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# Post-disaster waste management with carbon tax policy consideration

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**Abstract**

Generally, the activities of post-disaster waste management usually produce high carbon emissions, which can cause damage to the environment. However, the issue of carbon emissions in the post-disaster waste supply chain is neglected. Hence, this paper aims to propose a mixed-integer linear programming model to address the post-disaster waste processing supply chain network design problem with the consideration of a carbon tax policy. The proposed model is developed based on the concept of a mixed strategy of waste separation to reduce carbon emissions. Not only the carbon emission perspective but also the financial perspective for post-disaster waste supply chain management is determined in the objective function. The proposed model was verified and validated by employing a numerical example based on realistic data. Based on the numerical example, the results show that the implementation of a carbon tax policy with the mixed strategy for waste separation can reduce carbon emissions in the post-disaster waste supply chain efficiently.


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*Keywords:* Post-disaster waste management; Carbon tax policy; Mathematical model; Mixed strategy for waste separation

## 1. Introduction

In a large-scale disaster, thousands of tonnes of mixed wastes are generated. The mixed waste is usually composed of building rubble, household materials, electrical appliances, a small amount of concrete, wood chips, plastics, glass, soil, sand, and so on [1]. The mixed waste is removed and disposed of after the disaster. Normally, the activities of mixed waste management involve waste collection, transfer, recycling, and disposal, all of which can produce $CO_2$, causing damage to the environment, and can threaten the health of the disaster victims and workers in the affected area [2,3]. According to Ritchie and Roser [4], the average annual growth rate of $CO_2$ emissions was 30.36 billion tonnes from 1950 to 2017. In 2017, the world emitted 36.15 billion tonnes of $CO_2$, while in 2000 the figure was 11.59 billion tonnes. Due to the issue of carbon emissions, $CO_2$ emissions reduction has become

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an effective way to reduce the pressure on many countries [5]. Nowadays, several policies have been proposed to reduce $CO_2$ emissions, such as carbon taxes, carbon caps, cap and trade, and so on [6,7]. The Energy Information Administration stated that "the real constraint lies not in our ability to develop the necessary technologies but in our political will to deploy them" [8]. Nowadays, low-carbon supply chains are becoming more and more popular in many organizations. Many organizations usually apply carbon tax policies because this policy has been successful in many countries. However, consideration of a carbon tax policy in the post-disaster waste supply chain is still neglected. Most policymakers pay attention to the cost or time only [2,9].

To reduce carbon emissions, the carbon tax policy in the post-disaster waste supply chain should be determined. Therefore, this paper aims to propose a mathematical model for post-disaster waste management with consideration of a carbon tax policy. The proposed mathematical model is developed based on the concept of a mixed strategy of waste separation (on-site and off-site separation) to reduce carbon emissions. Not only the carbon emissions but also the total cost for the post-disaster waste supply chain management is determined in the proposed model.

## 2. Framework and model formation

The framework of this research is designed with respect to a hierarchical model as shown in Fig. 1. This research is developed and modified from [1,2] and [10] based on the concept of a mixed strategy for waste separation. The structure of this framework considers all networks in the supply chain consisting of the affected zones, temporary disaster waste collection and separation sites (TDWCSSs), temporary disaster waste processing and recycling sites (TDWPRSs), landfill sites, incinerators, and markets. Initially, the mixed waste is assigned from the affected zone to a TDWCSS or TDWPRS for collection and separation by manual or preliminary technologies, with the waste from some affected zones being separated on-site by a TDWCSS while the rest is transferred to an off-site separation facility identified as a TDWPRS. After that, the separated waste from the TDWCSS is assigned to a TDWPRS for processing and recycling, while other separated wasted from the TDWCSS is allocated to landfill sites, incineration sites, and market sites, respectively. After the processing and recycling operation at the TDWPRS, the remaining waste is also assigned to landfill, incineration, and market sites as well. According to the carbon tax policy during the occurrence of the disaster, the government is regarded as a policymaker and a macroscopic regulator for the formulation of a carbon tax policy during the whole operation of the post-disaster waste supply chain. The government sets a price for carbon which is the unit price of carbon emissions and levies a tax to restrain carbon emissions.

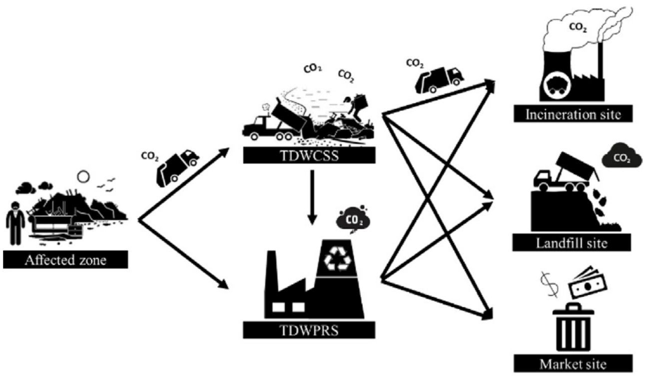


**Fig. 1.** The framework of post-disaster waste management with consideration of a carbon tax policy.

In this study, the facility location and distribution model are used to formulate the proposed model. The proposed mathematical model is formulated as a mixed-integer linear programming problem (MILP), and its basic assumptions are as follows: (1) the structure consists of affected zones, TDWCSSs, TDWPRSs, landfill sites, incineration sites, and market sites; (2) all waste needs to be separated before it is assigned for recycling, disposal, and sale; (3) the carbon price in the carbon tax policy is set by the government, combined with various elements; and (4) all of the parameters used are known, constant, and deterministic. The output of this model aims to select the TDWCSSs, TDWPRSs, landfill sites, and incineration sites, minimize financial costs, minimize carbon emissions, maximize revenue, and provide waste flow decisions throughout the supply chain. The model is formulated as follows:

*Objective function*

$$\text{Min Z} \quad FC + TC + OC + CE - R \tag{1}$$

*Constraints*

$$FC = \sum_j F_j^{TDWCSS} x_j + \sum_k F_k^{TDWPRS} y_k + \sum_l F_l^{Landfill} z_l + \sum_n F_n^{Incineration} w_n + \sum_j V_j^{TDWCSS} x_j + \sum_k \sum_o V_{ko}^{TDWPRS} a_{ko} + \sum_n \sum_p V_{np}^{Incineration} b_{np} \tag{2}$$

$$OC = \sum_i \sum_j O_j^{TDWCSS} VIJ_{ij} + \sum_i \sum_j \sum_k \sum_o O_{ko}^{TDWPRS} (VIK_{ik}\beta_o + VJK_{jko}) + \sum_j \sum_k \sum_l O_l^{Landfill} (VJL_{jl} + VKL_{kl}) + \sum_j \sum_k \sum_n \sum_p O_{np}^{Incineration} (VJN_{jnp} + VKN_{knp}) \tag{3}$$

$$TC = \sum_i \sum_j TIJ_{ij} VIJ_{ij} + \sum_i \sum_k TIK_{ik} VIK_{ik} + \sum_j \sum_k \sum_o TJK_{jk} VJK_{jko} + \sum_j \sum_l TJL_{jl} VJL_{jl} + \sum_j \sum_m TJM_{jm} VJM_{jm} + \sum_j \sum_n \sum_p TJN_{jn} VJN_{jnp} + \sum_k \sum_l TKL_{kl} VKL_{kl} + \sum_k \sum_m TKM_{km} VKM_{km} + \sum_k \sum_n \sum_p TKN_{kn} VKN_{knp} \tag{4}$$

$$CE = \Bigg( \sum_i \sum_j E_j^{TDWCSS} VIJ_{ij} + \sum_i \sum_j \sum_k \sum_o E_{ko}^{TDWPRS} (VIK_{ik}\beta_o + VJK_{jko}) + \sum_j \sum_k \sum_l E_l^{Landfill} (VJL_{jk} + VKL_{kl}) + \sum_j \sum_k \sum_p \sum_n E_{np}^{Incineration} (VJN_{jnp} + VKN_{knp}) + \sum_i \sum_j EIJ_{ij} VIJ_{ij} + \sum_i \sum_k EIK_{ik} VIK_{ik} + \sum_j \sum_k \sum_o EJK_{jk} VJK_{jko} + \sum_j \sum_l EJL_{jl} VJL_{jl} + \sum_j \sum_m EJM_{jm} VJM_{jm} + \sum_j \sum_n \sum_p EJN_{jn} VJN_{jnp} + \sum_k \sum_l EKL_{kl} VKL_{kl} + \sum_k \sum_m EKM_{km} VKM_{km} + \sum_k \sum_n \sum_p EKN_{kn} VKN_{knp} \Bigg) * PC \tag{5}$$

$$R = \sum_j \sum_k \sum_m \mathrm{Rev}_m (VJM_{jm} + VKM_{km}) \tag{6}$$

$$\sum_i VIJ_{ij} \le C_j^{TDWCSS} x_j \qquad \forall j \tag{7}$$

$$\sum_i VIK_{ik}\beta_o + \sum_j VJK_{jko} \le C_{ko}^{RSR} a_{ko} \qquad \forall k, o \tag{8}$$

$$\sum_{j} VJL_{jl} + \sum_{k} VKL_{kl} \leq C_l^{Landfill} z_l \qquad \forall l \tag{9}$$

$$\sum_{j} (VJN_{jnp} + VKN_{knp}) \leq C_{np}^{Incineration} b_{np} \qquad \forall n, p \tag{10}$$

$$a_{ko} \leq y_k \qquad \forall k, o \tag{11}$$

$$b_{np} \leq w_n \qquad \forall n, p \tag{12}$$

$$\sum_{j} VIJ_{ij} + \sum_{k} VIK_{ik} = h_i \qquad \forall i \tag{13}$$

$$\sum_{i} VIJ_{ij} \beta_o = \sum_{k} VJK_{jko} \qquad \forall j, o (o \neq 1) \tag{14}$$

$$\sum_{i} VIJ_{ij} \lambda_1 (1 - \sum_{o=2}^{O} \beta_o) = \sum_{l} VJL_{jl} \qquad \forall j \tag{15}$$

$$\sum_{i} VIJ_{ij} \upsilon_1 (1 - \sum_{o=2}^{O} \beta_o) = \sum_{m} VJM_{jm} \qquad \forall j \tag{16}$$

$$\sum_{i} VIJ_{ij} \eta_1 (1 - \sum_{o=2}^{O} \beta_o) = \sum_{n} \sum_{p} VJN_{jnp} \qquad \forall j \tag{17}$$

$$\sum_{i} VIK_{ik} \lambda_1 (1 - \sum_{o=2}^{O} \beta_o) + \sum_{i} \sum_{o=2}^{O} VIK_{ik} \beta_o \lambda_o + \sum_{j} \sum_{o} VJK_{jko} \lambda_o = \sum_{l} VKL_{kl} \qquad \forall k \tag{18}$$

$$\sum_{i} VIK_{ik} \upsilon_1 (1 - \sum_{o=2}^{O} \beta_o) + \sum_{i} \sum_{o=2}^{O} VIK_{ik} \beta_o \upsilon_o + \sum_{j} \sum_{o} VJK_{jko} \upsilon_o = \sum_{m} VKM_{km} \qquad \forall k \tag{19}$$

$$\sum_{i} VIK_{ik} \eta_1 (1 - \sum_{o=2}^{O} \beta_o) + \sum_{i} \sum_{o=2}^{O} VIK_{ik} \beta_o \eta_o + \sum_{j} \sum_{o} VJK_{jko} \eta_o = \sum_{n} \sum_{p} VKN_{knp} \qquad \forall k \tag{20}$$

$$VIJ_{ij}, VIK_{ik}, VJK_{jko}, VJL_{jl}, VJM_{jm}, VJN_{jnp}, VKL_{kl}, VKM_{km}, VKN_{knp} \geq 0 \qquad \forall i, j, k, l, m, n, o, p \tag{21}$$

$$x_j, y_k, z_l, w_n, a_{ko}, b_{np} \in \{0, 1\} \qquad \forall j, k, l, n, o, p \tag{22}$$

where, $i$: index of affected zones $\{i = 1, 2, 3, \ldots, I\}$; $j$ : index of potential locations for TDWCSS $\{j = 1, 2, 3, \ldots, J\}$; $k$: index of potential locations for TDWPRS $\{k = 1, 2, 3, \ldots, K\}$; $l$: index of potential locations for landfill sites $\{l = 1, 2, 3, \ldots, L\}$; $m$: index of market sites $\{m = 1, 2, 3, \ldots, M\}$; $n$: index of potential locations for incineration sites $\{n = 1, 2, 3, \ldots, N\}$; $o$: index of RSR technology $\{o = 1, 2, 3, \ldots, O\}$; $p$: index of incineration technology $\{p = 1, 2, 3, \ldots, P\}$; $h_i$: Volume of waste in affected zone $i$; $F_j^{TDWCSS}$: Fixed cost of opening and closing TDWCSS at location $j$; $F_k^{TDWPRS}$: Fixed cost of opening and closing TDWPRS at location $k$; $F_l^{Landfill}$: Fixed cost of opening and closing landfill at location $l$; $F_n^{Incineration}$: Fixed cost of opening and closing incineration site at location $n$; $V_j^{TDWCSS}$: Fixed cost of installing separated technology at TDWCSS location $j$ (On-site); $V_{ko}^{TDWPRS}$: Fixed cost of installing RSR technology $o$ at TDWPRS location $k$ (Off-site); $V_{np}^{Incineration}$: Fixed cost of installing incineration technology $p$ at incineration location $n$; $O_j^{TDWCSS}$: Operating cost at TDWCSS location $j$; $O_l^{Landfill}$: Operating cost at landfill site $l$; $O_{ko}^{TDWPRS}$: Operating cost RSR technology $o$ at TDWPRS location $k$; $O_{np}^{Incineration}$: Operating cost incineration technology $p$ at TDWPRS location $n$; $C_j^{TDWCSS}$: Capacity of TDWCSS at location $j$; $C_{ko}^{RSR}$: Capacity of RSR technology $o$ at TDWPRS location $k$; $C_l^{Landfill}$: Capacity of landfill site at location $l$; $C_{np}^{Incineration}$: Capacity of incineration technology $p$ at incineration location $n$; $E_j^{TDWCSS}$: Carbon emissions during waste collection and separation at TDWCSS location $j$; $E_l^{Landfill}$: Carbon emissions from waste disposed at landfill site $l$; $E_{ko}^{TDWPRS}$: Carbon emissions during waste processing and recycling at TDWPRS location $k$ with technology $o$; $E_{np}^{Incineration}$: Carbon emissions during incineration at incineration location $n$ with incineration technology $p$; $\mathrm{Re}\upsilon_m$: Revenue from saleable portion of debris at market $m$; $\beta_o$: Proportion of waste from affected zone that is eligible to be treated with RSR technology $o$; $\lambda_o$: Proportion of reduced waste from RSR technology $o$ for disposal at landfill; $\upsilon_o$: Proportion of reduced waste from RSR technology $o$ saleable as recycled material; $\eta_o$: Proportion of reduced waste from RSR technology $o$ for incineration at incineration location; $TIJ_{ij}$: Cost of transporting waste from affected zone $i$ to TDWCSS $j$; $TIK_{ik}$: Cost of transporting waste from affected zone $i$ to TDWPRS $k$; $TJK_{jk}$: Cost of transporting waste from TDWCSS $j$ to TDWPRS $k$; $TJL_{jl}$: Cost of transporting waste from TDWCSS $j$ to landfill site $l$; $TJM_{jm}$: Cost of transporting waste from TDWCSS $j$ to market site $m$; $TJN_{jn}$: Cost of transporting waste from TDWCSS $j$ to incineration site $n$; $TKL_{kl}$: Cost of transporting waste from TDWPRS $k$ to landfill site $l$; $TKM_{km}$: Cost of transporting waste from TDWPRS $k$ to market site $m$; $TKN_{kn}$: Cost of transporting waste from TDWPRS $k$ to incineration site $n$; $EIJ_{ij}$: Carbon emissions during waste transportation from affected zone $i$ to TDWCSS $j$; $EIK_{ik}$: Carbon emissions during waste transportation from affected zone $i$ to TDWPRS $k$; $EJK_{jk}$: Carbon emissions during waste transportation from TDWCSS $j$ to TDWPRS $k$; $EJL_{jl}$: Carbon emissions during waste transportation from TDWCSS $j$ to landfill site $l$; $EJM_{jm}$: Carbon emissions during waste transportation from TDWCSS $j$ to market site $m$; $EJN_{jn}$: Carbon emissions during waste transportation from TDWCSS $j$ to incineration site $n$; $EKL_{kl}$: Carbon emissions during waste transportation from TDWPRS $k$ to landfill site $l$; $EKM_{km}$: Carbon emissions during waste transportation from TDWPRS $k$ to market site $m$; $EKN_{kn}$: Carbon emissions during waste transportation from TDWPRS $k$ to incineration site $n$; $PC$: Price of carbon emissions per tonne; $VIJ_{ij}$: Volume of waste from affected zone $i$ to TDWCSS $j$; $VIK_{ik}$: Volume of waste from affected zone $i$ to TDWPRS $k$; $VJK_{jko}$: Volume of waste from TDWCSS $j$ to TDWPRS $k$ for recycling by RSR technology $o$; $VJL_{jl}$: Volume of waste from TDWCSS $j$ to landfill site $l$; $VJM_{jm}$: Volume of waste from TDWCSS $j$ to market site $m$; $VJN_{jnp}$: Volume of waste from TDWCSS $j$ to incineration site $n$ for recycling by incineration technology $p$; $VKL_{kl}$: Volume of waste from TDWPRS $k$ to landfill site $l$; $VKM_{km}$: Volume of waste from TDWCSS $k$ to market site $m$; $VKN_{knp}$: Volume of waste from TDWPRS $k$ to incineration site $n$ for recycling by incineration technology $p$; $x_j$: Binary variable that takes the value 1 if TDWCSS is opened at location $j$ and 0 if not; $y_k$: Binary variable that takes the value 1 if TDWPRS is opened at location $k$ and 0 if not; $z_l$: Binary variable that takes the value 1 if landfill is opened at location $l$ and 0 if not; $w_n$: Binary variable that takes the value 1 if incineration is opened at location $n$ and 0 if not; $a_{ko}$: Binary variable that takes the value 1 if RSR technology $o$ is available at TDWPRS $k$ and 0 if not; $b_{np}$: Binary variable that takes the value 1 if incineration technology $p$ is available at incineration location $n$ and 0 if not.

The objective function of the proposed model aims to minimize the total costs in the post-disaster waste management associated with carbon tax policy consideration as shown in Eq. (1). The objective function aims to balance the fixed costs (*FC*), operational costs (*OC*), transport costs (*TC*), cost of carbon emissions (*EC*), and potential revenue (*R*) as shown in Eqs. (2)–(6), respectively. To apply the carbon tax policy, Eq. (5) represents the cost of carbon emissions during waste processing. The first term depicts the total carbon emissions during disaster waste collection and separation at the TDWCSS. The second term estimates the carbon emissions during collection, separation, and recycling at the TDWPRS. The third term estimates the carbon emissions during waste landfill operations. The fourth term presents the carbon emissions during the incineration process. The fifth to thirteen terms denote the total carbon emissions during transportation form each location. Eqs. (7)–(10) ensure that the volume of waste assigned to each location site (TDWCSS, TDWPRS, landfill, incineration, and market) cannot exceed its maximum capacity. Eqs. (11)–(12) require that the TDWPRS and incineration site must be opened to make technologies available. Eq. (13) guarantees that the volume of waste in each affected zone is collected and processed. Eqs. (14)–(17) state that all collected waste in each selected TDWCSS is assigned to processing sites (TDWPRSs), landfills, incineration, and markets. Eqs. (18)–(20) state that the waste in each selected TDWPRS is assigned to landfills, incineration, and markets. Eqs. (21)–(22) describe non-negativity and the binary conditions of the decision variables.

## 3. Computational experiments

### 3.1. Experimental data design

To validate the proposed model, Chiang Mai province in Thailand was chosen. Chiang Mai is vulnerable to flooding every year due to its bowl-like shape. Assuming a situation of flooding, we have designed data for our proposed post-disaster waste processing supply chain optimization model based on the data of Habib and Sarkar [1] and Boonmee et al. [2]. There are nine affected zones, three candidate TDWCSSs, three candidate TDWPRSs,

**Table 1**. Fixed cost, operational cost, and capacity of each possible location.

| | TDWCSS | | | Landfill | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 1 | 2 | 3 | | | |
| Fixed cost ($) | 3000 | 4000 | 3500 | 8000 | 8100 | 8200 | | | |
| Operated cost ($ per tonne) | 1.50 | 1.45 | 1.40 | 2.50 | 2.50 | 2.50 | | | |
| Capacity (tonnes) | 150 000 | 200 000 | 175 000 | 150,000 | 180,000 | 200,000 | | | |
| Fixed cost for separated technology ($) | 5000 | 7500 | 6000 | | | | | | |
| TDWPRS | | 1 | | | 2 | | | 3 | |
| Fixed cost ($) | | 10 000 | | | 15 000 | | | 15 500 | |
| RSR technology | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| Fixed cost of making RSR technology ($) | 5000 | 5000 | 5000 | 7500 | 7500 | 7500 | 7500 | 7500 | 7500 |
| Operated cost ($ per tonne) | 1.50 | 2.10 | 1.50 | 2.10 | 2.20 | 2.10 | 2.00 | 2.10 | 2.00 |
| Capacity (tonnes) | 100 000 | 150 000 | 155 000 | 10 000 | 150 000 | 125 000 | 10 000 | 150 000 | 125 000 |
| Incineration site | | 1 | | | 2 | | | 3 | |
| Fixed cost ($) | | 12 000 | | | 11 000 | | | 11 500 | |
| Incineration technology | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| Fixed cost for incineration technology ($) | 6000 | 7000 | 75 000 | 6500 | 6900 | 7000 | 6000 | 6000 | 6000 |
| Operated cost ($ per tonne) | 0.83 | 0.72 | 0.89 | 0.7 | 0.75 | 0.72 | 0.81 | 0.78 | 0.83 |
| Capacity (tonnes) | 100 000 | 100 000 | 100 000 | 70 000 | 95 000 | 110 000 | 100 000 | 90 000 | 100 000 |

three candidate landfills, three candidate incineration sites, three market sites, three RSR technologies, and three incineration technologies. The volume of waste in the affected zones is 12,800, 7500, 19,000, 13,200, 17,000, 12,000, 7300, 19,500, and 13,700 tonnes, respectively. The data for the fixed cost, operational cost, and capacity of each possible location are tabulated in Table 1, while Table 2 presents the data for the waste transportation cost and carbon emissions during waste transportation. The three RSR technologies that were determined in this study consist of separation, sorting, and concrete crushing. The proportion of waste from the affected zone that is eligible to be treated with RSR technology for separation, sorting, and concrete crushing is 1, 0.4, and 0.3. We assume that after the waste is processed by each RSR technology, the waste from each RSR technology is sent to a landfill site, incineration site, or market site. The proportion of waste processed by each RSR technology and then sent for landfill disposal is 0.35, 0.25, and 0.30, respectively; the proportion sent for incineration is 0.35, 0.5, and 0.30, respectively; and the proportion sent to the market is 0.30, 0.25, and 0.4, respectively. The revenues from the saleable portion of waste at markets 1, 2, and 3 are assumed to be 2$, 3$, and 2.5$. Carbon emissions from the TDWCSS and TDWPRS, incineration, and the landfill process are taken as 0.3, 0.5, 0.8, and 1.0 tonnes of $CO_2$, respectively. Finally, the carbon price is assumed to be 2.25/tonne.

### *3.2. Results and discussion*

Using the data in Section 3.1, the proposed mathematical model was solved using the optimization software LINGO 14.0. All experiments were run on a personal computer with an Intel® Core™ i7-6700 CPU (3.40 GHz) and 16 GB of RAM. The solution could be found within a few seconds. The results showed that the best solution for the total cost is $7,769,949 (Scenario 1), which consists of $112,600 for the fixed cost, $3,600,475 for the operational cost, $1,604,000 for waste transportation, $340,110 in revenue, and $2,792,984 as the carbon price. The volume of carbon emissions in this case study is 1,241,326 tonnes of $CO_2$. In this post-disaster waste supply chain, TDWCSS 3 was selected for waste collection and separation on-site, while two TDWPRSs (TDWPRSs 1 and 2) were chosen for separating, processing, and recycling off-site. All RSR technologies were available at TDWPRS 1 and TDWPRS 2. For disposal of the waste by landfilling, two landfill sites were selected, namely Landfill Site 1 and Landfill Site 2. To dispose of the waste via incinerator, Incineration Site 2 was selected by operating the first incineration technology and the third incineration technology in this case. When we focused on the carbon emissions, the most carbon emissions were produced by the TDWPRS and equalled 936,900 tonnes of $CO_2$, while the incineration site, landfill site, and TDWCSS produced carbon emissions of 115,656, 107,970, and 600 tonnes of $CO_2$, respectively. However, the carbon emissions during waste transportation were only 80,200 tonnes of $CO_2$.

**Table 2**. Waste transportation cost ($ per tonne) and carbon emission during transportation (tonnes $CO_2$ eq per tonnes).

| From →To | TDWCSS 1 | TDWCSS 2 | TDWCSS 3 | TDWPRS 1 | TDWPRS 2 | TDWPRS 3 |
|---|---|---|---|---|---|---|
| Zone 1 | 2/0.10 | 1/0.05 | 3/0.15 | 7/0.35 | 5/0.25 | 8/0.40 |
| Zone 2 | 3/0.15 | 4/0.20 | 3/0.15 | 10/0.5 | 7/0.35 | 10/0.5 |
| Zone 3 | 6/0.30 | 1/0.05 | 5/0.25 | 9/0.45 | 7/0.35 | 8/0.40 |
| Zone 4 | 3/0.15 | 3/0.15 | 3/0.15 | 9/0.45 | 12/0.6 | 8/0.40 |
| Zone 5 | 3/0.15 | 4/0.20 | 4/0.20 | 12/0.6 | 5/0.25 | 12/0.6 |
| Zone 6 | 2/0.10 | 4/0.20 | 2/0.10 | 7/0.35 | 6/0.30 | 6/0.30 |
| Zone 7 | 5/0.25 | 4/0.20 | 5/0.25 | 9/0.45 | 9/0.45 | 8/0.40 |
| Zone 8 | 6/0.30 | 3/0.15 | 2/0.10 | 7/0.35 | 6/0.30 | 7/0.35 |
| Zone 9 | 4/0.20 | 2/0.10 | 2/0.10 | 12/0.6 | 10/0.5 | 10/0.5 |
| From →To | TDWPRS 1 | TDWPRS 2 | TDWPRS 3 | Landfill 1 | Landfill 2 | Landfill 3 |
| TDWCSS 1 | 8/0.40 | 9/0.45 | 10/0.5 | 10/0.5 | 9/0.45 | 10/0.5 |
| TDWCSS 2 | 6/0.30 | 9/0.45 | 5/0.25 | 7/0.35 | 8/0.40 | 8/0.40 |
| TDWCSS 3 | 7/0.35 | 6/0.30 | 5/0.25 | 8/0.40 | 8/0.40 | 6/0.30 |
| From →To | Market 1 | Market 2 | Market 3 | Incineration 1 | Incineration 2 | Incineration 3 |
| TDWCSS 1 | 6/0.30 | 10/0.5 | 11/0.55 | 9/0.45 | 7/0.35 | 5/0.25 |
| TDWCSS 2 | 10/0.5 | 6/0.30 | 10/0.5 | 8/0.40 | 9/0.45 | 6/0.30 |
| TDWCSS 3 | 11/0.55 | 10/0.5 | 7/0.35 | 6/0.30 | 6/0.30 | 8/0.40 |
| From →To | Landfill 1 | Landfill 2 | Landfill 3 | Market 1 | Market 2 | Market 3 |
| TDWPRS 1 | 5/0.25 | 6/0.30 | 7/0.35 | 6/0.30 | 5/0.25 | 5/0.25 |
| TDWPRS 2 | 9/0.45 | 5/0.25 | 6/0.30 | 5/0.25 | 6/0.30 | 7/0.35 |
| TDWPRS 3 | 5/0.25 | 9/0.45 | 5/0.25 | 9/0.45 | 5/0.25 | 6/0.30 |
| From →To | Incineration 1 | Incineration 2 | Incineration 3 | | | |
| TDWPRS 1 | 7/0.35 | 5/0.25 | 10/0.5 | | | |
| TDWPRS 2 | 9/0.45 | 7/0.35 | 5/0.25 | | | |
| TDWPRS 3 | 6/0.30 | 9/0.45 | 6/0.30 | | | |

When we omitted the consideration of the carbon tax policy (Scenario 2), the total cost was reduced to $4,971,365 due to the lack of a carbon price. The result showed that the total cost was composed of $114,600 for the fixed cost, $3,603,845 for the operational cost, $1,593,300 for waste transportation, and $340,380 in revenue. TDWCSS 2 was selected instead of TDWCSS 3 for waste collection and separation on-site, while TDWPRS 1 and TDWPRS 2 with all RSR technologies were still chosen for separating, processing, and recycling off-site. Landfill Site 1, Landfill Site 2, and Incineration Site 2 with the first and third incineration technologies were also selected for waste disposal, as in the previous scenario. Due to the omission from consideration of the carbon tax policy, the carbon emissions were increased to 1,100,374 tonnes of $CO_2$ (an increase of 11.3%). Therefore, consideration of the carbon tax policy is quite important.

When we assumed that the case study used the strategy of on-site separation (Scenario 3), the total cost of this case was $9,056,311, and the carbon emissions equalled 1,487,677 tonnes of $CO_2$. On the other hand, when we assumed that the case used the strategy of off-site separation (Scenario 4), we found that the total cost was $7,790,548 and the carbon emissions were equal to 1,236,788 tonnes of $CO_2$. According to the previous results, we found that the mixed strategy for separation could obtain the best solution in terms of a compromise between fixed cost, operational cost, transportation cost, carbon emission cost, and revenue.

Moreover, when we increased the capacity of the TDWPRS by each RSR technology to 150,000 tonnes (Scenario 5), we found that the total cost of post-disaster waste management decreased to $7,668,626 (a decrease of 1.3%). The total cost consists of $57,500 for the fixed cost, $3,436,035 for the operational cost, $1,719,000 for waste transportation, $340,380 in revenue, and $2,796,471 as the carbon price. The TDWCSS was not selected to operate in this supply chain, while TDWPRS 1 with all RSR technology, Landfill Site 1, and Incineration Site 2 with the first and third incineration technologies were selected. This means that on-site separation was not necessary for this waste supply chain. According to the result, we found that not only the fixed cost and operational cost but also the carbon price were reduced. On the other hand, the transportation cost was increased by 7.5% ($119,960). Although the transportation cost increased, the carbon emissions did not increase along with the transportation cost

**Table 3**. The solution of each scenarios.

| | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 |
|---|---|---|---|---|---|
| Total cost ($) | 7,769,949 | 4,971,365 | 9,056,311 | 7,790,548 | 7,668,626 |
| Fixed cost ($) | 112,600 | 114,600 | 84,500 | 158,600 | 57,500 |
| Operational cost ($) | 3,600,475 | 3,603,845 | 4,472,241 | 3,592,310 | 3,436,035 |
| Transportation cost ($) | 1,604,000 | 1,593,300 | 1,491,029 | 1,597,245 | 1,719,000 |
| Revenue ($) | 340,110 | 340,380 | 338,733 | 340,380 | 340,380 |
| Carbon price ($) | 2,792,984 | 2,805,955 | 3,347,274 | 2,782,774 | 2,796,471 |
| Total carbon emission (tonnes of $CO_2$) | 1,241,326 | 1,247,091 | 1,487,677 | 1,236,788 | 1,242,876 |
| Carbon emission in TDWCSS (tonnes of $CO_2$) | 600 | 1500 | 36,600 | – | – |
| Carbon emission in TDWOPRS (tonnes of $CO_2$) | 936,900 | 942,300 | 1,152,900 | 933,300 | 933,300 |
| Carbon emission in landfill (tonnes of $CO_2$) | 107,970 | 107,970 | 107,970 | 107,970 | 107,970 |
| Carbon emission in incineration site (tonnes of $CO_2$) | 115,656 | 115,656 | 115,656 | 115,656 | 115,656 |
| Carbon emission from transportation (tonnes of $CO_2$) | 80,200 | 79,665 | 74,551 | 79,862 | 85,950 |
| Selected TDWCSSs | #3 | #2 | #2 and #3 | – | – |
| Selected TDWPRSs | #1 and #2 | #1 and #2 | #1 | #1, #2, and #3 | #1 |
| Selected landfills | #1 and #2 | #1 and #2 | #1 | #1 and #2 | #1 |
| Selected incineration sites | #2 | #2 | #1 | #2 and #3 | #2 |

Note: # is the candidate number.

since the carbon emissions during transportation were only a small proportion of the total carbon emissions in the post-disaster waste supply chain. The solutions of all scenarios were tabulated in Table 3.

## 4. Conclusion

This study proposed a mixed-integer linear programming model to address the post-disaster waste processing supply chain network design problem considering a carbon tax policy. The proposed mathematical model is developed based on the concept of a mixed strategy of waste separation (on-site and off-site separation) to reduce carbon emissions. Using the proposed framework model, the decision-maker can seek suitable TDWCSSs, TDWPRSs, landfill sites, and incineration sites, minimize financial costs, minimize carbon emissions, maximize revenue, and provide waste flow decisions throughout the supply chain. To verify and validate the proposed model, a numerical example based on realistic data is employed. Based on the solution to the numerical example, this study found that a carbon tax policy with a mixed strategy for waste separation can decrease $CO_2$ emissions of the post-waste supply chain effectively and can decrease carbon emissions by adjusting the supply chain structure and changing the transportation path. Hence, the decision-maker should select each processing location carefully. Most carbon emissions were produced by several processing locations, especially the TDWPRS. Thus, the decision-maker should regard the TDWPRS as a key factor. However, if the waste transportation distance is too long, it may be a key objective with regard to carbon emissions as well. In another perspective, some governments might not interest in carbon emission during post-disaster waste management since the government might aim to mainly focus on time or cost. According to this point, the government is still able to employ the proposed mathematical model by eliminating the carbon emission constraints and adding some constraints related to the cost and time. Further studies that include other constraints such as traffic congestion, time schedules, modes of transportation, the uncertainty of data, and so on are recommended.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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