A multi-objective approach to sustainable disaster waste management

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Abstract

The phenomena of global warming have increased the frequency of natural disasters. These disasters generate thousands of tons of waste and cause loss of human lives, environmental damages, and economic losses every year. Increased resilience against future disasters can only be achieved by working on long-term planning and setting goals for ecological, economic and social sustainability in disaster response policies. Keeping in view the importance of the considered issue, this study proposed an optimization model for disaster waste processing supply chain network considering economic aspect via total waste processing cost, environmental aspect by Greenhouse Gas (GHG) emissions from waste processing, and social aspect by job opportunities from waste processing. A possibilistic programming approach is used to cope with the post-disaster uncertain environment and a generic interactive fuzzy solution methodology has been proposed to obtain preferred compromise solutions for proposed model. Finally, to demonstrate the applicability of the proposed supply chain network optimization model and solution methodology numerical experiments and sensitivity analysis are performed on a large scale case problem.

Keywords
Disaster waste management, possibilistic programming, disaster waste recycling, multi-objective optimization

1. Introduction and literature review

In the last few decades, the frequency of disasters has rapidly increased. Hurricane Katrina (2005), the Indian Ocean tsunami (2004), and the Japanese tsunami (2011) are a few large-scale disasters that have occurred since the start of the 21st century. Such mega-disasters generate thousands of tons of waste which is equivalent to the many years municipal waste (Brown *et al.*, 2016). For example, 8.9 scale earthquake and tsunami in Japan (2011) generated 28 million tons of waste (Ide, 2016). Proper treatment of such a huge amount of disaster waste is necessary, otherwise, it poses a serious threat to the environment and human health due to chemical decay that would ultimately contribute to decreasing the resilience for future disasters (Habib *et al.*, 2016). Amaratunga *et al.* (2011) suggested that increased resilience for future disasters in a region can only be achieved by working on long-term disaster waste planning and setting goals for ecological, economic and social sustainability. Keeping in view the importance of disaster resilience in this research disaster waste management (DWM) considering all three dimensions of sustainable disaster recovery: economic, environmental and social, has been discussed.

Most of the previous studies on disaster debris management provide a very good theoretical analysis of disaster waste management efforts, which are actually based on the guidelines proposed by professional disaster management bodies like Federal Emergency Management Agency (FEMA) of the

United States and United Nations Environment (UNEP). For example, Ide (2016) discussed the treatment methods adopted in the processing of disaster waste generated by the tsunami in the three prefectures: Iwate, Miyagi, and Fukushima of Japan. Brown *et al.* (2016) provided a detailed analysis of previous five disasters, on the basis of which they qualitatively determined seven disaster specific factors that influence the effectiveness and feasibility of disaster waste recycling. The aforementioned research works provide a very good theoretical analysis of disaster waste management efforts. However, there is still a lack of quantitative research in the area of disaster waste management (Onan *et al.*, 2015). When it comes to quantitative research in the area of disaster waste management, following studies with economic objectives are the most relevant. Lorca *et al.* (2015) proposed a multi-objective mathematical model for disaster debris processing in a post-disaster scenario with the aim to balance the objectives of financial cost, environmental cost, landfill utilization, and revenue from recycled debris. Fetter *et al.* (2012) suggested a mixed integer linear programming model with the objective to minimize the overall disaster waste processing cost by considering the revenue obtained from disaster waste recycling with the location and allocation decision for the sites of debris processing facilities. Hu *et al.* (2013) proposed a multi-objective linear programming disaster waste reverse logistics model. In this research, authors introduced a novel concept of psychological trauma cost, which is the cost experienced by the local residents when they wait for disaster waste removal and medical treatment. The environment is the second dimension of the sustainability. After analyzing the disaster waste processing literature it is concluded that a little attention has been paid to reduce greenhouse gas (GHG) emissions from disaster waste processing, as a measure to slow down the global warming phenomena, due to which frequency of disasters is increasing gradually. Mostly the studies in the area of disaster management consider environmental aspect quantitatively in the stream of infrastructure reconstruction in a post-disaster scenario. For example, Portugal-Pereira *et al.* (2016) evaluated the economic and environmental benefits of biomass waste-to-energy technologies for the waste generated by Japanese tsunami (2011). Pan *et al.* (2014) proposed a mathematical model for the assessment of carbon footprints of housing reconstruction after the occurrence of Japanese tsunami (2011). The social aspect being the third dimension of the sustainability framework must also be a part of decision making during disaster waste processing planning because it will help to alleviate the psychosocial impact of the disaster on the local population and speed up the long-term recovery. However, there are a few studies like Sanyal *et al.* (2016), Shimada (2015), and Brown *et al.* (2011) that address social aspect during disaster waste management operation. Particularly, quantitative research in this area is scarce and requires urgent attention of the researchers. To the best of our knowledge, there is no such quantitative research work in disaster waste management literature that developed a disaster waste supply chain framework considering all three dimensions of sustainability: economic, environment, and social. Following are the contributions of the proposed study to the existing literature of disaster waste management.

- Introducing a multi-objective disaster waste processing supply chain optimization model that considers all the stages of disaster waste treatment: recycling, incineration, landfilling and incineration ash disposal.
- The post-disaster situation is very haphazard, obtaining accurate information in such an environment is very difficult. This research takes the advantage of using fuzzy possibilistic programming to tackle the imprecise nature of available information.

2. Model formulation

2.1 Problem definition

In a large-scale disaster, thousands of tons of mixed waste is generated. This disaster waste consists of vegetative waste, electronics appliances, concrete rubbles and plastic goods. Mixed waste is collected from disaster affected regions and transported to a temporary disaster debris management site (TDDMS) where the process of waste separation is performed. After separation, each type of waste is sent to the respective processing site: recycling sites, incineration sites, or landfill sites. In Figure 1 framework of the proposed model is shown.

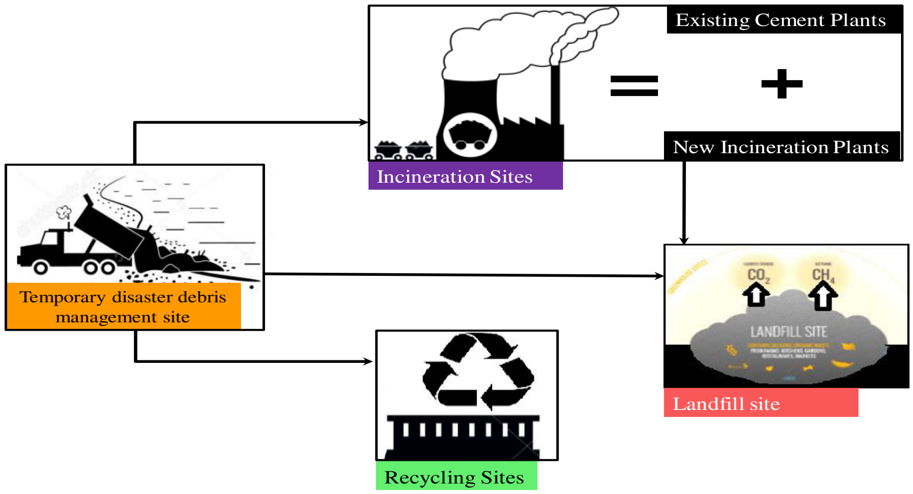

Figure 1. Framework of the proposed disaster waste processing supply chain model

The situation in the post-disaster environment is very uncertain and obtaining precise information is very difficult and time-consuming. Assigning crisp values to such uncertain parameters will not provide appropriate results. To model the lack of knowledge about imprecise parameter possibility programming approach is best suitable (Lai *et al.*, 1992; Pishvaee *et al.*, 2010). Possibility programming uses possibility distributions to control the ambiguity regarding the model parameters (Torabi *et al.*, 2008). Due to the highly uncertain environment in a post-disaster scenario, all input parameters are considered imprecise (fuzzy) in the proposed possibilistic optimization model and a triangular possibility distribution has been assumed for each imprecise parameter.

2.2 Model notations

Indices

i	index of TDDMS	$\{i = 1,2,3,...I\}$
j	index of potential locations for incineration sites	$\{j = 1,2,3,\ldots J\}$
k	index of potential locations for landfill sites	$\{k = 1,2,3,\ldots K\}$
l	index of potential locations for recycling sites	$\{l = 1,2,3,\ldots L\}$

Parameters

$\tilde{a}_j$	installation cost of incineration site j (\$)
$\tilde{b}_l$	installation cost of recycling site l (\$)
$\tilde{c}_k$	installation cost of the landfill site k (\$)
$\tilde{\theta}_i$	debris collection cost at TDDMS i (\$/ton debris)
$\tilde{\varepsilon}_j$	debris incineration cost at incineration site j (\$/ton debris)
$\tilde{\mu}_l$	debris recycling cost at recycling plant l (\$/ton debris)
$\tilde{\sigma}_k$	debris/ash disposing cost at landfill site k (\$/ton debris or ash)
$\tilde{t}_{ij}$	transportation cost of debris from TDDMS i to incineration site j (\$/ton debris)
$\tilde{t}_{il}$	transportation cost of debris from TDDMS i to recycling site l (\$/ton debris)
$\tilde{t}_{ik}$	transportation cost of debris from TDDMS i to landfill site k (\$/ton debris)
$\tilde{t}_{jk}$	transportation cost of ash from incineration site j to landfill site k (\$/ton ash)

π_i total amount of debris allocated from disaster affected regions to TDDMS *i* (tons)

$c\tilde{e}_i^{collec}$ carbon emissions during debris collection at TDDMS *i* (tons CO_2 eq /ton debris)

$c\tilde{e}_j^{incin}$ carbon emissions during debris incineration process at incineration site *j* (tons CO_2 eq /ton debris)

$c\tilde{e}_k^{landfill}$ carbon emissions from debris disposed at landfill site *k* (tons CO_2 eq /ton debris)

$c\tilde{e}_{ij}$ carbon emissions during debris transportation from TDDMS *i* to incineration site *j* (tons CO_2 eq /ton debris)

$c\tilde{e}_{il}$ carbon emissions during debris transportation from TDDMS *i* to recycling plant *l* (tons CO_2 eq /ton debris)

$c\tilde{e}_{ik}$ carbon emissions during debris transportation from TDDMS *i* to landfill *k* (tons CO_2 eq /ton debris)

$c\tilde{e}_{jk}$ carbon emissions during ash transportation from incineration site *j* to landfill site *k* (tons CO_2 eq /ton debris)

$\tilde{\lambda}_j$ processing capacity of incineration site *j* (tons/day)

$\tilde{\lambda}_l$ processing capacity of recycling plant *l* (tons/day)

$\tilde{\lambda}_k$ total capacity of landfill site *k* (tons)

ϑ_{j_ash} percent of total debris at incineration site *j* converted into ash (percent)

$\tilde{\delta}_j$ number of job opportunities per ton of debris processed at incineration site *j* (jobs/ton debris)

$\tilde{\delta}_l$ number of job opportunities per ton of debris processed at recycling site *l* (jobs/ton debris)

$\tilde{\delta}_k$ number of job opportunities per ton of debris dumped at landfill site *k* (jobs/ton debris)

Decision variables

π_{ij} quantity of debris transported from TDDMS *i* to incineration site *j* (tons)

π_{il} quantity of debris transported from TDDMS *i* to recycling plant *l* (tons)

π_{ik} quantity of debris transported from TDDMS *i* to landfill site *k* (tons)

π_{jk} quantity of ash transported from incineration site *j* to landfill site *k* (tons)

ϑ_{i_incin} percentage of total debris at TDDMS *i* need to be incinerated (percent)

ϑ_{i_rec} percentage of total debris at TDDMS *i* need to be recycled (percent)

$\vartheta_{i\_landfill}$ percentage of total debris at TDDMS *i* need to be landfilled (percent)

$$x_j = \begin{cases} 1 \\ 0 \end{cases}$$ if an incineration site *j* is open then 1, otherwise 0

$$y_l = \begin{cases} 1 \\ 0 \end{cases}$$ if recycling site *l* is open then 1, otherwise 0

$$z_k = \begin{cases} 1 \\ 0 \end{cases}$$ if a landfill site *k* is open then 1, otherwise 0

2.3 Model assumptions

- Reusable products are already collected from disaster waste in separation phase.
- Disaster waste has been collected from affected regions and transported to TDDMS.

- The quantity of disaster waste at each temporary disaster debris management site is known.
- For complete debris processing operation, the total duration of 2 years is considered.

2.4 Formulation of objective functions

The objectives of the proposed disaster waste supply chain model are to minimize total operation cost, minimize total carbon emissions, and maximize total number of jobs during the disaster waste processing. Detailed explanations about the estimation of each objective function are provided below.

a. Total disaster waste processing operation cost (Economic objective)

Different costs associated with disaster debris processing supply chain are shown in Equation (1). First three terms represent installation cost of incineration sites, recycling plants, and landfill sites, respectively. The fourth term represents the waste collection cost at TDDMS site. The fifth, sixth and seventh terms represent costs associated with the disaster waste incineration, recycling, and landfilling operations, respectively. Finally, the eighth term represents the cost associated with the ash disposal operations.

$$\begin{aligned}\sum_j \tilde{a}_j x_j + \sum_l \tilde{b}_l y_l + \sum_k \tilde{c}_k z_k + \sum_i \tilde{\theta}_i \pi_i + \sum_i \sum_j (\tilde{\varepsilon}_j + \tilde{t}_{ij}) \pi_{ij} + \sum_i \sum_l (\tilde{\mu}_l + \tilde{t}_{il}) \pi_{il} + \\ \sum_i \sum_k (\tilde{\delta}_k + \tilde{t}_{ik}) \pi_{ik} + \sum_j \sum_k (\tilde{\delta}_k + \tilde{t}_{jk}) \pi_{jk}\end{aligned} \tag{1}$$

b. Total carbon emissions during waste processing (Environmental objective)

Estimation of carbon emissions from the various process of disaster waste processes is shown in Equation (2). The first term estimates total carbon emissions during disaster waste collection at TDDMS. The second term depicts the carbon emissions during waste incineration process and disaster waste transportation from TDDMS to an incineration facility. Similarly, the third, fourth, and fifth terms represent the total carbon emissions during recycling, waste landfill, and ash landfill operations.

$$\begin{aligned}\sum_i c\tilde{e}_i^{collec} \pi_i + \sum_i \sum_j (c\tilde{e}_{ij} + c\tilde{e}_j^{incin}) \pi_{ij} + \sum_i \sum_l c\tilde{e}_{il} \pi_{il} + \\ \sum_i \sum_k (c\tilde{e}_{ik} + c\tilde{e}_k^{landfill}) \pi_{ik} + \sum_j \sum_k c\tilde{e}_{jk} \pi_{jk}\end{aligned} \tag{2}$$

c. Total number of job opportunities during disaster waste processing (Social objective)

Equation (3) depicts the estimation of a total number of job opportunities generated during disaster waste processing operations. The first, second and third terms depict number of job opportunities generated during disaster waste incineration, recycling, and landfill processes, respectively.

$$\tilde{\delta}_j \sum_i \sum_j \pi_{ij} + \tilde{\delta}_l \sum_i \sum_l \pi_{il} + \tilde{\delta}_k \left(\sum_i \sum_k \pi_{ik} + \sum_j \sum_k \pi_{jk} \right) \tag{3}$$

2.5 Formulation of constraints

$$\sum_i \pi_{ij} \le x_j \tilde{\lambda}_j \qquad \forall j \tag{4}$$

$$\sum_i \pi_{il} \le y_l \tilde{\lambda}_l \qquad \forall l \tag{5}$$

$$\sum_i \pi_{ik} + \sum_j \pi_{jk} \le z_k \tilde{\lambda}_k \qquad \forall k \tag{6}$$

$$\sum_i \pi_i - \sum_j \pi_{ij} - \sum_l \pi_{il} - \sum_k \pi_{ik} = 0 \qquad \forall i \tag{7}$$

$$\sum_k \pi_{jk} = \vartheta_{j\_ash} \sum_i \pi_{ij} \qquad \forall j \tag{8}$$

$$\sum_l \pi_{il} = \vartheta_{i\_incin}\, \pi_i \qquad \forall i \tag{9}$$

$$\sum_j \pi_{ij} = \vartheta_{i\_rec}\, \pi_i \qquad \forall i \tag{10}$$

$$\sum_k \pi_{ik} = \vartheta_{i\_landfill}\, \pi_i \qquad \forall i \tag{11}$$

$$\vartheta_{i\_rec} + \vartheta_{i\_incin} + \vartheta_{i\_landfill} = 1 \qquad \forall i \tag{12}$$

$$\pi_{ij}, \pi_{il}, \pi_{ik}, \pi_{jk}, \vartheta_{i\_rec}, \vartheta_{i\_incin}, \vartheta_{i\_landfill} \geq 0 \qquad \forall i, j, l, k \tag{13}$$

$$x_j, y_l, z_k \in \{0,1\} \qquad \forall\, j, l, k \tag{14}$$

Constraints (4)-(6) are the capacity constraints of the incineration facilities, recycling facilities, and landfill facilities, respectively. At landfill sites in addition to waste, ash generated by waste incineration will also be disposed of. Constraint (7) ensures that all the waste from each TDDMS has been processed. Constraint (8) shows the amount of ash (generated by incineration process) to be transported from incineration facility to the landfill site. Constraint (9)-(12) decide the total amount of disaster waste to be incinerated, recycled and landfilled at each temporary disaster debris management site. Constraint (13) and (14) ensure non-negativity and binary conditions to all the corresponding decision variables.

3. Computational experiments

To demonstrate the validity of the proposed model, Karachi the most populated city of Pakistan is chosen. As this city is located on the coastline of the Arabian Sea, so a hurricane is the most likely natural disaster that may occur. Assuming a situation of a hurricane we have designed data for our proposed post-disaster waste processing supply chain optimization model. There are three locations of TDDMS and the amount of waste at each TDDMS is known. In this study three types of disaster waste processes: incineration, recycling, and landfill are considered. There are eight possible locations of incineration facilities, five possible locations of recycling facilities, and seven possible location of landfill sites. In this model cement plants are also being used as incineration sites. The advantage of using cement kilns as incineration plants is that the facility and technology are already available. There is a rough estimate, that it would take around \$5 to \$10 million to convert a cement kiln into incineration facility whereas installing a new facility may cost around \$50 million (Ishikawa *et al.*, 2012).

3.1 Experimental data design

To solve the proposed disaster waste processing supply chain model numerical experiments are conducted after converting the fuzzy model into equivalent crisp form. In the crisp model, an input parameter (α) is obtained which represents the confidence level of the decision maker about available data, and its value may vary between 0 and 1. In addition to this, Werner's methodology has been used to convert the multi-objective model into single objective model. In this methodology, an input parameter (γ) is used which is called coefficient of compensation. Decision makers can obtain multiple solutions by varying the both parameters (α) and (γ). For numerical example collection of data was performed. Due to the highly uncertain environment, all the input parameters are considered uncertain (fuzzy). Based on the method proposed by Lai and Hwang (1992), the triangular fuzzy parameter is generated. In this method, each fuzzy parameter ($\tilde{\beta}$) requires three values: pessimistic (β^{pes}),most likely (β^{most}), and optimistic (β^{opt}).The most likely value is estimated from published papers and environmental protection professional bodies data like Federal Emergency Management Agency (FEMA), European Environment Agency (EEA). In order to estimate the pessimistic (β^{pes}) and optimistic (β^{opt}) values, two random numbers n_1 and n_2 are generated between 0.2 and 0.8 with uniform distribution. Then, using Equations

(15) and (16) pessimistic (β^{pes}) and optimistic (β^{opt}) values are estimated. Related data (most likely) values with their sources are provided below.

$$\beta^{pes} = (1 - n_1)\beta^{most} \tag{15}$$

$$\beta^{opt} = (1 + n_2)\beta^{most} \tag{16}$$

Amounts of disaster debris at each TDDMS-1, TDDMS-2, and TDDMS-3 are 1,980,000 tons, 1,115,552 tons, and 1,188,000 tons, respectively which are adapted from Habib *et al.* (2017). The debris transportation cost between TDDMS and selected locations of each type of debris processing facilities are provided in Tables 1-3, while ash transportation cost is provided in Table 4.

Table 1. Debris transportation cost between TDDMS and potential locations of incineration sites ($/ton debris)

	Cement plant-1	Cement plant-2	Cement plant-3	Cement plant-4	Cement plant-5	Cement plant-6	Incineration plant-1	Incinerati on plant-2
TDDMS -1	117	165	88	15	71	70	95	90
TDDMS -2	48	78	4	75	18	30	6	22
TDDMS -3	80	123	47	29	29	35	52	50

Table 2. Debris transportation cost between potential locations of TDDMS and recycling sites ($/ton debris)

	Recycling site-1	Recycling site-2	Recycling site-3	Recycling site-4	Recycling site-5
TDDMS -1	95	90	3	64	81
TDDMS -2	6	22	87	32	7
TDDMS -3	52	50	41	27	39

Table 3. Debris transportation cost between TDDMS and potential locations of landfill sites ($/ton debris)

	Landfill site -1	Landfill site -2	Landfill site -3	Landfill site -4	Landfill site -5	Landfill site -6	Landfill site -7
TDDMS -1	11	36	74	82	121	33	78
TDDMS -2	77	52	23	35	33	58	13
TDDMS -3	31	7	34	48	78	15	34

Table 4. Ash transportation cost between locations of incinerations sites and landfill sites ($/ton debris)

	Landfill site -1	Landfill site -2	Landfill site -3	Landfill site -4	Landfill site -5	Landfill site -6	Landfill site -7
Cement plant-1	108	80	45	34	53	96	64
Cement plant-2	153	129	98	102	44	132	87
Cement plant-3	78	54	26	38	31	58	46
Cement plant-4	5	23	63	74	107	17	64
Cement plant-5	60	35	10	27	51	42	13
Cement plant-6	62	39	7	12	60	49	30
Incineration plant-1	83	58	27	37	27	49	12
Incineration plant-2	80	55	15	14	45	64	30

Disaster debris processing costs at each stage are provided in Table 5. Potential incinerations sites with their processing capacities and installation costs are provided in Table 6. The cost for converting a cement plant kiln into disaster waste incineration site is adopted from Ishikawa *et al.* (2012), while the installation cost for erecting a new incineration plant are estimated using the formula proposed by Haghi (2015).

Table 5. Disaster debris processing cost at each stage ($/ton)

Disaster debris processing	Debris collection	Debris incineration	Debris recycling	Debris landfill
Processing cost ($/ton)	4	45	150	12

Table 6. Potential incinerations sites: processing capacities and installation costs

Disaster debris processing facility	Processing capacity (tons/year)	Installation cost ($)
Cement plant – 1	109,500	10,000,000
Cement plant – 2	219,000	20,000,000
Cement plant – 3	109,500	10,000,000
Cement plant – 4	109,500	10,000,000
Cement plant – 5	109,500	10,000,000
Cement plant – 6	219,000	20,000,000
New incineration plant – 1	328,500	210,000,000
New incineration plant – 2	328,500	210,000,000

Carbon emission from per ton debris collection, incineration, and landfill process are taken 0.346 Ton CO_2, 0.8 Ton CO_2, and 1.0 Ton CO_2, respectively. Potential recycling sites with their processing capacities and installation costs are provided in Table 7. Installation costs according to the recycling plant capacity are estimated from Tchobanoglous *et al.* (2002). Potential landfill sites with their processing capacities and installation costs are provided in Table 8 which are estimated from Fischer *et al.* (2013).

Table 7. Potential recycling sites: processing capacities and installation costs

Disaster debris recycling facilities	Recycling site -1	Recycling site - 2	Recycling site - 3	Recycling site - 4	Recycling site - 5
Recycling capacity (tons/year)	438,000	328,500	438,000	328,500	438,000
Installation cost ($)	36,000,000	27,000,000	36,000,000	27,000,000	36,000,000

Table 8. Potential landfill sites: processing capacities and installation costs

Debris landfilling facilities	Landfill site - 1	Landfill site - 2	Landfill site - 3	Landfill site - 4	Landfill site - 5	Landfill site - 6	Landfill site -7
Total landfill capacity (tons)	300,000	450,000	400,000	350,000	300,000	450,000	400,000
Installation cost ($)	6,000,000	9,000,000	8,000,000	7,000,000	6,000,000	9,000,000	8,000,000

After analyzing the waste at each TDDMS possible range for each type of debris processing is obtained which are provided in Table 9. Finally, total number of jobs generated by each process/10,000 tons debris processed are provided in Table 10 which are adapted from Chandrappa *et al.* (2012).

Table 9. Percentage range for each type of debris processing

Debris processing	Debris recycling	Debris incineration	Debris landfilling
TDDMS-1	25% ≥ Recycling ≥ 30%	35% ≥ Incineration ≥ 45%	Landfilling ≤ 35%
TDDMS-2	20% ≥ Recycling ≥ 25%	35% ≥ Incineration ≥ 50%	Landfilling ≤ 40%
TDDMS-3	25% ≥ Recycling ≥ 30%	40% ≥ Incineration ≥ 45%	Landfilling ≤ 35%

Table 10. Total number of jobs generated by each process/10,000 tons debris processed

Debris processing type	Debris recycling	Debris incineration	Debris landfilling
Job creating potential (jobs/10,000 tons)	36	1	6

3.2 Results and discussion

Using the provided data, the proposed model is solved using optimization software LINGO 16.0 and payoff values are obtained. The obtained payoff values for the proposed model are provided in Table 11.

Table 11. Pay off values of objectives at α=0.5

Objective functions	Waste processing cost ($)	Carbon emissions (tons)	Job opportunities (jobs)
Minimize total debris processing cost	580,945,200	5,185,008	12,453
Minimize total carbon emissions	983,185,200	4,759,963	13,025
Maximize number of jobs	591,028,800	4,836,051	13,269

Diagonal numerical values of the payoff table are the optimal solutions for each objective. Table 11 depicts that all three objectives: total waste processing cost, total carbon emissions, and total job opportunities are conflicting in nature. For example, at the optimal value of total debris processing cost objective (580,945,200 $), the value of total carbon emissions objective (5,185,008 tons) is maximum and the value of total jobs opportunities objective (12,453 jobs) is minimum that depicts, if we want to minimize total debris processing cost then we have to bear high carbon emissions along with cutting down of job opportunities.

In the next step membership functions for each objective are developed using payoff values. Equations (17-19) represent the fuzzy membership functions for the objectives of total waste processing cost, total carbon emissions, total job opportunities during disaster waste processing, respectively.

$$\mu_{tc}(x)=\begin{cases}0, & \text{If} \quad f_{tc}\geq 9.831852\times10^{8}\\ \dfrac{9.831852\times10^{8}-f_{tc}}{9.831852\times10^{8}-5.809452\times10^{8}}, & \text{If} \quad 5.809452\times10^{8}<f_{tc}<9.831852\times10^{8}\\ 1, & \text{If} \quad f_{tc}\leq 5.809452\times10^{8}\end{cases} \tag{17}$$

$$\mu_{tce}(x)=\begin{cases}0, & \text{If} \quad f_{tce}\geq 5.185008\times10^{6}\\ \dfrac{5.185008\times10^{6}-f_{tce}}{5.185008\times10^{6}-4.759963\times10^{6}}, & \text{If} \quad 4.759963\times10^{6}<f_{tce}<5.185008\times10^{6}\\ 1, & \text{If} \quad f_{tce}\leq 4.759963\times10^{6}\end{cases} \tag{18}$$

$$\mu_{tj}(x)=\begin{cases}0, & \text{If} \quad f_{tj}\leq 12453\\ \dfrac{f_{tj}-12453}{13269-12453}, & \text{If} \quad 12453<f_{tj}<13269\\ 1, & \text{If} \quad f_{tj}\geq 13269\end{cases} \tag{19}$$

Solution methodology used for this model is interactive in nature that incorporates robustness and flexibility in the multi-objective decision-making process. The advantage of using this approach is that the decision maker can obtain multiple efficient solutions of the proposed disaster waste processing supply chain model based on his/her preference by varying the values of coefficient of compensation (γ) and value of confidence level (α). Assume the results shown in Table 12 which are obtained at α = 0.7 and γ = 0.9, are chosen by the decision makers as the best depending upon specific preferences. At this specific point all three objectives: total waste processing cost minimization, total carbon emissions minimization, and total job opportunities maximization are achieved 81.54%, 76.38%, and 94.93%, respectively.

Table 12. Results using the solution methodology

(α) Confidence level	(γ) Coefficient of compensation	μ_{tc}	μ_{tce}	μ_{tj}	f_{tc} ($)	f_{tce} (tons)	f_{tj} (jobs)
0.7	0.9	81.54%	76.38%	94.93%	781,406,400	4,850,731	13,210

3.3 Sensitivity analysis

Sensitivity analysis is performed to consider multiple sets of optimal solutions and choose the best among them based on the preferences of the decision maker. The proposed model in this study considers three objectives which are conflicting in nature and sensitivity analysis will enable the decision makers to understand the relationship among objectives. Details of the sensitivity analysis using proposed methodology are provided in Table 13.

Table 13. Sensitivity analysis

(α) Confidence level	(γ) Coefficient of compensation	μ_{tc}	μ_{tce}	μ_{tj}	Total cost f_{tc} ($)	otal carbon emissions f_{tce} (tons)	Total job opportunities f_{tj}(jobs)
0.5	0.1 - 0.6	61.93%	84.54%	93.50%	734,097,500	4,825,664	13,215
	0.7	63.19%	80.44%	93.50%	728,999,200	4,843,095	13,215
	0.8	63.71%	71.98%	100.00%	726,933,000	4,879,079	13,269
	0.9	64.86%	64.86%	74.89%	22,302,400	4,909,334	13,064
	1	65.05%	65.05%	65.05%	721,513,000	4,908,500	12,983
0.6	0.1 - 0.6	63.34%	73.37%	99.20%	735,417,900	4,875,524	13,265
	0.7 - 0.8	64.52%	68.36%	99.20%	730,752,800	4,895,215	13,265
	0.9	64.53%	67.43%	100.00%	730,721,700	4,898,861	13,269
	1	65.07%	65.07%	78.19%	728,588,900	4,908,145	13,173
0.7	0.1 - 0.5	92.33%	67.46%	94.93%	754,138,900	4,876,597	13,210
	0.9 - 1.0	81.54%	76.38%	94.93%	781,406,400	4,850,731	13,210

Following conclusions can be drawn from the results of the sensitivity analysis:

1. If disaster waste managers want to achieve the minimum total debris processing cost while ignoring the rest of the two objectives, the maximum possible amount of disaster debris must be landfilled and the minimum possible amount of debris must be recycled because per ton debris recycling cost is the highest among all three possible debris processing techniques.
2. If disaster waste managers want to achieve a minimum level of total carbon emissions while ignoring the rest of the two objectives (economic and social), then the maximum possible amount of debris must be recycled and incinerated and the minimum possible amount of debris must be landfilled.
3. If disaster waste managers want to achieve the target of a maximum number of job opportunities, then the maximum amount of debris must be recycled and landfilled and the minimum possible amount of waste must be incinerated because incineration process has the lowest job opportunities potential.

4. Conclusion

This study proposed a multi-objective mixed integer linear programming model to address the disaster waste processing supply chain network design problem considering economic, environmental, and social objectives. Since the post-disaster environment is very uncertain and obtaining precise information is difficult, an interactive fuzzy possibilistic programming approach was applied. Using the aforementioned concepts and techniques, the model obtained a sustainable disaster waste processing supply chain network by which decision makers can obtain efficient solutions based on their preferences. An important contribution of this research was the incorporation of all three sustainability dimensions: economic, environmental, and social in disaster waste processing supply chain. Furthermore, to minimize the capital investment it considered the cement plant kilns as potential locations for disaster waste incineration in the optimization model. Finally, the results and sensitivity analysis of the numerical example, which was based on realistic data, demonstrated the viability of the proposed solution methodology in handling the uncertain environment of disaster waste processing.

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