraints was established by Ghosh and Roy [14] in fuzzy-rough environment. They analyzed fixed-charge by including product blending constraints and transfer station. Maity et al. [28] proposed an MOTP through time variation for SD with interval valued data. An MOTP with sustainability was introduced by Mehlawat et al. [30], where the problem was covered by three stages and fixed-charge. An MOSTP in IF environment was augmented by Midya et al. [31] for green supply chain with multiple stage and fixed-charge. Roy et al. [43] incorporated twofold uncertainty on MOSTP with fixed-charge that continued with multiple items. An MOTP with multiple items was discussed by Mardanya et al. [29] on the concept of just-in-time.

Carbon mechanism

Nowadays, global warming, environment contamination, health implications and green house gas (GHG) emissions become a big challenge from transportation or from industrial plant due to burning of fossil fuel or disposal of waste items. For global development and to augment ozone layer, sustainable transportation is needed and carbon mechanism is introduced to encourage the reduction of CO_2 emission. To reduce such CO_2 emission there exists an agreement such as Kyoto Protocol, such that rate of emissions from fossil fuel does not outstrip the assimilative capacity of the environment. Government as the third party helps to curb the emission by introducing carbon regulation. There exist several policies of carbon mechanism, such as “carbon tax, carbon cap, carbon cap-and-trade, carbon subsidy, carbon offset” policy. For such different policies, there exist various facilities and their combinations give a better profit which are, defined in some of the following ways:

Carbon tax with cap: For “carbon tax with cap” policy, the transportation system provides a tax to government for their regular carbon emissions and total emission is under a cap (i.e., free amount of maximum allowances). In this case the system does not give any penalty charge. For lower tax, the emission rate would not be reduced here.

Carbon tax with cap-and-trade: In this policy, the system gets an upper limit (i.e., cap) for emission and there exist two criteria. In the first criterion, if the transportation system emits more carbon than the cap unit, then the system would be penalized and will pay a penalty charge, and buy the shortage unit by paying an extra charge. In the second criterion, there exists a facility that if the system emits less carbon than the cap unit then the system can sell the extra unit in trading market and find a revenue. Therefore, for low emission, total carbon tax is decreased and for greater emission total tax is increased.

Carbon tax with offset: This policy consists of two agreements. First one is that, when total emission is less than the cap unit then the system cannot find any reward by selling their extra unit and total tax remains same. However, in second case, when total emission becomes the surplus of cap unit, then a penalty charge is to pay as an extra carbon tax and cannot buy the shortage carbon unit.

From literature we find various applications of carbon mechanism which are provided here as: Chiu et al. [9] launched carbon tax and trading theory on emissions for implementation of energy price. Das et al. [11] studied carbon emission tax, cap and offset policy on a green MOSTP in type-2 fuzzy environment and they found solution by fuzzy and non-fuzzy techniques with considering location and dwell time. Ghosh et al. [13] initiated carbon tax policy on a two-echelon supply chain and provided a collaborative model with uncertain demand. He et al. [19] represented cap-and-trade and carbon tax policy for a production with lot-sizing problem. Carbon subsidy policy for re-manufacturing closed-loop supply chain was defined by Li et al. [24]. In [25], the authors Li et al. analyzed single and multiple carbon policies for production and transportation in the supply chain by outsourcing the decisions. Trade-off between service time and carbon emissions on multi-echelon supply chains for safety stock was provided by Ni and Shu [36]. Palak et al. [37] applied the impacts of carbon mechanisms for bio-fuel supply chain with supplier and mode selection decision making problem. Cap-and-trade mechanism on production and pricing problems for supply chain was presented by Xu et al. [51]. Carbon emission constraint on global reverse supply chain was proposed by Xu et al. [52] for recycling waste items under uncertainties. Xu et al. [53] designed green supply chains and provided literature review of quantitative models based on carbon policies. A supply chain for energy saving and cost sharing was introduced by Yi and Li [55], where the emissions reduced by government subsidies and carbon tax policy. Yuyin and Jinxi [56] discussed the outcome of governmental policies as carbon taxes and energy-saving subsidies on a two-echelon supply chain to take enterprise decisions. Carbon pricing at variance with emissions trading on a supply chain was studied by Zakeri et al. [60]. Zhou et al. [62] showed the effects of carbon tariff by applying it on green supply chain design.

Environment selection

Sustainable MOSTP with SWM applied in realistic background, where all the data are not precisely defined for the presence of several hesitations, insufficient information, lack of evidence, competitive economic condition, fluctuations of financial market, etc. Some uncertain circumstances exist, where decision makers (DMs) cannot assign the precise value with their limited knowledge. These situations are evaluated by fuzzy, hesitant fuzzy, IF, neutrosophic, interval, rough, stochastic, randomness, PF, etc. Some uncontrolled realistic situations exist, where single uncertainty or traditional fuzzy set (FS) theory cannot sufficient to reflect the fact of decision making problem. In this state, we introduce a complex uncertainty as pythagorean hesitant fuzzy set (PHFS) which is the extension of PF set (PFS) [54] and hesitant fuzzy set (HFS) [49].

From literature we select some related works on HFS, PFS and PHFS as: Abbas et al. [2] presented cubic PFSs with unknown weight information and applied on multi-attribute decision making problem. Adhami and Ahmad [3] proposed an algorithm for solving MOTP in PHF uncertainty. Probabilistic HFSs for multiple criteria decision making problem was introduced by Farhadinia et al. [12]. Karaaslan and Ozlu [21] defined type-2 HFS with correlation coefficients and applied on clustering analysis. Pythagorean fuzzy approach applied by Kumar et al. [23] on TP. Peng and Selvachandran [39] discussed about the art and future directions of PFS. Nguyen et al. [35] explored PFS in decision making process by the application of exponential similarity measures. Qu et al. [40] implemented dual hesitant fuzzy linguistic uncertainty on stochastic multi-attribute method to measure the sustainability performance for supplier based and triple bottom line approach. Applications of correlation coefficients in PF situation was provided by Singh and Ganie [45]. Now, we place several research contributions in Table 1 which are connected with our work.

Research contributions of the present study

Table 1 highlights some research gaps and our current study provides some research contributions which are presented as follows:

- Comparing single objective TP form references [19,25,37,42,48], we fill the research gap by designing a mathematical model of MOSTP. Analyzing the references [3,5,33,42,43,48,52], we find that they were not concerned about three facts of sustainability and we augment such research by providing sustainable MOSTP that optimizes three factors of SD.
- References [3,28,30,33,42,43,48] are prepared without carbon emission or without carbon mechanism. We generate our present study that minimizes carbon emission by analyzing various policies of carbon mechanism. The attributes of carbon mechanism are focused through graphical presentation of results.
- The authors of the references [3,17,19,25,28,30,37,43,50,60–62] did not include SWM in their articles. We apply the project of SWM in our present model that converts an undeveloped rural area into an modern and smart urban area.
- The existing literature [5,19,25,30,37,42,50,60,62] did not investigate about any type of uncertainty for realistic problem, but our designed model is implemented by considering a new environment as PHFS which is a combination of PFS and HFS. In this situation, pythagorean hesitant fuzzy programming (PHFP) and fuzzy programming (FP) validate the proposed model by finding the Pareto-optimal solution.
- We provide managerial insights of this study after displaying a sensitivity analysis and we illustrate the comprehensive discussions with conclusions.

Organization of the paper

The rest of this paper is outlined as follows: Motivation of our study are presented in the next section. The fundamental definitions of FS, HFS, PFS, PHFS with some basic properties are described in the following section. The following section depicts the notations with assumptions and the mathematical model of sustainable MOSTP with PHF uncertainty in con-

Table 1 Contributions of authors' work and ongoing study

Author(s)	SWM	Environment	Multi-objective	Transportation mode	Cost	Job opportunity	CO_2 emission	Carbon mechanism
Adhami and Ahmad [3]		PHF	✓	✓	✓			
Asl et al. [5]	✓	Crisp	✓	✓	✓		✓	
Gupta et al. [17]		Fuzzy	✓	✓	✓		✓	
He et al. [19]		Crisp					✓	✓
Li et al. [25]		Crisp		✓	✓		✓	✓
Maity et al. [28]		Interval	✓	✓	✓			
Mehlawat et al. [30]		Crisp	✓	✓	✓			
Muneeb et al. [33]	✓	Uncertain	✓	✓	✓			
Palak et al. [37]		Crisp		✓	✓		✓	✓
Rathore and Sarmah [42]	✓	Crisp		✓	✓			
Roy et al. [43]		Twofold uncertainty	✓	✓	✓			
Tirkolaee et al. [48]	✓	Uncertain		✓	✓			
Vafaei et al. [50]		Crisp	✓	✓	✓	✓	✓	
Xu et al. [52]	✓	Uncertain	✓	✓	✓		✓	✓
Zakeri et al. [60]		Crisp	✓	✓	✓		✓	✓
Zhen et al. [61]		Uncertain	✓	✓	✓		✓	
Zhou et al. [62]		Crisp	✓	✓	✓		✓	✓
This investigation	✓	PHF	✓	✓	✓	✓	✓	✓

Table 2 Abbreviations with full names

Abbreviations	Full name
SWM	Solid waste management
SD	Sustainable development
TP	Transportation problem
PF	Pythagorean fuzzy
STP	Solid transportation problem
IF	Intuitionistic fuzzy
MOTP	Multi-objective transportation problem
MOSTP	Multi-objective solid transportation problem
GHG	Green house gas
DM	Decision maker
FS	Fuzzy set
PHFS	Pythagorean hesitant fuzzy set
PFS	Pythagorean fuzzy set
HFS	Hesitant fuzzy set
TrPHFN	Trapezoidal pythagorean hesitant fuzzy number
FP	Fuzzy programming
PHFP	Pythagorean hesitant fuzzy programming
PIS	Positive ideal solution
NIS	Negative ideal solution
NFS	No feasible solution

nection of SWM. Two approaches, namely, FP and PHFP method with related to the models are illustrated in the next section. Two numerical examples are described in the next section. The following section contains computational results for optimal allocation and discussions about objective values. Sensitivity analysis for carbon emission is presented in the following section. Managerial insights are summarized in the next section. Concluding remarks with the outlook of future research are placed in the last section.

Abbreviations: Table 2 represents all the abbreviations which are used in this study.

Motivation of the study

Due to rapid growth of urbanization or industrialization, different types of domestic and commercial wastes are created which called as municipal solid wastes, and these waste items generated by living community. Similarly, rural areas (agriculture field, forest department, cold storage) produce huge amount of waste items (e.g., vegetable waste, fruit waste, woody waste) in post-harvest, natural processes or in some commercial activities. India is successful in agriculture resources, where 30% of the vegetables or fruit items are wasted and thrown everyday, but these items are found by free of cost and convert into useful product (bio-fuel or compost) by proper treatment or recycle process. It is not so easy to collect, transport, recycle and reuse of these waste items in a systematic way with considering sustainability. Demand of petroleum products are increasing but these cannot be renewable, so bio-fuel generation from waste is an alternative renewable energy source that balancing between energy and pollution. Hence, an optimization strategy is required that provides an intellectual plan for converting waste to sustainable energy.

We observed that a simple uncertainty is presented by fuzzy data appears by the membership value that shows the amount of uncertainty of an event. The uncertainty of occurrence of such event is displayed by truth membership value and uncertainty of non-occurrence of that event is defined by the falsity membership value. The sum of membership value and non-membership value lies in $[0, 1]$ and such uncertainty is called as IF uncertainty. If the sum of membership value and non-membership value greater than 1, then such uncertainty converts into PF uncertainty. A hesitant situation of membership and non-membership grades cannot be presented by a single value and this type of uncertainty is noted as PHF uncertainty.

Example 1 Suppose a certain type of items is to be reached in destinations within a required time. For some natural conditions (e.g., bad weather, sudden road strike, or road accident) the items cannot be reached in destination that DMs expect. A situation arises that it is supported for yes as 0.7 which is the membership grade. If the non-membership grade for supporting to no criteria is 0.4, then this state is only covered by PFS, not by FS nor by IFS. Let there exist three DMs and they assign the membership values as 0.2, 0.7 and 0.8; then hesitancy occurs on membership values for their partial knowledge. Similarly, they assign the non-membership grades as 0.1, 0.4 and 0.5. This uncertain situation handles by PHFS, not by PFS for the hesitancy. In addition, this is not controlled by HFS for the existence of membership and non-membership grades. Connecting about such situation, we design an effective model on MOSTP which is concerned with waste management and sustainability in PHF uncertainty.

Basic definitions and operations

To establish our present model, certain constructive definitions with their specific properties and fundamental operations based on FS, PFS, HFS and PHFS are defined here.

Definition 3.1 (*Fuzzy set* (**FS**), [57]) An FS $\tilde{A}$ in a universal set X is specified by a membership function $\mu_{\tilde{A}}(x)$ that identifies each element x in X to a real number in the interval [0, 1]. In FS, trapezoidal fuzzy number is a quadruplet defined as $\tilde{A}^n = (a, b, c, d)$, where $a \le b \le c \le d$.

Definition 3.2 (*Pythagorean fuzzy set* (**PFS**), [54]) Let X be a universal set, then a PFS, $\tilde{A}^p$ in X is explained as: $\tilde{A}^p = \{\langle x, \mu_{\tilde{A}^p}(x), \gamma_{\tilde{A}^p}(x)\rangle : 0 \le \mu^2_{\tilde{A}^p}(x) + \gamma^2_{\tilde{A}^p}(x) \le 1, \mu_{\tilde{A}^p}(x), \gamma_{\tilde{A}^p}(x) \in [0,1], x \in X\}$, where $\mu_{\tilde{A}^p}(x), \gamma_{\tilde{A}^p}(x)$ are the membership and non-membership functions. The degree of indeterminacy of an element x in the set $\tilde{A}^p$ is defined as the function $\pi_{\tilde{A}^p}(x) = \sqrt{1 - \mu^2_{\tilde{A}^p}(x) - \gamma^2_{\tilde{A}^p}(x)}$. It may be in the form $\mu_{\tilde{A}^p}(x) + \gamma_{\tilde{A}^p}(x) \ge 1$ or $\mu_{\tilde{A}^p}(x) + \gamma_{\tilde{A}^p}(x) \le 1$.

Definition 3.3 (*Hesitant fuzzy set* (**HFS**), [49]) Let X be a universal set, then HFS, $\check{A}^h$ on X is stated as $\check{A}^h = \{x, \mu_{\check{A}^h}(x) : x \in X\}$, where $\mu_{\check{A}^h}(x)$ is a set of some different values in [0, 1], denoting the possible membership grades of the element $x \in X$.

Example A set $\check{A}^h = \{x, 0.2, 0.5, 0.7, 0.9\}$ is a HFS with membership degree 0.2, 0.5, 0.7, and 0.9 of the element x in the universal set.

Definition 3.4 (*Pythagorean hesitant fuzzy set* (**PHFS**), [26]) To express the hesitant situation of PFS, HFS is introduce which extends PFS into PHFS. For universal set X, PHFS $\tilde{\tilde{A}}$ is defined as: $\tilde{\tilde{A}} = \{x, \mu_{\tilde{\tilde{A}}}(x), \gamma_{\tilde{\tilde{A}}}(x) : x \in X\}$, where $\mu_{\tilde{\tilde{A}}}(x)$ and $\gamma_{\tilde{\tilde{A}}}(x)$ are the sets of some values in [0, 1] denoting the possible Pythagorean hesitant membership and Pythagorean hesitant non-membership degree of the element $x \in X$ to the set $\tilde{\tilde{A}}$, respectively, with the conditions $0 \le \theta, \eta \le 1$ and $0 \le \theta^2 + \eta^2 \le 1$, where $\theta \in \mu_{\tilde{\tilde{A}}}(x), \eta \in \gamma_{\tilde{\tilde{A}}}(x), \ \forall\, x \in X$. Here, the membership and non-membership degrees are as hesitant fuzzy elements.

Example A set $\tilde{\tilde{A}} = \{x, (0.4, 0.6), (0.2, 0.5, 0.7)\}$ is a PHFS of membership degree 0.4 and 0.6, and non-membership degree 0.2, 0.5 and 0.7 of the element x into the set.

If a PHFS is convex and defined on a closed and bounded interval then the set is called as Pythagorean hesitant fuzzy number (PHFN).

Trapezoidal Pythagorean hesitant fuzzy number (TrPHFN)

Let X be a universal set, then TrPHFN $\tilde{\tilde{A}}$ is defined as $\tilde{\tilde{A}} = \{\big(\langle (a, b, c, d), \mu_{\tilde{\tilde{A}}}(x), \gamma_{\tilde{\tilde{A}}}\rangle; \omega_1, \omega_2\big) : x \in X\}$, where $\mu_{\tilde{\tilde{A}}}(x)$ and $\gamma_{\tilde{\tilde{A}}}(x)$ are the sets of some values in [0, 1] denoting the possible Pythagorean hesitant membership and Pythagorean hesitant non-membership degrees of the element $x \in X$ with $a \le b \le c \le d$. Furthermore, $\omega_1, \omega_2 \in [0, 1]$ are the set of hesitant values for membership and non-membership functions, respectively, and $0 \le \omega_1^2 + \omega_2^2 \le 1$. The Pythagorean hesitant membership and non-membership function of $\tilde{\tilde{A}}$ defined as

$$\mu_{\tilde{\tilde{A}}}(x) = \begin{cases} \omega_1(\frac{x-a}{b-a}), & \text{if } \ a \le x < b, \\ \omega_1, & \text{if } \ b \le x \le c, \\ \omega_1(\frac{d-x}{d-c}), & \text{if } \ c < x \le d, \\ 0, & \text{if } \ x < a \ \text{ or } \ x > d, \end{cases}$$

$$\gamma_{\tilde{\tilde{A}}}(x) = \begin{cases} \omega_2\sqrt{1 - (\frac{x-a}{b-a})^2}, & \text{if } \ a \le x < b, \\ \omega_2, & \text{if } \ b \le x \le c, \\ \omega_2\sqrt{1 - (\frac{d-x}{d-c})^2}, & \text{if } \ c < x \le d, \\ 1, & \text{if } \ x < a \ \text{ or } \ x > d. \end{cases}$$

Arithmetic operation of TrPHFNs

Arithmetic operations of TrPHFNs are required for the calculations of several data taken as TrPHFNs. Several ranking approaches are chosen to convert TrPHFNs into crisp numbers by utilizing these operations which are extended into different forms and applied in multi-attribute decision making problem. Let two TrPHFNs $\tilde{\tilde{A}}_1 = \big(\langle (a_1^1, a_2^1, a_3^1, a_4^1); \mu_{\tilde{\tilde{A}}_1}, \gamma_{\tilde{\tilde{A}}_1}\rangle; \omega_1, \omega_2\big)$ and $\tilde{\tilde{A}}_2 = \big(\langle (a_1^2, a_2^2, a_3^2, a_4^2); \mu_{\tilde{\tilde{A}}_2} \gamma_{\tilde{\tilde{A}}_2}\rangle; \omega_3, \omega_4\big)$, where $\omega_1 \in \mu_{\tilde{\tilde{A}}_1}, \omega_2 \in \gamma_{\tilde{\tilde{A}}_1}, \omega_3 \in \mu_{\tilde{\tilde{A}}_2}, \omega_4 \in \gamma_{\tilde{\tilde{A}}_2}$, are possible values in [0, 1] and $0 \le \omega_1^2 + \omega_2^2 \le 1, 0 \le \omega_3^2 + \omega_4^2 \le 1$. The arithmetic operations are expounded as follows:

Addition: $\tilde{\tilde{A}}_1 \oplus \tilde{\tilde{A}}_2 = \big(\langle (a_1^1 + a_1^2, a_2^1 + a_2^2, a_3^1 + a_3^2, a_4^1 + a_4^2); \mu_{\tilde{\tilde{A}}_1} \wedge \mu_{\tilde{\tilde{A}}_2}, \gamma_{\tilde{\tilde{A}}_1} \vee \gamma_{\tilde{\tilde{A}}_2}\rangle; \theta_1, \theta_2\big)$, where $\theta_1 \in \{\mu_{\tilde{\tilde{A}}_1} \wedge \mu_{\tilde{\tilde{A}}_2}\}$, $\theta_2 \in \{\gamma_{\tilde{\tilde{A}}_1} \vee \gamma_{\tilde{\tilde{A}}_2}\}$ and $0 \le \theta_1^2 + \theta_2^2 \le 1$.

Subtraction: $\tilde{\tilde{A}}_1 \ominus \tilde{\tilde{A}}_2 = \big(\langle (a_1^1 - a_4^2, a_2^1 - a_3^2, a_3^1 - a_2^2, a_4^1 - a_1^2); \mu_{\tilde{\tilde{A}}_1} \wedge \mu_{\tilde{\tilde{A}}_2}, \gamma_{\tilde{\tilde{A}}_1} \vee \gamma_{\tilde{\tilde{A}}_2}\rangle; \theta_3, \theta_4\big)$, where $\theta_3 \in \{\mu_{\tilde{\tilde{A}}_1} \wedge \mu_{\tilde{\tilde{A}}_2}\}$, $\theta_4 \in \{\gamma_{\tilde{\tilde{A}}_1} \vee \gamma_{\tilde{\tilde{A}}_2}\}$ and $0 \le \theta_3^2 + \theta_4^2 \le 1$.

Multiplication: $\tilde{\tilde{A}}_1 \odot \tilde{\tilde{A}}_2 = \big(\langle (a_1^1 a_1^2, a_2^1 a_2^2, a_3^1 a_3^2, a_4^1 a_4^2); \mu_{\tilde{\tilde{A}}_1} \wedge \mu_{\tilde{\tilde{A}}_2}, \gamma_{\tilde{\tilde{A}}_1} \vee \gamma_{\tilde{\tilde{A}}_2}\rangle; \theta_5, \theta_6\big)$, where $\theta_5 \in \{\mu_{\tilde{\tilde{A}}_1} \wedge \mu_{\tilde{\tilde{A}}_2}\}$, $\theta_6 \in \{\gamma_{\tilde{\tilde{A}}_1} \vee \gamma_{\tilde{\tilde{A}}_2}\}$ and $0 \le \theta_5^2 + \theta_6^2 \le 1$.

Scalar multiplication: Scalar multiplication for any real k is described as

$$k\tilde{\tilde{A}}_1 = \begin{cases} \big(\langle (ka_1^1, ka_2^1, ka_3^1, ka_4^1); \mu_{\tilde{\tilde{A}}_1}, \gamma_{\tilde{\tilde{A}}_1}\rangle; \omega_1, \omega_2\big), & \text{if } \ k \ge 0, \\ \big(\langle (ka_4^1, ka_3^1, ka_2^1, ka_1^1); \mu_{\tilde{\tilde{A}}_1}, \gamma_{\tilde{\tilde{A}}_1}\rangle; \omega_1, \omega_2\big), & \text{if } \ k < 0. \end{cases}$$

Ranking function

To convert TrPHFNs to crisp numbers and to compare with TrPHFNs, defuzzification plays an important role. Different defuzzification methods exist in the literature, such as α-cut, possibility concept, integration method, linguistic approach, etc. Here, we introduce an advanced and simple ranking approach through integration in terms of the TrPHFN that transforms TrPHFN into crisp number, which is applied in our proposed problem. Let $\tilde{\tilde{A}}$ be a TrPHFN then ranking index is defined by $\Re(\tilde{\tilde{A}})$, which maps TrPHFNs to real line, i.e., $\Re : \mathbb{F}(\tilde{\tilde{A}}) \to \mathbb{R}$, where $\mathbb{F}(\tilde{\tilde{A}})$ is the collection of all TrPHFNs and $\mathbb{R}$ is the set of real numbers. Mathematically, the ranking index is defined for a TrPHFN $\tilde{\tilde{A}} = \langle\langle (a, b, c, d); \mu_{\tilde{\tilde{A}}}, \gamma_{\tilde{\tilde{A}}}\rangle; \omega_1, \omega_2\rangle$, as follows:

$$\Re(\tilde{\tilde{A}}) = \frac{\int_a^d x\mu^2_{\tilde{\tilde{A}}}dx + \int_a^d x\gamma^2_{\tilde{\tilde{A}}}dx}{\int_a^d \mu^2_{\tilde{\tilde{A}}}dx + \int_a^d \gamma^2_{\tilde{\tilde{A}}}dx} = \frac{1}{4}\frac{\omega_1^2(-a^2 - 3b^2 + 3c^2 + d^2 - 2ab + 2cd) + \omega_2^2(-5a^2 + 3b^2 - 3c^2 + 5d^2 + 2ab - 2cd)}{\omega_1^2(-a - 2b + 2c + d) + \omega_2^2(-2a + 2b - 2c + 2d)}. \quad (3.1)$$

Let $\tilde{\tilde{A}}_1$ and $\tilde{\tilde{A}}_2$ be TrPHFNs. Then, the ranking operation obeys the following comparisons as

Case (i) $\Re(\tilde{\tilde{A}}_1) > \Re(\tilde{\tilde{A}}_2) \implies \tilde{\tilde{A}}_1 >_{\Re} \tilde{\tilde{A}}_2$, i.e., $\min\{\tilde{\tilde{A}}_1, \tilde{\tilde{A}}_2\} = \tilde{\tilde{A}}_2$,

Case (ii) $\Re(\tilde{\tilde{A}}_1) < \Re(\tilde{\tilde{A}}_2) \implies \tilde{\tilde{A}}_1 <_{\Re} \tilde{\tilde{A}}_2$, i.e., $\min\{\tilde{\tilde{A}}_1, \tilde{\tilde{A}}_2\} = \tilde{\tilde{A}}_1$,

Case (iii) $\Re(\tilde{\tilde{A}}_1) = \Re(\tilde{\tilde{A}}_2) \implies \tilde{\tilde{A}}_1 =_{\Re} \tilde{\tilde{A}}_2$, i.e., $\min\{\tilde{\tilde{A}}_1, \tilde{\tilde{A}}_2\} = \tilde{\tilde{A}}_1$ or $\tilde{\tilde{A}}_2$.

Theorem 3.1 $\Re(\alpha.\tilde{\tilde{A}}) = \alpha.\Re(\tilde{\tilde{A}})$*; here,* $\alpha \in \mathbb{R}, \alpha \geq 0$.

Proof Let $\tilde{\tilde{A}}=\langle\langle (a, b, c, d); \mu_{\tilde{\tilde{A}}}, \gamma_{\tilde{\tilde{A}}}\rangle; \omega_1, \omega_2\rangle$, be a TrPHFN then from definition of ranking index (cf. Eq. (3.1)), we have

$$\alpha.\Re(\tilde{\tilde{A}}) = \alpha\frac{1}{4}\frac{\omega_1^2(-a^2 - 3b^2 + 3c^2 + d^2 - 2ab + 2cd) + \omega_2^2(-5a^2 + 3b^2 - 3c^2 + 5d^2 + 2ab - 2cd)}{\omega_1^2(-a - 2b + 2c + d) + \omega_2^2(-2a + 2b - 2c + 2d)}.$$

Now

$$\Re(\alpha.\tilde{\tilde{A}}) = \frac{1}{4}\Bigg[\frac{\omega_1^2(-\alpha^2a^2 - 3\alpha^2b^2 + 3\alpha^2c^2 + \alpha^2d^2 - 2\alpha^2ab + 2\alpha^2cd)}{\omega_1^2(-\alpha a - 2\alpha b + 2\alpha c + \alpha d) + \omega_2^2(-2\alpha a + 2\alpha b - 2\alpha c + 2\alpha d)} + \frac{\omega_2^2(-5\alpha^2a^2 + 3\alpha^2b^2 - 3\alpha^2c^2 + 5\alpha^2d^2 + 2\alpha^2ab - 2\alpha^2cd)}{\omega_1^2(-\alpha a - 2\alpha b + 2\alpha c + \alpha d) + \omega_2^2(-2\alpha a + 2\alpha b - 2\alpha c + 2\alpha d)}\Bigg]$$
$$= \alpha\frac{1}{4}\frac{\omega_1^2(-a^2 - 3b^2 + 3c^2 + d^2 - 2ab + 2cd) + \omega_2^2(-5a^2 + 3b^2 - 3c^2 + 5d^2 + 2ab - 2cd)}{\omega_1^2(-a - 2b + 2c + d) + \omega_2^2(-2a + 2b - 2c + 2d)} = \alpha.\Re(\tilde{\tilde{A}}).$$ □

Problem description and model formulation

This section contains some subsections which illustrate problem background, needed notations with assumptions and the proposed integrated model.

Problem background

We are to select an SWM and TP for agriculture field and forest department, such that sustainability criteria are followed up. At first the fresh fruits or grains or vegetables or other items are transported into cold storage for preservation and to use in future marketing. Various agriculture wastes are produced after harvesting and forestry wastes are produced from forest department as residue of main items, and some wastes are generated from cold storage by the deterioration of fresh items. These waste items are transported into bio-fuel production plant and compost production plant according to their nature. Various recycle processes produced bio-fuel and compost, and these are shifted to bio-energy supply centre and compost selling market for reuse and to achieve some revenues. This SWM is completed by performing several steps such that sustainability criteria (economical condition, social impact and environment improvement) are always fixed. For economical improvement, we try to minimize transportation cost, and for social impact we want to maximize the number of job opportunities. For environment protection, we incorporate carbon mechanism for reduction of carbon emission.

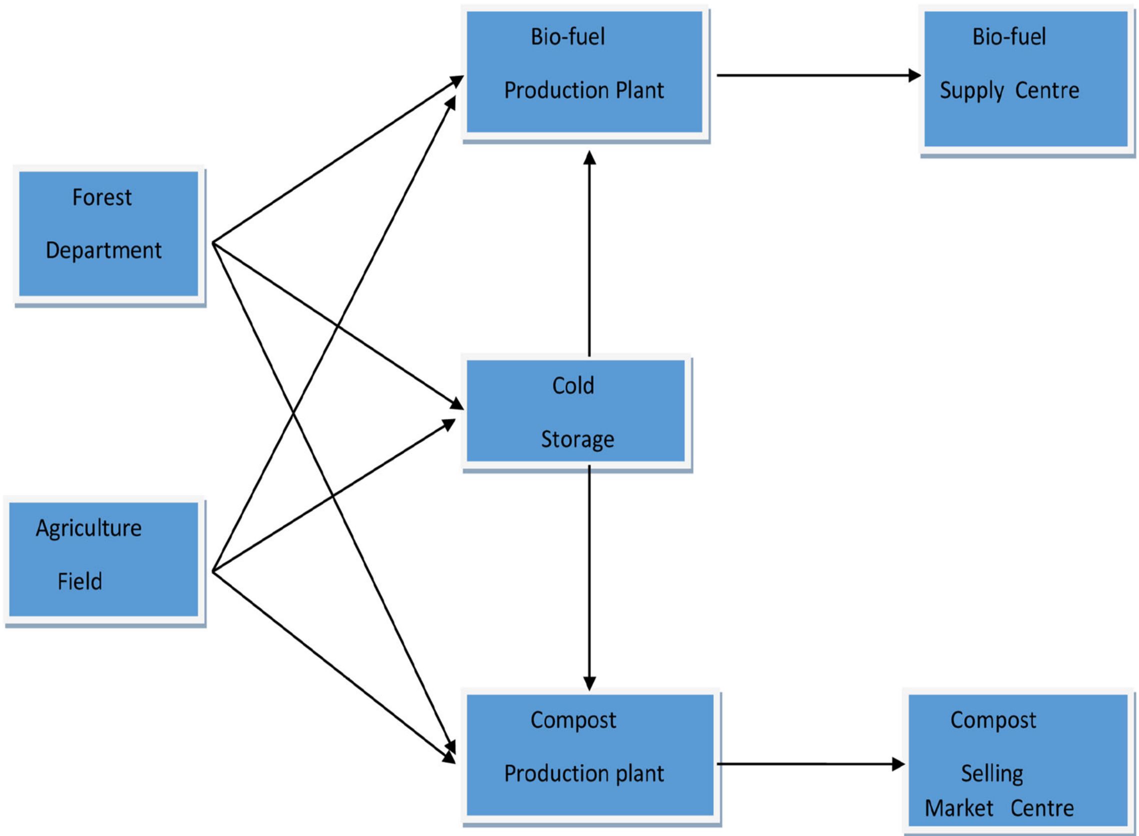

Fig. 1 Network design for processing steps of MOSTP with SWM

Here, the object of carbon mechanism is to minimize total carbon emission based on "carbon tax with cap", "carbon tax with cap-and-trade" and "carbon tax with offset" policy. Having these goals, we formulate an unpredicted mathematical model of MOSTP by including source, demand and conveyance constraints in the PHF environment for inconsistent and incomplete information. The performing stages of the formulated model are graphically described in Fig. 1.

Notations and assumptions of the proposed study

A list of notations with their nature, meaning, and required assumptions are selected to design the proposed model. These notations are illustrated in Tables 3 and 4.

Assumption

- $\tilde{\breve{a}}_i^1 > 0,\ \tilde{\breve{a}}_j^2 > 0,\ \tilde{\breve{b}}_k^{11} > 0,\ \tilde{\breve{b}}_l^{12} > 0,\ \tilde{\breve{b}}_m^{13} > 0,\ \tilde{\breve{b}}_n^{21} > 0,\ \tilde{\breve{b}}_r^{22} > 0,\ \tilde{\breve{e}}_p > 0,\ \forall\, i, j, k, l, m, n, p, r$. The positivity criteria is obeyed if every element of the quadruplet of TrPHFNs is positive.
- Only agriculture and forestry wastes with cold storage waste items are managed here.
- All the wastes should be distributed according to their nature.
- Cost of bio-fuel production and compost production are ignored.
- Total carbon emission during transportation of SWM: $E = E(e^1_{CO_2}; x, y, w, z) = e^1_{CO_2}\Big[\sum_{i=1}^{I}\sum_{p=1}^{P}\Big(\sum_{k=1}^{K} x^1_{ikp}d^{11}_{ikp} + \sum_{l=1}^{L} x^2_{ilp}d^{12}_{ilp} + \sum_{m=1}^{M} x^3_{imp}d^{13}_{imp}\Big) + \sum_{j=1}^{J}\sum_{p=1}^{P}\Big(\sum_{k=1}^{K} y^1_{jkp}d^{21}_{jkp} + \sum_{l=1}^{L} y^2_{jlp}d^{22}_{jlp} + \sum_{m=1}^{M} y^3_{jmp}d^{23}_{jmp}\Big) + \sum_{l=1}^{L}\sum_{p=1}^{P}\Big(\sum_{k=1}^{K} w^1_{lkp}d^{31}_{lkp} + \sum_{m=1}^{M} w^2_{lmp}d^{32}_{lmp}\Big) + \sum_{p=1}^{P}\Big(\sum_{k=1}^{K}\sum_{n=1}^{N} z^1_{knp}d^{41}_{knp} + \sum_{m=1}^{M}\sum_{r=1}^{R} z^2_{mrp}d^{42}_{mrp}\Big)\Big]$.

Integrated multi-objective optimization model

The transportation cost with other charges (emission charge) are fixed for each unit of transportation, and therefore, the cost is not of an imprecise nature. Similarly job opportunity, rate of carbon emission and tax per unit of item are fixed, not fluctuate, and considered in crisp nature. How-

Table 3 Useful notations with their nature and descriptions

	Description	Type
Index sets		
i	Index for source of forest department ($i = 1, 2, \ldots, I$)	Integer
j	Index for source of agriculture field ($j = 1, 2, \ldots, J$)	Integer
k	Index for bio-fuel production plant ($k = 1, 2, \ldots, K$)	Integer
l	Index for cold storage ($l = 1, 2, \ldots, L$)	Integer
m	Index for compost production plant ($m = 1, 2, \ldots, M$)	Integer
n	Index for bio-fuel supply centre ($n = 1, 2, \ldots, N$)	Integer
r	Index for compost selling market centre ($r = 1, 2, \ldots, R$)	Integer
p	Index for conveyance type ($p = 1, 2, \ldots, P$)	Integer
Decision variables		
x^1_{ikp}	Amount of forestry waste items that to be transported from ith forest department to kth bio-fuel production plant through pth conveyance	Real
x^2_{ilp}	Amount of fresh forestry items that to be transported from ith forest department to lth cold storage through pth conveyance	Real
x^3_{imp}	Amount of forestry waste items that to be transported from ith forest department to mth compost production plant through pth conveyance	Real
y^1_{jkp}	Amount of agriculture waste items that to be transported from jth agriculture field to kth bio-fuel production plant through pth conveyance	Real
y^2_{jlp}	Amount of fresh agriculture items that to be transported from jth agriculture field to lth cold storage through pth conveyance	Real
y^3_{jmp}	Amount of agriculture waste items that to be transported from jth agriculture field to mth compost production plant through pth conveyance	Real
w^1_{lkp}	Amount of waste items transported from lth cold storage to kth bio-fuel production plant through pth conveyance	Real
w^2_{lmp}	Amount of waste items transported from lth cold storage to mth compost production plant through pth conveyance	Real
z^1_{knp}	Amount of bio-fuel transported from kth bio-fuel production plant to nth bio-fuel supply centre through pth conveyance	Real
z^2_{mrp}	Amount of compost items transported from mth compost production plant to rth compost selling market centre through pth conveyance	Real
Parameters		
$\tilde{\tilde{a}}^1_i$	PHF available amount of items (fresh and waste) at ith source	Fuzzy
$\tilde{\tilde{a}}^2_j$	PHF available amount of items(fresh and waste) at jth source	Fuzzy
$\tilde{\tilde{b}}^{11}_k$	PHF capability of kth bio-fuel production plant	Fuzzy
$\tilde{\tilde{b}}^{12}_l$	PHF capability of lth cold storage	Fuzzy
$\tilde{\tilde{b}}^{13}_m$	PHF capability of mth compost production plant	Fuzzy
$\tilde{\tilde{b}}^{21}_n$	PHF demand of nth bio-fuel supply centre	Fuzzy
$\tilde{\tilde{b}}^{22}_r$	PHF demand of rth compost selling market centre	Fuzzy
$\tilde{\tilde{e}}_p$	PHF capacity of pth type of conveyance	Fuzzy
α, β	Rate of waste generation from lth cold storage that transported to kth bio-fuel production plant and mth compost production plant, respectively	Real
$e^1_{CO_2}$	Rate of carbon emission of the vehicle per unit item and per unit distance	Real
$e^2_{CO_2}$	Rate of carbon emission per unit item from bio-fuel production plant	Real
$e^3_{CO_2}$	Rate of carbon emission per unit item from compost production plant	Real
θ_1	Tax for carbon emission during transportation	Real
θ_2	Tax for carbon emission to bio-fuel production plant	Real
θ_3	Tax for carbon emission to compost production plant	Real
ϕ	Carbon trading (buying) cost per unit item	Real
ψ	Carbon trading (selling) cost per unit item	Real

Table 3 continued

	Description	Type
C	Carbon cap (maximum allowance of carbon emission)	Real
P	Penalty charge per unit item that emitted surplus carbon to cap	Real
Z_s	Objective function, ($s = 1, 2, 3$)	Real

Table 4 Symbols with their nature and descriptions

Parameters	Description	Type
c^{11}_{ikp}	Transportation cost per unit forestry waste item that transported from ith source to kth bio-fuel production plant through pth conveyance	Real
c^{12}_{ilp}	Transportation cost per unit forestry fresh item that transported from ith source to lth cold storage through pth conveyance	Real
c^{13}_{imp}	Transportation cost per unit forestry waste item that transported from ith source to mth compost production plant through pth conveyance	Real
c^{21}_{jkp}	Transportation cost per unit agriculture waste item that transported from jth source to kth bio-fuel production plant through pth conveyance	Real
c^{22}_{jlp}	Transportation cost per unit agriculture fresh item that transported from jth source to lth cold storage through pth conveyance	Real
c^{23}_{jmp}	Transportation cost per unit agriculture waste item that transported from jth source to mth compost production plant through pth conveyance	Real
c^{31}_{lkp}	Transportation cost per unit waste item that transported from lth cold storage to kth bio-fuel production plant through pth conveyance	Real
c^{32}_{lmp}	Transportation cost per unit waste items that transported from lth cold storage to mth compost production plant through pth conveyance	Real
c^{41}_{knp}	Transportation cost per unit bio-fuel that transported from kth bio-fuel production plant to nth bio-fuel supply centre through pth conveyance	Real
c^{42}_{mrp}	Transportation cost per unit compost that transported from mth compost production plant to rth compost selling market centre through pth conveyance	Real
d^{11}_{ikp}	Distance from ith source to kth destination through pth conveyance	Real
d^{12}_{ilp}	Distance from ith source to lth destination through pth conveyance	Real
d^{13}_{imp}	Distance from ith source to mth destination through pth conveyance	Real
d^{21}_{jkp}	Distance from jth source to kth destination through pth conveyance	Real
d^{22}_{jlp}	Distance from jth source to lth destination through pth conveyance	Real
d^{23}_{jmp}	Distance from jth source to mth destination through pth conveyance	Real
d^{31}_{lkp}	Distance from lth source to kth destination through pth conveyance	Real
d^{32}_{lmp}	Distance from lth source to mth destination through pth conveyance	Real
d^{41}_{knp}	Distance from kth source to nth destination through pth conveyance	Real
d^{42}_{mrp}	Distance from mth source to rth destination through pth conveyance	Real
η^1_i	Number of job opportunity at ith forest department	Real
η^2_j	Number of job opportunity at jth agriculture field	Real
η^3_k	Number of job opportunity at kth bio-fuel production plant	Real
η^4_l	Number of job opportunity at lth cold storage	Real
η^5_m	Number of job opportunity at mth compost production plant	Real
η^6_n	Number of job opportunity at nth bio-fuel supply centre	Real
η^7_r	Number of job opportunity at rth compost selling market centre	Real

ever, source, demand and vehicle capacity are effected due to several unpredictable conditions that are not previously detected. In such situations we consider these parameters as PHFNs and the corresponding model becomes in a PHF environment. The integrated optimization model of MOSTP with PHF environment is implemented in Model 1 to tackle real-life hesitation or uncertainty about SWM with sustainability. We strive to minimize transportation cost, maximize job opportunity and minimize carbon emission cost.

Implementation of uncertain model

Model 1

$$\text{minimize } Z_1(x,y,z,w) = \sum_{i=1}^{I}\sum_{p=1}^{P}\Bigg(\sum_{k=1}^{K} x^1_{ikp}c^{11}_{ikp} + \sum_{l=1}^{L} x^2_{ilp}c^{12}_{ilp} + \sum_{m=1}^{M} x^3_{imp}c^{13}_{imp}\Bigg) + \sum_{j=1}^{J}\sum_{p=1}^{P}\Bigg(\sum_{k=1}^{K} y^1_{jkp}c^{21}_{jkp} + \sum_{l=1}^{L} y^2_{jlp}c^{22}_{jlp} + \sum_{m=1}^{M} y^3_{jmp}c^{23}_{jmp}\Bigg) + \sum_{l=1}^{L}\sum_{p=1}^{P}\Bigg(\sum_{k=1}^{K} w^1_{lkp}c^{31}_{lkp} + \sum_{m=1}^{M} w^2_{lmp}c^{32}_{lmp}\Bigg) + \sum_{p=1}^{P}\Bigg(\sum_{k=1}^{K}\sum_{n=1}^{N} z^1_{knp}c^{41}_{knp} + \sum_{m=1}^{M}\sum_{r=1}^{R} z^2_{mrp}c^{42}_{mrp}\Bigg) \tag{4.1}$$

$$\text{maximize } Z_2(x,y,z,w) = \sum_{i=1}^{I}\sum_{p=1}^{P}\Bigg(\sum_{k=1}^{K} x^1_{ikp}(\eta^1_i + \eta^3_k) + \sum_{l=1}^{L} x^2_{ilp}(\eta^1_i + \eta^4_l) + \sum_{m=1}^{M} x^3_{imp}(\eta^1_i + \eta^5_m)\Bigg) + \sum_{j=1}^{J}\sum_{p=1}^{P}\Bigg(\sum_{k=1}^{K} y^1_{jkp}(\eta^2_j + \eta^3_k) + \sum_{l=1}^{L} y^2_{jlp}(\eta^2_j + \eta^4_l) + \sum_{m=1}^{M} y^3_{jmp}(\eta^2_j + \eta^5_m)\Bigg) + \sum_{l=1}^{L}\sum_{p=1}^{P}\Bigg(\sum_{k=1}^{K} w^1_{lkp}(\eta^4_l + \eta^3_k) + \sum_{m=1}^{M} w^2_{lmp}(\eta^4_l + \eta^5_m)\Bigg) + \sum_{p=1}^{P}\Bigg(\sum_{k=1}^{K}\sum_{n=1}^{N} z^1_{knp}(\eta^3_k + \eta^6_n) + \sum_{m=1}^{M}\sum_{r=1}^{R} z^2_{mrp}(\eta^5_m + \eta^7_r)\Bigg) \tag{4.2}$$

$$\text{minimize } Z_3(x,y,z,w) = \theta_1 E + \theta_2 e^2_{CO_2}\sum_{k=1}^{K}\sum_{p=1}^{P}\Bigg(\sum_{i=1}^{I} x^1_{ikp} + \sum_{j=1}^{J} y^1_{jkp} + \sum_{l=1}^{L} w^1_{lkp}\Bigg) + \theta_3 e^3_{CO_2}\sum_{m=1}^{M}\sum_{p=1}^{P}\Bigg(\sum_{i=1}^{I} x^3_{imp} + \sum_{j=1}^{J} y^3_{jmp} + \sum_{l=1}^{L} w^2_{lmp}\Bigg) \tag{4.3}$$

$$\text{subject to } \sum_{p=1}^{P}\Bigg(\sum_{k=1}^{K} x^1_{ikp} + \sum_{l=1}^{L} x^2_{ilp} + \sum_{m=1}^{M} x^3_{imp}\Bigg) \le \tilde{\tilde{a}}^1_i \quad (i = 1,2,\ldots,I), \tag{4.4}$$

$$\sum_{p=1}^{P}\Bigg(\sum_{k=1}^{K} y^1_{jkp} + \sum_{l=1}^{L} y^2_{jlp} + \sum_{m=1}^{M} y^3_{jmp}\Bigg) \le \tilde{\tilde{a}}^2_j \quad (j = 1,2,\ldots,J), \tag{4.5}$$

$$\sum_{p=1}^{P}\Bigg(\sum_{i=1}^{I} x^1_{ikp} + \sum_{j=1}^{J} y^1_{jkp} + \sum_{l=1}^{L} w^1_{lkp}\Bigg) \ge \tilde{\tilde{b}}^{11}_k \quad (k = 1,2,\ldots,I), \tag{4.6}$$

$$\sum_{p=1}^{P}\Bigg(\sum_{i=1}^{I} x^2_{ilp} + \sum_{j=1}^{J} y^2_{jlp}\Bigg) \ge \tilde{\tilde{b}}^{12}_l \quad (l = 1,2,\ldots,L), \tag{4.7}$$

$$\sum_{p=1}^{P}\Bigg(\sum_{i=1}^{I} x^3_{imp} + \sum_{j=1}^{J} y^3_{jmp} + \sum_{l=1}^{L} w^2_{lmp}\Bigg) \ge \tilde{\tilde{b}}^{13}_m \quad (m = 1,2,\ldots,M), \tag{4.8}$$

$$\sum_{p=1}^{P}\sum_{k=1}^{K} w^1_{lkp} = \alpha\sum_{p=1}^{P}\Bigg(\sum_{i=1}^{I} x^2_{ilp} + \sum_{j=1}^{J} y^2_{jlp}\Bigg) \quad (l = 1,2,\ldots,L), \tag{4.9}$$

$$\sum_{p=1}^{P}\sum_{m=1}^{M} w^2_{lmp} = \beta\sum_{p=1}^{P}\Bigg(\sum_{i=1}^{I} x^2_{ilp} + \sum_{j=1}^{J} y^2_{jlp}\Bigg) \quad (l = 1,2,\ldots,L), \tag{4.10}$$

$$\sum_{k=1}^{K}\sum_{p=1}^{P} z^1_{knp} \ge \tilde{\tilde{b}}^{21}_n \quad (n = 1,2,\ldots,N), \tag{4.11}$$

$$\sum_{m=1}^{M}\sum_{p=1}^{P} z^2_{mrp} \ge \tilde{\tilde{b}}^{22}_r \quad (r = 1,2,\ldots,R), \tag{4.12}$$

$$\sum_{i=1}^{I}\sum_{k=1}^{K} x_{ikp}^{1} \leq \tilde{\tilde{e}}_p \ \ (p = 1, 2, \ldots, P), \tag{4.13}$$

$$\sum_{i=1}^{I}\sum_{l=1}^{L} x_{ilp}^{2} \leq \tilde{\tilde{e}}_p \ \ (p = 1, 2, \ldots, P), \tag{4.14}$$

$$\sum_{i=1}^{I}\sum_{m=1}^{M} x_{imp}^{3} \leq \tilde{\tilde{e}}_p \ \ (p = 1, 2, \ldots, P), \tag{4.15}$$

$$\sum_{j=1}^{J}\sum_{k=1}^{K} y_{jkp}^{1} \leq \tilde{\tilde{e}}_p \ \ (p = 1, 2, \ldots, P), \tag{4.16}$$

$$\sum_{j=1}^{J}\sum_{l=1}^{L} y_{jlp}^{2} \leq \tilde{\tilde{e}}_p \ \ (p = 1, 2, \ldots, P), \tag{4.17}$$

$$\sum_{j=1}^{J}\sum_{m=1}^{M} y_{jmp}^{3} \leq \tilde{\tilde{e}}_p \ \ (p = 1, 2, \ldots, P), \tag{4.18}$$

$$\sum_{k=1}^{K}\sum_{l=1}^{L} w_{lkp}^{1} \leq \tilde{\tilde{e}}_p \ \ (p = 1, 2, \ldots, P), \tag{4.19}$$

$$\sum_{l=1}^{L}\sum_{m=1}^{M} w_{lmp}^{2} \leq \tilde{\tilde{e}}_p \ \ (p = 1, 2, \ldots, P), \tag{4.20}$$

$$\sum_{k=1}^{K}\sum_{n=1}^{N} z_{knp}^{1} \leq \tilde{\tilde{e}}_p \ \ (p = 1, 2, \ldots, P), \tag{4.21}$$

$$\sum_{m=1}^{M}\sum_{r=1}^{R} z_{mrp}^{2} \leq \tilde{\tilde{e}}_p \ \ (p = 1, 2, \ldots, P), \tag{4.22}$$

$$x_{ikp}^{1} \geq 0, x_{ilp}^{2} \geq 0, x_{imp}^{3} \geq 0, y_{jkp}^{1} \geq 0,$$
$$y_{jlp}^{2} \geq 0, y_{jmp}^{3} \geq 0, w_{lkp}^{1} \geq 0, w_{lmp}^{2} \geq 0, z_{knp}^{1} \geq 0,$$
$$z_{mrp}^{2} \geq 0, \forall\, i,\ j,\ k,\ l,\ m,\ n,\ p,\ r. \tag{4.23}$$

The feasibility conditions of this TP are set as: $\sum_{i=1}^{I} \tilde{\tilde{a}}_i^1 \geq \sum_{k=1}^{K} \tilde{\tilde{b}}_k^{11}$; $\sum_{i=1}^{I} \tilde{\tilde{a}}_i^1 \geq \sum_{l=1}^{L} \tilde{\tilde{b}}_l^{12}$; $\sum_{i=1}^{I} \tilde{\tilde{a}}_i^1 \geq \sum_{m=1}^{M} \tilde{\tilde{b}}_m^{13}$; $\sum_{j=1}^{J} \tilde{\tilde{a}}_j^2 \geq \sum_{k=1}^{K} \tilde{\tilde{b}}_k^{11}$; $\sum_{j=1}^{J} \tilde{\tilde{a}}_j^2 \geq \sum_{l=1}^{L} \tilde{\tilde{b}}_l^{12}$; $\sum_{j=1}^{J} \tilde{\tilde{a}}_j^2 \geq \sum_{m=1}^{M} \tilde{\tilde{b}}_m^{13}$; $\sum_{k=1}^{K} \tilde{\tilde{b}}_k^{11} \geq \sum_{n=1}^{N} \tilde{\tilde{b}}_n^{21}$; $\sum_{m=1}^{M} \tilde{\tilde{b}}_m^{13} \geq \sum_{r=1}^{R} \tilde{\tilde{b}}_r^{22}$; $\sum_{p=1}^{P} \tilde{\tilde{e}}_p \geq \sum_{k=1}^{K} \tilde{\tilde{b}}_k^{11}$; $\sum_{p=1}^{P} \tilde{\tilde{e}}_p \geq \sum_{l=1}^{L} \tilde{\tilde{b}}_l^{12}$; $\sum_{p=1}^{P} \tilde{\tilde{e}}_p \geq \sum_{m=1}^{M} \tilde{\tilde{b}}_m^{13}$; $\sum_{p=1}^{P} \tilde{\tilde{e}}_p \geq \sum_{n=1}^{N} \tilde{\tilde{b}}_n^{21}$; $\sum_{p=1}^{P} \tilde{\tilde{e}}_p \geq \sum_{r=1}^{R} \tilde{\tilde{b}}_r^{22}$.

Elementary information about the model

In Model 1, three objective functions are illustrated by Eqs. (4.1)–(4.3). The 1st objective function calculates the total transportation cost that to be minimized for transporting fresh items, waste items and recycled items. The 1st part consists of three parts which state the total transportation cost from ith forest department to kth bio-fuel production plant, to lth cold storage and to mth compost production plant through pth conveyance, respectively. The 2nd part contains three parts that describe the total transportation cost from jth agriculture field to kth bio-fuel production plant, lth cold storage and mth compost production plant by pth mode of vehicle, respectively. The 3rd part includes two parts which indicate the total transportation cost from lth cold storage to kth and mth destination, respectively, with pth set of conveyance. The 4th part composes two parts such as total transportation cost from kth bio-fuel production plant to nth bio-fuel supply centre and from mth compost production plant to rth compost selling market centre using pth type of conveyance.

The 2nd objective function is the total number of job opportunity which to be maximized for transporting the items and for other works (e.g., loading, unloading, treatment, marketing, managing, etc.) through this SWM problem. The 1st, 2nd and 3rd parts are the total number of job opportunity from ith source to kth bio-fuel production plant, lth cold storage and mth compost production plant, respectively, and transportation of items completed through pth conveyance. The 4th, 5th and 6th parts are the entire number of job opportunity from jth source to kth bio-fuel production plant, lth cold storage and mth compost production plant, respectively, by the pth class of vehicle. The 7th and 8th parts consider the total number of job opportunity from lth source to kth bio-fuel production plant and mth compost production plant, respectively, with pth model of conveyance. The 9th part is the total number of job opportunity from kth bio-fuel production plants to nth bio-fuel supply centre and items transported using pth kind of conveyance. The last part denotes the total number of job opportunity from mth compost production plant to rth compost selling market centre, where transportation of items covered by pth nature of conveyance.

The 3rd objective function is the total carbon emission cost which is to be minimized. The 1st part is the total emission cost as tax during all transportations from each source to each destination. Here, E is the total emission which is defined in assumption (Section "Notations and assumptions of the proposed study") to reduce the complexity of mathematical model. The 2nd part is the total penalty charge for carbon emission at kth bio-fuel production plant during bio-energy creation from waste items which are collected from ith, jth and lth sources by transporting pth class of conveyance. The 3rd part is the total penalty charge of mth compost production plant that emits carbon during compost production and the required waste items are supplied from ith, jth and lth origins, and transporting with pth mode of conveyance.

Constraints (4.4) and (4.5) describe the total source availability condition of ith and jth source. Demand capability of kth, lth and mth destinations ensured by the constraints (4.6), (4.7) and (4.8). Two types of waste items are produced from lth cold storage and the total rate of waste productions defined by constraints (4.9) and (4.10). First type of waste is transported into bio-fuel production plant and second type of waste is again transported into compost production plant. Constraints (4.11) and (4.12) indicate the demand constraint of second stage, i.e., demand aptitude of nth bio-fuel supply centre and rth compost selling market centre. Constraints (4.13)–(4.22) employ to show the conveyance capacity for pth set of vehicles. Constraints (4.23) define the non negativity restriction of the variables.

Identical deterministic model

The formulated model is in PHF environment for existence of uncertainty in source, demand and conveyance parameters. The proposed model cannot be easily evaluated, and therefore, defuzzification ranking index (from Eq. (3.1)) is introduced in the model that converts Model 1 into a deterministic form which is presented in Model 2 as follows:
Model 2

$$\begin{aligned}
&\text{minimize } Z_1(x,y,z,w)\\
&\text{maximize } Z_2(x,y,z,w)\\
&\text{minimize } Z_3(x,y,z,w)\\
&\text{subject to } \sum_{p=1}^{P}\left(\sum_{k=1}^{K}x_{ikp}^1+\sum_{l=1}^{L}x_{ilp}^2+\sum_{m=1}^{M}x_{imp}^3\right)\\
&\quad\le \Re(\tilde{\tilde{a}}_i^1)\ \ (i=1,2,\ldots,I), \qquad (4.24)\\
&\sum_{p=1}^{P}\left(\sum_{k=1}^{K}y_{jkp}^1+\sum_{l=1}^{L}y_{jlp}^2+\sum_{m=1}^{M}y_{jmp}^3\right)\\
&\quad\le \Re(\tilde{\tilde{a}}_j^2)\ \ (j=1,2,\ldots,J), \qquad (4.25)\\
&\sum_{p=1}^{P}\left(\sum_{i=1}^{I}x_{ikp}^1+\sum_{j=1}^{J}y_{jkp}^1+\sum_{l=1}^{L}w_{lkp}^1\right)\\
&\quad\ge \Re(\tilde{\tilde{b}}_k^{11})\ \ (k=1,2,\ldots,I), \qquad (4.26)\\
&\sum_{p=1}^{P}\left(\sum_{i=1}^{I}x_{ilp}^2+\sum_{j=1}^{J}y_{jlp}^2\right)\\
&\quad\ge \Re(\tilde{\tilde{b}}_l^{12})\ \ (l=1,2,\ldots,L), \qquad (4.27)\\
&\sum_{p=1}^{P}\left(\sum_{i=1}^{I}x_{imp}^3+\sum_{j=1}^{J}y_{jmp}^3+\sum_{l=1}^{L}w_{lmp}^2\right)\\
&\quad\ge \Re(\tilde{\tilde{b}}_m^{13})\ \ (m=1,2,\ldots,M), \qquad (4.28)\\
&\text{constraints (4.9)}-\text{(4.10)},\\
&\sum_{k=1}^{K}\sum_{p=1}^{P}z_{knp}^1\ge \Re(\tilde{\tilde{b}}_n^{21})\ \ (n=1,2,\ldots,N), \qquad (4.29)\\
&\sum_{m=1}^{M}\sum_{p=1}^{P}z_{mrp}^2\ge \Re(\tilde{\tilde{b}}_r^{22})\ \ (r=1,2,\ldots,R), \qquad (4.30)
\end{aligned}$$

$$\sum_{i=1}^{I}\sum_{k=1}^{K}x_{ikp}^1\le \Re(\tilde{\tilde{e}}_p)\ \ (p=1,2,\ldots,P), \qquad (4.31)$$

$$\sum_{i=1}^{I}\sum_{l=1}^{L}x_{ilp}^2\le \Re(\tilde{\tilde{e}}_p)\ \ (p=1,2,\ldots,P), \qquad (4.32)$$

$$\sum_{i=1}^{I}\sum_{m=1}^{M}x_{imp}^3\le \Re(\tilde{\tilde{e}}_p)\ \ (p=1,2,\ldots,P), \qquad (4.33)$$

$$\sum_{j=1}^{J}\sum_{k=1}^{K}y_{jkp}^1\le \Re(\tilde{\tilde{e}}_p)\ \ (p=1,2,\ldots,P), \qquad (4.34)$$

$$\sum_{j=1}^{J}\sum_{l=1}^{L}y_{jlp}^2\le \Re(\tilde{\tilde{e}}_p)\ \ (p=1,2,\ldots,P), \qquad (4.35)$$

$$\sum_{j=1}^{J}\sum_{m=1}^{M}y_{jmp}^3\le \Re(\tilde{\tilde{e}}_p)\ \ (p=1,2,\ldots,P), \qquad (4.36)$$

$$\sum_{k=1}^{K}\sum_{l=1}^{L}w_{lkp}^1\le \Re(\tilde{\tilde{e}}_p)\ \ (p=1,2,\ldots,P), \qquad (4.37)$$

$$\sum_{l=1}^{L}\sum_{m=1}^{M}w_{lmp}^2\le \Re(\tilde{\tilde{e}}_p)\ \ (p=1,2,\ldots,P), \qquad (4.38)$$

$$\sum_{k=1}^{K}\sum_{n=1}^{N}z_{knp}^1\le \Re(\tilde{\tilde{e}}_p)\ \ (p=1,2,\ldots,P), \qquad (4.39)$$

$$\sum_{m=1}^{M}\sum_{r=1}^{R}z_{mrp}^2\le \Re(\tilde{\tilde{e}}_p)\ \ (p=1,2,\ldots,P), \qquad (4.40)$$

$$\begin{aligned}
&x_{ikp}^1\ge 0,\ x_{ilp}^2\ge 0,\ x_{imp}^3\ge 0,\ y_{jkp}^1\ge 0,\ y_{jlp}^2\ge 0,\\
&y_{jmp}^3\ge 0,\ w_{lkp}^1\ge 0,\ w_{lmp}^2\ge 0,\ z_{knp}^1\ge 0,\\
&z_{mrp}^2\ge 0,\ \forall\ i,\ j,\ k,\ l,\ m,\ n,\ p,\ r. \qquad (4.41)
\end{aligned}$$

The feasibility conditions of this TP are considered as: $\sum_{i=1}^{I}\Re(\tilde{\tilde{a}}_i^1)\ge\sum_{k=1}^{K}\Re(\tilde{\tilde{b}}_k^{11})$; $\sum_{i=1}^{I}\Re(\tilde{\tilde{a}}_i^1)\ge\sum_{l=1}^{L}\Re(\tilde{\tilde{b}}_l^{12})$; $\sum_{i=1}^{I}\Re(\tilde{\tilde{a}}_i^1)\ge\sum_{m=1}^{M}\Re(\tilde{\tilde{b}}_m^{13})$; $\sum_{j=1}^{J}\Re(\tilde{\tilde{a}}_j^2)\ge\sum_{k=1}^{K}\Re(\tilde{\tilde{b}}_k^{11})$; $\sum_{j=1}^{J}\Re(\tilde{\tilde{a}}_j^2)\ge\sum_{l=1}^{L}\Re(\tilde{\tilde{b}}_l^{12})$; $\sum_{j=1}^{J}\Re(\tilde{\tilde{a}}_j^2)\ge\sum_{m=1}^{M}\Re(\tilde{\tilde{b}}_m^{13})$; $\sum_{k=1}^{K}\Re(\tilde{\tilde{b}}_k^{11})\ge\sum_{n=1}^{N}\Re(\tilde{\tilde{b}}_n^{21})$; $\sum_{m=1}^{M}\Re(\tilde{\tilde{b}}_m^{13})\ge\sum_{r=1}^{R}\Re(\tilde{\tilde{b}}_r^{22})$; $\sum_{p=1}^{P}\Re(\tilde{\tilde{e}}_p)\ge\sum_{k=1}^{K}\Re(\tilde{\tilde{b}}_k^{11})$; $\sum_{p=1}^{P}\Re(\tilde{\tilde{e}}_p)\ge\sum_{l=1}^{L}\Re(\tilde{\tilde{b}}_l^{12})$; $\sum_{p=1}^{P}\Re(\tilde{\tilde{e}}_p)\ge\sum_{m=1}^{M}\Re(\tilde{\tilde{b}}_m^{13})$; $\sum_{p=1}^{P}\Re(\tilde{\tilde{e}}_p)\ge\sum_{n=1}^{N}\Re(\tilde{\tilde{b}}_n^{21})$; $\sum_{p=1}^{P}\Re(\tilde{\tilde{e}}_p)\ge\sum_{r=1}^{R}\Re(\tilde{\tilde{b}}_r^{22})$.

Extended model for carbon mechanism

In the proposed model (Model 1 or Model 2), the third objective function is focused on minimum carbon emission. Due to existence of carbon mechanism with different combined policies as "carbon tax with cap", "carbon tax with cap-and-trade" and "carbon tax with offset" policy, the proposed model generates several feasible regions of solutions. In such situation the deterministic model is extended and designed into the following three Models 3–5:

Model 3 (Tax with cap):

$$\begin{aligned} & \text{minimize } Z_1(x, y, z, w) \\ & \text{maximize } Z_2(x, y, z, w) \\ & \text{minimize } Z_3(x, y, z, w) \\ \text{subject to } & \text{the constraints (4.9)–(4.10)}, \\ & \text{the constraints (4.24)–(4.41)}, \\ & E \leq C. \end{aligned}$$

This model is same as of Model 2, but an extra constraint $E \leq C$ is added as the restriction of cap policy.

Model 4 (Tax with cap-and-trade policy):

$$\begin{aligned} & \text{minimize } Z_1(x, y, z, w) \\ & \text{maximize } Z_2(x, y, z, w) \\ & \text{minimize } Z_3^*(x, y, z, w) \\ & \quad = \theta_1 E + \phi P\big[E - C\big]^+ - \psi\big[C - E\big]^+ \\ & \quad +\theta_2 e_{CO_2}^2 \sum_{k=1}^{K}\sum_{p=1}^{P}\Big(\sum_{i=1}^{I} x_{ikp}^1 + \sum_{j=1}^{J} y_{jkp}^1 + \sum_{l=1}^{L} w_{lkp}^1\Big) \\ & \quad +\theta_3 e_{CO_2}^3 \sum_{m=1}^{M}\sum_{p=1}^{P}\Big(\sum_{i=1}^{I} x_{imp}^3 + \sum_{j=1}^{J} y_{jmp}^3 + \sum_{l=1}^{L} w_{lmp}^2\Big) \\ & \text{subject to the constraints (4.9)–(4.10)}, \\ & \text{the constraints (4.24)–(4.41)}. \end{aligned}$$

Here, $\big[E - C\big]^+ = \max\big\{E - C, 0\big\}$ and $\big[C - E\big]^+ = \max\big\{C - E, 0\big\}$. Third objective minimizes total carbon emission cost under tax with cap-and-trade policy. Depending on the cap (C), there exist two feasible regions, and Model 4 splits into two different models. The first case is defined by Model 4A whenever $C \geq E$. In this case, the system sells their extra permission in trading market with cost ψ and total emission cost is reduced by $\psi[C - E]$. Second case is described by Model 4B when $C \leq E$. Hence, the system buys their slack emission permit with cost ϕ and pays a penalty charge P for such extra emission. Therefore, total emission cost is increased by $\phi P[E - C]$. We call these two separate cases by two models as follows:

Model 4A

$$\begin{aligned} & \text{minimize } Z_1(x, y, z, w) \\ & \text{maximize } Z_2(x, y, z, w) \\ & \text{minimize } Z_3^*(x, y, w, z) = \theta_1 E - \psi\big[C - E\big] \\ & +\theta_2 e_{CO_2}^2 \sum_{k=1}^{K}\sum_{p=1}^{P}\Big(\sum_{i=1}^{I} x_{ikp}^1 + \sum_{j=1}^{J} y_{jkp}^1 \\ & + \sum_{l=1}^{L} w_{lkp}^1\Big) + \theta_3 e_{CO_2}^3 \sum_{m=1}^{M}\sum_{p=1}^{P}\Big(\sum_{i=1}^{I} x_{imp}^3 \\ & + \sum_{j=1}^{J} y_{jmp}^3 + \sum_{l=1}^{L} w_{lmp}^2\Big) \\ & \text{subject to the constraints (4.9)–(4.10)}, \\ & \text{the constraints (4.24)–(4.41)}, \\ & E \leq C. \end{aligned} \tag{4.42}$$

Model 4B

$$\begin{aligned} & \text{minimize } Z_1(x, y, z, w) \\ & \text{maximize } Z_2(x, y, z, w) \\ & \text{minimize } Z_3^*(x, y, w, z) = \theta_1 E + \phi P\big[E - C\big] \\ & +\theta_2 e_{CO_2}^2 \sum_{k=1}^{K}\sum_{p=1}^{P}\Big(\sum_{i=1}^{I} x_{ikp}^1 + \sum_{j=1}^{J} y_{jkp}^1 \\ & + \sum_{l=1}^{L} w_{lkp}^1\Big) + \theta_3 e_{CO_2}^3 \sum_{m=1}^{M}\sum_{p=1}^{P}\Big(\sum_{i=1}^{I} x_{imp}^3 \\ & + \sum_{j=1}^{J} y_{jmp}^3 + \sum_{l=1}^{L} w_{lmp}^2\Big) \\ & \text{subject to the constraints (4.9)–(4.10)}, \\ & \text{the constraints (4.24)–(4.41)}, \\ & C \leq E. \end{aligned} \tag{4.43}$$

Model 5 (Tax with offset policy):

$$\begin{aligned} & \text{minimize } Z_1(x, y, z, w) \\ & \text{maximize } Z_2(x, y, z, w) \\ & \text{minimize } Z_3^{**}(x, y, z, w) = \theta_1 E + P\big[E - C\big]^+ \\ & +\theta_2 e_{CO_2}^2 \sum_{k=1}^{K}\sum_{p=1}^{P}\Big(\sum_{i=1}^{I} x_{ikp}^1 + \sum_{j=1}^{J} y_{jkp}^1 \\ & + \sum_{l=1}^{L} w_{lkp}^1\Big) + \theta_3 e_{CO_2}^3 \sum_{m=1}^{M}\sum_{p=1}^{P}\Big(\sum_{i=1}^{I} x_{imp}^3 \\ & + \sum_{j=1}^{J} y_{jmp}^3 + \sum_{l=1}^{L} w_{lmp}^2\Big) \\ & \text{subject to the constraints (4.9)–(4.10)}, \\ & \qquad \text{the constraints (4.24)–(4.41)}. \end{aligned}$$

In Model 5, the 3^{rd} objective function reveals that based on the value of cap, there exist two different feasible regions for carbon tax with offset policy. The problem is separated into two cases and the first is defined when cap is greater than the total carbon emission of transportation and second case is that when cap is less than the total carbon emission of transportation. First case is Model 5A, where no reward found for less emission and total emission cost is same as of Model 3, i.e., the problem becomes carbon emission with tax and cap. The second case is Model 5B, where penalty charge P is multiplied for extra emission $[E - C]$ and the system cannot buy their shortage permission with any cost. Therefore, total emission cost is increased by $P[E - C]$. For such two different cases, the models are elaborated as follows:

Model 5A

$$\begin{aligned}
&\text{minimize } Z_1(x, y, z, w)\\
&\text{maximize } Z_2(x, y, z, w)\\
&\text{minimize } Z_3^{**}(x, y, w, z) = \theta_1 E\\
&+\theta_2 e^2_{CO_2} \sum_{k=1}^{K} \sum_{p=1}^{P} \left(\sum_{i=1}^{I} x^1_{ikp} + \sum_{j=1}^{J} y^1_{jkp} + \sum_{l=1}^{L} w^1_{lkp} \right)\\
&+\theta_3 e^3_{CO_2} \sum_{m=1}^{M} \sum_{p=1}^{P} \left(\sum_{i=1}^{I} x^3_{imp} \right.\\
&\left. + \sum_{j=1}^{J} y^3_{jmp} + \sum_{l=1}^{L} w^2_{lmp} \right)
\end{aligned}$$

subject to the constraints (4.9)−(4.10),
the constraints (4.24)−(4.41),
the constraints (4.42).

Model 5B

$$\begin{aligned}
&\text{minimize } Z_1(x, y, z, w)\\
&\text{maximize } Z_2(x, y, z, w)\\
&\text{minimize } Z_3^{**}(x, y, w, z) = \theta_1 E + P\big[E - C\big]\\
&+\theta_2 e^2_{CO_2} \sum_{k=1}^{K} \sum_{p=1}^{P} \left(\sum_{i=1}^{I} x^1_{ikp} + \sum_{j=1}^{J} y^1_{jkp} \right.\\
&\left. + \sum_{l=1}^{L} w^1_{lkp} \right) + \theta_3 e^3_{CO_2} \sum_{m=1}^{M} \sum_{p=1}^{P} \left(\sum_{i=1}^{I} x^3_{imp} \right.\\
&\left. + \sum_{j=1}^{J} y^3_{jmp} + \sum_{l=1}^{L} w^2_{lmp} \right)
\end{aligned}$$

subject to the constraints (4.9)−(4.10),
the constraints (4.24)−(4.41),
the constraints (4.43).

The feasibility conditions of all the above models are same as of Model 2.

Proposition 4.1 *If we find the solutions of Model 4A and Model 4B then we compare them to select the final optimal solution of Model 4. However, if one of Model 4A or Model 4B provides a feasible solution and another cannot, then the feasible solution is the final optimal solution of Model 4. Similarly this holds for Model 5, Model 5A and Model 5B.*

Proposition 4.2 $Z_3^* \le Z_3^{**} \le Z_3$.

Proof The feasible region of "carbon tax with offset" policy is a strict subset of the feasible region of "carbon tax with cap-and-trade" policy. The feasible solution for carbon tax with offset policy has same objective value in both offset and cap-and-trade model. The first inequality is followed by this condition. Feasible region of carbon tax with cap policy is a strict subset of the feasible region of tax with offset policy. The emission cost for any solution that becomes feasible region of the carbon tax with cap policy has the same objective function in both tax with cap and tax with offset models. Thus, second inequality is fulfilled. This is the complete proof of the Proposition.

Definition 4.1 (*Pareto-optimal solution*) A solution $(x', y', z', w') \in F$ (where F is the feasible region) is said to be a Pareto-optimal solution (non-dominated solution) of Model 3 or Model 4A/Model 4B or Model 5A/Model 5B if and only if there is no other $(x, y, z, w) \in F$, such that $Z_s(x, y, z, w) \le Z_s(x', y', z', w')$, $s = 1, 3$, and $Z_2(x, y, z, w) \ge Z_2(x', y', z', w')$ for at least one inequality holds with strict inequality.

Solution methodology

In the proposed multi-objective optimization problem, each objective contradicts to each other objective, and there does not always exist a strategy for optimal solution which satisfies all the objective functions. That is the solution will be the best for one objective function and that may be worst for another objective function. Only Pareto-optimal solution exists on the border between feasible and non-feasible solutions, which is achieved by multi-objective optimization technique. From literature survey, we find various fuzzy and non-fuzzy techniques to provide Pareto-optimal solution of multi-objective decision making problem. Most of fuzzy techniques are FP, intuitionistic fuzzy programming, neutrosophic linear programming, PHFP, etc. From these methods, we choose two approved methods as FP and PHFP which generate Pareto-optimal solution through simple technical process. Established models are solved individually by utilizing these two methods that find Pareto-optimal solutions. The solution of each method for all models are analyzed. Thereafter we choose a preferable model for a better policy that provides a final Pareto-optimal solution.

FP

FP was initiated by Zimmermann [63] for solving any multi-objective linear programming problem. This is one of the simple fuzzy technique that provides Pareto-optimal solution in short elapsed time and simple way. To find the best Pareto-optimal solution, we utilize the facility of FP to solve our proposed MOSTP. The required steps are illustrated as follows:

- *Step 1:* Convert the PHF model to deterministic model and reformulate several crisp models for different policies of carbon mechanism.
- *Step 2:* Solve each problem individually with subject to all constraints.
- *Step 3:* Determine the positive ideal solution (PIS) and negative ideal solution (NIS) and formulate the membership function $\mu_s(Z_s(x))$ corresponding to each objective function $Z_s(x)$ by setting their tolerance. The membership function is defined as

$$\mu_s(Z_s(x)) = \begin{cases} 1, & \text{if } \; Z_s \le L_s^T, \\ \frac{U_s^T - Z_s}{U_s^T - L_s^T}, & \text{if } \; L_s^T \le Z_s \le U_s^T, \quad (s = 1, 3) \\ 0, & \text{if } \; Z_s \ge U_s^T, \end{cases}$$

and

$$\mu_s(Z_s(x)) = \begin{cases} 1, & \text{if } \; Z_s \ge U_s^T, \\ \frac{Z_s - L_s^T}{U_s^T - L_s^T}, & \text{if } \; L_s^T \le Z_s \le U_s^T, \quad (s = 2) \\ 0, & \text{if } \; Z_s \le L_s^T. \end{cases}$$

Here, PIS = $L_s^T = \min\{Z_{s1}, Z_{s2}, Z_{s3}\}$ and NIS = $U_s^T = \max\{Z_{s1}, Z_{s2}, Z_{s3}\}$, for $s = 1, 3$.
Again for $s = 2$, PIS = $U_s^T = \max\{Z_{s1}, Z_{s2}, Z_{s3}\}$ and NIS = $L_s^T = \min\{Z_{s1}, Z_{s2}, Z_{s3}\}$,
where $Z_{sr} = Z_s(X^r, Y^r)$ $(r = 1, 2, 3)$.

- *Step 4:* Maximize the degree of acceptance of each objective function and setting the degree of acceptance as θ, then Model 6 is developed with the help of FP as follows:
Model 6

$$\begin{aligned} &\text{maximize}\, \theta \\ &\text{subject to} \;\; \mu_s(Z_s(x)) \ge \theta \; (s = 1, 2, 3), \\ &\qquad \theta \in [0, 1], \\ &\qquad \text{the constraints } (4.9){-}(4.10), \\ &\qquad \text{the constraints } (4.24){-}(4.41), \\ &\qquad \text{the constraints } (4.42)/(4.43). \end{aligned}$$

Third objective is selected from Model 3, Model 4A/Model 4B and Model 5A/Model 5B, and added the constraints (4.42)/(4.43) with condition of cap.

- *Step 5:* Solve Model 6 by LINGO iterative scheme with finding maximum value of parameter θ and achieve the solution.

Theorem 5.1 *If $(x', y', z', w', \theta')$ is an optimal solution of Model 6 then it is also Pareto-optimal (non-dominated) solution of Model 3 or Model 4A/Model 4B or Model 5A/Model 5B or both.*

Proof Assuming that it is not true that (x', y', z', w') is a Pareto-optimal (non-dominated) solution of Model 3 or Model 4A/Model 4B or Model 5A/Model 5B or both. From Definition (4.1), we find that there exists at least one x, one y, one z and one w, such that $Z_s(x, y, z, w) \le Z_s(x', y', z', w')$ for $s = 1, 3$ and $Z_2(x, y, z, w) \ge Z_2(x', y', z', w')$ with at least one inequality holds for strict inequality. Membership function $\mu_s(Z_s(x, y, z, w))$ is strictly decreasing with respect to the corresponding objective function Z_s in [0, 1]. Hence, $\mu_s(Z_s(x, y, z, w)) \ge \mu_s(Z_s(x', y', z', w'))$ $\forall$ s and $\mu_s(Z_s(x, y, z, w)) > \mu_s(Z_s(x', y', z', w'))$ for at least one s. Now, $\theta = \min\; \mu_s(Z_s(x, y, z, w)) \ge \min\; \mu_s(Z_s(x', y', z', w')) = \theta'$ which contradicts that (x', y', z', w') is an optimal solution of Model 3 or Model 4A/Model 4B or Model 5A/Model 5B or both. Here, θ' is the value of θ at (x', y', z', w'). This completes the proof of the theorem. □

PHFP

For finding Pareto-optimal solution of the proposed MOSTP, a new modified programming approach PHFP based on PHFS is introduced here. PHFP maximizes Pythagorean hesitant membership grade and minimizes Pythagorean hesitant non-membership grade. The decision making concept through fuzzy set was first initialized by Bellman and Zadeh [6]. The fuzzy decision set ($\tilde{D}$) on a decision making problem can be defined by the intersection of fuzzy objective function ($\tilde{O}$) and fuzzy constraint ($\tilde{C}$). Pythagorean hesitant fuzzy decision ($\tilde{\tilde{D}}$) is an extension of fuzzy decision that can be described as $\tilde{\tilde{D}} = \tilde{\tilde{O}} \cap \tilde{\tilde{C}} = \{x, \mu_{\tilde{\tilde{D}}}, \nu_{\tilde{\tilde{D}}}\}$, where $\{\mu_{\tilde{\tilde{D}}}(x) \in (\mu_{\tilde{\tilde{O}}}(x) \cap \mu_{\tilde{\tilde{C}}}(x)) : \mu_{\tilde{\tilde{D}}}(x) \le \min\{\max(\mu_{\tilde{\tilde{O}}}(x) \cap \mu_{\tilde{\tilde{C}}}(x))\}\}$ and $\{\nu_{\tilde{\tilde{D}}}(x) \in (\nu_{\tilde{\tilde{O}}}(x) \cap \nu_{\tilde{\tilde{C}}}(x)) : \nu_{\tilde{\tilde{D}}}(x) \ge \max\{\min(\nu_{\tilde{\tilde{O}}}(x) \cap \nu_{\tilde{\tilde{C}}}(x))\}\}$. $\mu_{\tilde{\tilde{D}}}(x)$ and $\nu_{\tilde{\tilde{D}}}(x)$ are the sets of membership value of acceptance and rejection of PHF solution under PHF decision set, respectively, and $\tilde{\tilde{O}}$, $\tilde{\tilde{C}}$ are the hesitant fuzzy objective function and hesitant fuzzy constraint, respectively. Using such PHF solution criteria we represent the stepwise procedure for solving the proposed model(s) as follows:

- *Step 1:* Converting the PHF model into crisp model and solve each crisp objective problem independently with subject to all constraints for finding the solution.

- *Step 2:* Substituting the obtained solution of Step 1 in each objective function and determine PIS and NIS as of Step 3 (from PHFP).
- *Step 3:* Utilizing PIS and NIS, formulate the membership and non-membership function corresponding to each objective function in PHF environment as:
For $s = 1, 3$:

$$\mu_h^P(Z_s(x)) = \begin{cases} 1, & \text{if } Z_s(x) \le L_s, \\ \alpha_s\left(\frac{U_s - Z_s(x)}{U_s - L_s}\right), & \text{if } L_s \le Z_s(x) \le U_s, \\ 0, & \text{if } Z_s(x) \ge U_s, \end{cases}$$

$$\nu_h^P(Z_s(x)) = \begin{cases} 0, & \text{if } Z_s(x) \le L_s, \\ \beta_s\left(\frac{Z_s(x) - L_s}{U_s - L_s}\right), & \text{if } L_s \le Z_s(x) \le U_s, \\ 1, & \text{if } Z_s(x) \ge U_s. \end{cases}$$

For $s = 2$:

$$\mu_h^P(Z_s(x)) = \begin{cases} 0, & \text{if } Z_s(x) \le L_s, \\ \alpha_s\left(\frac{Z_s(x) - L_s}{U_s - L_s}\right), & \text{if } L_s \le Z_s(x) \le U_s, \\ 1, & \text{if } Z_s(x) \ge U_s, \end{cases}$$

$$\nu_h^P(Z_s(x)) = \begin{cases} 1, & \text{if } Z_s(x) \le L_s, \\ \beta_s\left(\frac{U_s - Z_s(x)}{U_s - L_s}\right), & \text{if } L_s \le Z_s(x) \le U_s, \\ 0, & \text{if } Z_s(x) \ge U_s. \end{cases}$$

The parameters $\alpha_s, \beta_s \in [0, 1]$ are the sets of hesitant values correspond to membership and non-membership functions, respectively, and selected by the DMs' own choice in PHF environment.
- *Step 4:* To find the highest degree for satisfaction and lowest degree for rejection, the PHFP model (modified from [3]) corresponding to MOSTP can be newly clarified in the following model:
Model 7

$$\begin{aligned} \text{maximize } & \xi^2 - \eta^2 \\ \text{subject to } & [\mu_h^P(Z_s(x))]^2 \ge \xi^2 \ (s = 1, 2, 3), \\ & [\nu_h^P(Z_s(x))]^2 \le \eta^2 \ (s = 1, 2, 3), \\ & \xi^2 \ge \eta^2, \\ & \xi^2 + \eta^2 \in [0, 1], \xi^2 \in [0, 1], \eta^2 \in [0, 1], \\ & \text{the constraints } (4.9)-(4.10), \\ & \text{the constraints } (4.24)-(4.41), \\ & \text{the constraints } (4.42)/(4.43). \end{aligned}$$

Here, ξ and η are the grades of membership and non-membership of each objective function.
- *Step 5:* Solving Model 7 by any mathematical programming with parameters ξ and η, and obtain Pareto-optimal solution of proposed model(s).

Theorem 5.2 *If $(x', y', z', w', \xi', \eta')$ is an optimal solution of Model 7 then it becomes a Pareto-optimal (non-dominated) solution of Model 3 or Model 4A/Model 4B or Model 5A/Model 5B or both.*

Proof Let (x', y', z', w') is not a Pareto-optimal (non-dominated) solution of Model 3 or Model 4A/Model 4B or Model 5A/Model 5B or both. From Definition (4.1), we consider that there exist at least one x, one y, one z and one w, such that $Z_s(x, y, z, w) \le Z_s(x', y', z', w')$ for $s = 1, 3$ and $Z_2(x, y, z, w) \ge Z_2(x', y', z', w')$ with at least one inequality holds for strict inequality. The membership function $\mu_s(Z_s(x, y, z, w))$ is strictly decreasing with respect to the corresponding objective function Z_s in [0, 1]. $\mu_s(Z_s(x, y, z, w)) \ge \mu_s(Z_s(x', y', z', w'))\ \forall\ s$ and $\mu_s(Z_s(x, y, z, w)) > \mu_s(Z_s(x', y', z', w'))$ for at least one s. The non-membership function $\nu_s(Z_s(x, y, z, w))$ is strictly increasing with respect to the corresponding objective function Z_s in [0, 1]. Hence, $\nu_s(Z_s(x, y, z, w)) \le \nu_s(Z_s(x', y', z', w'))\ \forall\, s$ and $\nu_s(Z_s(x, y, z, w)) < \nu_s(Z_s(x', y', z', w'))$ for at least one s. $\xi = \min\ \mu_s(Z_s(x, y, z, w)) \ge \min\ \mu_s(Z_s(x', y', z', w')) = \xi'$ and $\eta = \max\ \nu_s(Z_s(x, y, z, w)) \le \max\ \nu_s(Z_s(x', y', z', w')) = \eta'$. Thus, $\xi^2 - \eta^2 \ge \xi'^2 - \eta'^2$ contradicts that (x', y', z', w') is an optimal solution of Model 3 or Model 4A/Model 4B or Model 5A/Model 5B or both. ξ' and η' are the values of ξ and η at (x', y', z', w'), respectively. This completes the proof of the theorem. □

Remark 1 If the consequential part of the Pareto sets is nonconvex then Pascoletti–Serafini runs (Pascoletti and Serafini [38]) are required to approximate the part inside the vital accuracy. Combination of Sandwich and Hyperboxing algorithm finds the samples in both convex and non-convex regions. Sandwich approximation is suited to approximate the convex part, whereas non-convex part is efficiently computed by hyperboxing scheme. More details can be seen from

Küfer et al. [22]. The DMs navigate (see the Appendix B of Bortz et al. [7]) on the whole Pareto set to find a tradeoff between best compromises, and reach a final decision by comparing several alternatives with respect to distinct objectives.

Advantages and limitations

Some advantages with limitations are provided in this section.

- We have generated a model of MOSTP by the link of SWM and SD. The contribution of this model is that the three sections of sustainability are optimized in the sense of urban or rural development.
- Three types of combined policy of carbon mechanism are analyzed to minimize carbon emission by providing some facilities or relaxations to the user and to government or a third party. This is the supporting fact to reduce GHG

emission and the study provides an opportunity to choose an appropriate choice among several policies which are suitable for the user.

- Extending PFS and HFS, we select a new environment as PHFS in our study. The facility is that this study is prepared to challenge any difficult uncertainty.
- A new programming approach PHFP is implemented to find the Pareto-optimal solution of the proposed model. The advantage is that this method is always capable to find the solution of any multi-objective decision making problem.
- One of the limitations is that here we did not introduce any type of vehicle that emits zero carbon. We are not considered the carbon emission from deterioration, but nowadays this is a common issue of transportation when transporting perishable items. Here, we did not choose the deterioration rate, but some perishable items are transported here, and we did not impose any type of preservation technology that may help to prevent deterioration.
- Our selected environment (PHF) is differ from stochastic environment, as the models may be solved by several methods and provided more space for uncertain factors. However, stochastic system always focuses on data. PHF environment measures the degree of uncertainty of event that may occur or may not occurs. In contrast for stochastic environment, the randomness always presents the uncertainty of the event of occurrence.
- The proposed methods (FP and PHFP) have advantages as the arithmetic mean and standard deviation are not necessary, but in stochastic programming these are required. The disadvantage of FP and PHFP is that in these programming all the parameters must be in deterministic form, but in stochastic programming some or each parameter(s) are in uncertain nature. Stochastic programming [59] not only optimizes the criteria of decision maker, but also measures the uncertainty of parameters in approximate value, whereas this measure cannot be found in FP and PHFP.

Real-life experiments

In this section, we study two real-life problems to examine the effectiveness of our proposed model. Connecting with industrial organizations and for rural/urban development we start with two types of sources as $I(=2)$ and $J(=3)$ for agriculture field and forest department, respectively. Mainly SWM with transportation system controls such problem by transporting the fresh items and waste items into three types (K, L, M) of destinations for future storage and for recycle. The recycle plants are as $K(=2)$ for bio-fuel production and $M(=2)$ for compost production from waste items. Here, $L(=2)$ is considered for cold storage that stores fresh items for future marketing with high profit. After producing bio-fuel and compost, these items are transported into market for resell and we select $N(=3)$ for bio-fuel supply centre and $R(=3)$ for compost selling market centre. For transporting the items, $P(=2)$ types of vehicles are considered here. All the required data are presented in Tables 5, 6, 7, 8 and 9. Source, demand and conveyance are considered here as TrPHFN and we use ranking index for defuzzification of the parameters. To find most simplified ranking value, we select the set of two hesitant values (corresponding to Pythagorean hesitant membership and non-membership function) as minimum of membership grades and maximum of non-membership grades, respectively. For SD, three objective functions are optimized by minimizing transportation cost, maximizing job opportunity and minimizing carbon emission with carbon mechanism. For "carbon tax with cap-and-trade" policy and for "carbon tax with offset" policy, the designed problem is divided into two cases separately. For "carbon tax with cap" policy, the problem becomes another case which is different from the other two policies.

Experimental data design

Example 2 In this example we input carbon cap $C = 25000$ gm, and carbon tax, penalty charge, buying or selling permission cost for surplus or slack carbon emission are provided. For two types of recycle plants, there exist two types of carbon tax. Here, all types of cost is in \$, job opportunity in job, distance in kilometers (km), unit of items in ton are defined.

Example 3 Here, we reduce carbon cap as $C = 18000$ gm to check the effect of carbon mechanism. Except cap value, all the other parameters remain identical as of Example 2.

Now, we solve two examples with considering three policies of carbon mechanism by keeping fixed the carbon cap.

Results and comparison analysis

This section includes the results of two numerical examples, provides graphical presentation for comparison analysis, and reports the model validation.

Allocation from case study

Here, we find the optimal allocations by evaluating two examples by regarding three policies and by the help of PHFP and FP. In Example 2, cap $C = 25000$ gm provides feasible solutions of three policies with all cases and solutions are presented in Table 10. For Example 3, when cap $C = 18000$ gm then only second case of second policy (i.e., tax with

Table 5 Supply, demand of 1st stage, demand of 2nd stage, conveyance capacity in TrPHFNs and their ranking values

$\tilde{\tilde{a}}_1^1 = (\langle(150, 250, 350, 450); (0.6, 0.7), (0.1, 0.3, 0.6)\rangle; 0.6, 0.6); \Re(\tilde{\tilde{a}}_1^1) = 300$
$\tilde{\tilde{a}}_2^1 = (\langle(325, 350, 375, 400); (0.4, 0.6), (0.1, 0.2, 0.4)\rangle; 0.4, 0.4); \Re(\tilde{\tilde{a}}_2^1) = 362.5$
$\tilde{\tilde{a}}_1^2 = (\langle(250, 300, 350, 400); (0.25, 0.6), (0.1, 0.25)\rangle; 0.25, 0.25); \Re(\tilde{\tilde{a}}_1^2) = 325$
$\tilde{\tilde{a}}_2^2 = (\langle(180, 240, 300, 360); (0.5, 0.6, 0.7), (0.3, 0.5)\rangle; 0.5, 0.5); \Re(\tilde{\tilde{a}}_2^2) = 270$
$\tilde{\tilde{a}}_3^2 = (\langle(265, 290, 315, 340); (0.3, 0.5), (0.1, 0.2, 0.3)\rangle; 0.3, 0.3); \Re(\tilde{\tilde{a}}_3^2) = 302.5$
$\tilde{\tilde{b}}_1^{11} = (\langle(96, 119, 142, 165); (0.45, 0.65), (0.1, 0.2, 0.45)\rangle; 0.45, 0.45); \Re(\tilde{\tilde{b}}_1^{11}) = 130.5$
$\tilde{\tilde{b}}_2^{11} = (\langle(120, 150, 180, 210); (0.35, 0.45, 0.55), (0.1, 0.35)\rangle; 0.35, 0.35); \Re(\tilde{\tilde{b}}_2^{11}) = 165$
$\tilde{\tilde{b}}_1^{12} = (\langle(165, 180, 195, 210); (0.3, 0.6), (0.1, 0.2, 0.3)\rangle; 0.3, 0.3); \Re(\tilde{\tilde{b}}_1^{12}) = 187.5$
$\tilde{\tilde{b}}_2^{12} = (\langle(133.5, 172, 210.5, 249); (0.6, 0.9), (0.1, 0.4, 0.6)\rangle; 0.6, 0.6); \Re(\tilde{\tilde{b}}_1^{12}) = 191.25$
$\tilde{\tilde{b}}_1^{13} = (\langle(60, 113, 166, 219); (0.4, 0.7), (0.2, 0.3, 0.4)\rangle; 0.4, 0.4); \Re(\tilde{\tilde{b}}_1^{13}) = 139.5$
$\tilde{\tilde{b}}_2^{13} = (\langle(97.5, 130, 162.5, 195); (0.5, 0.7), (0.1, 0.2, 0.5)\rangle; 0.5, 0.5); \Re(\tilde{\tilde{b}}_1^{13}) = 146.25$
$\tilde{\tilde{b}}_1^{21} = (\langle(34, 50, 66, 82); (0.6, 0.9), (0.2, 0.4, 0.6)\rangle; 0.6, 0.6); \Re(\tilde{\tilde{b}}_1^{21}) = 58$
$\tilde{\tilde{b}}_2^{21} = (\langle(25, 40, 55, 70); (0.55, 0.95), (0.15, 0.35, 0.55)\rangle; 0.55, 0.55); \Re(\tilde{\tilde{b}}_2^{21}) = 47.5$
$\tilde{\tilde{b}}_3^{21} = (\langle(55, 70, 85, 100); (0.45, 0.75), (0.1, 0.2, 0.45)\rangle; 0.45, 0.45); \Re(\tilde{\tilde{b}}_3^{21}) = 77.5$
$\tilde{\tilde{b}}_1^{22} = (\langle(22.5, 30, 37.5, 45); (0.65, 0.85, 0.95), (0.3, 0.65)\rangle; 0.65, 0.65); \Re(\tilde{\tilde{b}}_1^{22}) = 33.75$
$\tilde{\tilde{b}}_2^{22} = (\langle(68, 80, 92, 104); (0.45, 0.8), (0.25, 0.35, 0.45)\rangle; 0.45, 0.45); \Re(\tilde{\tilde{b}}_2^{22}) = 86$
$\tilde{\tilde{b}}_3^{22} = (\langle(35, 45, 55, 65); (0.55, 0.95), (0.15, 0.55)\rangle; 0.55, 0.55); \Re(\tilde{\tilde{b}}_3^{22}) = 50$
$\tilde{\tilde{e}}_1 = (\langle(100, 200, 300, 400); (0.4, 0.6, 0.8), (0.1, 0.4)\rangle; 0.4, 0.4); \Re(\tilde{\tilde{e}}_1) = 250$
$\tilde{\tilde{e}}_2 = (\langle(325, 350, 375, 400); (0.7, 0.9), (0.1, 0.3, 0.7)\rangle; 0.7, 0.7); \Re(\tilde{\tilde{e}}_2) = 362.5$

Table 6 Transportation cost

c_{ikp}^{11}	$c_{111}^{11} = 7, c_{112}^{11} = 8; c_{121}^{11} = 6, c_{122}^{11} = 9; c_{211}^{11} = 7, c_{212}^{11} = 9.5; c_{221}^{11} = 11, c_{222}^{11} = 6;$
c_{ilp}^{12}	$c_{111}^{12} = 17, c_{112}^{12} = 11; c_{121}^{12} = 9, c_{122}^{12} = 13; c_{211}^{12} = 12, c_{212}^{12} = 16; c_{221}^{12} = 16, c_{222}^{12} = 10;$
c_{imp}^{13}	$c_{111}^{13} = 6, c_{112}^{13} = 8; c_{121}^{13} = 10, c_{122}^{13} = 7; c_{211}^{13} = 9, c_{212}^{13} = 11; c_{221}^{13} = 6, c_{222}^{13} = 10;$
c_{jkp}^{21}	$c_{111}^{21} = 7.5, c_{112}^{21} = 8; c_{121}^{21} = 7, c_{122}^{21} = 5.5; c_{211}^{21} = 6.5, c_{212}^{21} = 8; c_{221}^{21} = 9, c_{222}^{21} = 8.5; c_{311}^{21} = 9.5, c_{312}^{21} = 5.5; c_{321}^{21} = 5, c_{322}^{21} = 9;$
c_{jlp}^{22}	$c_{111}^{22} = 8, c_{112}^{22} = 12; c_{121}^{22} = 14, c_{122}^{22} = 9; c_{211}^{22} = 16, c_{212}^{22} = 13; c_{221}^{22} = 9, c_{222}^{22} = 15; c_{311}^{22} = 17, c_{312}^{22} = 8.5; c_{321}^{22} = 10, c_{322}^{22} = 14;$
c_{jmp}^{23}	$c_{111}^{23} = 5, c_{112}^{23} = 7; c_{121}^{23} = 6, c_{122}^{23} = 8; c_{211}^{23} = 7, c_{212}^{23} = 9; c_{221}^{23} = 6, c_{222}^{23} = 8; c_{311}^{23} = 5, c_{312}^{23} = 10; c_{321}^{23} = 8, c_{322}^{23} = 9.5;$
c_{lkp}^{31}	$c_{111}^{31} = 7, c_{112}^{31} = 9; c_{121}^{31} = 6, c_{122}^{31} = 8; c_{211}^{31} = 6, c_{212}^{31} = 7.5; c_{221}^{31} = 5, c_{222}^{31} = 9;$
c_{lmp}^{32}	$c_{111}^{32} = 6, c_{112}^{32} = 5; c_{121}^{32} = 6, c_{122}^{32} = 8; c_{211}^{32} = 5, c_{212}^{32} = 6.5; c_{221}^{32} = 9, c_{222}^{32} = 7;$
c_{knp}^{41}	$c_{111}^{41} = 9, c_{112}^{41} = 8; c_{121}^{41} = 10, c_{122}^{41} = 8.5; c_{211}^{41} = 10, c_{212}^{41} = 8; c_{221}^{41} = 7.5, c_{222}^{41} = 9; c_{131}^{41} = 10.5, c_{132}^{41} = 9.5; c_{231}^{41} = 10, c_{232}^{41} = 8;$
c_{mrp}^{42}	$c_{111}^{42} = 8, c_{112}^{42} = 10; c_{121}^{42} = 9, c_{122}^{42} = 8.5; c_{211}^{42} = 6, c_{212}^{42} = 9.5; c_{221}^{42} = 6.5, c_{222}^{42} = 9; c_{131}^{42} = 5.5, c_{132}^{42} = 7.5; c_{231}^{42} = 8, c_{232}^{42} = 10;$

Table 7 Job opportunity of whole process

η_i^1	$\eta_1^1 = 3, \eta_2^1 = 4$
η_j^2	$\eta_1^2 = 5, \eta_2^2 = 6, \eta_3^2 = 7$
η_k^3	$\eta_1^3 = 9, \eta_2^3 = 10$
η_l^4	$\eta_1^4 = 5, \eta_2^4 = 6$
η_m^5	$\eta_1^5 = 7, \eta_2^5 = 8$
η_n^6	$\eta_1^6 = 2, \eta_2^6 = 3, \eta_3^6 = 5$
η_r^7	$\eta_1^7 = 2, \eta_2^7 = 4, \eta_3^7 = 6$

cap-and-trade policy) and second case of third policy (i.e., tax with offset policy) provide the feasible solutions defined in Table 11. If total emission is less than carbon cap then this example provides no feasible solution (NFS). The objective values in both examples with two methods are summarized in Table 12 and the preferable method, PHFP is highlighted by bold face for suitable comparison. Observing all over the objective values for the considered methods, we pick an appropriate solution to specify the final Pareto-optimal solution of both examples and star mark uses to select a bet-

Table 8 Distance in km for transportation

d_{ikp}^{11}	$d_{111}^{11}=65, d_{112}^{11}=75; d_{121}^{11}=52, d_{122}^{11}=45; d_{211}^{11}=67, d_{212}^{11}=58; d_{221}^{11}=37, d_{222}^{11}=30;$
d_{ilp}^{12}	$d_{111}^{12}=33, d_{112}^{12}=58; d_{121}^{12}=47, d_{122}^{12}=28; d_{211}^{12}=40, d_{212}^{12}=25; d_{221}^{12}=47, d_{222}^{12}=68;$
d_{imp}^{13}	$d_{111}^{13}=71, d_{112}^{13}=48; d_{121}^{13}=37, d_{122}^{13}=66; d_{211}^{13}=77, d_{212}^{13}=58; d_{221}^{13}=65, d_{222}^{13}=41;$
d_{jkp}^{21}	$d_{111}^{21}=40, d_{112}^{21}=75; d_{121}^{21}=47, d_{122}^{21}=82; d_{211}^{21}=72, d_{212}^{21}=53; d_{221}^{21}=74, d_{222}^{21}=41; d_{311}^{21}=93, d_{312}^{21}=45; d_{321}^{21}=83, d_{322}^{21}=70;$
d_{jlp}^{22}	$d_{111}^{22}=30, d_{112}^{22}=18; d_{121}^{22}=87, d_{122}^{22}=23; d_{211}^{22}=90, d_{212}^{22}=33; d_{221}^{22}=17, d_{222}^{22}=38; d_{311}^{22}=15, d_{312}^{22}=28; d_{321}^{22}=10, d_{322}^{22}=48;$
d_{jmp}^{23}	$d_{111}^{23}=30, d_{112}^{23}=54; d_{121}^{23}=71, d_{122}^{23}=48; d_{211}^{23}=36, d_{212}^{23}=23; d_{221}^{23}=30, d_{222}^{23}=62; d_{311}^{23}=80, d_{312}^{23}=43; d_{321}^{23}=30, d_{322}^{23}=64;$
d_{lkp}^{31}	$d_{111}^{31}=60, d_{112}^{31}=42; d_{121}^{31}=97, d_{122}^{31}=68; d_{211}^{31}=56, d_{212}^{31}=65; d_{221}^{31}=40, d_{222}^{31}=22;$
d_{lmp}^{32}	$d_{111}^{32}=40, d_{112}^{32}=70; d_{121}^{32}=87, d_{122}^{32}=33; d_{211}^{32}=41, d_{212}^{32}=70; d_{221}^{32}=43, d_{222}^{32}=66;$
d_{knp}^{41}	$d_{111}^{41}=77, d_{112}^{41}=40; d_{121}^{41}=57, d_{122}^{41}=38; d_{211}^{41}=77, d_{212}^{41}=52; d_{221}^{41}=67, d_{222}^{41}=88; d_{311}^{41}=62, d_{312}^{41}=41; d_{321}^{41}=65, d_{322}^{41}=80;$
d_{mrp}^{42}	$d_{111}^{42}=48, d_{112}^{42}=69; d_{121}^{42}=71, d_{122}^{42}=83; d_{211}^{42}=92, d_{212}^{42}=50; d_{221}^{42}=85, d_{222}^{42}=67; d_{311}^{42}=79, d_{312}^{42}=93; d_{321}^{42}=40, d_{322}^{42}=81;$

Table 9 Carbon emission rate, tax, carbon trading cost, penalty charge, rate of waste creation from cold storage

Parameters with their values
$e_{CO_2}^1=0.60$ gm/km, $e_{CO_2}^2=0.40$ gm/kg, $e_{CO_2}^3=0.50$ gm/kg, $\theta_1=0.30, \theta_2=0.50, \theta_3=0.40, \phi=0.5, \psi=0.3, P=0.6, \alpha=10\%, \beta=15\%$

ter policy among three policies of carbon mechanism which declares as final result.

Discussion with graphical presentation

Tables 10 and 11 provide the Pareto-optimal solution of two numerical examples, respectively. From these tables, we find the objective values which define the main differences between the solutions. Table 10 shows that here the cap value is greater, and therefore, all the policies provide feasible solution in two methods. In Table 11, where cap value is lower and hence only Model 4B and Model 5B give solution. That is the two tables does not display the same type of solutions of two numerical examples, respectively.

From Table 12, we highlight the different optimal solutions in FP and PHFP for several reasons. FP supports only on the membership grades of the objective functions, but PHFP considers both the membership and non-membership grades of the objectives. FP maximizes the membership grade but PHFP maximizes the degree of satisfaction by finding highest value of Pythagorean hesitant membership grade and minimizes the degree of rejection by providing lowest value of Pythagorean hesitant non-membership grade. The hesitancy of membership and non-membership is tackled in PHFP, whereas FP cannot face to any hesitancy. PHFP overcomes different complexities, and displays more efficient Pareto-optimal solutions than FP as DMs have a privilege to choose the efficient solution in a technical way by setting the hesitant values for each membership and non-membership function.

Between FP and PHFP, we select PHFP as a better method which provides final Pareto-optimal solution of both examples. From Table 12, we note that Example 2 provides feasible

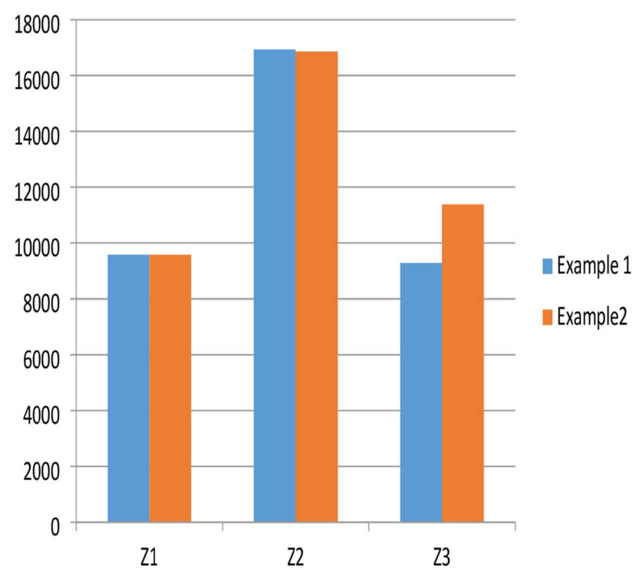

Fig. 2 Graphical presentation of three objective values for two examples

solution in two methods with all of three policies. However, for Example 3, only Model 4B and Model 5B provide objective values, whereas the other cases have NFS in both methods. We compare three policies of both examples in two methods and notice that "carbon tax with cap-and-trade" policy (i.e., Model 4A and Model 4B) provides appropriate result than other two policies. In this policy we analyze that when total emission is less than carbon cap (i.e., Model 4A) then the organization can sell extra unused carbon units and find a profit that reduced emission cost 7214.13$. If total emission is greater than carbon cap (i.e., Model 4B) then organization

Table 10 Solution of Example 2

	FP	PHFP
Model 3	$\theta = 0.4055$; $x^1_{222} = 141.36$; $y^1_{111} = 45.14$, $y^1_{312} = 66.11$, $y^2_{112} = 187.5$, $y^2_{321} = 236.39$, $y^3_{212} = 136.99$, $y^3_{221} = 101.65$; $w^1_{111} = 18.75$, $w^1_{222} = 23.64$, $w^2_{122} = 28.12$, $w^2_{211} = 2.51$, $w^2_{221} = 16.48$; $z^1_{112} = 58$, $z^1_{122} = 47.5$, $z^1_{132} = 77.5$, $z^2_{111} = 33.75$, $z^2_{222} = 86$, $z^2_{231} = 50$; the other variables are zero	$\xi = 0.6504179$, $\eta = 0.3489311 \times 10^{-3}$; $x^1_{222} = 145.88$; $y^1_{111} = 109.93$, $y^1_{312} = 1.32$, $y^2_{112} = 187.5$, $y^2_{321} = 191.25$, $y^3_{111} = 27.57$, $y^3_{212} = 111.93$, $y^3_{221} = 103.78$; $w^1_{111} = 18.75$, $w^1_{222} = 19.12$, $w^2_{122} = 28.12$, $w^2_{221} = 14.34$; $z^1_{112} = 58$, $z^1_{122} = 47.5$, $z^1_{132} = 77.5$, $z^2_{111} = 33.75$, $z^2_{222} = 86$, $z^2_{231} = 50$; the other variables are zero
Model 4A	$\theta = 0.4040012$; $x^1_{222} = 141.37$; $y^1_{111} = 45$, $y^1_{312} = 66.24$, $y^2_{112} = 187.5$, $y^2_{321} = 236.25$, $y^3_{212} = 137.79$, $y^3_{221} = 101.26$; $w^1_{111} = 18.75$, $w^1_{222} = 23.62$, $w^2_{122} = 28.12$, $w^2_{211} = 1.71$, $w^2_{221} = 16.87$; $z^1_{112} = 58$, $z^1_{122} = 47.5$, $z^1_{132} = 77.5$, $z^2_{111} = 33.75$, $z^2_{222} = 86$, $z^2_{231} = 50$; the other variables are zero	$\xi = 0.6893016$, $\eta = 0.3106915 \times 10^{-5}$; $x^1_{222} = 145.88$; $y^1_{111} = 98.46$, $y^1_{312} = 12.79$, $y^2_{112} = 187.5$, $y^2_{321} = 191.25$, $y^3_{111} = 39.04$, $y^3_{212} = 100.46$, $y^3_{221} = 103.78$; $w^1_{111} = 18.75$, $w^1_{222} = 19.12$, $w^2_{122} = 28.12$, $w^2_{221} = 14.34$; $z^1_{112} = 58$, $z^1_{122} = 47.5$, $z^1_{132} = 77.5$, $z^2_{111} = 33.75$, $z^2_{222} = 86$, $z^2_{231} = 50$; the other variables are zero
Model 4B	$\theta = 0.5593774$; $x^1_{121} = 250$, $x^1_{222} = 362.5$; $y^1_{121} = 0.62$, $y^1_{312} = 268.12$, $y^2_{111} = 153.12$, $y^2_{122} = 94.38$, $y^2_{221} = 96.88$, $y^2_{312} = 34.38$, $y^3_{111} = 76.88$, $y^3_{221} = 173.12$; $w^1_{111} = 18.75$, $w^1_{212} = 362.5$, $w^1_{221} = 9.56$, $w^2_{111} = 28.12$, $w^2_{112} = 18.68$, $w^2_{211} = 28.69$; $z^1_{122} = 47.5$, $z^1_{212} = 237.5$, $z^1_{232} = 77.5$, $z^2_{111} = 33.75$, $z^2_{122} = 13.87$, $z^2_{221} = 72.12$, $z^2_{231} = 144.12$; other variables are zero.	$\xi = 0.9642012$, $\eta = 0.357892 \times 10^{-6}$; $x^1_{222} = 155.44$; $y^1_{312} = 111.25$, $y^2_{111} = 58.75$, $y^2_{221} = 128.75$, $y^2_{312} = 128.75$, $y^2_{321} = 62.5$, $y^3_{111} = 87.69$, $y^3_{221} = 141.25$; $w^1_{111} = 18.75$, $w^1_{221} = 9.56$, $w^2_{111} = 23.12$, $w^2_{122} = 5$, $w^2_{211} = 28.69$; $z^1_{112} = 58$, $z^1_{122} = 47.5$, $z^1_{132} = 77.5$, $z^2_{111} = 33.75$, $z^2_{221} = 62.29$, $z^2_{222} = 23.71$, $z^2_{231} = 50$; the other variables are zero
Model 5A	$\theta = 0.4055$; $x^1_{222} = 141.36$; $y^1_{111} = 45.14$, $y^1_{312} = 66.11$, $y^2_{112} = 187.5$, $y^2_{321} = 236.39$, $y^3_{212} = 136.99$, $y^3_{221} = 101.65$; $w^1_{111} = 18.75$, $w^1_{222} = 23.64$, $w^2_{122} = 28.12$, $w^2_{211} = 2.51$, $w^2_{221} = 16.48$; $z^1_{112} = 58$, $z^1_{122} = 47.5$, $z^1_{132} = 77.5$, $z^2_{111} = 33.75$, $z^2_{222} = 86$, $z^2_{231} = 50$; the other variables are zero	$\xi = 0.6504179$, $\eta = 0.3489311 \times 10^{-3}$; $x^1_{222} = 145.88$; $y^1_{111} = 109.93$, $y^1_{312} = 1.32$, $y^2_{112} = 187.5$, $y^2_{321} = 191.25$, $y^3_{111} = 27.57$, $y^3_{212} = 111.93$, $y^3_{221} = 103.78$; $w^1_{111} = 18.75$, $w^1_{222} = 19.12$, $w^2_{122} = 28.12$, $w^2_{221} = 14.34$; $z^1_{112} = 58$, $z^1_{122} = 47.5$, $z^1_{132} = 77.5$, $z^2_{111} = 33.75$, $z^2_{222} = 86$, $z^2_{231} = 50$; the other variables are zero
Model 5B	$\theta = 0.560517$; $x^1_{121} = 250$, $x^1_{222} = 362.5$; $y^1_{121} = 0.62$, $y^1_{312} = 268.12$, $y^2_{111} = 153.12$, $y^2_{122} = 94.38$, $y^2_{221} = 96.88$, $y^2_{312} = 34.38$, $y^3_{111} = 76.88$, $y^3_{221} = 173.12$; $w^1_{111} = 18.75$, $w^1_{212} = 362.5$, $w^1_{221} = 9.56$, $w^2_{111} = 28.12$, $w^2_{112} = 35.10$, $w^2_{211} = 28.69$; $z^1_{122} = 47.5$, $z^1_{212} = 237.5$, $z^1_{232} = 77.5$, $z^2_{111} = 33.75$, $z^2_{122} = 3.28$, $z^2_{221} = 82.72$, $z^2_{231} = 133.53$; the other variables are zero.	$\xi = 0.968533$, $\eta = 0.3137012 \times 10^{-5}$; $x^1_{222} = 155.44$; $y^1_{312} = 111.25$, $y^2_{111} = 80.94$, $y^2_{122} = 22.19$, $y_{221} = 123.75$, $y^2_{312} = 106.56$, $y^2_{321} = 45.31$, $y^3_{111} = 82.69$, $y^3_{221} = 146.25$; $w^1_{111} = 18.75$, $w^1_{221} = 9.56$, $w^2_{111} = 28.12$, $w^2_{211} = 28.69$; $z^1_{112} = 58$, $z^1_{122} = 47.5$, $z^1_{132} = 77.5$, $z^2_{111} = 33.75$, $z^2_{221} = 86$, $z^2_{231} = 50$; the other variables are zero

Table 11 Solution of Example 3

	FP	PHFP
Model 3	NFS	NFS
Model 4A	NFS	NFS
Model 4B	$\theta = 0.5597309$; $x_{121}^1 = 250$, $x_{222}^1 = 362.5$; $y_{121}^1 = 0.62$, $y_{312}^1 = 268.12$, $y_{111}^2 = 153.12$, $y_{122}^2 = 94.38$, $y_{221}^2 = 96.88$, $y_{312}^2 = 34.38$, $y_{111}^3 = 76.88$, $y_{221}^3 = 173.12$; $w_{111}^1 = 18.75$, $w_{212}^1 = 362.5$, $w_{221}^1 = 9.56$, $w_{111}^2 = 28.12$, $w_{112}^2 = 18.02$, $w_{211}^2 = 28.69$; $z_{122}^1 = 47.5$, $z_{212}^1 = 237.5$, $z_{232}^1 = 77.5$, $z_{111}^2 = 33.75$, $z_{122}^2 = 13.49$, $z_{221}^2 = 72.51$, $z_{231}^2 = 143.74$; the other variables are zero.	$\xi = 0.964209$, $\eta = 0.3578132 \times 10^{-6}$; $x_{222}^1 = 155.44$; $y_{312}^1 = 111.25$, $y_{111}^2 = 58.75$, $y_{221}^2 = 151.88$, $y_{312}^2 = 128.75$, $y_{321}^2 = 39.38$, $y_{111}^3 = 110.81$, $y_{221}^3 = 118.12$; $w_{111}^1 = 18.75$, $w_{221}^1 = 9.56$, $w_{122}^2 = 28.12$, $w_{211}^2 = 28.69$; $z_{112}^1 = 58$, $z_{122}^1 = 47.5$, $z_{132}^1 = 77.5$, $z_{111}^2 = 33.75$, $z_{221}^2 = 62.21$, $z_{222}^2 = 23.79$, $z_{231}^2 = 50$; the other variables are zero
Model 5A	NFS	NFS
Model 5B	$\theta = 0.5598021$; $x_{121}^1 = 250$, $x_{222}^1 = 362.5$; $y_{121}^1 = 0.62$, $y_{312}^1 = 268.12$, $y_{111}^2 = 153.12$, $y_{122}^2 = 94.38$, $y_{221}^2 = 96.88$, $y_{312}^2 = 34.38$, $y_{111}^3 = 76.88$, $y_{221}^3 = 173.12$; $w_{111}^1 = 18.75$, $w_{212}^1 = 362.5$, $w_{221}^1 = 9.56$, $w_{111}^2 = 28.12$, $w_{112}^2 = 19.04$, $w_{211}^2 = 28.69$; $z_{122}^1 = 47.5$, $z_{212}^1 = 237.5$, $z_{232}^1 = 77.5$, $z_{111}^2 = 33.75$, $z_{122}^2 = 12.83$, $z_{221}^2 = 73.17$, $z_{231}^2 = 143.08$; the other variables are zero.	$\xi = 0.9640934$, $\eta = 0.3581019 \times 10^{-5}$; $x_{222}^1 = 155.44$; $y_{312}^1 = 111.25$, $y_{111}^2 = 58.75$, $y_{221}^2 = 151.88$, $y_{312}^2 = 128.75$, $y_{321}^2 = 39.38$, $y_{111}^3 = 110.81$, $y_{221}^3 = 118.12$; $w_{111}^1 = 18.75$, $w_{221}^1 = 9.56$, $w_{122}^2 = 28.12$, $w_{211}^2 = 28.69$; $z_{112}^1 = 58$, $z_{122}^1 = 47.5$, $z_{132}^1 = 77.5$, $z_{111}^2 = 33.75$, $z_{221}^2 = 61.97$, $z_{222}^2 = 24.03$, $z_{231}^2 = 50$; the other variables are zero

purchases the deficit carbon unit and pays a penalty charge for extra emission. In such case total carbon emission cost is increased and it is 9283.47\$. We find that carbon emission cost 7390.37\$ (Model 3 and Model 5A) and 10527.32\$ (Model 5B) are obtained for "carbon tax with cap" and "carbon tax with offset" policy, which indicate that emission cost is increased that of the previous policy. In this policy, when total emission is greater than carbon cap (i.e., Model 5B) then the organization pays a penalty charge but could not purchase their deficit carbon units. Whenever total emission is less than carbon cap (i.e., Model 3 and Model 5A) then the system cannot sell their surplus carbon unit and emission cost is not decreased. Therefore, Model 4A is better than Model 5A and Model 3, and Model 4B is better than Model 5B. Model 5A has a disadvantage that for low emission the system does not find any reward, whereas Model 4A finds such reward by selling their extra permission. Between Model 4A and Model 4B, we fix Model 4B of Example 2 and also Model 4B of Example 3, to provide final Pareto-optimal solution, as this model minimizes transportation cost and at the same time maximizes job opportunity. However, Model 4A only provides less emission cost than of Model 4B. For better comparison, we define three objective values of both example in Fig. 2. This graph defines the effect of carbon mechanism by the third objective value which variates for several cap values, i.e., these show that total emission cost of Example 2 is less than that of Example 3. Carbon market has made "carbon tax with cap-and-trade" mechanism that becomes a larger policy and attractive in many countries for reduction of carbon emission, and this policy measures the limit index of carbon emission for a sustainable transportation as well as for industrial problem. The case when the carbon cap is high (i.e., Example 2) then the system can choose high emission vehicles with minimum transportation cost, and therefore, carbon emission cost will be reduce, as at this time penalty charge is not included. If carbon cap is low (cf. Example 3), then the organization prefers low emission car with high transportation cost. Here carbon emission cost is increased for penalty charge as for exceed emission. The advantage of carbon mechanism is that it encourages the user to use alternative source of energy and always selects a better policy. Analyzing all the three policies of carbon mechanism we prefer "carbon tax with cap-and-trade" policy.

Model validation

In this subsection, we inspect the affect of hesitant parameters α_s and β_s on three objective functions (Model 4B and Example 2). We validate the proposed PHFP model by selecting 9 random achievements of the parameters under 10 violations. Each hesitant parameter generates a random number in [0, 1]. The optimal values of objective functions are resulted by PHFP model. Tables 13 and 14 display the objective val-

Table 12 Objective values of two examples

Models	Methods	Example 2 (Cap C=25000)	Example 3 (Cap C=18000)
Model 3	FP	(11784.86 ,17419.2, 7501.48)	NFS
Model 3	PHFP	**(11342.77, 16666.05, 7390.37)**	NFS
Model 4A	FP	(11787.48, 17417.45, 7383.03)	NFS
Model 4A	PHFP	**(11273.95, 16677.52, 7214.13)**	NFS
Model 4B	FP	(18052.4, 34824.3, 34775.09)	(18045.27, 34811.69, 36853.44)
Model 4B	PHFP	**(9572.09, 16935.56, 9283.47)***	**(9572.27, 16861.18, 11379.91)***
Model 5A	FP	(11784.86, 17419.2, 7501.48)	NFS
Model 5A	PHFP	**(11342.77, 16666.05, 7390.37)**	NFS
Model 5B	FP	(18028.67, 34883.92, 48659.99)	(18043.87, 34821.83, 52445.68)
Model 5B	PHFP	**(9479.52, 16856.8, 10527.32)**	**(9572.87, 16861.18, 14311.95)**

Bold form highlight that the results obtained in Pythagorean hesitant fuzzy programming (PHFP) are better than in fuzzy programming (FP)

Table 13 Performance of proposed model under several hesitant values corresponding membership and non-membership function

Cases	Fixed hesitant values	Adjusted hesitant values	Objective values
1	$\alpha_2 = 0.1 = \beta_2; \alpha_3 = 0.1 = \beta_3$	$\alpha_1 = 0.1, \beta_1 = 0.1$	(9572.093, 16686.06, 9283.474)
		$\alpha_1 = 0.2, \beta_1 = 0.2$	(10672.28, 16526.62, 7647.084)
		$\alpha_1 = 0.3, \beta_1 = 0.3$	(9910.767, 16609.66, 8591.418)
		$\alpha_1 = 0.4, \beta_1 = 0.4$	(9750.938, 16662.94, 8821.572)
		$\alpha_1 = 0.5$–$0.6, \beta_1 = 0.5-0.6$	(9512.812, 16639.81, 9437.127)
		$\alpha_1 = 0.7, \beta_1 = 0.7$	(9411.562, 16426.06, 9801.627)
		$\alpha_1 = 0.8, \beta_1 = 0.8$	(9883.438, 16472.94, 9926.502)
		$\alpha_1 = 0.9, \beta_1 = 0.9$	(9275.425, 16386.53, 10533.10)
		$\alpha_1 = 1.0, \beta_1 = 1.0$	(9246.297, 16300.09, 10698.43)
2	$\alpha_2 = 0.5 = \beta_2; \alpha_3 = 0.5 = \beta_3$	$\alpha_1 = 0.1, \beta_1 = 0.1$	(9512.812, 16639.81, 9437.127)
		$\alpha_1 = 0.2, \beta_1 = 0.2$	(9225.203, 16328.22, 10845.24)
		$\alpha_1 = 0.3, \beta_1 = 0.3$	(8993.953, 16483.22, 12963.84)
		$\alpha_1 = 0.4, \beta_1 = 0.4$	(8974.306, 16542.16, 13338.71)
		$\alpha_1 = 0.5, \beta_1 = 0.5$	(9572.093, 16686.06, 9283.474)
		$\alpha_1 = 0.6$–$08, \beta_1 = 0.6-0.8$	(10714.74, 16521.38, 7616.15)
		$\alpha_1 = 0.9$–$1.0, \beta_1 = 0.9-1.0$	(10672.28, 16526.62, 7647.084)
3	$\alpha_2 = 1.0 = \beta_2; \alpha_3 = 1.0 = \beta_3$	$\alpha_1 = 0.1, \beta_1 = 0.1$	(10087, 16551.17, 8337.829)
		$\alpha_1 = 0.2, \beta_1 = 0.2$	(9512.812, 16686.06, 9437.127)
		$\alpha_1 = 0.3, \beta_1 = 0.3$	(9372.92, 16464.52, 9985.568)
		$\alpha_1 = 0.4, \beta_1 = 0.4$	(9225.203, 16328.22, 10845.24)
		$\alpha_1 = 0.5, \beta_1 = 0.5$	(9088.718, 16420.20, 12025.55)
		$\alpha_1 = 0.6$–$0.7, \beta_1 = 0.6-0.7$	(8993.953, 16483.22, 12963.84)
		$\alpha_1 = 0.8, \beta_1 = 0.8$	(8974.305, 16542.16, 13338.73)
		$\alpha_1 = 0.9, \beta_1 = 0.9$	(8955.874, 16597.45, 13690.39)
		$\alpha_1 = 1.0, \beta_1 = 1.0$	(9572.093, 16639.81, 9283.474)
4	$\alpha_1 = 0.1 = \beta_1; \alpha_3 = 0.1 = \beta_3$	$\alpha_2 = 0.1-0.3, \beta_2 = 0.1-0.3$	(9572.093, 16686.06, 9283.474)
		$\alpha_2 = 0.4, \beta_2 = 0.4$	(9572.093, 16640.31, 9283.474)
		$\alpha_2 = 0.5, \beta_2 = 0.5$	(9572.093, 16686.06, 9283.474)
		$\alpha_2 = 0.6, \beta_2 = 0.6$	(9572.093, 16683.81, 9283.474)
		$\alpha_2 = 0.7, \beta_2 = 0.7$	(9572.093, 16639.81, 9283.474)
		$\alpha_2 = 0.8, \beta_2 = 0.8$	(9572.477, 16634.12, 9284.63)
		$\alpha_2 = 0.9, \beta_2 = 0.9$	(9573.584, 16617.71, 9287.96)
		$\alpha_2 = 1.0, \beta_2 = 1.0$	(9574.473, 16604.56, 9290.632)

Table 13 continued

Cases	Fixed hesitant values	Adjusted hesitant values	Objective values
5	$\alpha_1 = 0.5 = \beta_1; \alpha_3 = 0.5 = \beta_3$	$\alpha_2 = 0.1, \beta_2 = 0.1$	(9793.588, 15955.21, 9949.655)
		$\alpha_2 = 0.2, \beta_2 = 0.2$	(10520.44, 15009.56, 12135.77)
		$\alpha_2 = 0.3–0.4, \beta_2 = 0.3-0.4$	(10768.55, 14889.66, 12881.99)
		$\alpha_2 = 0.5, \beta_2 = 0.5$	(9572.093, 16686.06, 9283.474)
		$\alpha_2 = 0.6–0.9, \beta_2 = 0.6-0.9$	(9572.093, 16639.81, 9283.474)
		$\alpha_2 = 1.0, \beta_2 = 1.0$	(9572.093, 16642.43, 9283.474)
6	$\alpha_1 = 1.0 = \beta_1; \alpha_3 = 1.0 = \beta_3$	$\alpha_2 = 0.1, \beta_2 = 0.1$	(9593.572, 16367.28, 9348.096)
		$\alpha_2 = 0.2, \beta_2 = 0.2$	(9804.995, 15933.99, 9983.962)
		$\alpha_2 = 0.3, \beta_2 = 0.3$	(10208.24, 15285.88, 11196.77)
		$\alpha_2 = 0.4, \beta_2 = 0.4$	(10520.44, 15009.56, 12135.77)
		$\alpha_2 = 0.5, \beta_2 = 0.5$	(10549.95, 14988.44, 12224.52)
		$\alpha_2 = 0.6–0.8, \beta_2 = 0.6-0.8$	(10768.55, 14889.66, 12881.99)
		$\alpha_2 = 0.9, \beta_2 = 0.9$	(10228.61, 15265.66, 11258.04)
		$\alpha_2 = 1.0, \beta_2 = 1.0$	(9572.093, 16639.81, 9283.474)

Table 14 Performance of proposed model under several hesitant values corresponding membership and non-membership function

Cases	Fixed hesitant values	Adjusted hesitant values	Objective values
7	$\alpha_1 = 0.1 = \beta_1; \alpha_2 = 0.1 = \beta_2$	$\alpha_3 = 0.1, \beta_3 = 0.1$	(9572.093, 16686.06, 9283.474)
		$\alpha_3 = 0.2, \beta_3 = 0.2$	(9088.715, 16420.20, 12025.57)
		$\alpha_3 = 0.3, \beta_3 = 0.3$	(9258.438, 16372.94, 10628.5)
		$\alpha_3 = 0.4, \beta_3 = 0.4$	(9411.562, 16426.06, 9801.627)
		$\alpha_3 = 0.5, \beta_3 = 0.5$	(9512.812, 16639.81, 9437.127)
		$\alpha_3 = 0.6, \beta_3 = 0.6$	(9691.042, 16639.81, 8975.156)
		$\alpha_3 = 0.7–0.8, \beta_3 = 0.7–0.8$	(9750.938, 16662.94, 8821.572)
		$\alpha_3 = 0.9, \beta_3 = 0.9$	(9927.365, 16604.13, 8567.517)
		$\alpha_3 = 1.0, \beta_3 = 1.0$	(10087.32, 16551.10, 8337.394)
8	$\alpha_1 = 0.5 = \beta_1; \alpha_2 = 0.5 = \beta_2$	$\alpha_3 = 0.1, \beta_3 = 0.1$	(9512.812, 16639.81, 9437.127)
		$\alpha_3 = 0.2, \beta_3 = 0.2$	(10230.38, 16553.31, 8144.367)
		$\alpha_3 = 0.3, \beta_3 = 0.3$	(10683.28, 16526.62, 7638.804)
		$\alpha_3 = 0.4, \beta_3 = 0.4$	(10714.74, 16521.38, 7616.15)
		$\alpha_3 = 0.5, \beta_3 = 0.5$	(9572.093, 16686.06, 9283.474)
		$\alpha_3 = 0.6, \beta_3 = 0.6$	(8945.678, 16628.04, 13884.93)
		$\alpha_3 = 0.7–0.8, \beta_3 = 0.7–0.8$	(8993.953, 16483.22, 12963.84)
		$\alpha_3 = 0.9, \beta_3 = 0.9$	(9031.061, 16483.22, 12576.44)
		$\alpha_3 = 1.0, \beta_3 = 1.0$	(9088.717, 16420.20, 12025.55)
9	$\alpha_1 = 1.0 = \beta_1; \alpha_2 = 1.0 = \beta_2$	$\alpha_3 = 0.1, \beta_3 = 0.1$	(9246.297, 16300.09, 10698.43)
		$\alpha_3 = 0.2, \beta_3 = 0.2$	(9512.812, 16662.45, 9437.127)
		$\alpha_3 = 0.3, \beta_3 = 0.3$	(9750.937, 16662.94, 8821.572)
		$\alpha_3 = 0.4, \beta_3 = 0.4$	(10230.38, 16553.31, 8144.367)
		$\alpha_3 = 0.5, \beta_3 = 0.5$	(10672.28, 16526.62, 7647.084)
		$\alpha_3 = 0.6, \beta_3 = 0.6$	(10683.28, 16526.62, 7638.804)
		$\alpha_3 = 0.7–0.9, \beta_3 = 0.7–0.9$	(10714.74, 16521.38, 7616.15)
		$\alpha_3 = 1.0, \beta_3 = 1.0$	(9572.093, 16639.81, 9283.474)

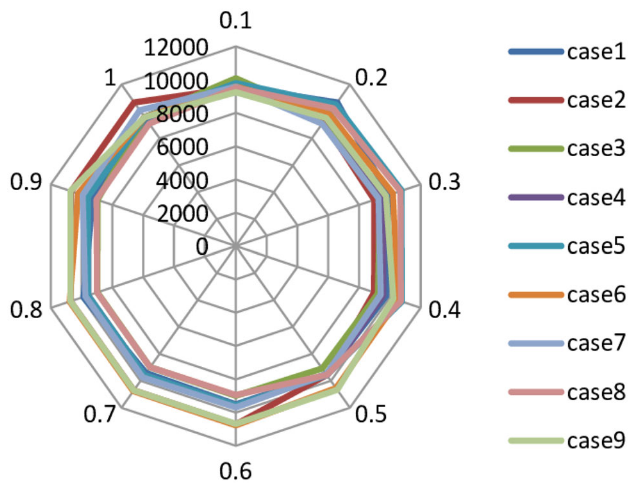

Fig. 3 Model validation for first objective values

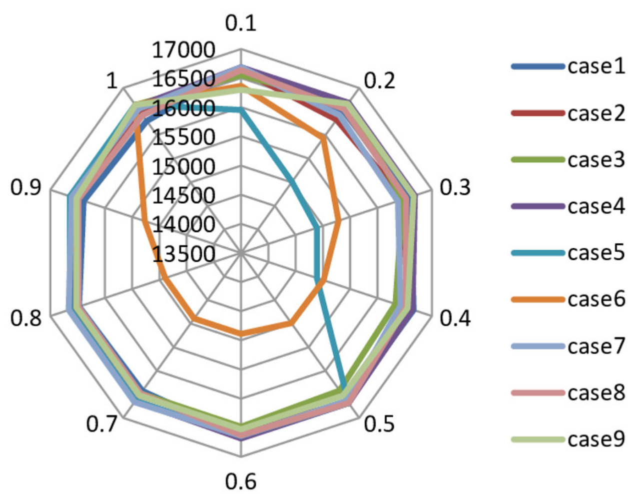

Fig. 4 Model validation for second objective values

ues whenever four values of α_s and β_s are fixed at 0.1, 0.5 and 1.0, whereas other two values of α_s and β_s are violated at 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and 1.0. All these cases are highlighted in Figs. 3, 4 and 5. According to the validation of the model, we find that the objective values are violated in the realization model for the cause of hesitant values and most selected optimal values appear in any middle or end or stating situation, where objectives are not increased or decreased corresponding to the increased or decreased valued of α_s and β_s. From this perspective, it can be decided that the proposed PHFP model offers an opportunity to the DMs for selecting a better decision in an uncertain situation. Important novelty of this approach is that the obtained solution of feasible region provides a spectrum of uncertainty which is different from fuzzy and IF.

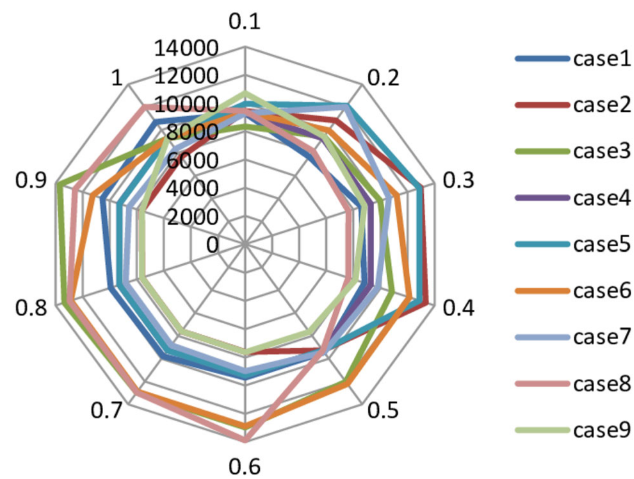

Fig. 5 Model validation for third objective values

Sensitivity analysis on carbon emission

This section analyzes the impact of cap parameter of MOSTP. Today, carbon policy is a challenging task to keep green world and a largest flexible range of this parameter is required for future study. Table 15 represents the ranges by the variation of cap parameter C with carbon emission tax is attached. We study the sensitivity analysis based on our proposed method PHFP and this investigation is allowable only when one parameter is changed at a time and other parameters have fixed with their initial values. Cap parameter is analyzed with three policies in different cases and for both examples. The analysis is performed by changing the parameter C into C^*. We utilize an easy method [15], such that basic variables remain stable, but their values may have changed. The processing steps are defined as follows:

- *Step 1:* Include the basic variables of the optimal allocation for MOSTP which are derived by PHFP.
- *Step 2:* Oscillate the value of the parameter by keeping rigid to the other parameters at that time and solve by LINGO 13 iterative scheme.
- *Step 3:* Go to Step 2, till NFS occurs or the basic variable replaces in optimal solution.
- *Step 4:* Collect the range of parameters obtained in Step 3.

Observation and managerial insights

Three objective functions connecting with SD are minimum transportation cost, maximum job opportunity and minimum carbon emission cost which are included in the proposed model, that should be relevant to any industrial problem with transportation system. The objective functions are chosen for

Table 15 Sensitivity analysis for carbon cap of both examples

Real value of C	Range of C^*
Example 2	
C = 25000 (Model 3)	$24236.76 \leq C^* < \infty$
C = 25000 (Model 4A)	$24236.76 \leq C^* < \infty$
C = 25000 (Model 4B)	$21667.32 \leq C^* \leq 43572.15$
C = 25000 (Model 5A)	$24236.76 \leq C^* < \infty$
C = 25000 (Model 5B)	$21141.30 \leq C^* \leq 38225.40$
Example 3	
C = 18000 (Model 4B)	$17884.30 \leq C^* \leq 18683.98$
C = 18000 (Model 5B)	$17505.54 \leq C^* \leq 18550.86$

the focus of SWM, such that the proposed model provides a plan to optimize all the objectives by considering source, demand and conveyance constraints. The following managerial insights are traced out from this study as follows:

- Introduction of SWM in the proposed model has several benefits with different sides that can be managed in vast areas, advices that urban or rural areas are developed comfortably and provided green or smart city certainly.
- Sustainability criteria are developed by regarding three main objectives as minimum transportation cost for economical opportunity, maximum job opportunity for social content and minimum carbon emission for safety of environment. At the time when these factors meet, then the system becomes more adaptable.
- Considering the analysis of carbon mechanism with different combined policies, the organization can select a suitable policy for predicting the positive impact of it which drops down the carbon emission. Utilizing appropriate policy, industrial organisation can also reduce the carbon emission from the production plant to prevent global warming.
- The suggested model is established on the basis of TP, waste management, SD and in the presence of PHF environment. As DM tackles such complicated uncertainty with multiple criteria, therefore, he/she is prepared to challenge any type of difficult uncertain situation with several criteria.
- From Pareto-optimal solution, it is decided that all the objectives provide a satisfactory result which can help to formulate any network design related with transportation, waste management or SD.

Concluding remarks and outlook to future research

In this research, for the first time in MOSTP with SWM has been rigorously initiated for SD under PHF uncertain situation. The proposed new model and solution methodology becomes highly applicable in real-life decision making problems as three conflicting objective functions have been concentrated on minimum transportation cost for economical aspect, maximum job opportunity for social impact and low carbon emission for environment effect. Three different types of scenarios (models) have been presented by considering three policies of carbon mechanism and all these objective functions are optimized in the presence of such carbon mechanism, and adding with all required constraints. The problem has been divided into different stages for waste management and that controlled by considering multiple variables. Source, demand and conveyance are taken as TrPHFNs to overcome deep uncertainty by extending two uncertainty as hesitant fuzzy and PF. An advance ranking index has been utilized here to defuzzify the uncertainty in the problem. Proposed models have been solved technically by utilizing two fuzzy techniques as FP and PHFP. Two realistic examples have been experimented that show the advantages of the proposed model based on the improved methods. A vast discussion has been elaborated in view of carbon mechanism for choosing a better policy among other different policies which mitigate CO_2 emission of sustainable transportation with SWM. Model validation is investigated based on the preferable policy.

Our existing study has some limitations and modifying all the drawbacks, and extending our proposed study, researchers can provide various opportunities for future research scope. Preservation technology may be included for transporting perishable items and effect of carbon emission during preservation can be included in our model. One may improve our model in new environment, such as polygonal fuzzy, type-2 neutrosophic, fuzzy-rough [14], type-2 zigzag uncertainty, interval PF, soft set, Pythagorean probablistic hesitant fuzzy, etc., with different ranking approaches on nonlinear membership functions (e.g., hyperbolic, exponential, quadratic, etc.). Our model can be remodelled using green supply chain management with stochastic data, fixed-charge, robust ranking, supplier selection, portfolio optimization, etc. Another scope is that a large industrial problem concerning with probabilistic industrial waste, mining waste, other several combination of carbon emission policy, etc., may be added in our model. Some sophisticated methods, such as ant colony optimization [47], genetic algorithm, particle swarm optimization, robust optimization model [48], etc., can be introduced in our model as well. Such directions of investigation can be pursued for future research.

Declarations

Conflict of interest The authors announce that there is no conflict of interest.

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