



# Interactive strategy of carbon cap-and-trade policy on sustainable multi-objective solid transportation problem with twofold uncertain waste management

Shyamali Ghosh<sup>1</sup> · Sankar Kumar Roy<sup>1</sup> · Gerhard-Wilhelm Weber<sup>2</sup>

Accepted: 11 April 2023 / Published online: 5 May 2023

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## Abstract

An appropriate and sustainable waste management plan is required in different scenarios for global development. The main goal of this paper is to evaluate a waste management problem by investigating an integrated multi-objective environment through solid transportation problem. To develop sustainability, three objective functions are optimized by choosing as cost for economical opportunity, time for social satisfaction and carbon emission for environmental view. Cap and trade policy is regarded here to minimize carbon emission and to provide some economical opportunities to the system. To control hesitancy of this scenario, twofold uncertainty (type-2 intuitionistic fuzzy) is incorporated here, and this uncertainty is defuzzified by a ranking operator. A strategy is proposed here to optimize three factors of sustainability by an intellectual model formulation of solid waste management. To check the appropriateness of the proposed model, two numerical problems are evaluated using two advanced methods, namely, neutrosophic linear programming and  $\epsilon$ -constraint method. The Pareto-optimal solutions are derived by the variation of cap value and fulfilling the criteria of sustainability. The obtained results indicate that cap and trade policy or waste management, or both are highly sophisticated for applying in real-world application. The overall conclusions recommend that a government or NGO should encourage transportation system, or the industry to minimize carbon emission by utilizing several carbon policies. It can assist to establish different new project of waste management in a discrete environment, based on sustainability.

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✉ Sankar Kumar Roy  
sankroy2006@gmail.com ; roysank@mail.vidyasagar.ac.in

Shyamali Ghosh  
shyamalighosh1989@gmail.com

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

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

<sup>2</sup> Faculty of Engineering Management, Poznan University of Technology, Poznan, Poland

**Keywords** Waste management · Multi-objective decision making · Sustainability · Solid transportation problem · Cap-and-trade policy · Type-2 intuitionistic fuzzy · Neutrosophic linear programming and  $\epsilon$ -Constraint method

**Mathematics Subject Classification** 90C08 · 90C29 · 90C70.

## 1 Introduction

To present the state-of-the-art of this work, this section introduces the motive of the proposed study. All the activities of waste management (WM), sustainability, generation of multi-objective solid transportation problem (MOSTP) and appearance of uncertainty are focused in the subsequent subsections.

### 1.1 Motive of study

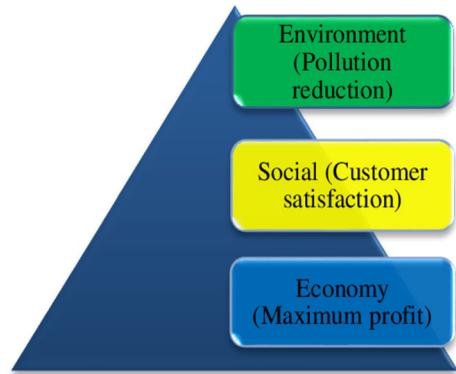
In the last twenty years, several types of solid waste (SW) and consumption have led to growth rapidly from metropolitan cities in India due to massive residency or urbanization or industrialization. Living community generates domestic and commercial wastes, called as municipal solid wastes (MSWs). These wastes are now the most significant affairs for municipality or other related organizations. Fly ash is an waste example which is generated by coal combustion on power plant and trashed typically in adjacent pond area. This hazardous waste pollutes air and water, deteriorate soil and surrounding atmosphere, and causes silicosis, fibrosis of lungs, bronchitis. Organic biodegradable wastes create bad smell, attract to virus and bacteria, and non-biodegradable wastes blocked drainage systems, polluted water, air, soil, i.e., as a whole, these affect the entire environment. It is very tough to manage these waste items in a sustainable way by setting up a master plan and reducing all the negative effects of waste items as well as WM. Global development is now standing by the pillar of sustainability. Regarding the optimum threats of hazardous waste to public health and environment, an optimization strategy is needed to estimate the generation of solid waste management (SWM) technically by considering sustainability.

### 1.2 Waste management

The volume and characteristic of SW are ranging from place to place, and time to time. Some SWs loss their activity of first user, but it may be reused in second time by recycling with proper investment that properly or improperly affect on economy, environment and social side of sustainability. An intellectual SWM plan protects urban ecosystem, makes green and smart cities by use of compost, CNG (compressed natural gas) as replace of LPG (liquefied petroleum gas), diesel, petroleum, and by reusing of recyclable non-hazardous waste (plastic, glass, metal). The collection bins are neither correctly used nor properly maintained. SWM is developed by starting the activity of transfer station (TS) as:

- (i) Systematic way to collect SW from different source points and sort out the collected waste as biodegradable and non-biodegradable.
- (ii) TS is a platform that operates between source point and treatment plant of SW by increasing the frequency of SW collection with minimum investment charge, minimum elapsed time and minimum pollution.

**Fig. 1** Schematic scenario of sustainability



- (iii) The treatment plants (landfills/backfills centre, recycling plants, disposal facility areas) exist far away from TS, as well as residential areas. As a result, the health risk will be minimized, and traffic system will get information of collected vehicles that passed through TS.

**Treatment, recycling and disposal of SW:** Intellectual way of treatment, recycling and disposal of SW items is beneficial for environmental pollution reduction and generated an income by trading the renewed recyclable materials. Two creative mechanisms like treatment and recycling of SW are approved in India, which are composting and waste to energy. Wastes are converted into various useful products when to reach in different treatment plants and performed several operations. These treatments may be *composting/vermi-composting, recycling, landfilling/backfilling, bio-methanation, incineration* and *pyrolysis*. Organic SWs are decomposed in these treatments and transformed into rich soil. Biological and hospitalized hazardous wastes are generally transported into an incineration plant for getting quickly disposed. Incineration is a thermal process that converts an SW into water, CO<sub>2</sub> and bottom ash. Asphalt pavements are increasingly recycled on site into a new pavement. The concept of civil engineering is applied for certain proportion of recycled glass in construction purposes. Fly ash is recycled by the replacement of cement for binding property, in coastal land reclamation, manufacturing of bricks, tiles, blocks and construction of roads. It is an attractive and an alternative option for sand backfilling. The government of India proposes mandatory to use fly ash in backfilling of underground and opencast mines for reducing negative impact of river ecosystem. Transportation agencies transport such materials with minimum carrying cost and high landfill and tipping fees that provide economic profit. The loop of WM completes by reaching all the recycled products to the customers (who initially dump waste to collection centres), and return the natural resources to the environment with minimum pollution, and ensuring sustainability.

### 1.3 Sustainable development

Sustainability is the economic condition where the demand fulfills by the people from environment without reducing the position of environment, which is not harmful to present or future generations. Sustainable development (SD) is a dual-edged concept whose one side involves sustainability and another side connects with development. SD with intersection of three parameters is presented in Fig. 1.

The term *sustainable development* was introduced in 1980 and popularised in 1987 [according to the report of “World Commission on Environment and Development”—the Brundtland Commission (Brundtland et al., 1987)], and the status was given by “United Nations Conference on Environment and Development” (UNCED) which held in Rio de Janeiro in 1992. According to Brundtland Commission (1987) and Themes Sustainable Development (2004), the definition of SD is defined as: “Development which meets the demands of the present without compromising the capability of the future generations to meet their own demands”.

“Sustainable development is the achievement of continued economic development without detriment to the environmental and natural resources”.

### **Sustainability on transportation and WM:**

Traditional transportation systems and appropriate WM plans mean decision making processes that only focus increasing mobility to achieve economical and environmental consideration. In the recent days, SD is a qualitative process on transportation systems and on WM plans for both developed and developing countries. On the other hand, transportation system and WM provide a big activity for SD by keeping the balance between three major sections which are society, economy and environment. The useful criteria of these parts are described as follows:

*Society:* The strategies of social responsibility are fulfilling public demand, road management, pricing policies, advance vehicle technology, transportation planning, quick disposal of hazardous waste items. An important activity in the course of SD from a social point of view is a correlation among various customers of an end product with minimum time values.

*Economy:* Economical issues and transportation system are two correlated section of a sustainable transportation system which cannot be separated any time. An optimum investment of an intellectual WM plan supports economical sustainability. For such an WM problem, minimum transportation cost, maximum profit and minimum time, and making more trips instead of larger trip in a technical way make an economic progression of sustainability.

*Environment:* Hazardous waste items and fatal carbon emission from transportation system can severely damage global health, and they are a challenging task for urban ecosystem. A sustainable WM and transportation system need to support energy efficiency by using low emission car, or by utilizing other natural resources (e.g., CNG obtained from WM). An appropriate WM plan finds environmental sustainability by decreasing most of the negative effects of waste items. For environmental improvement, there exist agreements like Kyoto Protocol of CO<sub>2</sub> reduction. Consumption rate of renewable resources should not overtake their rate of regeneration, and conversely a using rate of non-renewable resources should not beat their rate at which renewable substitutes are evolved. Another target is to the rate of emissions from fossil fuel does not outstrip the assimilative capacity of the environment.

*Society, Economy and Environment:* Sustainable transportation and WM plans are one side protect human health and environment, and on the other side they consist of the economical opportunity.

There exists a continued balance among the three attributes of sustainability, and in this sense the WM plan becomes a multi-objective decision making problem.

## **1.4 Generation of multi-objective transportation problem**

An improper way to transport hazardous or highly hazardous SW creates a problem on air, land, water at local and global levels. For this reason these waste items are transported by closed type of conveyances to prevent scattering and to control odour. Local govern-

ment/NGO/municipal authority tries to solve such a problem by considering a sustainable transportation problem (TP), as an important fact of urban development of India. TP is a particular type of a linear programming problem, introduced by Hitchcock (1941), and it is so called as Hitchcock–Koopmans TP. Different types of conveyances are utilized for transporting the items from sources to destinations through many incidents. Under such existing additional conveyance constraints on classical TP, the new type of a TP is defined as a solid transportation problem (STP), which was first established by Haley (1962). Common type of vehicles for carrying waste elements are dumper placer, hydraulic compactor vehicle and tripper. Electric vehicle transportations are now selected for economical and environmental sustainability. For a sustainable economic policy of TP with WM, the transportation cost, treatment cost, selection cost, retail price, transporting time, carbon emission, are appended at the time of shipment of SW items from a source to different destinations in several steps. A single objective function is not enough to prescribe such situations. The selected problem balances all the sustainability criteria by establishing multi-objective optimization problem, and a traditional single objective TP/STP becomes a multi-objective transportation problem (MOTP)/multi-objective solid transportation problem (MOSTP) in view of WM. For controlling these multiple objectives under real-life scenarios, a certain type of uncertainty is attached to the problem.

### 1.5 Appearance of uncertainty

A decision maker (DM) always asserts about the nature of parameters of MOSTP. WM with sustainability concept appears in realistic applications, where all the parameters may not precisely defined. An uncertainty arises due to existence of some hesitations, insufficient information, lack of evidence, competitive economic condition, fluctuations of financial market. Various uncertainties have been reported in the literature as fuzzy, interval, rough, stochastic, randomness, intuitionistic fuzzy (IF), neutrosophic, Pythagorean fuzzy (PF), etc. Investigating on several types of MOSTP under various sets of single uncertainty, it is noticed that some critical realistic situations appear where a single uncertainty is not enough to evaluate the situation. Due to this fact, this research introduces type-2 intuitionistic fuzzy (T2IF) (Roy & Bhaumik, 2018) in the proposed MOSTP.

### 1.6 Organization of the paper

The rest of this paper is outlined as follows: Literature review with research gap and contribution of the proposed study are summarized in Sect. 2. The fundamental definitions of fuzzy set (FS), intuitionistic fuzzy set (IFS), neutrosophic set (NS) and T2IF with some basic properties are described in Sect. 3. Section 4 depicts the notations, assumptions and the mathematical model on sustainable MOSTP for WM in twofold uncertainty. Two approaches namely neutrosophic linear programming (NLP) and  $\epsilon$ -constraint method are illustrated in Sect. 5. Advantages including limitations of the proposed study are depicted in Section 6. Two numerical examples are described in Sect. 7. Section 8 contains computational results for optimal allocation and discussions. Managerial insights are displayed in Sect. 9. Concluding remarks with the outlook of future research are placed in Sect. 10.

## 2 Literature review on the proposed study

This section presents a literature review on the intersection of WM project, SD and TP in several areas. Sustainability with SD from different directions are described in the first part. The second part defines several issues of WM for SD, and the third part elaborates various research activities on TP. Research gaps of previous works, contribution, and novelty with the relevance of the present study are analyzed thereafter.

A sustainable transportation with WM provides a new window for SD. Previous researchers developed sustainability by considering several parameters. They optimized the factors of sustainability from distinct sides or situations through different process and then applied in separate area. Some related articles are presented here. To develop sustainability, a network for waste collection problem was designed by Farrokhi-Asl et al. (2020). They considered the objectives of the problem as cost, transportation risk and population size in network collection. Bektur (2020) focused on sustainability for a four-phase supplier selection and order allocation problem. Kilic and Yalcin (2021) compared the municipalities in respect of environmental sustainability through neutrosophic DEMATEL based TOPSIS approach. Liuzzi et al. (2022) proposed a multiple criteria model for developing sustainability and selected the objectives as economical improvement, environmental view by electric consumption and green house gas (GHG) emission. Another object was employment level through the number of job opportunity. In the same way, the job opportunity as one objective function for SD was selected by Ghosh et al. (2022). They selected other two objectives as carbon emission reduction for environmental sustainability and profit for economic growth. Mondal et al. (2021) developed sustainability by proposing an MOSTP model in IF situation. This model was optimized by choosing the objectives as social aspect, customer satisfaction and economic sustainability. A transportation model was formulated by Maity et al. (2019) for SD, and the selected objective functions are cost, time and environment factors. Mehlawat et al. (2019) explored their study on sustainability by selecting a TP that inserted profit, fixed-charge, DEA efficiency score, customer to customer relationship. Reza-Gharehbagh et al. (2022) introduced a three-level green supply chain model for sustainability in digital platform by including two sustainable factors as economic influence and social welfare. Sherafati et al. (2019) designed a supply chain network in cable industry that established the sustainability criteria by incorporating economical profit, CO<sub>2</sub> emission, water consumption and regional development. Soleimani et al. (2022) proposed a closed loop supply chain which involved in a process of recycling, re-manufacturing and disposing of returned products. Total profit, number of job opportunity and energy consumption are chosen in this problem as the criteria of sustainability. Vafaei et al. (2020) followed the sustainability criteria in a supply chain on a distribution network by optimized cost, CO<sub>2</sub> emission and job opportunity. Zhen et al. (2019) developed sustainability by balancing cost and environment on a green closed loop supply chain under uncertain demand. Reviewing these research works, the present study cannot find any research work in hybrid uncertain environment (except Ghosh et al., 2022) that developed sustainability by selecting the objectives from an WM problem. The proposed study selects the three pillars of sustainability as social (time management), economical (profit optimization) and environmental (carbon emission reduction) factors from an WM problem in T2IF environment.

Many successful performances on WM were defined in literature. The authors Tirkolae et al. (2020a) described a technique for SWM with multiple trip in urban area under hybrid augmented ant colony optimization. To design an WM in urban area, a robust green location-allocation inventory model was proposed by the authors Tirkolae et al. (2020b). For a

capacitated arc routing MSW management problem, Tirkolaee et al. (2022) proposed a mixed-integer linear programming model. A multi-objective Pareto-based optimization algorithm was represented by Mahmoudsoltani et al. (2018) to transfer the hazardous materials into safety storage. Rabbani et al. (2018) established a multi-objective problem to collect industrial hazardous waste. Abdullah and Goh (2019) initiated a decision making method for SWM in PF environment. The affect of WM and a case study of Russia for green and smart cities were discussed by Mingaleva et al. (2019). How to SW items are recycled and managed for cost reliability in uncertain situation were discussed by Muneeb et al. (2018). Rathore and Sarmah (2019) represented a case study of Bilaspur city (India) about the location of TS in urban location that segregate the SW items. Xu et al. (2017) designed another approach to recycle SW items through a global reverse supply chain including carbon emission as constraint. Observing these research works on WM, the present study incorporates a multi-objective WM problem with transportation from real-life scenario that includes a hybrid uncertainty, called as T2IF, as this type of multi-objective WM problem is not incorporated in these researches.

TP with its various generations and solving approaches in different environments were available in literature. Most of articles on TP or STP included one or more objective functions with or without developing sustainability. A few selected important works in this direction are appended here. Rizk-Allah et al. (2018) presented a transportation system with multiple objectives in neutrosophic environment. An STP was recommended by Ghosh et al. (2021) with fully IF situation and multi-objective scenario by considering fixed-charge. Midya et al. (2021) covered an MOSTP for green supply chain by taking multiple stages, fixed-charge and IF situation. A new and easy approach for the evaluation of MOTP under IF uncertainty was discussed by Roy et al. (2018). These MOTP or MOSTP were incorporated by choosing different types of objective functions and then analyzed in different situations without regarding three factors of sustainability. These literature studies encourage to establish an MOTP by considering conveyance capacity and to develop sustainability in the ground of WM problem.

In transportation and industrial application, carbon emission is a major issue. Huge amount of toxic gases, CO<sub>2</sub> gas, harmful toxic smog are released from transport system, incineration plant, thermal plant and by disposal of SWs. As a result, peoples of the locality suffered by various diseases, postpone of schools, offices, flights. In October, 2019, New Delhi (in India) reached a concentration of toxic mark 999 parts per million (p.p.m.), crossed the deadly limit as the normal concentration is 60 marks (prescribed by air quality index (AQI) limit). Some researchers proposed different approaches in their research works to reduce such emission. They were included different mechanisms which are presented as: To reduce carbon emission from a re-manufacturing system, Bai et al. (2022) imposed cap and trade policy. Chen et al. (2022) incorporated a three-stage hybrid model to forecast the carbon prices in future. Carbon cap and trade policy was analyzed by Das and Roy (2019) in an MOTP, where carbon emission was chosen as an objective function with  $p$ -facility location in neutrosophic environment. Relating to an WM project, Ghosh et al. (2022) proposed different types of combined policy of carbon mechanism for CO<sub>2</sub> emission reduction in a multi-objective scenario of TP. A profit maximization green inventory model was established by Paul et al. (2022), where the mathematical model was formulated by choosing carbon tax for carbon emission reduction. The research work of Tsai et al. (2022) incorporated different types of carbon emission cost (carbon tax, carbon cap and trade) and their several effects in model formulation of a production company. To manage the customer demands and carbon prices of a closed loop supply chain, Xu et al. (2022) presented a stochastic model by considering a carbon trading and uncertain demand. Analyzing all these research works, it is noted that any

multi-objective WM problem with SD is not initiated to reduce carbon emission through an intellectual policy. For this sense, the proposed study influences to select carbon tax with cap and trade policy for an WM problem, and this strategy is presented by an objective function of the sustainable MOSTP.

**Research gap and contributions based on the present study:** From the literature review, the present study finds several research contributions which are shown in Table 1 in connection with the proposed work.

This study traces the research gaps from Table 1 and these gaps are filled by presenting the contributions as follows:

- Comparing the works [cf. Abdullah and Goh (2019), Das and Roy (2019), Midya et al. (2021), Muneeb et al. (2018), Rathore and Sarmah (2019), Roy et al. (2018), Tirkolae et al. (2020a), Tirkolae et al. (2020b), and Xu et al. (2017)], it is observed that the authors proposed their study neither introducing any sustainability criteria nor SD. Extending these research works, the present study designs a mathematical model of sustainable MOSTP by optimizing three factors (economical, social and environmental) of SD.
- The authors of articles [cf. Das and Roy (2019), Maity et al. (2019), Mehlawat et al. (2019), Midya et al. (2021), and Roy et al. (2018)] did not propose any project on WM in their research works. The present work enriches these articles by focusing a project of WM that included its several criteria through model formulation. The proposed work helps to design green cities with smart technology also.
- Equating the works [(cf. Abdullah and Goh (2019), Maity et al. (2019), Mehlawat et al. (2019), Muneeb et al. (2018), Rathore and Sarmah (2019), Roy et al. (2018), and Tirkolae et al. (2020a)] it is noticed that the authors formulated their models without considering carbon emission in objective function(s). The authors of articles [cf. Farrokhi-Asl et al. (2020), Midya et al. (2021), and Xu et al. (2017)] chose carbon emission in their study without any carbon policy. To drop down carbon emission, the proposed study imposes tax with cap and trade policy by observing the works [cf. Bai et al. (2022), Das and Roy (2019), Ghosh et al. (2022), Tsai et al. (2022)]. The carbon emission reduction through this policy is chosen here for environmental improvement, as well as to get an economical opportunity and to prevent global warming.
- The authors of articles [cf. Abdullah and Goh (2019), Farrokhi-Asl et al. (2020), Das and Roy (2019), Midya et al. (2021), Roy et al. (2018), Tirkolae et al. (2020a), Tirkolae et al. (2020b) and Xu et al. (2017)] were not integrated about profit of multi-objective decision making process. They selected only a simple cost without including multiple criteria related with several charges (selling price, selection charge, treatment charge for WM). This research applies a project on WM to find maximum profit through three criteria. It is a financial improvement from economical aspects of sustainability.
- The existing literature [cf. Abdullah and Goh (2019), Farrokhi-Asl et al. (2020), Mehlawat et al. (2019), Muneeb et al. (2018), Xu et al. (2017)] did not yet concern an elapsed time during transportation. The present study modifies these existing articles by designing the proposed model following elapsed time with a maximum time budget for social satisfaction.
- The researchers [cf. Farrokhi-Asl et al. (2020), Mehlawat et al. (2019), Rathore and Sarmah (2019)] organized their articles without any type of uncertainty, and the researchers [cf. Abdullah and Goh (2019), Das and Roy (2019), Maity et al. (2019), Midya et al. (2021), Muneeb et al. (2018), Roy et al. (2018), Tirkolae et al. (2020a), Tirkolae et al. (2020b), and Xu et al. (2017)] inserted single type of uncertainty on their study. Thinking on real-life critical scenario and improving these single type uncertain-



**Table 1** Contributions of authors' work with the designed study

Author(s)	Environment	Profit	Transportation time	CO <sub>2</sub> emission	Cap and trade policy	WM	SD
Abdullah and Goh (2019)	PF	No	No	No	No	Yes	No
Farrokhi-Asl et al. (2020)	Crisp	No	No	Yes	No	Yes	Yes
Das and Roy (2019)	Neutrosophic	No	Yes	Yes	Yes	No	No
Maity et al. (2019)	Interval	Yes	Yes	No	No	No	Yes
Mehlawat et al. (2019)	Crisp	Yes	No	No	No	No	Yes
Midya et al. (2021)	IF	No	Yes	Yes	No	No	No
Muneeb et al. (2018)	Uncertain	Yes	No	No	No	Yes	No
Rathore and Sarmah (2019)	Crisp	Yes	Yes	No	No	Yes	No
Tirkolaei et al. (2020a)	Fuzzy	No	Yes	No	No	Yes	No
Tirkolaei et al. (2020b)	Uncertain	No	Yes	Yes	Yes	Yes	No
Xu et al. (2017)	Uncertain	No	No	Yes	No	Yes	No
This investigation	T2IF	✓	✓	✓	✓	✓	✓

ties, the present study incorporates a new environment as twofold uncertainty (i.e., type-2 IF) in the formulated model.

The main contribution of this research is to:

- Formulating a model on MOSTP for optimizing three factors of sustainability and analyzing the effect of cap and trade policy from environmental and economical point of view. Transportation time with time budget is chosen from a social point of view, and profit is selected from economic criteria.
- Generating the application of SWM in multi-objective decision making process and finding a correlation between SD and WM in the presence of a complex uncertain situation such as type-2 IF environment.
- Evaluating the formulated model by two advanced approaches in non-fuzzy ( $\epsilon$ -constraint method) and fuzzy (NLP) techniques, and justifying the appropriateness of the designed model. The overall conclusions and discussions are revealed at last after presenting managerial insights for model applicability.

The novelty and the relevance of this study are as follows:

- An WM plan is incorporated in an intellectual way through several stages and by including several decision variables. This study is now able to control a multi-stage decision making problem by handling several decision variables.
- This research considers three objective functions under green principle to mitigate CO<sub>2</sub> emission and to waste reduction by 3R (Reduce, Reuse, Recycle) principle.
- Sustainability is developed here by the intersection of three parameters as economical, social and environmental. For global development, sustainability is now a major support in every object.
- The emission of transportation is reduced by incorporating cap and trade policy. The novelty of this strategy is that, it supports to reduce GHG emission, as well as provides an economical opportunity to the user and to the third party.
- Twofold uncertainty (T2IF) is introduced here to control more uncertainty and to overcome the hesitation of realistic critical conditions. As per authors' concern, this study is to challenge any type of formulated model with hybrid uncertainty.
- An easy and appropriate ranking index is utilized here to convert the T2IFN into a crisp form. The problem does not incorporate any type of complexity when to convert fuzzy data into crisp data.
- The Pareto-optimal solution of the proposed MOSTP is determined by NLP and  $\epsilon$ -constraint method. This research has an ability to tackle both fuzzy and non-fuzzy techniques.

### 3 Useful definitions

To design the proposed model, some relevant definitions with fundamental properties and basic operations based on FS (Zadeh, 1965), IFS, intuitionistic fuzzy number (IFN), T2IF and neutrosophic set (NS) are defined here.

**Definition 3.1** (Atanassov, 1986) Let  $X$  be a universal set. An IFS  $\tilde{A}^I$  in  $X$  is described as follows:  $\tilde{A}^I = \{ \langle x, \mu_{\tilde{A}^I}(x), \gamma_{\tilde{A}^I}(x) \rangle : x \in X \}$ , where  $\mu_{\tilde{A}^I}(x), \gamma_{\tilde{A}^I}(x) : X \rightarrow [0, 1]$  are the degrees of membership and non-membership which satisfy:  $0 \leq \mu_{\tilde{A}^I}(x) + \gamma_{\tilde{A}^I}(x) \leq 1$ ,  $x \in X$ . The degree of hesitation of an element  $x$  in the set  $\tilde{A}^I$  is defined as a function  $\pi_{\tilde{A}^I}(x) = 1 - \mu_{\tilde{A}^I}(x) - \gamma_{\tilde{A}^I}(x)$ . If  $\pi_{\tilde{A}^I}(x) = 0$ ,  $x \in X$  then the IFS transforms into FS.

**Definition 3.2** (Li, 2014) An intuitionistic fuzzy subset of real numbers is said to be an IFN  $\hat{A}^I$  if it satisfies the following properties:

- 3.2.1:  $\hat{A}^I$  is normal, i.e.,  $\exists x \in X$  such that  $\mu_{\hat{A}^I}(x) = 1$ .
- 3.2.2:  $\hat{A}^I$  is convex, i.e., for the membership function  $\mu_{\hat{A}^I}(x)$ , with  $\mu_{\hat{A}^I}[\lambda x_1 + (1 - \lambda)x_2] \geq \min\{\mu_{\hat{A}^I}(x_1), \mu_{\hat{A}^I}(x_2)\}$  for  $x_1, x_2 \in \mathbb{R}$ ,  $\lambda \in [0, 1]$ .
- 3.2.3:  $\hat{A}^I$  is concave, i.e., for the non-membership function  $\gamma_{\hat{A}^I}(x)$ , with  $\gamma_{\hat{A}^I}[\lambda x_1 + (1 - \lambda)x_2] \leq \max\{\gamma_{\hat{A}^I}(x_1), \gamma_{\hat{A}^I}(x_2)\}$  for  $x_1, x_2 \in \mathbb{R}$ ,  $\lambda \in [0, 1]$ .
- 3.2.4:  $\mu_{\hat{A}^I}(x)$  is piecewise continuous.

**Definition 3.3** If a triangular IFN (TIFN) is defined as  $\hat{A}^I = \langle (a_1, a_2, a_3); \mu_{\hat{A}^I}, \gamma_{\hat{A}^I} \rangle$  with  $a_1 \leq a_2 \leq a_3$  then the membership and non-membership functions of  $\hat{A}^I$  are determined as:

$$\mu_{\hat{A}^I}(x) = \begin{cases} \frac{x-a_1}{a_2-a_1}, & \text{if } a_1 \leq x \leq a_2, \\ \frac{a_3-x}{a_3-a_2}, & \text{if } a_2 \leq x \leq a_3, \\ 0, & \text{otherwise,} \end{cases} \text{ and } \gamma_{\hat{A}^I}(x) = \begin{cases} \frac{a_2-x}{a_2-a_1}, & \text{if } a_1 \leq x \leq a_2 \\ \frac{x-a_2}{a_3-a_2}, & \text{if } a_2 \leq x \leq a_3, \\ 1, & \text{otherwise.} \end{cases}$$

**Definition 3.4** (Smarandache, 1999) Let  $X$  be a universal set, then a single valued NS is defined in the form as:  $\tilde{A}^n = \{ \langle x, \mu_{\tilde{A}^n}(x), \sigma_{\tilde{A}^n}(x), \gamma_{\tilde{A}^n}(x) \rangle : x \in X \}$ , where  $\mu_{\tilde{A}^n}(x) : X \rightarrow [0, 1]$ ,  $\sigma_{\tilde{A}^n}(x) : X \rightarrow [0, 1]$ ,  $\gamma_{\tilde{A}^n}(x) : X \rightarrow [0, 1]$  with  $0 \leq \sup\{\mu_{\tilde{A}^n}(x)\} + \sup\{\sigma_{\tilde{A}^n}(x)\} + \sup\{\gamma_{\tilde{A}^n}(x)\} \leq 3, \forall x \in X$ . Here  $\mu_{\tilde{A}^n}(x)$ ,  $\sigma_{\tilde{A}^n}(x)$  and  $\gamma_{\tilde{A}^n}(x)$  are the degrees of truth membership, indeterminacy membership and falsity membership of  $x$  in  $\tilde{A}^n$ , respectively.

**Type-2 fuzzy set:** (Mendel & John, 2002) A type-2 fuzzy set (T2FS)  $\tilde{\tilde{A}}$  is characterized by a membership function

$$\mu_{\tilde{\tilde{A}}}(x) : X \times [0, 1] \rightarrow [0, 1], \text{ i.e., } \mu_{\tilde{\tilde{A}}}(x) : X \times P \rightarrow Q.$$

Here,  $X$  and  $P$  are considered for the primary domain and the secondary domain, respectively, of the T2FS, and  $Q$  is selected as the secondary membership of  $x$  such that  $x \in X$ . T2FS can be rewritten as:

$$\tilde{\tilde{A}} = \{ \langle (x, p), \mu_{\tilde{\tilde{A}}}(x, p) \rangle : \forall x \in X, \forall p \in W_x \subseteq [0, 1] \}, \tag{3.1}$$

where  $0 \leq \mu_{\tilde{\tilde{A}}}(x, p) \leq 1$ . From Eq. (3.1),  $\tilde{\tilde{A}}$  can be expressed as

$$\begin{aligned} \tilde{\tilde{A}} &= \left\{ \int_{x \in X} \int_{p \in W_x} \mu_{\tilde{\tilde{A}}}(x, p) / (x, p), W_x \subseteq [0, 1] \right\} \\ &= \left\{ \int_{x \in X} \left\{ \int_{p \in W_x} \mu_{\tilde{\tilde{A}}}(x, p) / p \right\} / x, W_x \subseteq [0, 1] \right\}. \end{aligned} \tag{3.2}$$

Here,  $W_x$  is the primary membership function,  $W_x \subseteq [0, 1]$ , with  $x$  as the primary variable and  $\{ \int_{p \in W_x} \mu_{\tilde{\tilde{A}}}(x, p) / p \}$  is the secondary membership function for secondary variable  $p$ .  $\int \int$  uses to denote the union over all acceptable  $x$  and  $p$ . For discrete domain of discussions,  $\int$  is replaced by  $\sum$ .

### 3.1 Triangular type-2 intuitionistic fuzzy number (TT2IFN)

TT2IFN is the extension of the triangular type-1 IFN or TIFN. The definitions with arithmetic operations of TT2IFNs are defined for formulation of the proposed model. Type-2

IF number is chosen to describe the twofold uncertainty which can tackle complex uncertain environment. Let a TT2IFN  $\tilde{A}$  on  $X$  is represented as  $\tilde{A} = \langle (\hat{a}, \hat{b}, \hat{c}); \mu_{\tilde{A}}, \gamma_{\tilde{A}} \rangle$ , where  $\hat{a}, \hat{b}$  and  $\hat{c}$  are again TIFNs, and  $\mu_{\tilde{A}}, \gamma_{\tilde{A}}$  are the membership and non-membership degrees of  $\tilde{A}$ , respectively.  $\tilde{A}$  can be briefly defined as  $\tilde{A} = \langle (\hat{a}, \hat{b}, \hat{c}); \omega_1, \omega_2 \rangle = \langle \langle \langle (a_1, a_2, a_3); \mu_{\hat{a}}, \gamma_{\hat{a}} \rangle, \langle (b_1, b_2, b_3); \mu_{\hat{b}}, \gamma_{\hat{b}} \rangle, \langle (c_1, c_2, c_3); \mu_{\hat{c}}, \gamma_{\hat{c}} \rangle \rangle; \omega_1, \omega_2 \rangle$ , in which  $\omega_1 = \min\{\mu_{\hat{a}}, \mu_{\hat{b}}, \mu_{\hat{c}}\}$  denotes the degree of membership and  $\omega_2 = \max\{\gamma_{\hat{a}}, \gamma_{\hat{b}}, \gamma_{\hat{c}}\}$  indicates the non-membership degree of  $\tilde{A}$ .

**Arithmetic Operations on TT2IFNs:** Let two TT2IFNs  $\tilde{A} = \langle (\hat{a}_1, \hat{b}_1, \hat{c}_1); \omega_{11}, \omega_{12} \rangle = \langle \langle \langle (a_1^1, a_1^2, a_1^3); \mu_{\hat{a}_1}, \gamma_{\hat{a}_1} \rangle, \langle (b_1^1, b_1^2, b_1^3); \mu_{\hat{b}_1}, \gamma_{\hat{b}_1} \rangle, \langle (c_1^1, c_1^2, c_1^3); \mu_{\hat{c}_1}, \gamma_{\hat{c}_1} \rangle \rangle; \omega_{11}, \omega_{12} \rangle$  and  $\tilde{B} = \langle (\hat{a}_2, \hat{b}_2, \hat{c}_2); \omega_{21}, \omega_{22} \rangle = \langle \langle \langle (a_2^1, a_2^2, a_2^3); \mu_{\hat{a}_2}, \gamma_{\hat{a}_2} \rangle, \langle (b_2^1, b_2^2, b_2^3); \mu_{\hat{b}_2}, \gamma_{\hat{b}_2} \rangle, \langle (c_2^1, c_2^2, c_2^3); \mu_{\hat{c}_2}, \gamma_{\hat{c}_2} \rangle \rangle; \omega_{21}, \omega_{22} \rangle$ , where  $\omega_{11} = \min\{\mu_{\hat{a}_1}, \mu_{\hat{b}_1}, \mu_{\hat{c}_1}\}$ ,  $\omega_{12} = \max\{\gamma_{\hat{a}_1}, \gamma_{\hat{b}_1}, \gamma_{\hat{c}_1}\}$ ,  $\omega_{21} = \min\{\mu_{\hat{a}_2}, \mu_{\hat{b}_2}, \mu_{\hat{c}_2}\}$  and  $\omega_{22} = \max\{\gamma_{\hat{a}_2}, \gamma_{\hat{b}_2}, \gamma_{\hat{c}_2}\}$ . The arithmetic operations are defined as:

**Addition:**  $\tilde{A} \oplus \tilde{B} = \langle \langle \langle (a_1^1 + a_1^2, a_1^2 + a_1^2, a_1^3 + a_1^3); \mu_{\hat{a}_1} \wedge \mu_{\hat{a}_2}, \gamma_{\hat{a}_1} \vee \gamma_{\hat{a}_2} \rangle, \langle (b_1^1 + b_1^2, b_1^2 + b_1^2, b_1^3 + b_1^3); \mu_{\hat{b}_1} \wedge \mu_{\hat{b}_2}, \gamma_{\hat{b}_1} \vee \gamma_{\hat{b}_2} \rangle, \langle (c_1^1 + c_1^2, c_1^2 + c_1^2, c_1^3 + c_1^3); \mu_{\hat{c}_1} \wedge \mu_{\hat{c}_2}, \gamma_{\hat{c}_1} \vee \gamma_{\hat{c}_2} \rangle \rangle; \theta_1, \theta_2 \rangle$ , where  $\theta_1 = \min\{\mu_{\hat{a}_1} \wedge \mu_{\hat{a}_2}, \mu_{\hat{b}_1} \wedge \mu_{\hat{b}_2}, \mu_{\hat{c}_1} \wedge \mu_{\hat{c}_2}\}$  and  $\theta_2 = \max\{\gamma_{\hat{a}_1} \vee \gamma_{\hat{a}_2}, \gamma_{\hat{b}_1} \vee \gamma_{\hat{b}_2}, \gamma_{\hat{c}_1} \vee \gamma_{\hat{c}_2}\}$ .

**Subtraction:**  $\tilde{A} \ominus \tilde{B} = \langle \langle \langle (a_1^1 - c_2^3, a_1^2 - c_2^2, a_1^3 - c_2^1); \mu_{\hat{a}_1} \wedge \mu_{\hat{c}_2}, \gamma_{\hat{a}_1} \vee \gamma_{\hat{c}_2} \rangle, \langle (b_1^1 - b_2^3, b_1^2 - b_2^2, b_1^3 - b_2^1); \mu_{\hat{b}_1} \wedge \mu_{\hat{b}_2}, \gamma_{\hat{b}_1} \vee \gamma_{\hat{b}_2} \rangle, \langle (c_1^1 - a_2^3, c_1^2 - a_2^2, c_1^3 - a_2^1); \mu_{\hat{c}_1} \wedge \mu_{\hat{a}_2}, \gamma_{\hat{c}_1} \vee \gamma_{\hat{a}_2} \rangle \rangle; \theta_3, \theta_4 \rangle$ , where  $\theta_3 = \min\{\mu_{\hat{a}_1} \wedge \mu_{\hat{c}_2}, \mu_{\hat{b}_1} \wedge \mu_{\hat{b}_2}, \mu_{\hat{c}_1} \wedge \mu_{\hat{a}_2}\}$  and  $\theta_4 = \max\{\gamma_{\hat{a}_1} \vee \gamma_{\hat{c}_2}, \gamma_{\hat{b}_1} \vee \gamma_{\hat{b}_2}, \gamma_{\hat{c}_1} \vee \gamma_{\hat{a}_2}\}$ .

**Scalar Multiplication:** Scalar multiplication for any real number  $k$  is interpreted as  $k \cdot \tilde{A} = \langle \langle \langle (ka_1^1, ka_1^2, ka_1^3); \mu_{\hat{a}_1}, \gamma_{\hat{a}_1} \rangle, \langle (kb_1^1, kb_1^2, kb_1^3); \mu_{\hat{b}_1}, \gamma_{\hat{b}_1} \rangle, \langle (kc_1^1, kc_1^2, kc_1^3); \mu_{\hat{c}_1}, \gamma_{\hat{c}_1} \rangle \rangle; \omega_{11}, \omega_{12} \rangle$ , if  $k \geq 0$ , and  $\langle \langle \langle (kc_1^1, kc_1^2, kc_1^3); \mu_{\hat{a}_1}, \gamma_{\hat{a}_1} \rangle, \langle (kb_1^1, kb_1^2, kb_1^3); \mu_{\hat{b}_1}, \gamma_{\hat{b}_1} \rangle, \langle (ka_1^1, ka_1^2, ka_1^3); \mu_{\hat{c}_1}, \gamma_{\hat{c}_1} \rangle \rangle; \omega_{11}, \omega_{12} \rangle$ , if  $k < 0$ .

Symbols “ $\wedge$ ” and “ $\vee$ ” are used for min and max operators, respectively.

### 3.2 Ranking function

To find the crisp value and for comparison of fuzzy numbers (TT2IFNs), defuzzification plays an important role. Several defuzzification approaches such as  $\alpha$ -cut, critical value (CV)-based reduction method, possibility concept, integration method, linguistic approach are available in the literature. Roy and Bhaumik (2018) proposed an advanced and simple ranking approach to transform TT2IFN into crisp number. The proposed study considers this ranking operator  $\mathfrak{R}(\tilde{A})$ , which maps TT2IFNs to real line, i.e.,  $\mathfrak{R} : \mathbb{F}(\tilde{A}) \rightarrow \mathbb{R}$ , where  $\mathbb{F}(\tilde{A})$  is the collection of all TT2IFNs, and  $\mathbb{R}$  is the set of real numbers. Mathematically the ranking is defined for a TT2IFN  $\tilde{A} = \langle (\hat{a}, \hat{b}, \hat{c}); \omega_1, \omega_2 \rangle = \langle \langle \langle (a_1, a_2, a_3); \mu_{\hat{a}}, \gamma_{\hat{a}} \rangle, \langle (b_1, b_2, b_3); \mu_{\hat{b}}, \gamma_{\hat{b}} \rangle, \langle (c_1, c_2, c_3); \mu_{\hat{c}}, \gamma_{\hat{c}} \rangle \rangle; \omega_1, \omega_2 \rangle$ , as:

$$\mathfrak{R}(\tilde{A}) = \left( \frac{\omega_1 + \omega_2}{2} \right) \left( \frac{1}{3} \right) \left( \frac{a_1 + b_1 + c_1}{3} + \frac{a_2 + b_2 + c_2}{3} + \frac{a_3 + b_3 + c_3}{3} \right), \quad (3.3)$$

which satisfies the linearity and additive properties.

Let  $\tilde{A}$  and  $\tilde{B}$  be TT2IFNs, then the following comparisons are followed by ranking operation as:

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

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

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

## 4 Model identification

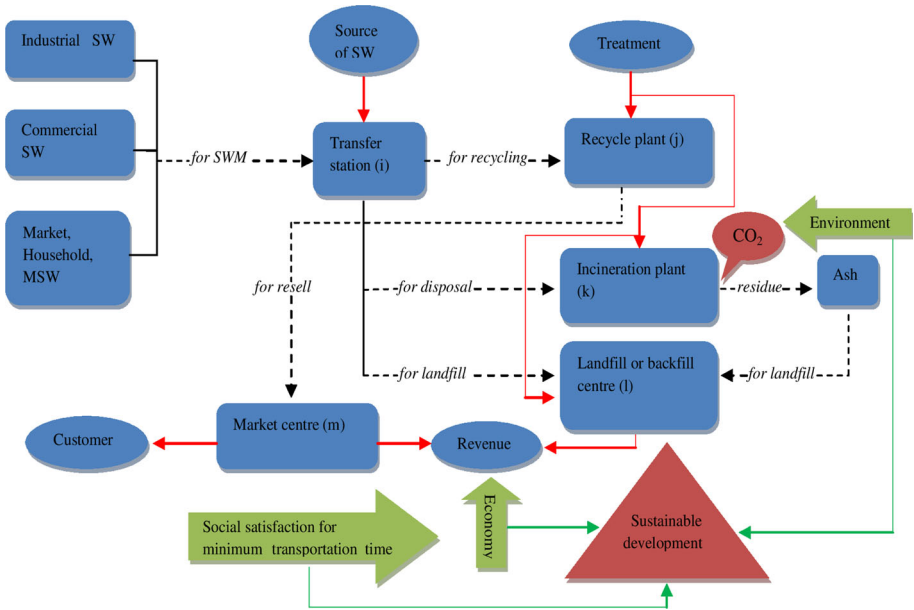
This section consists of several subsections which describe problem background, required notations with assumptions, and then implement of the integrated multi-objective optimization model. The deterministic model and the extension of this model due to cap and trade policy are displayed thereafter.

### 4.1 Problem background

The loop of an SWM process involves a number of steps. This study selects an WM problem in uncertain environment which concerns in two stages and three plants are as, (1) waste collection centre(s), (2) treatment plant(s), and (3) market centre(s). The TS is the source of SW as this station collects SW from industrial, commercial place, market, household. For intellectual way of WM [as of works Mahmoudsoltani et al. (2018), Mingaleva et al. (2019), Muneeb et al. (2018), Rabbani et al. (2018) and Xu et al. (2017)], TS separates the collected waste items according to their nature. The process starts in first stage by selecting the waste items from TS [article Rathore and Sarmah (2019)], and thereafter shifting them in three ways as:

- (i) One type of SW is transported into recycle plant for re-manufacturing or producing new items which shall be resold in market for second time utilization.
- (ii) To reduce different harmful pollutions, second type of waste items (hazardous) is transported into incineration plant for quickly disposed.
- (iii) Third type of waste (e.g., fly ash) is directly transported to landfill/backfill centre.

In second stage, the produced recycle items from treatment plants are transferred into market centre for reselling them with an appropriate price based on their quality and demand. The target is to obtain a high retail price to maximize the economical profit which is one factor of SD [concerned from references Maity et al. (2019), Mehlawat et al. (2019) and Zhen et al. (2019)]. In the incineration centre, the wastes are disposed and generated a huge amount of CO<sub>2</sub> gas with other toxic gases and a non-combustion residue produced named as ashes. This type of ashes is transported for landfill/backfill and to obtain a credit price for such servicing. The aim is to minimize such emitted CO<sub>2</sub> gas from incineration plant by imposing a tax that helps to decrease environmental pollution. Some wastes (fly ashes) are directly transferred from TS to landfill/backfill centre, and to provide a retail price from this WM. The focus is to maximize such retail price in first and second stages for economical support of sustainability. A charge of SWM is defined here as treatment cost which exists at recycle plant, incineration plant and landfill/backfill centre. Selection charge is paid to TS for servicing various activities such as cost of separation, cost of loading, cost of sanitization of vehicles and station, charge for security/staff, cost for maintenance, penalty cost of environment pollution. A transportation cost exists for shifting the waste items from TS to treatment plants and treatment plant to landfill/backfill centre, and again shifting the recycle items from treatment plant to market. All the processing steps of WM are handled with low pollution,



**Fig. 2** A network design for waste management

low investment cost (i.e., selection cost, treatment cost and transportation cost), minimum elapsed time and maximum retail price for the focus of SD. At the end of this process, the corresponding organization/municipality/NGO (who controls the system) calculates the total profit from the investment cost and the revenue, and tries to maximize the profit. To explicit all the steps of WM for SD in the proposed model, a network design is depicted in Fig. 2.

During the transportation of SW items, an affective issue arises as CO<sub>2</sub> emission [followed by references Farrokhi-Asl et al. (2020), Das and Roy (2019), Sherafati et al. (2019) and Vafaei et al. (2020)] that depends on transported amount of items, distance, fuel quality, rate of energy consumption, transportation time. To reduce air pollution, this research tries to minimize such GHG emission from transportation by applying the effect of cap and trade policy. At the same time, this policy provides an economical opportunity to the transportation system, i.e., to the user(s) who emit(s) carbon. Governments and the additional organizations of policy makers initiate a blueprint for the reduction of carbon emission with respect to cap and trade policy. A particular and limited amount of CO<sub>2</sub> is emitted due to an annual permission allocated by the governments and the organizations. In the cap and trade policy, the term “cap” assigns as a restriction for the total emission. This policy is stated that: “whenever the total emission outstrips the cap value then the corresponding system (who emits) pays a penalty charge and buys the shortage permit of emission; otherwise the system is capable to increase its emission upto the cap value and efficient to sell the extra permit”. For SD with green principles, the most important features are required as:

- (i) Clear air with minimum rate of CO<sub>2</sub> emission from vehicles or other industrial process.
- (ii) Maximum reuse and recycle the waste elements.
- (iii) Minimum use of non-renewable energy and maximum use of renewable energy.

An integrated model is established by choosing the three objectives functions as total profit, total elapsed time (transportation time, loading and unloading time) and total carbon emission (from transportation and from incineration plant), and taking other conditions are as the constraints. Total profit is calculated by subtracting the total investment cost (transportation cost, selected cost and treatment charge) from the total revenue. The aims of the objective functions are described as follows:

- Objective 1:** maximize  $Z_1 =$  total profit (economical aspect).
- Objective 2:** minimize  $Z_2 =$  total elapsed time (social impact).
- Objective 3:** minimize  $Z_3 =$  total carbon emission (environmental effect).

### 4.2 Notations and assumptions

This subsection contains a list of notations with their usual meanings in Tables 2 and 3. The necessary assumptions are designed to formulate the proposed sustainable model of MOSTP for WM.

#### Assumptions:

- $\tilde{a}_i > 0, \tilde{a}_j^R > 0, \tilde{a}_k^C > 0, \tilde{a}_l^{D1+D2} > 0, \tilde{b}_m^M > 0, \tilde{e}_n > 0 \forall i, j, k, l, m, n.$
- All the mixed waste should be segregated according to their nature.
- Total transported waste is equal to the sum of collected waste of TS. All the collected waste items are completely distributed for recycling, disposal and for landfill.

### 4.3 Integrated multi-objective optimization model

The integrated optimization model of MOSTP under T2IF environment is shown in Model 1. In this sustainable model, source, demand and conveyance are selected as TT2IFNs, due to real-life hesitation or uncertainty on WM.

#### 4.3.1 Implementation of model

The mathematical model of MOSTP based on carbon cap and trade policy can be formulated as:

#### Model 1

$$\begin{aligned}
 \text{maximize } Z_1(x, y) = & \left[ \sum_{i=1}^I \sum_{l=1}^L \sum_{n=1}^N (r_{iln}^{D1} - c_{iln}^{D1} - m_{iln}^{D1} - s_{iln}^{D1})x_{iln}^{D1} + \sum_{j=1}^J \sum_{m=1}^M \sum_{n=1}^N (r_{jmn}^T \right. \\
 & - c_{jmn}^T)y_{jmn}^T + \sum_{k=1}^K \sum_{l=1}^L \sum_{n=1}^N (r_{kln}^{D2} - c_{kln}^{D2} - m_{kln}^{D2})y_{kln}^{D2} \left. \right] - \left[ \sum_{i=1}^I \sum_{j=1}^J \sum_{n=1}^N (c_{ijn}^R \right. \\
 & \left. + m_{ijn}^R + s_{ijn}^R)x_{ijn}^R + \sum_{i=1}^I \sum_{k=1}^K \sum_{n=1}^N (c_{ikn}^C + m_{ikn}^C + s_{ikn}^C)x_{ikn}^C \right] \tag{4.4}
 \end{aligned}$$

**Table 2** Useful notations with their nature and description

Index set	Description	Type
$I$	Index for TS (source) ( $i = 1, 2, \dots, I$ )	Integer
$J$	Index for recycle plant of SWM ( $j = 1, 2, \dots, J$ )	Integer
$K$	Index for incineration plant of SWM ( $k = 1, 2, \dots, K$ )	Integer
$L$	Index for landfill centre of SWM ( $l = 1, 2, \dots, L$ )	Integer
$M$	Index for market centre for selling recycle items ( $m = 1, 2, \dots, M$ )	Integer
$N$	Index for conveyances ( $n = 1, 2, \dots, N$ )	Integer
Decision variable		
Continuous variable:		
$x_{ij}^R$	Amount of SW items that to be transported from $i$ th TS to $j$ th recycle plant through $n$ th conveyance	Real
$x_{ikn}^C$	Amount of SW items that to be transported from $i$ th TS to $k$ th incineration plant through $n$ th conveyance	Real
$x_{iln}^{D1}$	Amount of SW items that to be transported from $i$ th TS to $l$ th landfill centre through $n$ th conveyance	Real
$y_{kln}^{D2}$	Amount of ashes produced from $k$ th incineration plant of SWM that to be transported to $l$ th landfill centre through $n$ th conveyance	Real
$y_{jmn}^T$	Amount of reusable items produced at $j$ th recycle plant by recycle of SW that to be transported at $m$ th market centre through $n$ th conveyance	Real
Binary variable:		
$\eta_{ij}^R$	Binary variable takes the value "1" if the $x_{ij}^R > 0$ and "0" otherwise	–
$\eta_{ikn}^C$	Binary variable chooses the value "1" if the $x_{ikn}^C > 0$ and "0" otherwise	–
$\eta_{iln}^{D1}$	Binary variable selects the value "1" if the $x_{iln}^{D1} > 0$ and "0" otherwise	–
$\eta_{kln}^{D2}$	Binary variable permits the value "1" if the $y_{kln}^{D2} > 0$ and "0" otherwise	–
$\eta_{jmn}^T$	Binary variable considers the value "1" if the $y_{jmn}^T > 0$ and "0" otherwise	–



Table 2 continued

Index set	Description	Type
Parameter:		
$\tilde{a}_i$	TT2IF available amount of SW at $i$ th TS	Fuzzy
$\tilde{a}_j^R$	TT2IF capability of $j$ th recycle plant of SWM	Fuzzy
$\tilde{a}_k^C$	TT2IF capability of $k$ th incineration plant of SWM	Fuzzy
$\tilde{a}_l^{D1+D2}$	TT2IF capability of $l$ th landfill centre of SWM	Fuzzy
$\tilde{b}_m$	TT2IF capability of $m$ th market centre for demand of reusable items	Fuzzy
$\tilde{e}_n$	TT2IF capacity of $n$ th conveyance	Fuzzy
$\alpha$	Percentage rate of ash production from SW items in incineration plant.	Real
$e^{CO_2}_1$	Rate of carbon emission of the vehicle per unit item and per unit distance	Real
$e^{CO_2}_2$	Rate of carbon emission per unit item from incineration plant for incinerating SW	Real
$\theta$	Tax of carbon emission from incineration plant	Real
$\phi$	Carbon trading (buying) charge per unit transported item	Real
$\psi$	Carbon trading (selling) charge per unit transported item	Real
$C$	Carbon cap (Permitted capacity of maximum carbon emission)	Real
$P$	Penalty charge per unit transported item that released surplus carbon to the cap	Real
$Z_u$	Objective function ( $u = 1, 2, 3$ )	Real
$c_{ijn}^R$	Transportation cost of SW items transported from $i$ th TS to $j$ th recycle plant through $n$ th conveyance	Real
$c_{ikn}^C$	Transportation cost of SW items transported from $i$ th TS to $k$ th incineration plant through $n$ th conveyance	Real
$c_{iln}^{D1}$	Transportation cost of SW items transported from $i$ th TS to $l$ th landfill centre through $n$ th conveyance	Real
$c_{kin}^{D2}$	Transportation cost of ashes from $k$ th incineration plant to $l$ th landfill centre through $n$ th conveyance	Real
$c_{jmn}^T$	Transportation cost of reusable items transported from $j$ th recycle plant to $m$ th market centre through $n$ th conveyance	Real

**Table 3** Symbols with their nature and description

Notation Parameter:	Description	Type
$s_{ij}^R$	Selection cost of SW items transported from $i$ th TS to $j$ th recycle plant through $n$ th conveyance	Real
$s_{ikn}^C$	Selection cost of SW items transported from $i$ th TS to $k$ th incineration plant through $n$ th conveyance	Real
$D1_{i n}$	Selection cost of SW items transported from $i$ th TS to $l$ th landfill centre through $n$ th conveyance	Real
$R_{i jn}$	Treatment cost of SW items transported from $i$ th TS to $j$ th recycle plant through $n$ th conveyance	Real
$T_{i kn}$	Treatment cost of SW items transported from $i$ th TS to $k$ th incineration plant through $n$ th conveyance	Real
$D1_{i ln}$	Treatment cost of SW items transported from $i$ th TS to $l$ th landfill centre through $n$ th conveyance	Real
$D2_{m kn}$	Treatment cost of ash transported from $k$ th incineration plant to $l$ th landfill centre through $n$ th conveyance	Real
$r_{i n}^{D1}$	Revenue from SW items transported from $i$ th TS to $l$ th landfill centre through $n$ th conveyance	Real
$r_{k n}^{D2}$	Revenue from ash transported from $k$ th incineration plant to $l$ th landfill centre through $n$ th conveyance	Real
$r_{j mn}^T$	Revenue of reusable items transported from $j$ th recycle plant to $m$ th market centre through $n$ th conveyance	Real
$d_{i jn}^R$	Distance from $i$ th TS to $j$ th recycle plant through $n$ th conveyance	Real
$d_{i kn}^C$	Distance from $i$ th TS to $k$ th incineration plant through $n$ th conveyance	Real
$d_{i ln}^{D1}$	Distance from $i$ th TS to $l$ th landfill centre through $n$ th conveyance	Real
$d_{k ln}^{D2}$	Distance from $k$ th incineration plant to $l$ th landfill centre through $n$ th conveyance	Real
$d_{j mn}^T$	Distance from $j$ th recycle plant to $m$ th market centre through $n$ th conveyance	Real
$t_{i jn}^R$	Elapsed time from $i$ th TS to $j$ th recycle plant through $n$ th conveyance	Real
$t_{i kn}^C$	Elapsed time from $i$ th TS to $k$ th incineration plant through $n$ th conveyance	Real
$t_{i ln}^{D1}$	Elapsed time from $i$ th TS to $l$ th landfill centre through $n$ th conveyance	Real
$t_{k ln}^{D2}$	Elapsed time from $k$ th incineration plant to $l$ th landfill centre through $n$ th conveyance	Real
$t_{j mn}^T$	Elapsed time from $j$ th recycle plant to $m$ th market centre through $n$ th conveyance	Real
$T_{max}$	Maximum time budget	Real

$$\begin{aligned} \text{minimize } Z_2(x, y) &= \sum_{i=1}^I \sum_{j=1}^J \sum_{n=1}^N t_{ijn}^R \eta_{ijn}^R + \sum_{i=1}^I \sum_{k=1}^K \sum_{n=1}^N t_{ikn}^C \eta_{ikn}^C + \sum_{i=1}^I \sum_{l=1}^L \sum_{n=1}^N t_{iln}^{D1} \eta_{iln}^{D1} \\ &+ \sum_{j=1}^J \sum_{m=1}^M \sum_{n=1}^N t_{jmn}^T \eta_{jmn}^T + \sum_{k=1}^K \sum_{l=1}^L \sum_{n=1}^N t_{kln}^{D2} \eta_{kln}^{D2} \end{aligned} \tag{4.5}$$

$$\begin{aligned} \text{minimize } Z_3(x, y) &= \phi P \left[ e_{CO_2}^1 \left( \sum_{i=1}^I \sum_{j=1}^J \sum_{n=1}^N d_{ijn}^R x_{ijn}^R + \sum_{i=1}^I \sum_{k=1}^K \sum_{n=1}^N d_{ikn}^C x_{ikn}^C + \sum_{i=1}^I \sum_{l=1}^L \sum_{n=1}^N d_{iln}^{D1} x_{iln}^{D1} \right. \right. \\ &\left. \left. d_{iln}^{D1} x_{iln}^{D1} + \sum_{j=1}^J \sum_{m=1}^M \sum_{n=1}^N d_{jmn}^T y_{jmn}^T + \sum_{k=1}^K \sum_{l=1}^L \sum_{n=1}^N d_{kln}^{D2} y_{kln}^{D2} \right) - C \right]^+ - \psi \left[ C - e_{CO_2}^1 \right. \\ &\left. \left( \sum_{i=1}^I \sum_{j=1}^J \sum_{n=1}^N d_{ijn}^R x_{ijn}^R + \sum_{i=1}^I \sum_{k=1}^K \sum_{n=1}^N d_{ikn}^C x_{ikn}^C + \sum_{i=1}^I \sum_{l=1}^L \sum_{n=1}^N d_{iln}^{D1} x_{iln}^{D1} + \right. \right. \\ &\left. \left. \sum_{j=1}^J \sum_{m=1}^M \sum_{n=1}^N d_{jmn}^T y_{jmn}^T + \sum_{k=1}^K \sum_{l=1}^L \sum_{n=1}^N d_{kln}^{D2} y_{kln}^{D2} \right) \right]^+ + \theta e_{CO_2}^2 \sum_{i=1}^I \sum_{k=1}^K \sum_{n=1}^N x_{ikn}^C \end{aligned} \tag{4.6}$$

$$\text{subject to } \sum_{i=1}^I \sum_{n=1}^N x_{ijn}^R = \tilde{a}_j^R \quad (j = 1, 2, \dots, J), \tag{4.7}$$

$$\sum_{i=1}^I \sum_{n=1}^N x_{ikn}^C = \tilde{a}_k^C \quad (k = 1, 2, \dots, K), \tag{4.8}$$

$$\sum_{i=1}^I \sum_{n=1}^N x_{iln}^{D1} + \sum_{k=1}^K \sum_{n=1}^N y_{kln}^{D2} = \tilde{a}_l^{D1+D2} \quad (l = 1, 2, \dots, L), \tag{4.9}$$

$$\sum_{j=1}^J \sum_{n=1}^N x_{ijn}^R + \sum_{k=1}^K \sum_{n=1}^N x_{ikn}^C + \sum_{l=1}^L \sum_{n=1}^N x_{iln}^{D1} = \tilde{a}_i \quad (i = 1, 2, \dots, I), \tag{4.10}$$

$$\sum_{k=1}^K \sum_{l=1}^L y_{kln}^{D2} = \alpha \sum_{i=1}^I \sum_{k=1}^K x_{ikn}^C \quad (n = 1, 2, \dots, N), \tag{4.11}$$

$$\sum_{j=1}^J \sum_{n=1}^N y_{jmn}^T = \tilde{b}_m \quad (m = 1, 2, \dots, M), \tag{4.12}$$

$$\sum_{i=1}^I \sum_{j=1}^J x_{ijn}^R \leq \tilde{e}_n \quad (n = 1, 2, \dots, N), \tag{4.13}$$

$$\sum_{i=1}^I \sum_{k=1}^K x_{ikn}^C \leq \tilde{e}_n \quad (n = 1, 2, \dots, N), \tag{4.14}$$

$$\sum_{i=1}^I \sum_{l=1}^L x_{iln}^{D1} \leq \tilde{e}_n \quad (n = 1, 2, \dots, N), \tag{4.15}$$

$$\sum_{j=1}^J \sum_{m=1}^M y_{jmn}^T \leq \tilde{e}_n \quad (n = 1, 2, \dots, N), \tag{4.16}$$

$$\sum_{k=1}^K \sum_{l=1}^L y_{kln}^{D2} \leq \tilde{e}_n \quad (n = 1, 2, \dots, N), \tag{4.17}$$

$$\begin{aligned} & \sum_{i=1}^I \sum_{j=1}^J \sum_{n=1}^N t_{ijn}^R \eta_{ijn}^R + \sum_{i=1}^I \sum_{k=1}^K \sum_{n=1}^N t_{ikn}^C \eta_{ikn}^C + \sum_{i=1}^I \sum_{l=1}^L \sum_{n=1}^N t_{iln}^{D1} \eta_{iln}^{D1} \\ & + \sum_{j=1}^J \sum_{m=1}^M \sum_{n=1}^N t_{jmn}^T \eta_{jmn}^T + \sum_{k=1}^K \sum_{l=1}^L \sum_{n=1}^N t_{kln}^{D2} \eta_{kln}^{D2} \leq T_{max}, \end{aligned} \tag{4.18}$$

$$x_{ijn}^R \geq 0, x_{ikn}^C \geq 0, x_{iln}^{D1} \geq 0, y_{jmn}^T \geq 0, y_{kln}^{D2} \geq 0, \forall i, j, k, l, m, n. \tag{4.19}$$

The feasibility conditions of this MOSTP are defined as:  $\sum_{i=1}^I \tilde{a}_i \geq \sum_{j=1}^J \tilde{a}_j^R$ ;  $\sum_{i=1}^I \tilde{a}_i \geq \sum_{k=1}^K \tilde{a}_k^C$ ;  $\sum_{i=1}^I \tilde{a}_i \geq \sum_{l=1}^L \tilde{a}_l^{D1+D2}$ ;  $\sum_{n=1}^N \tilde{e}_n \geq \sum_{j=1}^J \tilde{a}_j^R$ ;  $\sum_{n=1}^N \tilde{e}_n \geq \sum_{k=1}^K \tilde{a}_k^C$ ;  $\sum_{n=1}^N \tilde{e}_n \geq \sum_{l=1}^L \tilde{a}_l^{D1+D2}$ ;  $\sum_{n=1}^N \tilde{e}_n \geq \sum_{m=1}^M \tilde{b}_m$ .

The coefficients of carbon emission are defined in two ways as follows:

$$\begin{aligned} & \left[ e_{CO_2}^1 \left( \sum_{i=1}^I \sum_{j=1}^J \sum_{n=1}^N d_{ijn}^R x_{ijn}^R + \sum_{i=1}^I \sum_{k=1}^K \sum_{n=1}^N d_{ikn}^C x_{ikn}^C + \sum_{i=1}^I \sum_{l=1}^L \sum_{n=1}^N d_{iln}^{D1} x_{iln}^{D1} \right. \right. \\ & \left. \left. + \sum_{j=1}^J \sum_{m=1}^M \sum_{n=1}^N d_{jmn}^T y_{jmn}^T + \sum_{k=1}^K \sum_{l=1}^L \sum_{n=1}^N d_{kln}^{D2} y_{kln}^{D2} \right) - C \right]^+ \\ & = \max \left[ e_{CO_2}^1 \left( \sum_{i=1}^I \sum_{j=1}^J \sum_{n=1}^N d_{ijn}^R x_{ijn}^R + \sum_{i=1}^I \sum_{k=1}^K \sum_{n=1}^N d_{ikn}^C x_{ikn}^C + \sum_{i=1}^I \sum_{l=1}^L \sum_{n=1}^N d_{iln}^{D1} x_{iln}^{D1} \right. \right. \\ & \left. \left. + \sum_{j=1}^J \sum_{m=1}^M \sum_{n=1}^N d_{jmn}^T y_{jmn}^T + \sum_{k=1}^K \sum_{l=1}^L \sum_{n=1}^N d_{kln}^{D2} y_{kln}^{D2} \right) - C, 0 \right], \end{aligned}$$

and

$$\begin{aligned} & \left[ C - e_{CO_2}^1 \left( \sum_{i=1}^I \sum_{j=1}^J \sum_{n=1}^N d_{ijn}^R x_{ijn}^R + \sum_{i=1}^I \sum_{k=1}^K \sum_{n=1}^N d_{ikn}^C x_{ikn}^C + \sum_{i=1}^I \sum_{l=1}^L \sum_{n=1}^N d_{iln}^{D1} x_{iln}^{D1} \right. \right. \\ & \left. \left. + \sum_{j=1}^J \sum_{m=1}^M \sum_{n=1}^N d_{jmn}^T y_{jmn}^T + \sum_{k=1}^K \sum_{l=1}^L \sum_{n=1}^N d_{kln}^{D2} y_{kln}^{D2} \right) \right]^+ \\ & = \max \left[ C - e_{CO_2}^1 \left( \sum_{i=1}^I \sum_{j=1}^J \sum_{n=1}^N d_{ijn}^R x_{ijn}^R + \sum_{i=1}^I \sum_{k=1}^K \sum_{n=1}^N d_{ikn}^C x_{ikn}^C + \sum_{i=1}^I \sum_{l=1}^L \sum_{n=1}^N d_{iln}^{D1} x_{iln}^{D1} \right. \right. \\ & \left. \left. + \sum_{j=1}^J \sum_{m=1}^M \sum_{n=1}^N d_{jmn}^T y_{jmn}^T + \sum_{k=1}^K \sum_{l=1}^L \sum_{n=1}^N d_{kln}^{D2} y_{kln}^{D2} \right), 0 \right]. \end{aligned}$$

### 4.3.2 Fundamental information of model 1

In Model 1, three objective functions are illustrated by Eqs.(4.4)–(4.6). The first objective function determines the total profit in more precise form. In the first objective function, the first part states the total profit obtained from  $l$ th landfill/backfill centre by reusing SW items selected from  $i$ th source (i.e., TS) and transported through  $n$ th conveyance. Subtracting total transportation cost, treatment cost and selection cost from revenue of SW items, find the profit in this part. The second part considers the profit obtained from  $m$ th market by selling

of some reusable items (such as CNG, compost, plastic, metal, glass, cement, tiles, bricks) obtained by recycling the SW from  $j$ th recycle plant, and the profit is calculated by deducting transportation cost from the revenue. The third part defines the profit determined by subtracting the transportation cost and treatment cost from the revenue by landfilling/backfilling of waste items which obtained from  $k$ th incineration plant (i.e., second time created ash by disposing SW). The 4th and 5th parts include the total transportation cost, treatment cost and selection cost of SW which are selected from  $i$ th TS and shifted to  $j$ th recycle plant and  $k$ th incineration plant, respectively. The second objective function is the total elapsed time for loading, unloading and shifting the SW items. The transportation in first stage completed from  $i$ th TS to  $j$ th recycling plant,  $k$ th incineration plant and  $l$ th landfill centre, and in second stage from  $j$ th recycling plant to  $m$ th market centre and from  $k$ th incineration plant to  $l$ th landfill/backfill centre. The third objective function is the total carbon emission from transportation and from  $k$ th incineration plant during disposal of SW items. The first and second parts define in this state for the application of cap and trade policy. The last part describes the total tax for regular carbon emission in the incineration plant. The constraints (4.7), (4.8) and (4.9) indicate the total demand capability of  $j$ th recycle plant,  $k$ th incineration plant and  $l$ th landfill/backfill centre, respectively. Total amount of availability of SW items at  $i$ th TS are transported to distribution plants for the management which is ensured by constraints (4.10). Total amount of ashes produced from  $k$ th incineration plant after disposing the waste items are shown by the constraints (4.11). The demand of  $m$ th market centre for selling recycled reusable product obtained from  $j$ th recycle plant are described by the constraints (4.12). The conveyance capacity of  $n$ th type of vehicle are considered by the constraints (4.13)–(4.17). Total elapsed time will be always less than the maximum budget time for customer satisfaction which is expressed by the constraint (4.18). The non-negativity restrictions of the variables are defined by the constraints (4.19).

### 4.3.3 Equivalent deterministic formulation of model

Due to the existence of twofold uncertainty (TT2IF) on source, demand and conveyance parameters, the proposed model of MOSTP cannot be optimized directly in a simple way. A ranking defuzzification method defined in Eq. (3.3) is introduced to find the deterministic form of Model 1. The deterministic form of Model 1 is Model 2 is described as:

#### Model 2

Objective functions Equations (4.4)–(4.6)

$$\text{subject to } \sum_{i=1}^I \sum_{n=1}^N x_{ijn}^R = \Re(\tilde{a}_j^R) \quad (j = 1, 2, \dots, J), \tag{4.20}$$

$$\sum_{i=1}^I \sum_{n=1}^N x_{ikn}^C = \Re(\tilde{a}_k^C) \quad (k = 1, 2, \dots, K), \tag{4.21}$$

$$\sum_{i=1}^I \sum_{n=1}^N x_{iln}^{D1} + \sum_{k=1}^K \sum_{n=1}^N y_{kln}^{D2} = \Re(\tilde{a}_l^{D1+D2}) \quad (l = 1, 2, \dots, L) \tag{4.22}$$

$$\sum_{j=1}^J \sum_{n=1}^N x_{ijn}^R + \sum_{k=1}^K \sum_{n=1}^N x_{ikn}^C + \sum_{l=1}^L \sum_{n=1}^N x_{iln}^{D1} = \Re(\tilde{a}_i) \quad (i = 1, 2, \dots, I), \tag{4.23}$$

$$\sum_{k=1}^K \sum_{l=1}^L y_{kln}^{D2} = \alpha \sum_{i=1}^I \sum_{k=1}^K x_{ikn}^C \quad (n = 1, 2, \dots, N), \tag{4.24}$$

$$\sum_{j=1}^J \sum_{n=1}^N y_{jmn}^T = \Re(\tilde{b}_m) \quad (m = 1, 2, \dots, M), \tag{4.25}$$

$$\sum_{i=1}^I \sum_{j=1}^J x_{ijn}^R \leq \Re(\tilde{e}_n) \quad (n = 1, 2, \dots, N), \tag{4.26}$$

$$\sum_{i=1}^I \sum_{k=1}^K x_{ikn}^C \leq \Re(\tilde{e}_n) \quad (n = 1, 2, \dots, N), \tag{4.27}$$

$$\sum_{i=1}^I \sum_{l=1}^L x_{iln}^{D1} \leq \Re(\tilde{e}_n) \quad (n = 1, 2, \dots, N), \tag{4.28}$$

$$\sum_{j=1}^J \sum_{m=1}^M y_{jmn}^T \leq \Re(\tilde{e}_n) \quad (n = 1, 2, \dots, N), \tag{4.29}$$

$$\sum_{k=1}^K \sum_{l=1}^L y_{kln}^{D2} \leq \Re(\tilde{e}_n) \quad (n = 1, 2, \dots, N), \tag{4.30}$$

$$\begin{aligned} &\sum_{i=1}^I \sum_{j=1}^J \sum_{n=1}^N t_{ijn}^R \eta_{ijn}^R + \sum_{i=1}^I \sum_{k=1}^K \sum_{n=1}^N t_{ikn}^C \eta_{ikn}^C + \sum_{i=1}^I \sum_{l=1}^L \sum_{n=1}^N t_{iln}^{D1} \eta_{iln}^{D1} \\ &+ \sum_{j=1}^J \sum_{m=1}^M \sum_{n=1}^N t_{jmn}^T \eta_{jmn}^T + \sum_{k=1}^K \sum_{l=1}^L \sum_{n=1}^N t_{kln}^{D2} \eta_{kln}^{D2} \leq T_{max}, \end{aligned} \tag{4.31}$$

$$x_{ijn}^R \geq 0, x_{ikn}^C \geq 0, x_{iln}^{D1} \geq 0, y_{jmn}^T \geq 0, y_{kln}^{D2} \geq 0, \forall i, j, k, l, m, n. \tag{4.32}$$

The feasibility conditions of this MOSTP are considered as:  $\sum_{i=1}^I \Re(\tilde{a}_i) \geq \sum_{j=1}^J \Re(\tilde{a}_j^R)$ ;  $\sum_{i=1}^I \Re(\tilde{a}_i) \geq \sum_{k=1}^K \Re(\tilde{a}_k^C)$ ;  $\sum_{i=1}^I \Re(\tilde{a}_i) \geq \sum_{l=1}^L \Re(\tilde{a}_l^{D1+D2})$ ;  $\sum_{n=1}^N \Re(\tilde{e}_n) \geq \sum_{j=1}^J \Re(\tilde{a}_j^R)$ ;  $\sum_{n=1}^N \Re(\tilde{e}_n) \geq \sum_{k=1}^K \Re(\tilde{a}_k^C)$ ;  $\sum_{n=1}^N \Re(\tilde{e}_n) \geq \sum_{l=1}^L \Re(\tilde{a}_l^{D1+D2})$ ;  $\sum_{n=1}^N \Re(\tilde{e}_n) \geq \sum_{m=1}^M \Re(\tilde{b}_m)$ .

### 4.3.4 Extensions of the model

In Model 2, the third objective function reveals that based on the cap value, there exist two feasible regions. The problem (i.e., Model 2) is now separated into two cases. In first case the cap is greater than the total carbon emission of transportation, and in second case the cap is less than the total emitted carbon from transportation. The first case is depicted mathematically in Model 3A whereas the second case is in Model 3B, as follows:

#### Model 3A

Objective functions Equations (4.4)–(4.5)

$$\text{minimize } Z_3(x, y) = \theta e_{CO_2}^2 \sum_{i=1}^I \sum_{k=1}^K \sum_{n=1}^N x_{ikn}^C - \psi \left[ C - e_{CO_2} \left( \sum_{i=1}^I \sum_{j=1}^J \sum_{n=1}^N \right. \right.$$

$$\begin{aligned}
 & \left. \begin{aligned}
 & d_{ijn}^R x_{ijn}^R + \sum_{i=1}^I \sum_{k=1}^K \sum_{n=1}^N d_{ikn}^C x_{ikn}^C + \sum_{i=1}^I \sum_{l=1}^L \sum_{n=1}^N d_{iln}^{D1} x_{iln}^{D1} + \sum_{j=1}^J \sum_{m=1}^M \sum_{n=1}^N \\
 & d_{jmn}^T y_{jmn}^T + \sum_{k=1}^K \sum_{l=1}^L \sum_{n=1}^N d_{kln}^{D2} y_{kln}^{D2} \end{aligned} \right]
 \end{aligned}$$

subject to constraints (4.20)–(4.32),

$$\begin{aligned}
 & e_{CO_2}^1 \left( \sum_{i=1}^I \sum_{j=1}^J \sum_{n=1}^N d_{ijn}^R x_{ijn}^R + \sum_{i=1}^I \sum_{k=1}^K \sum_{n=1}^N d_{ikn}^C x_{ikn}^C + \sum_{i=1}^I \sum_{l=1}^L \sum_{n=1}^N d_{iln}^{D1} x_{iln}^{D1} \right. \\
 & \left. + \sum_{j=1}^J \sum_{m=1}^M \sum_{n=1}^N d_{jmn}^T y_{jmn}^T + \sum_{k=1}^K \sum_{l=1}^L \sum_{n=1}^N d_{kln}^{D2} y_{kln}^{D2} \right) \leq C. \tag{4.33}
 \end{aligned}$$

**Model 3B**

Objective functions Equations (4.4)–(4.5)

$$\begin{aligned}
 & \text{minimize } Z_3(x, y) = \theta e_{CO_2}^2 \sum_{i=1}^I \sum_{k=1}^K \sum_{n=1}^N x_{ikn}^C + \phi P \left[ e_{CO_2}^1 \left( \sum_{i=1}^I \sum_{j=1}^J \sum_{n=1}^N \right. \right. \\
 & \left. \left. d_{ijn}^R x_{ijn}^R + \sum_{i=1}^I \sum_{k=1}^K \sum_{n=1}^N d_{ikn}^C x_{ikn}^C + \sum_{i=1}^I \sum_{l=1}^L \sum_{n=1}^N d_{iln}^{D1} x_{iln}^{D1} + \sum_{j=1}^J \sum_{m=1}^M \sum_{n=1}^N \right. \right. \\
 & \left. \left. d_{jmn}^T y_{jmn}^T + \sum_{k=1}^K \sum_{l=1}^L \sum_{n=1}^N d_{kln}^{D2} y_{kln}^{D2} \right) - C \right]
 \end{aligned}$$

subject to constraints (4.20)–(4.32),

$$\begin{aligned}
 & e_{CO_2}^1 \left( \sum_{i=1}^I \sum_{j=1}^J \sum_{n=1}^N d_{ijn}^R x_{ijn}^R + \sum_{i=1}^I \sum_{k=1}^K \sum_{n=1}^N d_{ikn}^C x_{ikn}^C + \sum_{i=1}^I \sum_{l=1}^L \sum_{n=1}^N \right. \\
 & \left. d_{iln}^{D1} x_{iln}^{D1} + \sum_{j=1}^J \sum_{m=1}^M \sum_{n=1}^N d_{jmn}^T y_{jmn}^T + \sum_{k=1}^K \sum_{l=1}^L \sum_{n=1}^N d_{kln}^{D2} y_{kln}^{D2} \right) \geq C. \tag{4.34}
 \end{aligned}$$

The feasibility conditions of Models 3A and 3B are same as Model 2.

**Proposition 4.1** *If both Model 3A and Model 3B give the Pareto-optimal solution, then the Pareto-optimal solution of Model 2 is finalized by comparing both. If one of Model 3A or Model 3B allows for providing a feasible solution, but another cannot, then this feasible solution is declared as the final optimal solution of Model 2.*

**Definition 4.1** A solution  $(x^*, y^*) \in F$  ( $F$  is the feasible region) is said to be a Pareto-optimal solution (non-dominated solution) of Model 3A/Model 3B if and only if there is no other  $(x, y) \in F$  such that  $Z_u(x, y) \leq Z_u(x^*, y^*)$ ,  $u = 2, 3$ , and  $Z_1(x, y) \geq Z_1(x^*, y^*)$  for at least one inequality holds as strict inequality.

**4.3.5 Complexity and practicality of the mathematical model**

The complexity of the proposed models is as follows:

- (i) A large number of variables and equations are tackled here, which is a laborious process.
- (ii) Depending on the cap value, Model 3A or Model 3B may not provide a feasible solution, but both the models are to be evaluated for searching a feasible solution without any prediction. Again if both the models have a feasible solution, then a comparison is required to select the final solution, which is a long-term process.
- (iii) For getting a final Pareto-optimal solution and to check the model validation, more than one methodologies are necessary to utilize and then being compared. This is time dependent procedure.

The practically of the mathematical model is described subsequently:

- (i) Multiple objective functions are controlled here and all of them are optimized together. This type of model is applicable in any multi-objective optimization problem.
- (ii) The type-2 uncertain model (Model 1) is converted easily to a crisp model (Model 2) without any loss of data. This model is therefore prepared to tackle any type of uncertainty from realistic application.
- (iii) Fuzzy or non-fuzzy technique is confirmed to provide Pareto-optimal solution of any one model, i.e., Model 3A or Model 3B.
- (iv) The model is started by choosing a waste management procedure and then established by optimizing all the criteria of sustainability through transportation. This model is therefore to be applied in several practical applications.

## 5 Waste flow allocation in strategic level

In a multi-objective optimization problem, the objective functions are conflicting to each other, and there does not always exist a unique solution which is the best to 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. Literature survey shown that, various fuzzy and non-fuzzy techniques were utilized to generate Pareto-optimal solution of multi-objective decision making problems. Most of fuzzy techniques are fuzzy programming, intuitionistic fuzzy programming, NLP, whereas non-fuzzy techniques are goal programming, weighted goal programming,  $\epsilon$ -constraint method, global criterion method. From these methods, this study selects one fuzzy technique namely NLP [defined by Ye (2018)], and another non-fuzzy technique is  $\epsilon$ -constraint method [as initiated by Haines (1971)]. Solving Model 3A and Model 3B individually, these two methods generate Pareto-optimal solutions in a technical as well as intellectual way. The solutions of both models are compared, and a better solution is selected as final Pareto-optimal solution of Model 2. The final Pareto-optimal solution of Model 2 is picked even if one model (Model 3A or Model 3B) provides the feasible solution and other generates no feasible solution (NFS).

The stepwise procedure of two methods are defined in the following Subjects. 5.1 and 5.2 as follows.

### 5.1 Neutrosophic linear programming (NLP)

The NLP is a modified and improved programming method that provides the Pareto-optimal solution of multi-objective optimization problem. In this programming, truth membership function, indeterminacy membership function and falsity membership function are formulated corresponding to each objective function. NLP maximizes the truth and indeterminacy



membership functions whereas it minimizes the falsity membership function. To solve the proposed model by NLP, the steps are described as:

- *Step 5.1.1:* Converting Model 1 in TT2IF environment into deterministic problem (Model 2) by ranking value index (defined by Eq. 3.3).
- *Step 5.1.2:* Solving each objective function individually with subject to all constraints.
- *Step 5.1.3:* Determining the positive ideal solution (PIS) and negative ideal solution (NIS) corresponding to every objective function as follows:  
 For  $u = 1$ ; PIS =  $U_u^T = \max\{Z_{u1}, Z_{u2}, Z_{u3}\}$  and NIS =  $L_u^T = \min\{Z_{u1}, Z_{u2}, Z_{u3}\}$ .  
 For  $u = 2, 3$ ; PIS =  $L_u^T = \min\{Z_{u1}, Z_{u2}, Z_{u3}\}$  and NIS =  $U_u^T = \max\{Z_{u1}, Z_{u2}, Z_{u3}\}$ .  
 Here  $Z_{ur} = Z_u(X^r, Y^r)$  ( $r = 1, 2, 3$ ).
- *Step 5.1.4:* Designing the truth membership function and indeterminacy membership function with highest degree and falsity membership function with least degree.
- *Step 5.1.5:* Setting the tolerance and constructing the membership functions according to the bounds as:

For  $u = 1$ ,

$$T_u(Z_u(x, y)) = \begin{cases} 1, & \text{if } Z_u(x, y) > U_u^T, \\ \frac{Z_u(x,y)-L_u^T}{U_u^T-L_u^T}, & \text{if } L_u^T \leq Z_u(x, y) \leq U_u^T, \\ 0, & \text{if } Z_u(x, y) < L_u^T, \end{cases}$$

$$I_u(Z_u(x, y)) = \begin{cases} 1, & \text{if } Z_u(x, y) > U_u^I, \\ \frac{Z_u(x,y)-L_u^I}{U_u^I-L_u^I}, & \text{if } L_u^I \leq Z_u(x, y) \leq U_u^I, \\ 0, & \text{if } Z_u(x, y) < L_u^I, \end{cases}$$

$$F_u(Z_u(x, y)) = \begin{cases} 0, & \text{if } Z_u(x, y) > U_u^F, \\ \frac{U_u^F-Z_u(x,y)}{U_u^F-L_u^F}, & \text{if } L_u^F \leq Z_u(x, y) \leq U_u^F, \\ 1, & \text{if } Z_u(x, y) < L_u^F. \end{cases}$$

For  $u = 2$  and  $3$ ,

$$T_u(Z_u(x, y)) = \begin{cases} 1, & \text{if } Z_u(x, y) < L_u^T, \\ \frac{U_u^T-Z_u(x,y)}{U_u^T-L_u^T}, & \text{if } L_u^T \leq Z_u(x, y) \leq U_u^T, \\ 0, & \text{if } Z_u(x, y) > U_u^T, \end{cases}$$

$$I_u(Z_u(x, y)) = \begin{cases} 1, & \text{if } Z_u(x, y) < L_u^I, \\ \frac{U_u^I-Z_u(x,y)}{U_u^I-L_u^I}, & \text{if } L_u^I \leq Z_u(x, y) \leq U_u^I, \\ 0, & \text{if } Z_u(x, y) > U_u^I, \end{cases}$$

$$F_u(Z_u(x, y)) = \begin{cases} 0, & \text{if } Z_u(x, y) < L_u^F, \\ \frac{Z_u(x,y)-L_u^F}{U_u^F-L_u^F}, & \text{if } L_u^F \leq Z_u(x, y) \leq U_u^F, \\ 1, & \text{if } Z_u(x, y) > U_u^F. \end{cases}$$

Here  $U_u^F = U_u^T, L_u^F = L_u^T + t_u(U_u^T - L_u^T)$ ;  $L_u^I = L_u^T, U_u^I = L_u^T + s_u(U_u^T - L_u^T)$ ;  $t_u, s_u$  are the tolerances chosen by decision maker's own choice.

- *Step 5.1.6:* Selecting the values of  $\xi, \eta$  and  $\zeta$  in  $[0, 1]$  as the truth, indeterminacy and falsity degrees, respectively, and then construct NLP model that represents as Model 4A.

**Model 4A**

maximize  $T_u(Z_u(x, y))$  ( $u = 1, 2, 3$ )

maximize  $I_u(Z_u(x, y))$  ( $u = 1, 2, 3$ )

$$\begin{aligned} & \text{minimize } F_u(Z_u(x, y)) \quad (u = 1, 2, 3) \\ & \text{subject to } \text{the constraints (4.20)–(4.32),} \\ & \quad \text{the constraints (4.33) or (4.34).} \end{aligned}$$

To find Pareto-optimal solution, the simplified model for NLP is Model 4B as follows:

#### Model 4B

$$\begin{aligned} & \text{maximize } \xi + \eta - \zeta \\ & \text{subject to } Z_u(x, y) + (U_u^T - L_u^T)\xi \leq U_u^T, \\ & \quad Z_u(x, y) + (U_u^I - L_u^I)\eta \leq U_u^I, \\ & \quad Z_u(x, y) - (U_u^F - L_u^F)\zeta \leq U_u^F, \\ & \quad \xi + \eta + \zeta \leq 3, \quad \xi \geq \zeta, \quad \xi \geq \eta, \\ & \quad \xi, \eta, \zeta \in [0, 1], \quad (u = 1, 2, 3), \\ & \quad \text{the constraints (4.20)–(4.32),} \\ & \quad \text{the constraints (4.33) or (4.34).} \end{aligned}$$

- *Step 5.1.7:* Solving Model 4B by LINGO iterative scheme and determining Pareto-optimal solution.

**Theorem 5.1** *If  $(x^*, y^*, \xi, \eta, \zeta)$  is an optimal solution of Model 4B then it is also a Pareto-optimal (non-dominated) solution of Model 3A/Model 3B or both.*

**Proof** The proof of this theorem is apparent from Lemma 3 of work (Das & Roy, 2019).  $\square$

## 5.2 $\epsilon$ -Constraint method

Several non-fuzzy techniques are convenient for solving MOSTP. Among these methods,  $\epsilon$ -constraint method is an effective and useful method. This method generates Pareto-optimal solutions by varying the values of  $\epsilon$  along Pareto-optimal front to each objective function. For each value of  $\epsilon$ , there exists a new optimization problem. This method solves the crisp problem to minimize/maximize the objective function, then the MOSTP transforms into a single objective STP by choosing one objective at that time, and the remaining objective functions treat as constraints by defining their aspiration levels. The necessary steps for solving the problem are described below:

- *Step 5.2.1:* Redesigning the fuzzy MOSTP into crisp MOSTP with the help of ranking index, i.e., using Eq.(3.3).
- *Step 5.2.2:* Calculating the solution of each objective function at a time by omitting the other objective functions but treat these as constraints in addition to the existing constraints.
- *Step 5.2.3:* Finding the best value and the worst value of every objective function.
- *Step 5.2.4:* Selecting any one objective function  $Z_{u'}$  among  $Z_u$ , ( $u, u' = 1, 2, 3 : u \neq u'$ ) and choosing the other objective functions into constraints, and the equivalent single objective deterministic model is as follows:

#### Model 5

$$\begin{aligned} & \text{minimize } Z_{u'}(u' = 2, 3)/\text{maximize } Z_{u'}(u' = 1) \\ & \text{subject to } Z_u \leq \epsilon_u \quad (u, u' = 1, 2, 3 : u \neq u'), \end{aligned}$$

the constraints (4.20)–(4.32),  
the constraints (4.33) or (4.34).

Range of  $\epsilon_u$  is defined by DM who represents the maximum entrance values of the objective functions. Varying the values of  $\epsilon_u$  along Pareto-optimal front for each objective function, find the Pareto-optimal solution.

- *Step 5.2.5:* Choosing LINGO iterative scheme and determining the value of the objective function for each case, and finding the Pareto-optimal solution of Model 3A/Model 3B.

## 6 Pros and cons of the proposed approach

This section presents the major advantages with some limitations of the proposed study.

- The proposed study designs a model of MOSTP by considering an SWM project with the main focus for SD. The main contribution of this study is to provide an optimal strategy for finding a Pareto-optimal solution.
- Here an WM process is completed in an intellectual way through two stages. In first stage, wastes are distributed into treatment plants, and in second stage, recycle elements are obtained by intellectual process for using second time, and landfill/backfill process is completed at the same time.
- TS separates the waste items according to their nature and transfers them with minimum maintenance cost. The proposed problem is handled by considering two decision variables, one from TS to various treatment plants (recycle plant, incineration plant, landfill/backfill centre) and another from a treatment plant to final destination by keeping fixed with all other required conditions as constraints.
- SD is established by the intersection of three parameters which are economical, social and environment, and explicitly defined by Fig. 1. In the proposed model, the economical aspect is improved by maximizing profit; the social impact, i.e., customer satisfaction is established by minimizing elapsed time with time budget (defined in constraints 4.18), and the third one is environment effect that obtained by minimizing total carbon emission. The emission of transportation is reduced by incorporating cap and trade policy and emission from incineration plant is minimized by imposing carbon tax policy.
- This study implements twofold uncertainty (T2IF) in the formulated model to control more uncertainty and to overcome the hesitation of realistic critical conditions.
- A simple and appropriate ranking index using membership and non-membership functions is introduced to convert the TT2IFN into a crisp form and this ranking index obeys the linearity property.
- For finding a Pareto-optimal solution of the suggested MOSTP, two preferable approaches are included, as the NLP and  $\epsilon$ -constraint method. Graphical presentations of Pareto-optimal solution of  $\epsilon$ -constraint method are illustrated in Figs. 3, 4, 5, 6, 7 and 8 for better understanding.
- The main limitation of the proposed MOSTP is that this study does not consider any fixed-charge and treatment time of WM to the formulated model.
- Penetration of leachate into the soil is a major drawback in landfills. Leachate can pollute surface water and ground water that can harm human and natural systems. These drawbacks are not considered in the designed model.
- Illegal burning of hazardous waste elements in incineration plant has been inefficient and highly toxic to the air, health and environment, as this process emits a huge amount of CO<sub>2</sub> gas and other polluted gases. These are effected as to reduce ozone layer, to increase

**Table 4** Supply, demand of 1st stage, demand of 2nd stage, conveyance capacity in TT2IFNs and their ranking values

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$\tilde{a}_1 = \langle \langle \langle (500, 600, 700); 0.75, 0.15 \rangle, \langle (550, 650, 750); 0.65, 0.15 \rangle, \langle (600, 700, 800); 0.8, 0.1 \rangle \rangle; 0.65, 0.15 \rangle; \mathfrak{R}(\tilde{a}_1) = 260$
$\tilde{a}_2 = \langle \langle \langle (550, 650, 750); 0.8, 0.2 \rangle, \langle (600, 700, 800); 0.7, 0.1 \rangle, \langle (650, 750, 850); 0.6, 0.1 \rangle \rangle; 0.6, 0.2 \rangle; \mathfrak{R}(\tilde{a}_2) = 280$
$\tilde{a}_1^R = \langle \langle \langle (150, 200, 250); 0.6, 0.1 \rangle, \langle (200, 250, 300); 0.8, 0.1 \rangle, \langle (250, 300, 350); 0.5, 0.4 \rangle \rangle; 0.56, 0.4 \rangle; \mathfrak{R}(\tilde{a}_1^R) = 120$
$\tilde{a}_2^R = \langle \langle \langle (180, 200, 220); 0.7, 0.2 \rangle, \langle (210, 220, 230); 0.6, 0.3 \rangle, \langle (200, 240, 280); 0.5, 0.5 \rangle \rangle; 0.5, 0.5 \rangle; \mathfrak{R}(\tilde{a}_2^R) = 110$
$\tilde{a}_1^C = \langle \langle \langle (100, 110, 120); 0.65, 0.25 \rangle, \langle (110, 120, 130); 0.8, 0.2 \rangle, \langle (120, 130, 140); 0.55, 0.35 \rangle \rangle; 0.55, 0.35 \rangle; \mathfrak{R}(\tilde{a}_1^C) = 54$
$\tilde{a}_2^C = \langle \langle \langle (120, 130, 140); 0.5, 0.2 \rangle, \langle (130, 140, 150); 0.7, 0.1 \rangle, \langle (140, 150, 160); 0.8, 0.2 \rangle \rangle; 0.5, 0.2 \rangle; \mathfrak{R}(\tilde{a}_2^C) = 49$
$\tilde{a}_1^{D1+D2} = \langle \langle \langle (200, 220, 240); 0.6, 0.3 \rangle, \langle (220, 240, 260); 0.5, 0.4 \rangle, \langle (240, 260, 280); 0.7, 0.2 \rangle \rangle; 0.5, 0.4 \rangle; \mathfrak{R}(\tilde{a}_1^{D1+D2}) = 108$
$\tilde{a}_2^{D1+D2} = \langle \langle \langle (250, 260, 270); 0.9, 0.1 \rangle, \langle (260, 270, 280); 0.8, 0.1 \rangle, \langle (270, 280, 290); 0.6, 0.2 \rangle \rangle; 0.6, 0.2 \rangle; \mathfrak{R}(\tilde{a}_2^{D1+D2}) = 108$
$\tilde{b}_1^T = \langle \langle \langle (100, 105, 110); 0.6, 0.5 \rangle, \langle (105, 110, 115); 0.8, 0.1 \rangle, \langle (110, 115, 120); 0.5, 0.3 \rangle \rangle; 0.5, 0.3 \rangle; \mathfrak{R}(\tilde{b}_1^T) = 44$
$\tilde{b}_2^T = \langle \langle \langle (90, 100, 110); 0.7, 0.2 \rangle, \langle (100, 110, 120); 0.8, 0.2 \rangle, \langle (110, 120, 130); 0.6, 0.3 \rangle \rangle; 0.6, 0.3 \rangle; \mathfrak{R}(\tilde{b}_2^T) = 49.5$
$\tilde{e}_1 = \langle \langle \langle (300, 320, 340); 0.6, 0.2 \rangle, \langle (320, 340, 360); 0.9, 0.1 \rangle, \langle (340, 360, 380); 0.75, 0.15 \rangle \rangle; 0.6, 0.2 \rangle; \mathfrak{R}(\tilde{e}_1) = 136$
$\tilde{e}_2 = \langle \langle \langle (350, 360, 370); 0.55, 0.25 \rangle, \langle (360, 370, 380); 0.75, 0.15 \rangle, \langle (370, 380, 390); 0.8, 0.1 \rangle \rangle; 0.55, 0.25 \rangle; \mathfrak{R}(\tilde{e}_2) = 148$

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surface temperature, to raise sea levels, also animals are unable to adjust such ecosystem. The situation is of high risk mainly for developed as well as developing countries. That case is not included in the present study.

## 7 Application of model

Two numerical examples are displayed in this section to illustrate the effectiveness of the proposed model.

### 7.1 Input data

**Example 1** In this example two TSs ( $I = 2$ ) are defined as source of waste items. An industrial organization/NGO/municipal system handles WM problem by transporting waste into three types ( $J, K, L$ ) of treatment plant for recycle, disposal (by incineration) and landfill/backfill process. Each type of treatment plant is considered two centres ( $J = 2, K = 2, L = 2$ ). By treatment of the waste items, some recycle items are resell in market centre ( $M = 2$ ) for using second time, and these provide some revenue. From landfill/backfill centre ( $L = 2$ ) a credit cost is found. All the required parameters are defined in Tables 4, 5, 6, 7, 8, 9, 10 and 11. The source, demand and conveyance are considered as TT2IFN, and ranking index for defuzzification of the parameters are used. Here, the three objective functions are optimized by maximizing profit, minimizing time and minimizing carbon emission under the cap and trade policy. For such policy, the designed problem is divided into two cases. We choose the carbon cap  $C = 6800$  gm for this example, and all the parameters unit, e.g., cost in Rupees (INR), time in hour (h), distance in kilometre (km) are defined in Tables 4, 5, 6, 7, 8, 9, 10 and 11.

**Example 2** In this example, we take the carbon cap  $C = 5700$  gm, and all other parameters are same as Example 1. If the system releases less/more carbon than the cap  $C$ , then the system can sell/buy the extra permit in carbon trading market. If the system emits surplus

**Table 5** Transportation cost  $c_{ijn}^R, c_{ikn}^C, c_{iln}^{D1}, c_{jmn}^T, c_{kln}^{D2}$

Source–destination–conveyance	$c_{ijn}^R$	$c_{ikn}^C$	$c_{iln}^{D1}$	$c_{jmn}^T$	$c_{kln}^{D2}$
1–1–1	2.4	3.2	9.0	3.8	9.2
1–2–1	2.6	2.8	8.0	5.75	10.8
1–1–2	2.45	2.7	10.0	4.4	8.4
1–2–2	2.2	3.25	11.0	4.2	11.7
2–1–1	2.0	2.5	7.6	4.5	14.5
2–1–2	3.75	2.1	13.0	5.4	11.7
2–2–1	2.6	3.2	10.4	5.4	9.6
2–2–2	3.15	3.4	12.8	5.8	12.0

**Table 6** Selection cost  $s_{ijn}^R, s_{ikn}^C, s_{iln}^{D1}$

Source–destination–conveyance	$s_{ijn}^R$	$s_{ikn}^C$	$s_{iln}^{D1}$
1–1–1	6.3	3.15	10.8
1–2–1	4.8	4.25	11.7
1–1–2	5.0	3.5	11.25
1–2–2	6.75	3.75	10.4
2–1–1	4.4	4.05	11.0
2–1–2	4.6	4.5	9.6
2–2–1	5.2	4.25	15.0
2–2–2	5.8	4.0	11.2

**Table 7** Treatment cost  $m_{ijn}^R, m_{ikn}^C, m_{iln}^{D1}, m_{kln}^{D2}$

Source–destination–conveyance	$m_{ijn}^R$	$m_{ikn}^C$	$m_{iln}^{D1}$	$m_{kln}^{D2}$
1–1–1	7.65	1.6	5.2	7.0
1–2–1	4.95	2.2	6.0	4.2
1–1–2	9.0	3.6	4.95	4.8
1–2–2	5.6	3.15	4.55	5.6
2–1–1	5.4	3.375	4.8	4.4
2–1–2	5.8	2.25	6.3	5.4
2–2–1	5.75	2.275	6.5	6.3
2–2–2	7.45	2.2	5.4	7.0

carbon than the cap value, then authority has to pay extra cost, called as penalty charge. All the objective functions of two examples are optimized under sustainability and under cap and trade policy.

### 8 Results implication and discussion

Two numerical examples are evaluated by considering two cases with the help of mentioned methods as NLP and  $\epsilon$ -constraint method. In Example 1, where cap  $C = 6800$  gm provides feasible solutions of two cases. Between the extracted solutions from the methods, a better

**Table 8** Revenue  $r_{iln}^{D1}, r_{kln}^{D2}, r_{jmn}^T$

Source–destination–conveyance	$r_{iln}^{D1}$	$r_{kln}^{D2}$	$r_{jmn}^T$
1–1–1	99	84	36
1–2–1	84	120	36
1–1–2	76	90	31.5
1–2–2	110	104	45
2–1–1	72.8	90	36
2–1–2	76.5	95	26.8
2–2–1	94	73.8	28
2–2–2	68	67.5	39.15

**Table 9** Elapsed time  $t_{ijn}^R, t_{ikn}^C, t_{iln}^{D1}, t_{jmn}^T, t_{kln}^{D2}$

Source–destination–conveyance	$t_{ijn}^R$	$t_{ikn}^C$	$t_{iln}^{D1}$	$t_{jmn}^{D2}$	$t_{kln}^T$
1–1–1	2.5	3.15	4.15	5.0	3.0
1–2–1	3.0	2.5	4.0	5.4	4.0
1–1–2	2.4	2.25	4.25	4.3	3.3
1–2–2	2.15	3.15	5.0	5.3	4.15
2–1–1	2.0	2.15	3.5	6.15	4.3
2–1–2	3.2	2.0	5.5	5.25	5.0
2–2–1	3.0	3.55	5.15	5.0	4.45
2–2–2	2.45	3.5	6.0	5.35	5.3

**Table 10** Distance  $d_{ijn}^R, d_{ikn}^C, d_{iln}^{D1}, d_{jmn}^T, d_{kln}^{D2}$

Source–destination–conveyance	$d_{ijn}^R$	$d_{ikn}^C$	$d_{iln}^{D1}$	$d_{jmn}^T$	$d_{kln}^{D2}$
1–1–1	80	82	125	80	118
1–2–1	100	70	115	90	130
1–1–2	85	75	105	75	85
1–2–2	75	90	110	82	122
2–1–1	83	65	85	95	135
2–1–2	105	60	112	103	100
2–2–1	110	78	115	98	120
2–2–2	95	70	120	107	105

**Table 11** Carbon emission rate, tax, carbon trading (selling cost, buying cost), penalty charge, rate of ash production

Parameters with their values
$e_{CO_2}^1 = 0.15 \text{ gm/km}, e_{CO_2}^2 = 2.5 \text{ gm/kg}, \theta = 0.40, \psi = 0.8, \phi = 0.7, P = 0.9, \alpha = 25\%$

**Table 12** Pareto optimal solution in  $\epsilon$ -constraint method when  $C = 6800$  gm (case of Model 3A)

Case	$Z_1(A)$	$Z_2(A)$	$Z_3(A)$
$\epsilon_1$	<b>9409.10</b>	<b>20.65</b>	<b>36.84</b>
$\epsilon_2$	8876.2	25.4	79.68
$\epsilon_3$	10289.47	23.15	74.709
$\epsilon_4$	8907.02	27.9	74.7
$\epsilon_5$	8875.62	29.8	44.605

**Table 13** Pareto optimal solution in  $\epsilon$ -constraint method when  $C = 6800$  gm (case of Model 3B)

Case	$Z_1(B)$	$Z_2(B)$	$Z_3(B)$
$\epsilon_1$	8758.743	30.45	103.004
$\epsilon_2$	10552.05	23.8	93.737
$\epsilon_3$	<b>10,410.225</b>	<b>23.65</b>	<b>93.5</b>
$\epsilon_4$	8950.129	27.85	101.388
$\epsilon_5$	8758.666	27.85	102.987
$\epsilon_6$	8758.75	27.85	103
$\epsilon_7$	9949.73	27.15	93.5
$\epsilon_8$	5831.216	35.8	93.5

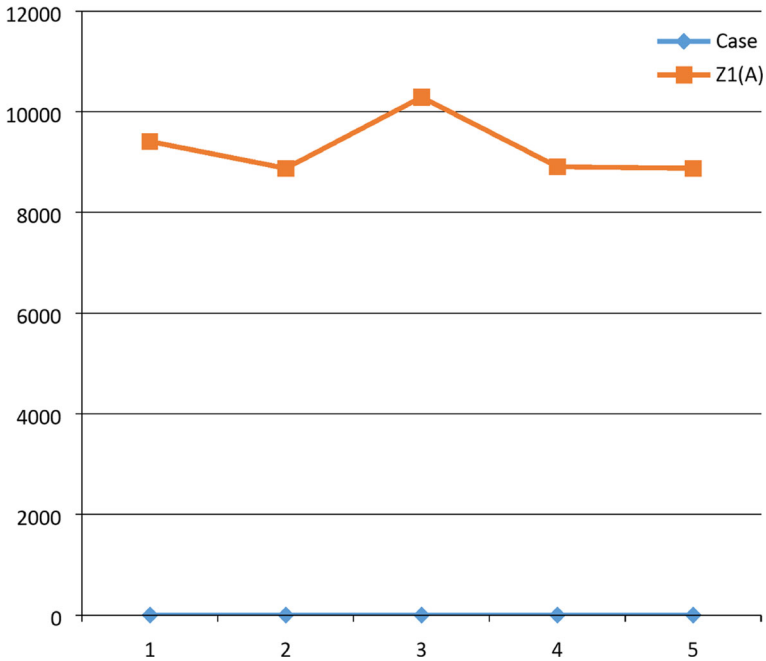
**Table 14** Pareto optimal solution in  $\epsilon$ -constraint method when  $C = 5700$  gm (case of Model 3B)

Case	$Z_1(B)$	$Z_2(B)$	$Z_3(B)$
$\epsilon_1$	11790.83	23.75	1089.052
$\epsilon_2$	12910.37	23.75	1368.074
$\epsilon_3$	11473.45	27.25	868.603
$\epsilon_4$	8876.2	25.4	777.636
$\epsilon_5$	<b>9409.1</b>	<b>20.65</b>	<b>743.899</b>
$\epsilon_6$	10047.170	26.5	747.695

solution is chosen to denote as Pareto-optimal solution of Example 1. For Example 2, when cap  $C = 5700$  gm then only second case gives the feasible solution, and it is the final solution of this example. The  $\epsilon$ -constraint method provides a set of optimal solutions by varying the values of  $\epsilon$  for every value of  $Z_u$ , ( $u = 1, 2, 3$ ) which are defined in Tables 12, 13, and 14. From each table, the exact Pareto-optimal solution is found (represented in bold form). Pareto-optimal front of  $\epsilon$ -constraint method of Tables 12 and 14 are defined graphically in Figs. 3, 4, 5, 6, 7 and 8, which are declared as final Pareto-optimal solutions of both examples. The optimal allocations of two examples obtained by NLP in both cases are defined in Table 15. The final Pareto-optimal solutions (objective values) in both examples with two methods are summarized in Table 16.

## 8.1 Graphical presentation of the Pareto-optimal solution

Here the Pareto-optimal solutions of both examples are presented by graphically. The variation of  $\epsilon$  corresponding to each objective function is highlighted in Figs. 3, 4 and 5 for first example and in Figs. 6, 7 and 8 for our second example. These figures help to select the final



**Fig. 3** Pareto-optimal for Z1(A),  $C = 6800$  gm

Pareto-optimal solution of  $\epsilon$ -constraint method. The trade-off between cap and trade policy and carbon emission reduction are focused in Fig. 9.

## 8.2 Measuring quality with discussion

It is comprehended from Table 16 that when cap  $C = 6800$  gm, then the case A gives a better result than case B in both NLP and  $\epsilon$ -constraint method, and these results are noted in bold form. When carbon cap  $C = 5700$  gm then only the case B provides objective values but the case A does not have feasible solution in both methods. Since  $\epsilon$ -constraint method provides a better results than NLP in two examples, so the results of  $\epsilon$ -constraint method are selected only. In this method, the obtained objective values of two examples show that the maximum profit is 9409.10 in INR and minimum elapsed time is 20.65 h and these two objectives are same in both cases, whereas carbon emission costs are 36.84 in INR and 743.899 in INR are different due to the variation of cap value in cap and trade regulation.

### Comparison analysis:

From Table 1, it is seen that the work of Farrokhi-Asl et al. (2020), Midya et al. (2021) and Xu et al. (2017) have a linked with the proposed study by the consideration of WM, multi-objective scenario, and carbon emission. In this regard, both the examples are evaluated using these approaches (from these three references) in  $\epsilon$ -constraint method (as it is selected as a better method in the proposed study), and the results are displayed in Table 17.

It is clear from Table 17 that Farrokhi-Asl et al. (2020) and Midya et al. (2021) displays same results in both examples. Xu et al. (2017) and the proposed study provide the the result of Example 1, when  $C = 6800$  gm. This difference appears due to Farrokhi-Asl et al. (2020)



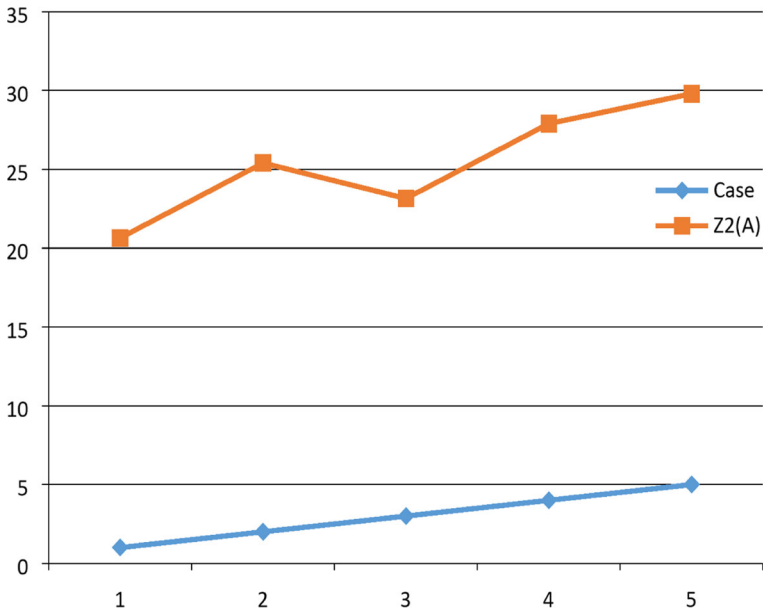


Fig. 4 Pareto-optimal for Z2(A),  $C = 6800$  gm

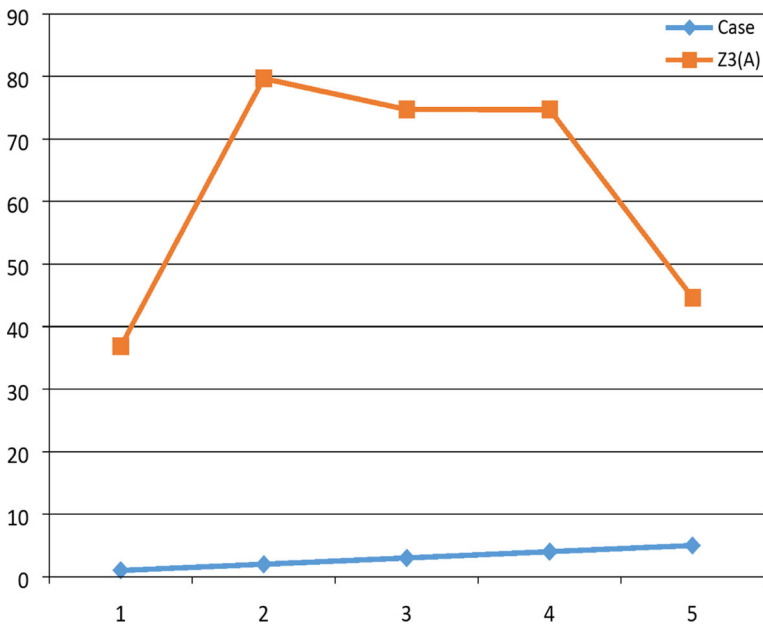


Fig. 5 Pareto-optimal for Z3(A),  $C = 6800$  gm

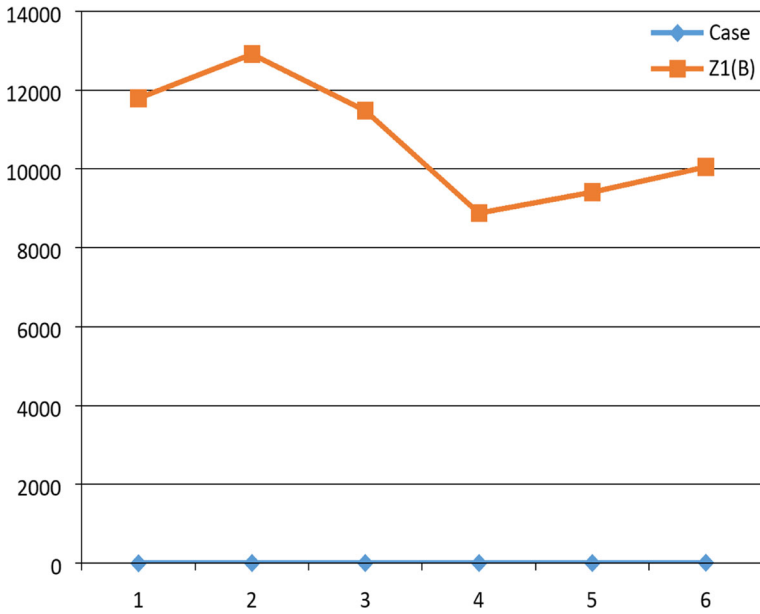


Fig. 6 Pareto-optimal for Z1(B),  $C = 5700$  gm

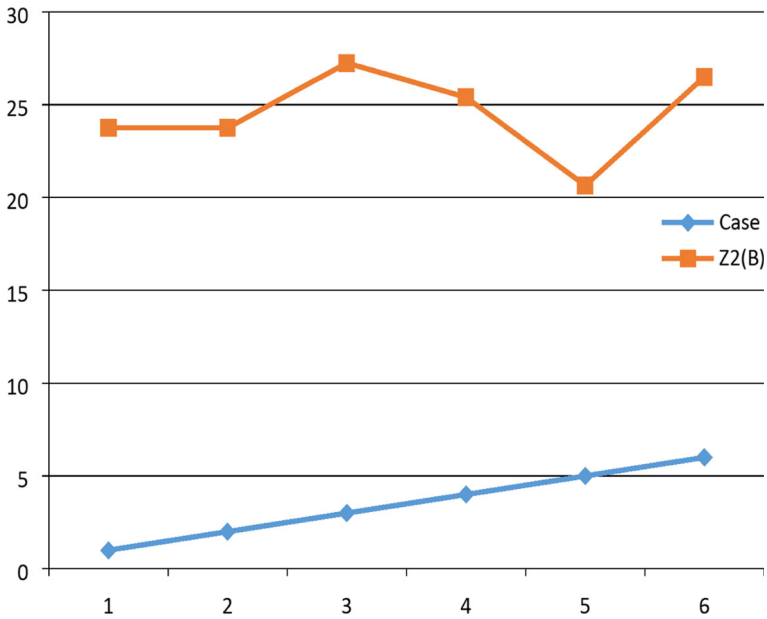
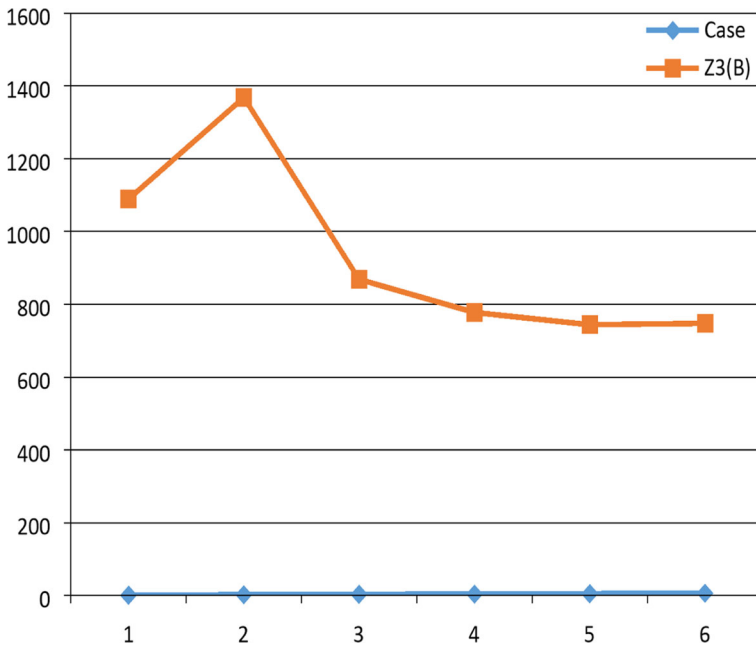


Fig. 7 Pareto-optimal for Z2(B),  $C = 5700$  gm



**Fig. 8** Pareto-optimal for Z3(B),  $C = 5700$  gm

and Midya et al. (2021) optimized the multiple objective values by considering one objective as minimum carbon emission without any restriction. In Xu et al. (2017) and proposed study the optimization of three objective functions, as well as the minimization of carbon emission is determined by including cap restriction. It is also noted that in Example 1, all these four research works display the profit and elapsed time as same. Only the proposed study defines a better and different carbon emission charge in third objective function  $Z_3(A)$ . This difference is occurred by the strategy of carbon cap-and-trade policy in proposed study; though (Xu et al., 2017) included cap restriction without providing any economical opportunity which is highlighted in the proposed study. For this convenience, the present work is appropriate as well advanced with respect to these literature review.

Sustainability is a major part of global issue in recent scenario. The recommended model focuses deeply on carbon cap  $C$ , as it acts a significant role to improve environment by imposing a restriction for reduction of carbon emission. It is observed that for different cap values, the objective functions are varied by the intellectual effect of cap and trade policy. Watching Fig. 9, the proposed study finds that how the cap value and emission cost are inversely proportional to each other. From Table 16, this research analyzes the emission cost of both examples and finds the contradictory nature of carbon cap and emission cost. If the cap value increases then total emission cost decreases. For greater cap value, the system finds a relaxation to emit more emissions by using low expansible vehicle. If total emission is under cap for large cap value, then the transportation system/organization(s) is capable to sell the extra permit in trade market for getting a credit cost. This supports the reduction of the total emission cost. The situation, when the cap is low then transportation system utilizes high expansible vehicle that emits low carbon and total emission will be under cap. For lower cap value, total emission easily crosses the cap and then transportation system/organization(s) should pay a penalty charge for extra emission and buy shortage

**Table 15** Optimal allocation of NLP

Carbon cap	Allocation and membership grade
C=6800 gm (A)	$\xi = 1, \eta = 1, \zeta = 0.00489; x_{121}^{D1} = 24.175, x_{122}^{D1} = 74.325, x_{211}^{D1} = 108,$ $x_{111}^R = 33.214, x_{122}^R = 110, x_{211}^{D1} = 87.286, x_{121}^C = 18.286, x_{212}^C = 54,$ $x_{222}^C = 30.714,$ other variables are zero
C=6800 gm(B)	$\xi = 1, \eta = 1, \zeta = 0.00003; x_{112}^{D1} = 6.786, x_{121}^{D1} = 34.786,$ $x_{122}^{D1} = 63.588, x_{211}^{D1} = 101.214, x_{222}^{D1} = 0.218, x_{122}^R = 105.932,$ $x_{211}^R = 120.5, x_{222}^R = 4.068, x_{121}^C = 48.909, x_{212}^C = 54,$ other variables are zero
=5700 gm (B)	$\xi = 1, \eta = 1, \zeta = 0.00003;$ $x_{112}^{D1} = 1.923, x_{121}^{D1} = 29.923, x_{122}^{D1} = 68.348, x_{211}^{D1} = 106.077,$ $x_{222}^{D1} = 0.228, x_{111}^R = 0.805, x_{122}^R = 110, x_{211}^R = 119.695, x_{121}^C = 49,$ $x_{212}^C = 54,$ other variables are zero

**Table 16** Solution of NLP and  $\epsilon$ -constraint method

Approach	Cap (C)	Z <sub>1</sub> (A)	Z <sub>2</sub> (A)	Z <sub>3</sub> (A)	Z <sub>1</sub> (B)	Z <sub>2</sub> (B)	Z <sub>3</sub> (B)
NLP	6800 gm	<b>8876.195</b>	<b>27.15</b>	<b>57.928</b>	8758.690	33.85	102.919
$\epsilon$ -constraint	6800 gm	<b>9409.10</b>	<b>20.65</b>	<b>36.84</b>	10410.225	23.65	93.5
NLP	5700 gm	NFS	NFS	NFS	<b>8876.718</b>	<b>33.9</b>	<b>776.249</b>
$\epsilon$ -constraint	5700 gm	NFS	NFS	NFS	<b>9409.10</b>	<b>20.65</b>	<b>743.899</b>

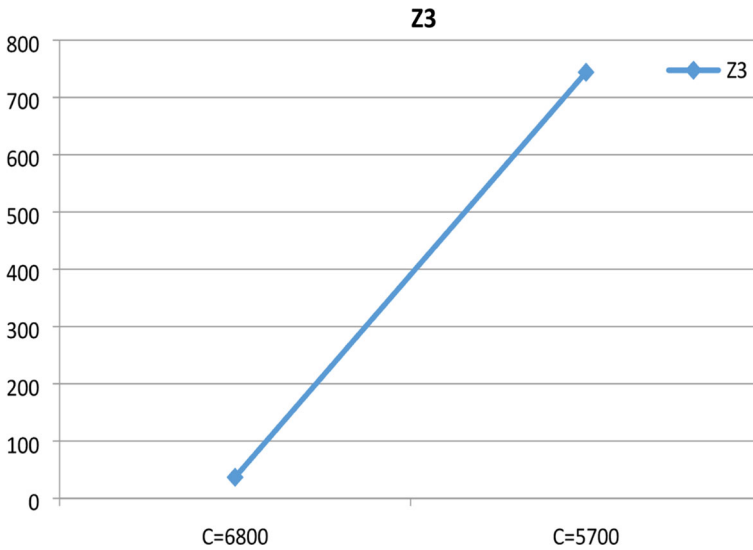
**Table 17** Comparison analysis

Example Approach	Example 1			Example 2		
	Z <sub>1</sub> (A)	Z <sub>2</sub> (A)	Z <sub>3</sub> (A)	Z <sub>1</sub> (B)	Z <sub>2</sub> (B)	Z <sub>3</sub> (B)
Farrokhi-Asl et al. (2020)	9409.10	20.65	4805.11	9409.10	20.65	4805.11
Midya et al. (2021)	9409.10	20.65	4805.11	9409.10	20.65	4805.11
Xu et al. (2017)	9409.10	20.65	4805.11	NFS	NFS	NFS
Proposed study	9409.10	20.65	36.84	NFS	NFS	NFS

emission permits against another cost. Total emission cost is therefore increased here and profit of the organization is also decreased. Thus the cap and trade policy is highly affected for reduction of carbon emission, and this policy measures the limit of carbon emission for a sustainable transportation as well as for industrial application.

### 8.3 Comparative study

For the advantage of carbon regulation, an organization or a transportation system chooses the suitable policy [also see the article Ghosh et al. (2022)] that would be benefit from both economical and environmental aspect. This research demonstrates the effectiveness of the proposed model by analyzing two numerical examples, and displaying the results in graphical presentation, where as the articles [cf. Farrokhi-Asl et al. (2020), Midya et al. (2021) and Xu et al. (2017)] did not impose any type of mechanism for conscious of emission reduction. The present study incorporates three factors of sustainability, where the authors of works



**Fig. 9** Effect of cap-and-trade policy

[cf. Abdullah and Goh (2019), Das and Roy (2019), Midya et al. (2021), Muneeb et al. (2018), Rathore and Sarmah (2019), Roy et al. (2018), Tirkolae et al. (2020a), Tirkolae et al. (2020b) and Xu et al. (2017)] investigated only one or two factor(s) of sustainability without selecting all major parts and did not develop sustainability. The proposed study targets to reach the destination of sustainability by optimizing each part of SD and finds a correlation among them by integrating an WM project through multi-objective scenario of transportation problem. But, the researchers [Abdullah and Goh (2019), Mahmoudsoltani et al. (2018), Mingaleva et al. (2019), Rabbani et al. (2018), Rathore and Sarmah (2019), Tirkolae et al. (2020a), Tirkolae et al. (2020b), Xu et al. (2017)] proposed their study only for waste management, did not introduce any sustainable waste management project.

## 9 Managerial insights

The following managerial insights are outlined from the proposed study as:

- To develop a green or smart city, or to improve the urban/rural area, an introduction of SWM in the proposed model has distinct facilities from several sides.
- Sustainable development is established by maximizing profit for economical opportunity, minimizing time for social context and minimizing carbon emission for environment improvement. The related system will be benefited when these objects get together.
- From the effect of carbon cap and trade policy, an organization can select a suitable choice to emit low carbon by observing the supplied cap value. At the same time, the users get an economical opportunity from this policy. Applying the appropriate criteria of this policy, an industrial organisation can also drop down the carbon emission from the production plant to avoid global warming, and may be free from any penalty charge.
- The proposed transportation model is formulated on the base of multi-objective scenario under type-2 IF environment. As the DM tackles such complex uncertainty with multiple

criteria (SD, WM, time budget), he/she takes to challenge any type of critical uncertain situation with different criteria.

- The obtained Pareto-optimal solution shows that the proposed model is significant option to design any network with multiple directions and different objects.

## 10 Concluding remarks and outlook to future research

For the first time in research, both WM and SD have been investigated on MOSTP in the presence of twofold uncertainty (T2IF). All these factors have not yet inspected by the effect of carbon cap and trade regulation which has some benefits. To develop sustainability, three objective functions have been focused which are maximum profit for economical aspect, minimum elapsed time for social impact and low carbon emission for environment effect. All these objective functions are optimized under cap and trade policy and a time budget by adding with all the required constraints. The problem has been divided into two stages to complete the loop of SWM, and source, demand and conveyance, that are taken as TT2IFN to control more uncertainty than type-1 IF. A simple and easy ranking approach has been utilized to defuzzify the uncertainty involving in the problem. The problem has been evaluated technically by using a fuzzy technique (NLP) and a non-fuzzy technique ( $\epsilon$ -constraint method). Two numerical examples have been evaluated to verify the advantages of the proposed study and the considered methods.

In present situation, world is facing some critical issues as global warming and waste generation, and these are the vital challenges for industry/researcher/academy. Most researchers have analyzed WM problems without sustainability (Abdullah and Goh, 2019; Muneeb et al., 2018; Xu et al., 2017), or without multi-objective scenario. Otherwise, WM problems have been selected without considering uncertainty (Farrokhi-Asl et al., 2020; Rathore and Sarmah, 2019), which is an essential criterion when the source, demand or other parametric values are fluctuate. Again some of the research works (Abdullah and Goh, 2019; Maity et al., 2019; Tirkolae et al., 2020a; Rathore and Sarmah, 2019) did not include carbon emission factor. In contrast, Farrokhi-Asl et al. (2020), Midya et al. (2021) and Xu et al. (2017) focus only on carbon tax. Observing such situation, sustainability criteria have been applied in this study to improve these critical sitchs. A vast discussion has been elaborated by watching the sustainable objective values for different cap values of numerical results. A novelty of this study is that here three conflicting objective functions are optimized together for investigating a WM problem by the criteria of sustainability and the hybrid uncertain ground. The first objective gives the maximum economical profit which provides benefits to all sectors involved in WM. The second one is minimum elapsed time that provides two advantages. The first advantage is that the consumers get the recycled items within short period and another is that public or environment are satisfied by quick disposal of hazardous waste items. So, the plan of this WM problem is completed by an optimal time investment which supports the reduction of negative effect of WM. The last one is the minimum carbon emission that protects the environment by imposing a cap and trade policy as a restriction and including a tax for carbon emission from an incineration plant. This policy gives the benefit by providing an economical opportunity to the users. The empirical results of the proposed coordinated model are thus converging, so to speak to the target point (i.e., SD) from multiple directions, and providing a strong correlation among these factors by the media of WM and transportation. The WM plan of this study always supports SD and improves the urban ecosystem, it reduces pollution by disposing or recycling the hazardous or non-hazardous waste items.

In this study, both WM and sustainability meet to upgrade the world's critical state from a combined economic, social and environmental point of view. Finally, SD and WM under uncertain data are closely related which signifies that the new model is the most practicable in any situation of real-world application, be it in logistics, transport or waste management.

This research has been discussed with some limitations in the proposed study. Withdrawing these limitations, this study can be extended to provide various opportunities for future research scope. One may implement the proposed model in new environment such as, polygonal fuzzy, type-2 neutrosophic, Pythagorean hesitant fuzzy (Ghosh et al., 2022) with nonlinear membership functions such as hyperbolic, exponential, quadratic. The present model can be enhanced by using green supply chain (Midya et al., 2021) with WM, stochastic data, fixed-charge (Ghosh et al., 2021), robust ranking under other carbon policies. An extensive industrial problem connecting with probabilistic industrial waste, mining waste, and high production of renewable energy/resource will be implicated in the current model for further research. Some metaheuristic approaches such as ant colony optimization (Tirkolaee et al., 2020a), genetic algorithm, particle swarm optimization, stochastic optimal control (Tirkolaee et al., 2020b), can be applied with incorporating other sustainable parameters (Farrokhi-Asl et al., 2020; Maity et al., 2019; Mehawat et al., 2019; Ghosh et al., 2022) in this model for promoting as an extension of future research.

**Acknowledgements** The authors are very much grateful to the Editor-in-Chief and anonymous reviewers for their intelligent comments that helped too much for improving the manuscript and to maintain the quality of the manuscript.

## Declarations

**Conflict of interest** Authors announce that there is no conflict of interest.

**Data availability statement** All data utilized for supporting the findings of this study.

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