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Multi-objective two-stage stochastic optimization model for post-disaster waste management

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Abstract
Post-disaster waste management is one of the most crucial tasks in the recovery phase of the disaster cycle, and it was created to assist affected communities in returning to a stable state following a disaster. To develop an efficient post-disaster waste management strategy, this study presents a multi-objective two-stage stochastic mixed integer linear programming model for post-disaster waste management. The proposed mathematical model was developed based on a mixed strategy of on-site and off-site waste separation in the supply chain. This study aims to minimize not only the total cost and the environmental impact to provide waste flow decisions and choose collection and separation sites, recycling sites, landfill sites, and incineration sites throughout the supply chain under the uncertain situation. To solve a multi-objective problem, a normalized weighted sum method is used to find the solution. A numerical case based on realistic data is presented to validate and verify the proposed model. Based on the numerical example, the results demonstrated that the implementation of the mixed strategy for waste separation with the consideration of uncertain situations can reduce the total cost, balance the environmental impact, and determine the unexpected situation in the post-disaster waste supply chain efficiently.

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1. Introduction

Since the 1950s, the magnitude of disasters has been continuously increasing. In 2021, 432 natural disasters were recorded, with 10,492 deaths (affecting 101.8 million people) and economic damage estimated to be 252.1 billion US$ (CRED, 2022). To deal with an unexpected disaster, the activities in each phase of disaster management should be prepared. The activity of disaster management is divided into four phases that comprise mitigation, preparedness, response, and recovery. The recovery phase is one of the most important phases that recovers and restores conditions to a normal situation after the disaster (Coppola, 2006). Post-disaster waste management is one of the crucial tasks in the recovery phase and involves the removal and disposal of waste from the affected communities. A large-scale disaster can generate thousands of tonnes of mixed waste. The mixed waste consists of wood chips, household materials, plastics, glass, and so on (Habib and Sarkar, 2018). Generally, the activities of mixed waste management involve collection, separation, recycling, transfer, and disposal (Boonmee et al., 2018; Boonmee et al., 2021). To prepare for all these activities, potential waste management facilities such as collection sites, separation sites, processing sites, recycling sites, landfill sites, incineration sites, and market sites should be determined (Karunasena et al., 2010).

Post-disaster waste supply chain management involves waste collection sites, where the post-disaster waste is transferred from affected communities to temporary processing sites, where it may go through containment processes such as sorting, grinding, concrete crushing, separation, and wood chipping. Then, all or parts of the post-disaster waste may be transferred to incinerator sites or landfill sites for disposal, or parts of it may be processed further to be recycled and either sold or reused. Nevertheless, many countries have also developed different strategies that are more suitable to their circumstances (New Zealand Department of Labour, 2022; Boonmee et al., 2018; Boonmee et al., 2021).

Nowadays, the environmental context is becoming an important issue. Poor waste management can affect not only the clean-up time and budget but also the environment. Ineffective waste management causes air pollution CO_2, SO_x, NO_x, and

PM pollution, ranging from non-existent collection systems to ineffective disposal. Hence, all activities of post-disaster waste supply chain management should be concentrated in order to reduce environmental effects that might harm the community and people in affected communities during disaster situations. To develop sustainable post-disaster waste management, the environmental context should be considered.

Many activities of post-disaster waste management systems have been continually improved. Separation is a major activity in the structure of a post-disaster waste management system because this can affect the economy, clean-up time, and the environment of the area. The separation of recyclable materials is a critical component of the structure that can affect the feasibility of recycling, and it can be divided into two strategies: on-site and off-site separation. The separation process can typically be completed primarily on-site, with all trash being sorted into separate piles for removal and to identify the waste intended for off-site recycling sites, landfills, incineration sites, and market sites (Boonmee et al., 2018). This is commonly known as “on-site separation”. The other alternative, normally known as “off-site separation”, is where all waste is transferred off-site to separate processing centers for separation and recycling, after which the waste is then removed to incinerations, landfills, and markets (Boonmee et al., 2018). To select the separation strategy, the decision-makers have to consider five main criteria (Brown and Milke, 2016): (1) cost, (2) time constraints, (3) the presence of any potential human and environmental hazards (4) the necessary degree of mixing of the waste, and (5) resource availability. In this situation, decision-makers need to determine the potential locations for the post-disaster waste management site planning process and select the appropriate strategy for each case. To achieve a level of sustainable management in the post-waste problem, an optimization technique is applied. The previous works are concluded in Table 1. Table 1 presents the objective function, separation strategy, mathematical model type, data modeling type, and objective type. Based on the conclusion of reviews in Table 1, we found that many papers have proposed mathematical models for post-waste management. However, each paper is different in its objective functions and constraints. The main objective function of an effective post-disaster management system is to minimize not only the cost but also the environmental impact. Several papers considered the system cost in the waste supply chain management system, such as Fetter and Rakes (2012), Habib and Sarkar (2017), Lorca et al. (2016), Onan et al. (2015), and Pramudita et al. (2014). However, a few papers determined the environmental impact, such as Lorca et al. (2016) and Wakabayashi et al. (2017). Fetter and Rakes (2012) presented a mixed-integer linear optimization model for decision-making about post-disaster waste processing location, post-disaster waste processing availability, and post-disaster waste flow. The objective function of the proposed model aims to minimize waste management system costs by considering the fixed and variable costs of waste collection, RSR (Reduction, Separation, and Recycling) operations, and disposal. This framework was constructed by using the off-site separation strategy for post-disaster waste management. Hu and Sheu (2013) presented a linear programming model for post-waste management with an on-site separation strategy in a study focused on the transporting, recycling, and storing of disaster waste in the disaster recovery phase. The objective function minimizes the reverse logistical costs, psychological costs, and risk penalties. The risk penalty refers to both environmental and operational risks. Onan et al. (2015) presented a mathematical model for the employment of a framework to determine the location of a temporary disaster management facility. This model aims to minimize the cost and risk of exposure to hazardous waste. The framework was developed based on the off-site separation strategy. To consider the environmental context, few papers proposed this issue to the main objective function. Wakabayashi et al. (2017) presented an approach for the environmental and economic evaluation of an integrated disaster waste management system that takes into account the spatial scale of disaster waste removal, transport, and treatment. The mathematical models were formulated to manage the transport network of post-disaster waste in which not only the total cost of transport but also the quantity of CO_2 emissions or cost per tonne of combustibles is set as objective functions. However, Wakabayashi et al. (2017) lack the consideration of CO_2 emissions in landfills. Boonmee et al. (2018) presented a mixed-integer linear programming model for post-disaster debris management. The proposed model aims to minimize the total cost of fixed costs, transport costs, operational costs, penalty costs, and potential revenue. The environmental context was included in penalty costs that determine CO_2, SO_x, NO_x, and PM that may occur during the transport process along with the operational process within the network. Nowadays, carbon emission is a concern. Boonmee et al. (2021) proposed post-disaster waste management with carbon tax policy consideration to reduce carbon during a disaster situation. Based on the literature, both the cost aspect and environmental aspect are quite important to post-disaster waste management. Hence, this research aims to focus on the cost and the environmental impact simultaneously.

To provide an effective separation strategy for recyclable materials, most articles usually employ either an on-site separation strategy or an off-site separation strategy. As the above-mentioned papers, Fetter and Rakes (2012), Onan et al. (2015), and Wakabayashi et al. (2017) formulated the post-waste management framework with off-site separation strategy, while Pramudita et al. (2014) and Hu and Sheu (2013) selected to use on-site separation strategy. However, Brown and Milke (2016) recommend an integrated decision-making process for on-site and off-site separation of recyclable materials because this can balance the advantages of both strategies efficiently through the five main criteria. To reach these goals, a few papers applied a hybrid strategy for separation to enhance the management of the post-disaster waste supply chain system. Boonmee et al. (2018) proposed a mixed integer linear programming model for integrating the on-site and off-site separation systems for recyclable materials for the post-disaster waste supply chain management. Then, Boonmee et al. (2021) modified the model of Boonmee et al. (2018) by adding consideration of the incineration sites and carbon tax policy.

Table 1. A review study of the optimization model for post-disaster waste management

Author	Objective function			Separation Strategy	Math Model	Data Modeling Type	Objective type
	Cost	Environment	Other				
Fetter and Rakes (2012)	✓			Off-site	MILP	Deterministic	Single
Onan et al. (2015)	✓		Risk	Off-site	MILP	Deterministic	Multi
Pramudita et al. (2014)	✓			On-site	MILP	Deterministic	Single
Wakabayashi et al. (2017)	✓	✓		Off-site	LP	Deterministic	Single, Multi
Hu and Sheu (2013)	✓	✓	Risk	On-site	LP	Deterministic	Multi
Boonmee et al. (2018)	✓	✓		Mixed	MILP	Deterministic	Single
Boonmee et al. (2021)	✓		CO_2	Mixed	MILP	Deterministic	Single
This work	✓	✓		Mixed	MILP	Stochastic	Multi

MILP = Mixed-Integer Linear Programming, LP = Linear Programming.

Based on the application of the mixed strategy for waste separation in Boonmee et al. (2018) and Boonmee et al. (2021), it is confirmed that the proposed strategy can balance the advantages of both approaches efficiently. However, Boonmee et al. (2018) and Boonmee et al. (2021) fail to determine the uncertain situation of disasters, which might affect the decisions made on location selection and waste flow. Moreover, the goal of the environmental impact is lacking. Hence, this research aims to develop a multi-objective two-stage stochastic optimization model for post-disaster waste management with a mixed strategy for separation to support the unexpected situation of a disaster. Moreover, not only the cost criterion but also the environmental criterion is determined in this research as well.

2. Model Formulation

2.1. Conceptual model

The conceptual model of this research is illustrated as shown in Fig. 1.

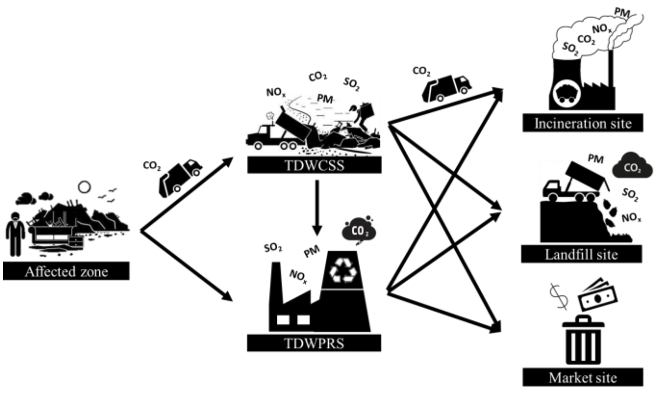

Fig. 1. The conceptual model of research (Boonmee et al., 2021)

This study is based on the framework of a mixed strategy for on-site and off-site waste separation in the supply chain proposed by Boonmee et al. (2018), Boonmee et al. (2021), and Brown and Milke (2016). The structure of this research consists of the affected communities, Temporary Disaster Waste Collection and Separation Sites (TDWCSSs), Temporary Disaster Waste Processing and Recycling Sites (TDWPRSs), landfill sites, incineration sites, and market sites. To begin, the mixed waste in the affected community is transferred to a TDWCSS or TDWPRS for collection and separation by manual or preliminary technologies, with the waste from some affected communities being separated on-site by a TDWCSS while the remaining waste is assigned to an off-site separation facility identified as a TDWPRS. After that, the separated wastes from the TDWCSS are transferred to a TDWPRS for processing and recycling, while other separated wastes from the TDWCSS are transferred to incineration sites, landfill sites, and market sites, respectively. After the processing and recycling operation at the TDWPRS, the remaining waste is also transferred to incineration sites, landfill sites, and market sites.

2.2. Proposed mathematical model

The proposed mathematical model is formulated from the facility location problem and distribution problem. According to the uncertain situation during the disaster, two-stage stochastic programming is applied in this research to consider the uncertainty of situations. This model is formulated as a multi-objective two-stage stochastic mixed integer linear programming problem, and assumptions are as follows:

1) Only affected communities, TDWCSSs, TDWPRSs, incineration sites, landfill sites, and market sites are determined in this study.
2) All waste must be separated before it can be recycled, disposed of, or sold.
3) The market's capacity is assumed to be infinite.
4) All types of saleable waste can be sold at all markets.
5) the first RSR technology at TDWPRS is separation technology.
6) the environmental impact is estimated by the government, combined with various elements.
7) all the parameters used are known, deterministic, and constant.

The output of the proposed model aims to choose the TDWCSSs, TDWPRSs, landfill sites, incineration sites, RSR technologies, and incineration technologies, minimize financial costs, maximize revenues, minimize the environmental impact and provide waste flow decisions throughout the supply chain under the uncertain situation of disasters. The model is formulated as follows:

Indies

I: Set of affected communities $\{ i \in I \}$
J: Set of candidate sites for TDWCSS $\{ j \in J \}$
K: Set of candidate sites for TDWPRS $\{ k \in K \}$
L: Set of candidate sites for landfill sites $\{ l \in L \}$
M: Set of market sites $\{ m \in M \}$
N: Set of candidate sites for incineration sites $\{ n \in N \}$;
O: Set of RSR technologies $\{ o \in O \}$
P: Set of incineration technologies $\{ p \in P \}$
S: Set of scenarios $\{ s \in S \}$

Parameters

$h_i(s)$: Amount of waste in affected community i in scenario s
F_j^{TDWCSS} : Fixed cost of opening and closing TDWCSS at site j
F_k^{TDWPRS} : Fixed cost of opening and closing TDWPRS site k
$F_l^{Landfill}$: Fixed cost of opening and closing landfill at site l
$F_n^{Incineration}$: Fixed cost of opening and closing incineration site at site n
V_j^{TDWCSS} : Fixed cost of installing separated technology at TDWCSS site j (On-site)
V_{ko}^{TDWPRS} : Fixed cost of installing RSR technology o at TDWPRS site k (Off-site)
$V_{np}^{Incineration}$: Fixed cost of installing incineration technology p at incineration site n
O_j^{TDWCSS} : Operational cost at TDWCSS site j
$O_l^{Landfill}$: Operational cost at landfill site l
O_{ko}^{TDWPRS} : Operational cost RSR technology o at TDWPRS site k
$O_{np}^{Incineration}$: Operational cost incineration technology p at TDWPRS site n
C_j^{TDWCSS} : Capacity of TDWCSS at site j
C_{ko}^{RSR} : Capacity of RSR technology o at TDWPRS site k;
$C_l^{Landfill}$: Capacity of landfill site at site l
$C_{np}^{Incineration}$: Capacity of incineration technology p at incineration site n
$\mathrm{Re}\,v_m$: Revenue from saleable portion of waste at market m
β_o : Proportion of waste from affected community that is eligible to be treated with RSR technology o
λ_o : Proportion of reduced waste from RSR technology o for disposal at landfill
υ_o : Proportion of reduced waste from RSR technology o saleable as recycled material
η_o : Proportion of reduced waste from RSR technology o for incineration at incineration site
TIJ_{ij} : Transport cost of waste from affected community i to TDWCSS j
TIK_{ik} : Transport cost of waste from affected community i to TDWPRS k
TJK_{jk} : Transport cost of waste from TDWCSS j to TDWPRS k
TJL_{jl} : Transport cost of waste from TDWCSS j to landfill site l
TJM_{jm} : Transport cost of waste from TDWCSS j to market site m
TJN_{jn} : Transport cost of waste from TDWCSS j to incineration site n
TKL_{kl} : Transport cost of waste from TDWPRS k to landfill site l
TKM_{km} : Transport cost of waste from TDWPRS k to market site m
TKN_{kn} : Transport cost of waste from TDWPRS k to incineration site n
EIJ_{ij} : Environmental impact during waste transport from affected community i to TDWCSS j
EIK_{ik} : Environmental impact during waste transport from affected community i to TDWPRS k
EJK_{jk} : Environmental impact during waste transport from TDWCSS j to TDWPRS k
EJL_{jl} : Environmental impact during waste transport from TDWCSS j to landfill site l
EJM_{jm} : Environmental impact during waste transport from TDWCSS j to market site m
EJN_{jn} : Environmental impact during waste transport from TDWCSS j to incineration site n
EKL_{kl} : Environmental impact during waste transport from TDWPRS k to landfill site l
EKM_{km} : Environmental impact during waste transport from TDWPRS k to market site m
EKN_{kn} : Environmental impact during waste transport from TDWPRS k to incineration site n
E_j^{TDWCSS} : Environmental impact during the operation at TDWCSS j
E_{ko}^{TDWPRS} : Environmental impact during the operation at TDWPRS k by using RSR technologies o
$E_l^{Landfill}$: Environmental impact during the disposal at landfill l
$E_{np}^{Inciceration}$: Environmental impact during the operation at incineration site n by using incineration technology p
U^{TDWCSS} : Maximum of selected TDWCSS
U^{TDWPRS} : Maximum of selected TDWPRS
$U^{Landfill}$: Maximum of selected landfill
$U^{Incineration}$: Maximum of selected incineration
$Prob(s)$: Probability of scenario s
ω : the penalty cost in the case of the overcapacity of wastes

Decision variables

$VIJ_{ij}(s)$: Amount of waste from affected community *i* to TDWCSS *j* in scenario *s*

$VIK_{ik}(s)$: Amount of waste from affected community *i* to TDWPRS *k* in scenario *s*

$VJK_{jko}(s)$: Amount of waste from TDWCSS *j* to TDWPRS *k* for recycling by RSR technology *o* in scenario *s*

$VJL_{jl}(s)$: Amount of waste from TDWCSS *j* to landfill site *l* in scenario *s*

$VJM_{jm}(s)$: Amount of waste from TDWCSS *j* to market site *m* in scenario *s*

$VJN_{jnp}(s)$: Amount of waste from TDWCSS *j* to incineration site *n* for recycling by incineration technology *p* in scenario *s*

$VKL_{kl}(s)$: Amount of waste from TDWPRS *k* to landfill site *l* in scenario *s*

$VKM_{km}(s)$: Amount of waste from TDWCSS *k* to market site *m* in scenario *s*

$VKN_{knp}(s)$: Amount of waste from TDWPRS *k* to incineration site *n* for recycling by incineration technology *p* in scenario *s*

x_j : If a TDWCSS *j* is opened then 1, otherwise 0

y_k : If a TDWPRS *k* is opened then 1, otherwise 0

z_l : If a landfill *l* is opened then 1, otherwise 0

w_n : If an incineration *n* is opened then 1, otherwise 0

a_{ko} : If a RSR technology *o* is available at TDWPRS *k* then 1, otherwise 0

b_{np} : If an incineration technology *p* is available at incineration location *n* then 1, otherwise 0

Px_j : Amount of waste exceeding the maximum capacity at TDWCSS *j*

Pz_l : Amount of waste exceeding the maximum capacity at landfill *l*

Pa_{ko} : Amount of waste exceeding the maximum capacity by RSR technology *o* at TDWPRS *k*

Pb_{np} : Amount of waste exceeding the maximum capacity by incineration technology *p* at incineration location *n*

FC : Fixed cost

$OC(s)$: operational cost in scenario *s*

$TC(s)$: Transport cost in scenario *s*

$PC(s)$: Penalty cost in scenario *s*

$R(s)$: Revenue in scenario *s*

$EE(s)$: Environmental impact in scenario *s*

Objective Functions

$$\text{Min } Z1 = FC + E(s)[Q(x_i, y_k, z_l, w_n, a_{ko}, b_{np}, s)] \quad (1)$$

$$\text{Min } Z2 = \sum_s prob(s) * EE(s) \quad (2)$$

Subject to

$$E(s)[Q(x_i, y_k, z_l, w_n, a_{ko}, b_{np}, s)] = \sum_s prob(s) * Q(x_i, y_k, z_l, w_n, a_{ko}, b_{np}, s) \quad (3)$$

$$Q(x_i, y_k, z_l, w_n, a_{ko}, b_{np}, s) = OC(s) + TC(s) + PC(s) - R(s) \quad \forall s \quad (4)$$

$$FC = \sum_j F_j^{TDWCSS} x_j + \sum_k F_k^{TDWPRS} y_k + \sum_l F_l^{Landfill} z_l + \sum_n F_n^{Incineration} w_n + \sum_j V_j^{TDWCSS} x_j + \sum_k \sum_o V_{ko}^{TDWPRS} a_{ko} + \sum_n \sum_p V_{np}^{Incineration} b_{np} \quad (5)$$

$$OC(s) = \sum_i \sum_j O_j^{TDWCSS} VIJ_{ij}(s) + \sum_i \sum_j \sum_k \sum_o O_{ko}^{TDWPRS} (VIK_{ik}(s)\beta_o + VJK_{jko}(s)) + \sum_j \sum_k \sum_l O_l^{Landfill} (VJL_{jl}(s) + VKL_{kl}(s)) + \sum_j \sum_k \sum_n \sum_p O_{np}^{Incineration} (VJN_{jnp}(s) + VKN_{knp}(s)) \quad \forall s \quad (6)$$

$$TC(s) = \sum_i \sum_j TIJ_{ij} VIJ_{ij}(s) + \sum_i \sum_k TIK_{ik} VIK_{ik}(s) + \sum_j \sum_k \sum_o TJK_{jk} VJK_{jko}(s) + \sum_j \sum_l TJL_{jl} VJL_{jl}(s) + \sum_j \sum_m TJM_{jm} VJM_{jm}(s) + \sum_j \sum_n \sum_p TJN_{jn} VJN_{jnp}(s) + \sum_k \sum_l TKL_{kl} VKL_{kl}(s) + \sum_k \sum_m TKM_{km} VKM_{km}(s) + \sum_k \sum_n \sum_p TKN_{kn} VKN_{knp}(s) \quad \forall s \quad (7)$$

$$PC(s) = \omega \left[\sum_j Px_j(s) + \sum_l Pz_l(s) + \sum_k \sum_0 Pa_{ko}(s) + \sum_n \sum_p Pb_{np}(s) \right] \quad \forall s \quad (8)$$

$$R(s) = \sum_j \sum_k \sum_m \mathrm{Re}\,v_m (VJM_{jm}(s) + VKM_{km}(s)) \quad \forall s \quad (9)$$

$$EE(s) = \Bigg(\sum_i \sum_j E_j^{TDWCSS} VIJ_{ij} + \sum_i \sum_j \sum_k \sum_o E_{ko}^{TDWPRS} (VIK_{ik}\beta_o + VJK_{jko}) + \sum_j \sum_k \sum_l E_l^{Landfill} (VJL_{jk} + VKL_{kl}) + \sum_j \sum_k \sum_p \sum_n E_{np}^{Incineration} (VJN_{jnp} + VKN_{knp}) + \sum_i \sum_j EIJ_{ij} VIJ_{ij} + \sum_i \sum_k EIK_{ik} VIK_{ik} + \sum_j \sum_k \sum_o EJK_{jk} VJK_{jko} + \sum_j \sum_l EJL_{jl} VJL_{jl} + \sum_j \sum_m EJM_{jm} VJM_{jm} + \sum_j \sum_n \sum_p EJN_{jn} VJN_{jnp} + \sum_k \sum_l EKL_{kl} VKL_{kl} + \sum_k \sum_m EKM_{km} VKM_{km} + \sum_k \sum_n \sum_p EKN_{kn} VKN_{knp} \Bigg) \quad \forall s \quad (10)$$

$$\sum_j x_j \le U^{TDWCSS} \quad (11)$$

$$\sum_k y_k \le U^{TDWPRS} \quad (12)$$

$$\sum_l z_l \le U^{Landfill} \quad (13)$$

$$\sum_n W_n \le U^{Incineration} \quad (14)$$

$$\sum_{i} VIJ_{ij}(s) \le C_{j}^{TDWCSS} x_{j} + Px_{j}(s) \qquad \forall i, s \qquad (15)$$

$$\sum_{i} VIK_{ik}(s)\beta_{o} + \sum_{j} VJK_{jko}(s) \le C_{ko}^{RSR} a_{ko} + Pa_{ko}(s) \qquad \forall k, o, s \qquad (16)$$

$$\sum_{j} VJL_{jl}(s) + \sum_{k} VKL_{kl}(s) \le C_{l}^{Landfill} z_{l} + Pz_{l}(s) \qquad \forall l, s \qquad (17)$$

$$\sum_{j} VJN_{jnp}(s) + \sum_{k} VKN_{knp}(s) \le C_{np}^{Incineration} b_{np} + Pb_{np}(s) \qquad \forall n, p, s \qquad (18)$$

$$a_{ko} \le y_{k} \qquad \forall k, o \qquad (19)$$

$$b_{np} \le w_{n} \qquad \forall n, p \qquad (20)$$

$$\sum_{j} VIJ_{ij}(s) + \sum_{k} VIK_{ik}(s) = h_{i}(s) \qquad \forall i, s \qquad (21)$$

$$\sum_{i} VIJ_{ij}(s)\beta_{o} = \sum_{k} VJK_{jko}(s) \qquad \forall j, s, o \ne 1 \qquad (22)$$

$$\sum_{i} VIJ_{ij}(s)\lambda_{1}(1-\sum_{o=2}^{O}\beta_{o}) = \sum_{l} VJL_{jl}(s) \qquad \forall j, s \qquad (23)$$

$$\sum_{i} VIJ_{ij}(s)\upsilon_{1}(1-\sum_{o=2}^{O}\beta_{o}) = \sum_{m} VJM_{jm}(s) \qquad \forall j, s \qquad (24)$$

$$\sum_{i} VIJ_{ij}(s)\eta_{1}(1-\sum_{o=2}^{O}\beta_{o}) = \sum_{n}\sum_{p} VJN_{jnp}(s) \qquad \forall j, s \qquad (25)$$

$$\sum_{i} VIK_{ik}(s)\lambda_{1}(1-\sum_{o=2}^{O}\beta_{o}) + \sum_{i}\sum_{o=2}^{O} VIK_{ik}(s)\beta_{o}\lambda_{o} + \sum_{j}\sum_{o} VJK_{jko}(s)\lambda_{o} = \sum_{l} VKL_{kl}(s) \qquad \forall k, s \qquad (26)$$

$$\sum_{i} VIK_{ik}(s)\upsilon_{1}(1-\sum_{o=2}^{O}\beta_{o}) + \sum_{i}\sum_{o=2}^{O} VIK_{ik}(s)\beta_{o}\upsilon_{o} + \sum_{j}\sum_{o} VJK_{jko}(s)\upsilon_{o} = \sum_{m} VKM_{km}(s) \qquad \forall k, s \qquad (27)$$

$$\sum_{i} VIK_{ik}(s)\eta_{1}(1-\sum_{o=2}^{O}\beta_{o}) + \sum_{i}\sum_{o=2}^{O} VIK_{ik}(s)\beta_{o}\eta_{o} + \sum_{j}\sum_{o} VJK_{jko}(s)\eta_{o} = \sum_{n}\sum_{p} VKN_{knp}(s) \qquad \forall k, s \qquad (28)$$

$$VIJ_{ij}(s), VIK_{ik}(s), VJK_{jko}(s), VJL_{jl}(s), VJM_{jm}(s), VJN_{jnp}(s), VKL_{kl}(s), VKM_{km}(s), VKN_{knp}(s), FC, OC(s), TC(s), PC(s), PC(s), Px_{j}(s), Pz_{l}(s), Pa_{ko}(s), Pb_{np}(s) \ge 0 \qquad \forall i, j, k, l, m, n, o, p, s \qquad (29)$$

$$x_{j}, y_{k}, z_{l}, w_{n}, a_{ko}, b_{np} \in \{0,1\} \qquad \forall j, k, l, n, o, p \qquad (30)$$

The goal of the proposed mathematical model consists of two objective functions. The first objective function aims to minimize the total costs in the post-disaster waste supply chain management under the uncertain situation associated with the mixed strategy for waste separation as shown in Eq. (1). This first objective function is separated into two terms. The first term proposes the opening cost of TDWCSSs, TDWPRSs, landfills, and incineration sites and the investment cost of separation technologies, RSR technologies, and incineration technologies as presented in Eq. (5). The second term presents the expected cost in the recovery phase for each disaster scenario. The expected cost of the recovery phase is expressed in Eq. (3), where, for each scenario, this includes the cost of the waste operation (Eq. 6), transport (Eq. 7), and penalty in the case of wastes exceeding the maximum capacity (Eq. 8), and the revenue from the saleable waste (Eq. 9), as shown in Eq. (3). The second objective function aims to minimize the environmental impacts as shown in Eq. (2) that are related to the transport and operational processes as shown in Eq. (10), in which CO_2, SO_x, NO_x, and PM pollution may be emitted during the transport process along with the operational process within the network. Eq. (11) – Eq. (14) ensure that the total number of selected locations cannot exceed the maximum limit of each location type. Eq. (15) – Eq. (18) state that the amount of waste assigned to each location site (TDWCSS, TDWPRS, landfill, and incineration) should not exceed its maximum capacity. When the amount of waste exceeds that capacity, a penalty cost is added to the objective function. Eq. (19) – Eq. (20) require that the TDWPRS and incineration site must be opened to make their technologies available. Eq. (21) ensures that the amount of waste in each affected community in each scenario is collected and processed. Eq. (22) – Eq. (25) guarantee that all the collected waste in each selected TDWCSS is assigned to processing sites (TDWPRSs), landfills, incineration sites, and market sites. Eq. (26) – Eq. (28) guarantee that the waste in each selected TDWPRS is assigned to landfills, incineration sites, and market sites. Eq. (29) – Eq. (30) describe non-negativity and the binary conditions of the decision variables.

2.3. Normalization in the weighted sum method

Now we determine the multiple objective problem, which is more difficult to solve than the single objective problem. Generally, a multiple objective function cannot generate a single global solution. Therefore, it is necessary to determine a set of points that fit a predetermined definition for an optimum solution (Wapee and Irohara, 2016). There are several approaches to solve the multiple objective problem, such as the weighted sum method, epsilon constraint method, LP-matrix, and non-preemptive goal programming. The most popular method for the multiple objective problem is the weighted sum method. This method modifies the multiple objective optimization model to a single objective optimization model. The objective function is formulated as the sum of the objective function ($f_i(x)$) multiplied by the weight coefficient (α) as shown in Eq. (31). However, the weighted sum method is suitable only when the objective functions are expressed in the same unit. To apply this method to the case of different units, a normalization objective is required for the Pareto optimal solution. To normalize the objective functions, they were constructed following Eq. (32) for the cost criterion and Eq. (33) for the benefit criterion. Because the objective functions of this research are not the same unit, this study applied the weighted sum method with normalization. Eq. (1) and Eq. (2) were normalized following Eq. (32) as shown in Eq. (34).

$$\sum_{i=1}^{k} \alpha_{i} f_{i}(x) \quad \text{Where } \alpha_{i} \ge 0 \quad \forall i = 1,\dots,k \text{ and } \sum_{i=1}^{k} \alpha_{i} = 1 \qquad (31)$$

$$\frac{f_i(x) - z_i^U}{z_i^N - z_i^U} \quad (32)$$

$$\frac{z_i^U - f_i(x)}{z_i^U - z_i^N} \quad (33)$$

Where:

z_i^U is a Utopia point with Min $f_i(x)$ for the cost criterion and Max $f_i(x)$ for the benefit criterion

z_i^N is a Nadir point with Max $f_i(x)$ for the cost criterion and Min $f_i(x)$ for the benefit criterion

$$Z3 = (\alpha)\left(\frac{Z1 - z_1^U}{z_1^N - z_1^U}\right) + (1-\alpha)\left(\frac{Z2 - z_2^U}{z_2^N - z_2^U}\right) \quad (34)$$

Hence, the proposed multiple objective programming model is reformulated as a single objective programming model as follows:

Objective Function

$$\text{Min} \quad Z3 = (\alpha)\left(\frac{Z1 - z_1^U}{z_1^N - z_1^U}\right) + (1-\alpha)\left(\frac{Z2 - z_2^U}{z_2^N - z_2^U}\right) \quad (35)$$

Subject to

$$Z1 = FC + E(s)[Q(x_i, y_k, z_l, w_n, a_{ko}, b_{np}, s)] \quad (36)$$

$$Z2 = \sum_s prob(s) * EE(s) \quad (37)$$

Eq. (3) – (30)

3. Computational Experiment

3.1. Experiment data design

In this section, we applied the case study of flooding reported in Boonmee et al. (2021) to validate the proposed mathematical model. The case study region is vulnerable to flooding every year due to its bowl-like shape. Based on the experiment data design of Boonmee et al. (2021) and the uncertain situation, we assumed that the experiment data is composed of nine affected communities, three candidate TDWCSSs, three candidate TDWPRSs, three candidate landfills, three candidate incineration sites, three market sites, three RSR technologies, three incineration technologies, and three scenarios. To test the proposed mathematical model, additional data is generated in Table 2. Table 2 presents the amount of waste in the affected communities for each scenario, the probability of each scenario, and the penalty cost. The other data can be seen in Boonmee et al. (2021). The weight of the first and second objective functions is assumed to be 0.5 and 0.5, respectively. To determine the environmental impact, this study considered only CO_2. The CO_2 data refers to Boonmee et al. (2021).

Table 2. The amount of waste in the affected communities for each scenario (Unit: tonnes), the probability of each scenario, and the penalty cost.

Affected communities	Scenario 1	Scenario 2	Scenario 3
1	12,800	15,360	17,920
2	7,500	9,000	10,500
3	19,000	22,800	26,600
4	13,200	15,840	18,480
5	17,000	20,400	23,800
6	12,000	14,400	16,800
7	7,300	8,760	10,220
8	19,500	23,400	27,300
9	13,700	16,440	19,180
Prob(s)	0.5	0.3	0.2
ω	$5		

3.2. Results and discussions

The proposed mathematical model was solved using the optimization software LINGO 14.0 (Education license). All experiments were run on a personal computer with an Intel® Core™ i5-8400 CPU (2.80 GHz) and 8 GB of RAM. After the proposed mathematical model was coded and all data were input in LINGO 14.0, the solution could be found within a few seconds. Firstly, the single objective programming model is solved; this consists of the expected total cost and the expected environmental impact one at a time. Table 3 presents the objective value of the single objective programming model. For the minimum expected total cost of $5,709,540, the expected environmental impact is 1,449,313 tonnes of CO_2. For the minimum expected environmental impact of 1,401,125 tonnes of CO_2, the expected total cost is $6,290,898. The details of the cost and the selection of each location type in each single objective programming model are presented in Table 4.

Table 3. Ideal values for the single objective programming model

Objective function value	Single objective model: Z1 ($)	Single objective model: Z2 (Tonne of CO_2)	Utopia point	Nadir point
Z1	5,709,540	6,290,898	5,709,540	6,290,898
Z2	1,449,313	1,401,125	1,401,125	1,491,391

Table 4. Detail of cost and selected locations from the single objective programming model

	Z1	Z2
Expected total cost	5,709,540	6,490,947
Fixed cost	125,100	314,700
Expected operational cost	4,228,495	4,926,797
Expected transport cost	1,743,978	1,644,589
Expected penalty cost	0	0
Expected revenue	388,033	280,488
Expected environmental impact	1,449,313	1,401,125
TDWCSSs	#2	#1 #2 #3
TDWPRSs	#1 #2	#1 #2 #3
Landfills	#1 #2	#1 #2 #3
Incineration sites	#2 #3	#1 #2 #3

The results above confirm that the two criteria are conflicting objectives, in which no solution simultaneously achieves both criteria. Based on the solution of the single objective programming model, the utopia and nadir point can be found and employed to transform the multiple objective programming model into a single objective programming model. When the proposed mathematical model was reformulated as a single objective programming model and solved, the results showed that the optimal solution for the expected total cost is $5,712,067, which consists of $125,100 for the fixed cost, $4,226,965 for the expected operational cost, $1,748,035 for waste transport, $388,033 in revenue, and a $0 penalty cost, while the expected environmental impact is 1,446,365 tonnes of CO_2. The TDWCSS 2 was selected for waste collection and separation on-site, while TDWPRS 1 and TDWPRS 2 were selected 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 by incineration, Incineration Site 2 and Incineration Site 3 were selected, operating the first incineration technology in Incineration Site 2 and the second incineration technology in Incineration Site 3. As the penalty cost is 0, this means that all the selected facility locations could support all of the waste in each affected community.

Table 5. Comparison of mixed separation, on-site separation, and off-site separation

	Mixed	On-site	Off-site
Expected total cost	5,712,067	6,490,947	5,751,751
Fixed cost	125,100	92,200	151,600
Expected operational cost	4,226,965	5,093,549	4,176,008
Scenario 1	3,601,030	4,468,026	3,591,340
Scenario 2	4,495,222	5,361,631	4,427,892
Scenario 3	5,389,414	6,255,236	5,259,853
Expected transport cost	1748035	1,687,228	1,812,176
Scenario 1	1,586,410	1,480,025	1,597,245
Scenario 2	1,806,492	1,776,030	1,896,588
Scenario 3	2,064,414	2,072,035	2,222,886
Expected penalty cost	0	0	0
Expected revenue	388,033	382,031	388,033
Scenario 1	340,380	335,115	340,380
Scenario 2	408,456	402,138	408,456
Scenario 3	476,532	469,161	476,532
Expected environmental impact	1,446,365	1,695,325	1,409,504
Scenario 1	1,240,446	1,487,127	1,236,788
Scenario 2	1,534,076	1,784,553	1,483,141
Scenario 3	1,829,597	2,081,978	1,730,841
TDWCSSs	#2	#1 #2	None
TDWPRSs	#1 #2	#1	#1 #2 #3
Landfills	#1 #2	#1 #3	#1 #2
Incineration sites	#2 #3	#2 #3	#2 #3

Note: # is the candidate number.

When we compared the mixed strategy for separation to on-site separation and off-site separation (see Table 5), we found that the performance of the mixed strategy is superior to the on-site and off-site separation from the economic perspective. The mixed separation improved on the on-site and off-site separation by 13.63% and 0.69%, respectively. However, the performance of on-site separation is superior to mixed separation in terms of the fixed cost and the expected transport cost, while off-site separation is superior to mixed separation in terms of the expected operational cost only. Based on the comparison, it is confirmed that the integrated decision on on-site separation and off-site separation could effectively balance the economic view. When the environmental impact perspective is analyzed, the mixed separation can balance the environmental impact between on-site and off-site separation. The performance of off-site separation is superior to on-site and mixed separation from the environmental impact perspective. However, the mixed strategy can balance the environmental impact between the on-site and off-site separation. Therefore, the mixed strategy for separation might be able to balance the other perspectives as well.

The weight of each objective function is very important for selecting locations and making waste flow decisions in the post-disaster waste supply chain. Presently, the weights of the objective functions are assumed to be the same. To understand the sensitivity of the weight parameter, this study presents a sensitivity analysis of the weight value, as shown in Fig. 2 and Table 6. This experiment generated the solution by increasing the value from 0 to 1 in increments of 0.1; the solution was solved in 11 sub-problems as shown in Fig. 2. From the solution, this study found that the minimum expected total cost ranged between $6,490,947 and $5,709,540, and the minimum expected environmental impact ranged between 1,401,125 and 1,449,313 tonnes of CO_2. From all the solutions, we see that the best expected total cost is reached at the maximum expected environmental impact, while the minimum expected environmental impact is reached at the maximum expected total cost. If we decrease the weight value (α) with its decrements, the expected total cost decreases, while the expected environmental impact increases exponentially.

To analyze the uncertain situations of disasters, we tested the proposed model with different probability sets. Two cases were proposed and compared to the current situation, as shown in Fig. 3 and Table 7, based on which we found that when the probability of each scenario was changed, the decision on the location selected also changed. As we focused on Case 1, we found that only Incineration site 2 was selected, while the other sites selected for TDWCSS, TDWPRS, and landfill were the same as in the current situation. This result means that when Scenario 1 was provided with a high probability, Scenario 1 was emphasized since most of the total costs and environmental impact were generated from this scenario. However, when the solutions of Case 2 were found, the separation strategy changed to off-site separation. No TDWCSS locations were selected, and all the waste was transferred directly to TDWPRSs, for which all candidate TDWPRS locations were selected. Therefore, the parameter of uncertainty of the scenario is quite important to generate the solution and select the strategy for separation.

Furthermore, a large-scale disaster was determined. We trialed increasing the amount of waste in Scenario 3 for each affected community as 89,600, 52,500, 133,000, 92,400, 119,000, 84,000, 51,100, 136,500, and 95,900, respectively. After the data were input and solved, we found that the optimization software was still able to find the solution. The expected environmental impact is 3,003,437 tonnes of CO_2 and the expected total cost is $ $100,477,079, which consists of $201,800 for the fixed cost, $9,376,026 for the expected operational cost, $ 3,365,686 for waste transport, $756,433 in revenue, and $88,290,000 for the penalty cost. All the candidate locations for each waste process were selected, except Incineration Site 1. As we focused on the objective values, we saw that the expected total cost was very high because the amount of waste was increased in Scenario 3 and not even using all the facility locations of each process was enough to support all the waste in this scenario. Therefore, the expected total cost was increased by adding the penalty cost in this case. When we focused on the expected environmental impact, this objective value also increased, since all the selected locations can generate an environmental impact. Since the variable for the amount of waste that cannot be supported is added in Eq. (15) – Eq. (20), the proposed mathematical model is still able to support this case and find a solution that is not infeasible. However, more location sites of each type should be added in this case to support the excess waste in the waste supply chain.

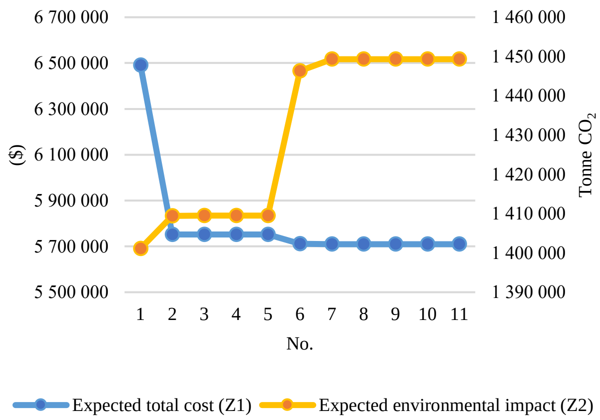

Fig. 2. Sensitivity analysis for objective weight parameters

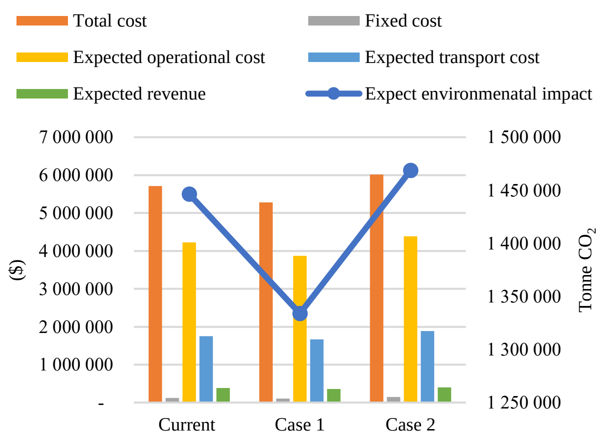

Fig. 3. Sensitivity analysis for probability parameters

4. Future Research Direction

To develop post-disaster waste supply chain management under a mixed strategy for separation in future research, the proposed model could determine other objectives and other constraints simultaneously, such as the waste clean-up time perspective, traffic congestion, time schedules, resource assignment, modes of transport, and so on, because all these perspectives are important for considering the facility location selection and waste flow decisions. Furthermore, the inherent uncertainty of the input parameters or fuzzy parameters could be determined, since some parameters might be unknown and inconstant. To test the performance of the proposed mathematical model, a large-scale case with realistic data should be applied. For such a large-scale case, an exact algorithm might not be able to find the optimal solution easily. Thus, a heuristic algorithm or meta-heuristic algorithm should be adopted for finding the solution within the time limitation. Based on the numerical example to test the proposed mathematical model, only CO_2 emission was determined. In further research, other environmental emissions should be considered such as SO_x, NO_x, and PM.

5. Conclusions

This research proposes a multi-objective two-stage stochastic optimization programming model for post-disaster waste supply chain management with an integrated decision on on-site separation and off-site separation. The proposed mathematical model aims to simultaneously minimize the environmental impact and the total cost in the post-disaster waste supply chain (composed of the fixed cost, operational cost, transport cost, penalty cost, and revenue) to provide waste flow decisions and select collection and separation sites, recycling sites, landfill sites, and incineration sites throughout the supply chain under the uncertain situation. The proposed mathematical model is formulated as a multi-objective two-stage stochastic mixed integer linear programming model.

To solve a multi-objective problem, a normalized weighted sum method is applied to find the solution. A numerical case based on realistic data is presented to validate and verify the proposed model. Based on the numerical example, the results demonstrated that the implementation of the mixed strategy for waste separation with the consideration of uncertain situations could outperform the on-site and off-site separation and balance the benefits of both strategies. This research will be of great significance in helping decision-makers consider the spatial aspect of the strategic placement of facility locations and waste flow decisions under the uncertainty of disaster. However, the proposed mathematical model might not be able to apply in some cases in some countries due to the waste management policy. Therefore, the users should recheck the waste management policy before applying the proposed mathematical model. If our proposed conceptual model could not apply directly, the users can add or cut some constraints and some data. For example, European legal standards in the field of waste management indicate that landfill is undesirable and should be limited and used only in situations where there are no other disposal methods. According to this policy, the users can provide limited conditions for landfill usage. Moreover, the users can add some transitional stages for individual groups of waste, which were subjected to activities focused on recovery (processing, for example, into alternative fuels) instead of going directly to the landfill. Further studies that include other objectives and constraints, such as waste clean-up time, traffic congestion, time schedules, modes of transport, the uncertainty of data, resource assignment, and so on, are recommended.

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Appendix A

Table 6. Details of sensitivity analysis for objective weight parameters.

No	Weight of Z1 (α)	Weight of Z2 ($1-\alpha$)	Z1	Z2	TDWCSS	TDWPRS	Landfill	Incineration site
1	0	1	6,490,947	1,401,125	None	#1 #2 #3	#1 #2 #3	#1 #2 #3
2	0.1	0.9	5,752,418	1,409,423	None	#1 #2 #3	#1 #2	#2 #3
3	0.2	0.8	5,751,751	1,409,504	None	#1 #2 #3	#1 #2	#2 #3
4	0.3	0.7	5,751,751	1,409,504	None	#1 #2 #3	#1 #2	#2 #3
5	0.4	0.6	5,751,751	1,409,504	None	#1 #2 #3	#1 #2	#2 #3
6	0.5	0.5	5,712,067	1,446,365	#1	#1 #2	#1 #2	#2 #3
7	0.6	0.4	5,709,540	1,449,313	#1	#1 #2	#1 #2	#2 #3
8	0.7	0.3	5,709,540	1,449,313	#1	#1 #2	#1 #2	#2 #3
9	0.8	0.2	5,709,540	1,449,313	#1	#1 #2	#1 #2	#2 #3
10	0.9	0.1	5,709,540	1,449,313	#1	#1 #2	#1 #2	#2 #3
11	1	0	5,709,540	1,449,313	#1	#1 #2	#1 #2	#2 #3

Table 7. Details of sensitivity analysis for probability parameters.

	(0.5,0.3,0.2) Current	(0.75,0.2,0.05) Case 1	(0.33,0.33,0.33) Case 2
Expect environmental impact	1,446,365	1,333,934	1,468,754
Total cost	5,712,067	5,282,314	6,015,844
Fixed cost	125,100	107,600	151,600
Expected operational cost	4,226,965	3,869,610	4,382,098
Expected transport cost	1,748,035	1,665,907	1,886,517
Expected revenue	388,033	360,803	404,371
TDWCSSs	#2	#2	None
TDWPRSs	#1 #2	#1 #2	#1 #2 #3
Landfills	#1 #2	#1 #2	#1 #2
Incineration sites	#2 #3	#2	#2 #3

灾后垃圾管理的多目标两阶段随机优化模型

關鍵詞
灾后
废物管理
多目标
两阶段随机模型

摘要
灾后废物管理是灾难周期恢复阶段中最重要的任务之一，它是为了协助受灾社区在灾难发生后恢复稳定状态而创建的。为了开发一种高效的灾后废物管理策略，本研究提出了一种用于灾后废物管理的多目标两阶段随机混合整数线性规划模型。该提出的数学模型是基于现场和离场废物分离的混合策略在供应链中开发的。本研究旨在不仅最小化总成本和环境影响，还提供废物流量决策和在不确定情况下在整个供应链中选择收集和分离站，回收站，垃圾填埋站和焚烧站。为了解决多目标问题，使用归一化加权和方法来找到解决方案。提供了一种基于现实数据的数值案例来验证和验证所提出的模型。根据数值示例，结果表明，在考虑不确定情况的情况下实施废物分离的混合策略可以降低总成本，平衡环境影响，并高效地确定灾后废物供应链中的意外情况。