



Location and allocation optimization for integrated decisions on post-disaster waste supply chain management: On-site and off-site separation for recyclable materials



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ABSTRACT

Post-disaster waste management is one of the most important operational management systems that have been developed to help affected communities recover and restore conditions back to a stable situation after a disaster. An effective post-disaster waste management strategy still needs to be further developed for optimum efficiency. Hence, this paper aims to present the developed system of post-disaster waste supply chain management strategy (PWSCM) along with the integrated decision-making system for the on-site and off-site separation of recyclable materials. A mathematical model of mixed-integer linear programming is proposed in which the objective aims are to minimize the financial effects through assessment of the fixed costs and variable costs, RSR (Reduction, Separation and Recycling) costs, and the penalty costs associated with the negative environmental and human effects of post-disaster scenarios and to maximize revenue from any sellable waste. The proposed model considers all networks in the debris operation process that consists of waste collection and separation sites, processing and recycling sites, disposal sites and market sites. Moreover, the RSR technologies have also been considered in the proposed model. Due to the limitations of competence of an exact solution method for such a large problem, this study also presents two effective metaheuristic approaches with particular encoding and decoding schemes; Particle Swarm Optimization (PSO) and Differential Evolution (DE) to solve PWSCM. Finally, the numerical tests for PWSCM improvement will be discussed. The performance of the proposed PWSCM improvement system was superior to both the on-site separation model and the off-site separation model.

1. Introduction

Disaster is any occurrence that causes damage, destruction, ecological disruption, loss of human life, human suffering, or the deterioration of health and health services on a scale sufficient to warrant an extraordinary response from outside the affected community or area [1]. Since the 1950s, the magnitude and number of disasters have exponentially increased, with the number of affected people having increased in proportion (about 235 million people per annum on average since the 1990s) [2]. In 2015, 376 naturally triggered disasters were recorded, with the economic damages estimated to be US\$ 70.3 billion, resulting in the deaths of 22,765 people and seriously impacting 110.3 million victims [3]. Due to an increasing number of disasters, many researchers have paid a great deal of attention to the concept of “Disaster Management (DM)” with the objective of helping at-risk persons to avoid and recover from the effects of a disaster [4]. The activity of DM consists of four major stages: mitigation, preparation, response, and

recovery. One of the most important stages is the recovery stage. This stage was defined as the act of restoring the affected community or area back to a normal situation after a disaster [5]. Two of the initial and most significant perspectives of disaster recovery management involve the removal and disposal of debris from the affected communities or areas [6]. This activity is a significant one, but often an overlooked aspect that is associated with post-disaster debris management [7].

Post-disaster debris or waste management is a discipline associated with the control of the concepts of the generation of debris, storage collection, transport and transfer, processing, recycling, reuse, and disposal. The post-disaster debris or waste management is considered a lengthy, economic, public health engineering, conservation of nature, aesthetics, and environmental challenge with a need to consider the attitude of the public. Currently, the U.S. Federal Emergency Management Agency (FEMA) has focused exclusively on reimbursing the costs of post-disaster debris operations along with the transportation costs, disposal costs, and collection costs [8]. Therefore, FEMA has

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changed its policies and announced a program offering financial incentives for municipalities in order to encourage the reuse and recycling of disaster debris [6]. This is considered an opportunity to reduce the costs associated with post-disaster supply chain management and the negative effects on environment. According to the policies and timeline employed by FEMA, before the disaster occurs, each community is required to provide potential waste management facilities such as waste collection sites, processing sites, recycling plants, disposal sites and market sites [9]. Generally, the recovery stage involves debris collection, where the disaster debris is transferred from the road and curb sides to temporary processing facilities, where it may go through containment processes such as separation, sorting, grinding incineration, concrete crushing and wood chipping. After that, all or parts of the disaster debris may be transferred to the landfill or incinerator for disposal, whereas parts of it may be processed further to be recycled and either reused or sold. However, many countries have also established different strategies that are more appropriate for their own circumstances. To comprehend the structure of a post-disaster waste management system, see [Appendix A.1](#) in the [Supplementary data](#) section.

Currently, post-disaster waste management is being developed in many countries. Concepts of economic development, social development, and environmental protection are the main dimensions of sustainability with regard to waste management. Protecting both the environment and productive resources are among the most significant factors of sustainability [10]. Post-disaster waste presents a significant threat to both the environment and society. Hence, post-disaster waste management is becoming an issue of great interest on a global scale. To achieve a level of sustainable management, the main goal of an effective post-disaster waste management system is not only to minimize system costs within the network, but also to minimize any negative effects on the environment, humans and society that are present in proximity to the network [11]. Many of the negative effects on the environment, humans and society are a factor of certain activities associated with post-disaster waste management systems, such as transportation, separation, recycling, treatment, and disposal. Each activity can produce air pollutants such as CO₂, SO_x, NO_x, and PM (particulate matter) that can cause damage to the environment and are a threat to the health of the disaster victims and workers in the affected area [12]. Moreover, recyclable waste can become contaminated with matter that is harmful and risky to humans and the environment [13]. Establishing facilities that can effectively process post-disaster waste can have an impact on the environment and the people that are in the immediate area of the proposed waste management facilities.

Several processes of post-disaster waste management systems have been used to develop and enhance the network in order to respond to the purposes of sustainable waste management. Waste separation is an important component of the main structure of a waste management system since it can affect the economy and the environment of the area. This is all pertinent to the feasibility of recycling for the purposes of sustainable waste management [13], see [Appendix A.1](#) with regard to separation approach presented in the [Supplementary data](#) section. To reach these goals, waste separation is used to enhance the management of the post-disaster waste supply chain. In this study, the optimization technique has been utilized. Optimization is becoming a powerful approach that is used to solve problems in waste management. Various published research studies have proposed that this technique be applied to waste management such as those of [10,14,15], etc.

In order to enhance and fulfill the research gaps that exist within sustainable post-disaster waste management, we aim to propose a developed post-disaster waste supply chain management strategy by using the location and allocation optimization tools under the integrated decision-making system for the on-site and off-site separation of recyclable materials. There are two goals of this paper. Our first goal is to develop the post-disaster debris supply chain management strategy under an integrated decision-making system for on-site and off-site

separation in handling recyclable materials using the optimization technique. The network structure considers waste collection and separation sites, processing sites, disposal sites and market sites. Our proposed mathematical model aims to select the suitable sites for post-disaster waste management system, including the collection and separation sites, processing sites and landfills, in order to provide a debris flow decision-making system as a supply chain while minimizing the total costs incurred in that the supply chain. The total costs consist of fixed and variable costs associated with the debris collection process, RSR, the disposal process, environmental penalty costs and takes into account revenue incurred from any sellable waste. Our second goal is to propose solution algorithms for the larger problem and this paper aims to propose solutions that are representative of two metaheuristics (Particle Swarm Optimization: PSO and Differential Evolution: DE) to address the problem.

The remainder of this paper is organized as follows: [Section 2](#) presents an overview of the existing literature. [Section 3](#) presents the conceptual model of the post-disaster waste supply chain management (PWSCM) strategy and formulates a mathematical model for the proposed system. [Section 4](#) presents the solution algorithms of PSO and DE intended to address the problem. [Section 5](#) proposed computational experiments for the PWSCM model. Finally, a conclusion is given in [Section 6](#).

2. Literature review

This section presents the overview of the relevant literature. Post-disaster debris management is a consideration of humanitarian logistics; for which comprehensive reviews have been proposed by [2] and [16–19]. The literature review on post-disaster debris management primarily focuses on the qualitative analysis and the documentation of past experiences [7]. Lin [20] proposed an analysis on policies, political process priorities, problems and aspects of the waste removal process after Katrina, while Brandon et al. [21] proposed an analysis of a case history of the waste recycling efforts of the US Army Corps of Engineers in Mississippi. Additionally, Karunasena et al. [22] proposed an analysis of post-disaster debris management in developing countries based on a case study in Sri Lanka, and Brown and Milke [13] studied recycling disaster waste management based on the past experiences of five international disaster events in developed countries. Moreover, this study also proposed an analysis of the benefits in a comparison of on-site and off-site separation. Ultimately, Brown and Milke [13] recommended that it is possible to have an integrated model where selected materials are separated on-site while the rest would go to an off-site separation facility. Not only have these academic papers described potential management techniques, but some organizations have also proposed guidelines for the post-disaster debris operations such as FEMA (2007) [8], USEPA [23], UNEP [24] and EPA [25]. Notably, an intensive summary article has been published and presented by [26–29].

According to the facility location and allocation problems that exist and the fact that the flow debris decision-making process has been based on post-disaster debris supply chain management, an optimization technique has been proposed that can potentially overcome this challenge. The optimization technique has been applied to address the relevant humanitarian logistics problems and to attempt to achieve positive results [30]. [Table 1](#) presents the important characteristics of the existing studies in this area comprising the objective function, mathematical model, exact approach, algorithm solution, structure of network, and type of separation. Fetter and Rakes [6] proposed a mixed-integer linear programming model for decision-making with regard to the location of the processing sites, aspects of processing availability, and the flow of disaster waste from each affected community to the relevant site and processing networks. This study aims to minimize the total costs of the debris management operations with consideration of the fixed and variable costs of debris collection, RSR costs (Reduction, Separation and Recycling Operations) and disposal

Table 1
Review study of the optimization model for post-disaster debris management.

Author	Objective	Math model	Multiple/Single Objective	Exact approach	Algorithm	FLP				On/Off site separation
						J	K	L	M	
Fetter and Rakes [6]	Total cost (The fixed and variable costs of debris collection, RSR, and disposal and revenue)	MILP	Single	Excel	-	-	-	-	*	Off-site separation
Habib and Sarkar [37]	Total transport cost	LP	Single	LINGO	-	-	-	-	None	On-site separation
Hu and Sheu [31]	Total reverse logistical costs, psychological cost, risk penalty	LP	Multiple	CPLEX	-	-	-	-	None	On-site separation
Kim et al. [33]	Total hauling distance	MILP	Single	-	Shortest path algorithm/ GIS	-	-	-	*	On-site separation
Lorca et al. [7]	Total cost (Financial cost, Environmental cost, revenue), total time (Collection time and disposal time) and land usage.	MILP	Multiple	GLPK	-	-	-	-	*	Mixed model separation
Onan et al. [35]	Total cost and risk	MILP	Multiple	-	NSGA-II	-	-	-	*	Off-site separation
Pramudita et al. [32]	Total cost (The travel cost and the cost of establishing intermediate depots)	MILP	Single	-	Tabu search	-	-	-	*	None
Takeda et al. [34]	Shortest distance	LP	Single	-	Warshall-Floyd	-	-	-	None	On-site separation
Wakabayashi et al. [36]	Total distance, total transport cost, and treatment and environmental cost	LP	Single and Multiple	Exact method	-	-	-	-	None	Off-site separation
This work	Total cost (The fixed and variable costs of debris collection, RSR, disposal, environmental penalty cost, and revenue)	MILP	Single	LINGO	PSO and DE (Large problem)	-	-	-	* * *	Mixed model separation

Note: J = storage and separation site, K = processing and recycling site, L = landfill, M = market, LP = linear programming, MILP = mixed integer linear programming, FLP = facility location problem.

costs while including the potential revenue of saleable debris. The method of separation being employed uses the off-site separation model. A case study in Chesapeake has been proposed for validating this model. Hu and Sheu [31] proposed the linear programming model in which this study focuses on the transportation, recycling, storage of disaster waste throughout the disaster recovery stage. The objective function aims to minimize the reverse logistical costs, psychological cost and risk penalty. Hu and Sheu [31] have recommended that the storage and separation techniques should be employed at the on-site stage of management. The system employed in Wenchuan City in China has been proposed in this study. Pramudita et al. [32] presented a location-capacitated arc routing problem that emphasizes the debris collection sites. The goal of this model is to minimize the travel costs and the costs of establishing intermediate depots in which tabu search meta-heuristics have been proposed to find an acceptable solution. Kim et al [33] proposed selecting a temporary debris management site for the effective debris operation system by using both geographical analysis and optimization analysis. The objective of this was to minimize the total hauling distance for the transportation services in which the shortest path algorithm was applied in response to this problem. Takeda et al. [34] proposed a transportation management system for post-disaster debris that would reduce the effects of earthquakes. This system considers a waste allocation operation and a route selection operation in which the structure of the system consists of arterial roads, temporary storage sites, and disposal sites. The Warshall-Floyd algorithm and linear programming method have been applied in this study. Onan et al. [35] proposed the employment of a framework to determine the location of a temporary disaster management facility with the objective of cost minimization and risk minimization from hazardous waste exposure. They determined the criteria for the planning of the collection and transportation of disaster debris. This paper proposed NSGA-II to find the solution. Wakabayashi et al. [36] presented a strategy of economic and environmental evaluation of a disaster debris management system that considers the spatial distribution of temporary storage sites and treatment facilities. This study applied linear programming to find solutions and has been tested with a real case study in Mie Prefecture, Japan. This strategy is provided as an example of an off-site separation system. Lorca et al. [7] proposed a decision-support tool for a post-disaster waste management system. The mathematical model being proposed optimizes the selection of the processing site, processing capacities, and debris flow decision-making that are related to the collection, transport and disposal systems. Moreover, this study has also considered balancing the costs and duration of the relevant disaster waste operation systems. Moreover, Habib and Sarkar [37] presented a two-phase framework for sustainable waste management in the response phase of disasters in which the Analytical Network Process (ANP), fuzzy TOPSIS and Optimization technique have been proposed to identify the suitable temporary disaster debris management site. In another related paper, but one that did not employ the optimization approach, Kawamoto and Kim [38], Tabata et al. [12], Gabrielli et al. [39], and Cheng and Thompson [40] proposed a system of post-disaster waste management.

Following on from the previous research studies, an effective post-disaster debris management strategy still needs to be further developed for optimum efficiency. Several studies have considered addressing a number of problems associated with developing the effective post-disaster debris operations such as those by [13,31]. The integrated decision-making process for the on-site and off-site separation of recyclable materials is an issue that has been recommended by many research papers in order to develop an effective post-disaster waste supply chain management system. According to the previous research studies, the merits of the on-site and off-site separation systems for recyclable materials in an overall post-disaster waste supply chain management system are not well known [13]. Integrating the on-site and off-site separation systems for recyclable materials can balance the advantages of both approaches efficiently while maintaining regard for the

economic view, environmental perspective, time constraints, resource availability, degree of mixing of the waste and human and public health hazards [13]. To this point, see the advantages of both approaches in Appendix A.1 (Table A1). The post-disaster debris supply chain management system now being employed that uses the optimization technique is lacking in consideration of an integrated decision-making process for the on-site and off-site separation of recyclable materials and the consideration of all networks simultaneously (debris collection sites, processing sites, disposal sites and market sites). Furthermore, an algorithm that would be employed to solve the larger problems in this study is lacking due to certain competence limitations of the exact solution method. Recently, Particle Swarm Optimization (PSO) and Differential Evolution (DE) have been successfully applied in several areas owing to their effectiveness and simplicity. However, to the best of our knowledge, no PSO and DE have been developed to solve the post-disaster waste management problem. Because of these research gaps, we aim to develop the post-disaster waste supply chain management strategy by presenting an integrated decision-making system for the on-site and off-site separation of recyclable materials, as well as a solution algorithm that would solve any larger related problems via the PSO and DE.

3. Post-disaster waste supply chain management (PWSCM) model

3.1. Conceptual model

The framework of the PWSCM model is designed with respect to a hierarchical model as is shown in Fig. 1. This conceptual model is developed and modified from [6,7]. The structure of this study considers all networks in the supply chain consisting of the affected zones, temporary disaster waste collection and separating centers (TDWCSC), temporary disaster waste processing and recycling centers (TDWPRC), landfills, and markets. According to [13], it has been proposed that the on-site and off-site separation should be simultaneously applied since both approaches have different advantages. When both approaches are merged, the post-disaster waste management process will be able to balance the advantages and disadvantages of both approaches. This integrated strategy was employed and succeeded in the 2011 Great East Japan Earthquake and the Canterbury earthquakes (see more details of assessment in [13]). Thus, this criterion is taken to apply in the PWSCM model. In our conceptual model, the process is separated into three stages that consist of: (1) collection and on-site or off-site separation, (2) off-site processing and recycling, (3) waste disposal and waste selling. Fig. 1 reveals that in Stage 1, debris removal is initiated after the emergency access routes are cleared. The waste is assigned from the

affected zones to TDWCSCs or TDWPRCs for collection and separation by manual or preliminary technologies. In this stage, the mixed model of on-site and off-site separation is applied. The waste in some affected communities is separated on-site by a TDWCSC, while the rest is transferred to an off-site separation facility identified as TDWPRC. In Stage 2, the separated waste at the TDWCSCs is divided into three parts. The first part is transferred to TDWPRCs for processing and recycling; the second part is transferred to landfills for waste disposal; the third part is transferred to markets for selling (reuse). After the waste is processed and recycled using a variety of technologies at the TDWPRCs, the final operation will be started. In stage 3, the waste at the TDWPRCs is classified into two separate stages for the disposal of the remaining waste and the selling of the sellable or reusable waste. The remaining waste at the TDWPRCs is allocated to the landfill for disposal, while the rest is transferred to the market for selling, respectively.

3.2. Proposed mathematical model

According to the conceptual model, we have modified the general facility location model and distribution model to formulate a model for the PWSCM strategy. The proposed mathematical model is formulated as a mixed-integer linear programming problem (MILP), and its basic assumptions are listed as follows:

- The structure of PWSCM strategic consists of affected zones, TDWCSCs, TDWPRCs, landfills, and markets.
- To protect bafflement of assignment, this study provides the assumptions for debris flow decisions as follows; each affected zone can be served by one node from TDWCSC or TDWPRC, each TDWCSC can be served by one landfill and one market, the waste from each TDWCSC that need to be treated with each RSR technology can be served by one TDWPRC and each TDWPRC can be served by one market.
- The capacity of the market is assumed to be infinite.
- All saleable waste types can be sold at all markets.
- All waste needs to be separated before it is assigned for recycling, disposal, and sale.
- All used parameters are known, constant and deterministic.

Based on the relevant functions of sustainable post-disaster waste management that are described in Section 1, this proposed mathematical model aims to consider an economic perspective and an environmental perspective, simultaneously. From an economic perspective, this mathematical model aims to minimize the total costs that are associated with establishing the specific cost of each facility, the operational cost

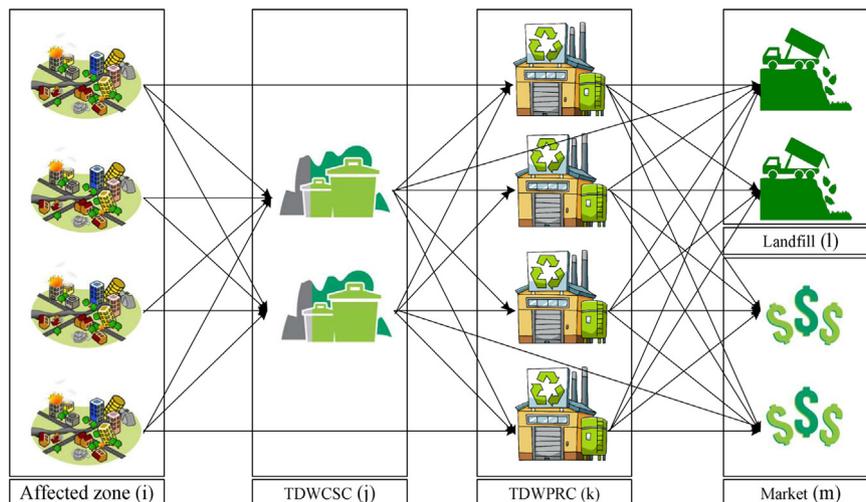


Fig. 1. The conceptual model of post-disaster waste supply chain management strategy.

of each process and the transportation cost of each stage, as well as to maximize the potential revenues obtained from the saleable waste. From an environmental perspective, this mathematical model aims to minimize the negative effects on the environment and humans. This value is determined as a penalty cost. The output of this model aims to select TDWCSCs, TDWPRCs, and landfills, minimize financial costs, minimize the effects on humans and the environment, maximize revenue and provide debris flow decisions throughout the supply chain.

The following notions and parameters are used:

I :	Number of affected zones ($i = 1, 2, \dots, I$)
J :	Number of possible TDWCSC facility locations ($j = 1, 2, \dots, J$)
K :	Number of possible TDWPRC facility locations ($k = 1, 2, \dots, K$)
L :	Number of possible landfill facility locations ($l = 1, 2, \dots, L$)
M :	Number of markets ($m = 1, 2, \dots, M$)
N :	Number of RSR technologies ($n = 1, 2, \dots, N$)
H_i :	Volume of debris in affected zone i
γ_n :	Proportion of debris from affected zone that is eligible to be treated with RSR technology n
η_n :	Proportion of reduced debris from RSR technology n saleable as recycled material
ρ_n :	Proportion of reduced debris from RSR technology n for disposal
U^{TDWCSC} :	Maximum number of selected TDWCSC
U^{TDWSRC} :	Maximum number of selected TDWPRC
$U^{Landfill}$:	Maximum number of selected landfill
P_T :	Fraction of penalty cost from transporting debris
P_O :	Fraction of penalty cost from operating debris
F_j^{TDWCSC} :	Fixed cost of opening and closing TDWCSC at location j
F_k^{TDWSRC} :	Fixed cost of opening and closing TDWPRC at location k
$F_l^{Landfill}$:	Fixed cost of opening and closing landfill at location l
V_j^{TDWCSC} :	Fixed cost of making separated technology at TDWCSC location j (On-site)
V_{kn}^{TDWSRC} :	Fixed cost of making RSR technology n at TDWPRC location k (Off-site)
O_j^{TDWCSC} :	Operating cost at TDWCSC location j
O_{kn}^{TDWSRC} :	Operating cost RSR technology n at TDWPRC location k
$O_l^{Landfill}$:	Operating cost at landfill l
C_j^{TDWCSC} :	Capacity of TDWCSC at location j
$C_l^{Landfill}$:	Capacity of landfill at location l
C_{kn}^{RSR} :	Capacity of RSR technology n at TDWPRC location k
δ_m :	Revenue from saleable portion of debris at market m
Ca_{ij} :	Cost of transporting debris from affected zone i to TDWCSC j
Cb_{ik} :	Cost of transporting debris from affected zone i to TDWPRC k
Cc_{jk} :	Cost of transporting debris from TDWCSC j to TDWPRC k
Cd_{jl} :	Cost of transporting debris from TDWCSC j to landfill l
Ce_{jm} :	Cost of transporting debris from TDWCSC j to market m
Cf_{kl} :	Cost of transporting debris from TDWPRC k to landfill l
Cg_{km} :	Cost of transporting debris from TDWPRC k to market m

The following decision variables are used:

x_j :	Binary variable that takes the value 1 if TDWCSC is opened at location j and 0 if not
y_k :	Binary variable that takes the value 1 if TDWPRC is opened at location k and 0 if not

z_l :	Binary variable that takes the value 1 if landfill is opened at location z and 0 if not
w_{kn} :	Binary variable that takes the value 1 if RSR technology n is available at TDWPRC k and 0 if not
a_{ij} :	Volume of debris from affected zone i to TDWCSC j
b_{ik} :	Volume of debris from affected zone i to TDWPRC k
c_{jkn} :	Volume of debris from TDWCSC j to TDWPRC k for recycling by RSR technology n
d_{jl} :	Volume of debris from TDWCSC j to landfill l
e_{jm} :	Volume of debris from TDWCSC j to market m
f_{kl} :	Volume of debris from TDWPRC k to landfill l
g_{km} :	Volume of debris from TDWPRC k to market m
ξ_{aj} :	Binary variable that takes the value 1 if the volume of debris from affected zone i is assigned to TDWCSC j and 0 if not
$\xi_{b_{ik}}$:	Binary variable that takes the value 1 if the volume of debris from affected zone i is assigned to TDWPRC k and 0 if not
$\xi_{c_{jkn}}$:	Binary variable that takes the value 1 if the volume of debris from TDWCSC j is assigned to TDWPRC k for recycling by RSR technology n and 0 if not
$\xi_{d_{jl}}$:	Binary variable that takes the value 1 if the volume of debris from TDWCSC j is assigned to landfill l and 0 if not
$\xi_{e_{jm}}$:	Binary variable that takes the value 1 if the volume of debris from TDWCSC j is assigned to market m and 0 if not
$\xi_{g_{km}}$:	Binary variable that takes the value 1 if the volume of debris from TDWPRC k is assigned to market m and 0 if not

The following auxiliary variables are used:

FC :	Total fixed cost
TC :	Total transport cost
OC :	Total operation cost
PC :	Total penalty cost for activities with environmental impact
R :	Total revenue

The mathematical model of the problem is formulated as follows:
Minimization of Total Cost:

$$\text{Min } Z = FC + TC + OC + PC - R \tag{1}$$

Subjected to constraints;

$$FC = \sum_j F_j^{TDWCSC} x_j + \sum_k F_k^{TDWSRC} y_k + \sum_l F_l^{Landfill} z_l + \sum_j V_j^{TDWCSC} x_j + \sum_k \sum_n V_{kn}^{TDWSRC} w_{kn} \tag{2}$$

$$TC = \sum_i \sum_j Ca_{ij} a_{ij} + \sum_i \sum_k Cb_{ik} b_{ik} + \sum_j \sum_k Cc_{jk} c_{jk} + \sum_j \sum_l Cd_{jl} d_{jl} + \sum_j \sum_m Ce_{jm} e_{jm} + \sum_k \sum_l Cf_{kl} f_{kl} + \sum_k \sum_m Cg_{km} g_{km} \tag{3}$$

$$OC = \sum_j \sum_i O_j^{TDWCSC} a_{ij} + \sum_i \sum_j \sum_k \sum_n O_{kn}^{TDWSRC} (b_{ik} \gamma_n + c_{jkn}) + \sum_j \sum_k \sum_l O_l^{Landfill} (d_{jl} + f_{kl}) \tag{4}$$

$$PC = P_T TC + P_O OC \tag{5}$$

$$R = \sum_j \sum_k \sum_m \delta_m (e_{jm} + g_{km}) \tag{6}$$

$$\sum_j x_j \leq U^{TDWCSC} \tag{7}$$

$$\sum_k y_k \leq U^{TDWSRC} \tag{8}$$

$$\sum_l z_l \leq U^{Landfill} \tag{9}$$

$$\sum_i a_{ij} \leq C_j^{TDWCSC} x_j \quad \forall j \tag{10}$$

$$\sum_i b_{ik} \gamma_n + \sum_j c_{jkn} \leq C_{kn}^{RSR} w_{kn} \quad \forall k, n \tag{11}$$

$$w_{kn} \leq y_k \quad \forall k, n \tag{12}$$

$$\sum_j d_{jl} + \sum_k f_{kl} \leq C_l^{Landfill} \quad \forall l \tag{13}$$

$$\sum_j a_{ij} + \sum_k b_{ik} = H_i \quad \forall i \tag{14}$$

$$\sum_i a_{ij} \gamma_n = \sum_k c_{jkn} \quad \forall j, n \left(n = 2, \dots, N \right) \tag{15}$$

$$\sum_i a_{ij} \eta_1 \left(1 - \sum_{n=2}^N \gamma_n \right) = \sum_l d_{jl} \quad \forall j \tag{16}$$

$$\sum_i a_{ij} \rho_1 \left(1 - \sum_{n=2}^N \gamma_n \right) = \sum_m e_{jm} \quad \forall j \tag{17}$$

$$\sum_i b_{ik} \eta_1 \left(1 - \sum_{n=2}^N \gamma_n \right) + \sum_i \sum_{n=2}^N b_{ik} \gamma_n \eta_n + \sum_j \sum_n c_{jkn} \eta_n = \sum_l f_{kl} \quad \forall k \tag{18}$$

$$\sum_i b_{ik} \rho_1 \left(1 - \sum_{n=2}^N \gamma_n \right) + \sum_i \sum_{n=2}^N b_{ik} \gamma_n \rho_n + \sum_j \sum_n c_{jkn} \rho_n = \sum_m g_{km} \quad \forall k \tag{19}$$

$$\sum_j \xi a_{ij} + \sum_k \xi b_{ik} \leq 1 \quad \forall i \tag{20}$$

$$\sum_k \xi c_{jkn} \leq 1 \quad \forall j, n \tag{21}$$

$$\sum_l \xi d_{jl} \leq 1 \quad \forall j \tag{22}$$

$$\sum_m \xi e_{jm} \leq 1 \quad \forall j \tag{23}$$

$$\sum_m \xi g_{km} \leq 1 \quad \forall k \tag{24}$$

$$a_{ij} \leq LN \xi a_{ij} \quad \forall i, j \tag{25}$$

$$b_{ik} \leq LN \xi b_{ik} \quad \forall i, k \tag{26}$$

$$c_{jkn} \leq LN \xi c_{jkn} \quad \forall j, k, n \tag{27}$$

$$d_{jl} \leq LN \xi d_{jl} \quad \forall j, l \tag{28}$$

$$e_{jm} \leq LN \xi e_{jm} \quad \forall j, m \tag{29}$$

$$g_{km} \leq LN \xi g_{km} \quad \forall k, m \tag{30}$$

$$x_j, y_k, z_l, w_{kn}, \xi a_{ij}, \xi b_{ik}, \xi c_{jkn}, \xi d_{jl}, \xi e_{jm}, \xi f_{kl}, \xi g_{km} \in \{0, 1\} \quad \forall j, k, l, m, n \tag{31}$$

$$a_{ij}, b_{ik}, c_{jkn}, d_{jl}, e_{jm}, f_{kl}, g_{km} \geq 0 \quad \forall i, j, k, l, m, n \tag{32}$$

The objective of the proposed model is to minimize the total costs associated with the management of the debris removal supply chain in post-disaster scenarios as is shown in Eq. (1). The objective function aims to balance the fixed costs, transport costs, operational costs, penalty costs and potential revenue as is shown in Eq. (2) – Eq. (6), respectively. Eq. (2) represents the fixed costs of the location opening of TDWCSCs, TDWPRCs, and landfills and the investing RSR technology at

each TDWPRC. Eq. (3) represents the transport cost through the supply chain network. Eq. (4) represents the operational cost of TDWCSCs, TDWPRCs, and the landfills. Eq. (5) presents the penalty costs for activities having environmental impacts that are related to the transport and operational processes. In this study; this cost is calculated by considering the total costs of transport and operations in which the fraction of the penalty cost (P_T and P_o) is provided by the decision maker's expectations. The decision maker can foresee this fraction from the negative effects on the environment and humans such as through certain types of contamination, air pollutants (CO_2 , SO_x , NO_x , and PM), etc. that may occur during the transport process along with the operational process within the network. This cost is incurred in treating the environment, humans and the greater society. Eq. (6) represents the potential revenue incurred from saleable waste obtained from the TDWCSCs and TDWPRCs. This is an opportunity to reduce the system costs within the post-disaster waste supply chain. In the case of indirect action, this can reduce the negative effects on the environment, humans and society in which the reusable wastes are sold instead of being disposed of. Eq. (7) – Eq. (9) state that the total number of selected locations cannot exceed the maximum limit of each location type, Eq. (7) enforces the limit of selected TDWCSCs, Eq. (8) enforces the limit of selected TDWPRCs and Eq. (9) enforces the limit of selected landfills. Eq. (10) – Eq. (13) limits the volume of debris assigned to each location type. Eq. (10) ensures that the volume of debris assigned to TDWCSC cannot exceed the maximum capacity of each TDWCSC. Eq. (11) limits the volume of debris assigned to TDWPRC according to the RSR technology capacity available at the TDWPRC. Eq. (12) requires that a TDWPRC must be opened in order to make RSR technologies available. Eq. (13) ensures that the volume of debris assigned to the landfill cannot exceed the maximum capacity of each landfill. Eq. (14) guarantees that the volume of debris in each affected zone is collected and processed. Eq. (15) – Eq. (17) state that all collected debris in each selected TDWCSC is transported to processing sites (TDWPRC), landfills and markets. Eq. (18) and Eq. (19) state that the debris in each selected TDWPRC is transported to landfills and markets. To protect against bafflement of the assignment, this study provides conditions according to the above assumptions, the conditions are represented as Eq. (20) – Eq. (24). Eq. (20) provides that each affected zone can be served by one node from TDWCSC or TDWPRC. Eq. (21) provides that the waste from each TDWCSC that needs to be treated with each RSR technology can be served by one TDWPRC. Eq. (22) – Eq. (23) provide that each TDWCSC can be served by one landfill and one market. Eq. (24) provides that each TDWPRC can be served by one market. Eq. (25) – Eq. (30) state that the binary variable of the assignment is set to 1 when the volume of debris in each node is assigned to each node. Lastly, Eq. (31) – Eq. (32) describe non-negativity and the binary conditions of the decision variables.

The solution of the proposed mathematical model is reached with consideration of the number of TDWCSCs, TDWPRCs, and landfills, the allocation of each node, the total planning budget, the penalty of environmental and human effects and the revenue from any sellable waste that can be calculated. An integrated model of on-site and off-site separation for recyclable materials can balance the benefits of both approaches in several ways [13]. This result can serve emergency management purposes. The first is to help in the preparation stage and includes the spatial distribution of waste collection and separation sites, processing and recycling sites, and disposal sites, assignment of waste in each affected community, and the expectations of the planning budget. The second way is to aid in the recovery stage in order to provide debris flow and directions at each step of the post-disaster waste supply chain management process and reduce the effects on humans and the environment in the post-disaster supply chain network as well.

3.3. Fundamental information

As is presented in Section 3.2, the prosperous implementation of the

proposed model is dependent upon the availability and accuracy of the number of data categories [7]. The requires information of the proposed model that is made up of (i) the potential debris volumes, (ii) the potential facility location in each type, (iii) the capacity in each potential facility location, (iv) the maximum selected location in each type, (v) the debris composition (reduction percentage) and (vi) the fixed and variable penalty costs associated with transportation, RSR processing and disposal. All input data can be determined, estimated and calibrated by the decision makers or experts (local government or emergency management agencies) before the disaster hits. Currently, there are several guidelines and tools that can support the determination of the input data in debris management operations. For instance, FEMA [8] has proposed the guidelines of how costs can be calculated, how the potential debris amounts can be determined and so on. The steps involved with generating fundamental information in this study have been followed according to the guidelines of FEMA [8].

In the first step, each community is required to generate potential disaster scenarios and the potential debris amounts that depend on the severity of those disasters, the disaster types and the demographic and geographic properties of the affected area. In order to guide the estimation process, FEMA [41] provides a set of guidelines for the debris estimation, along with easy-to-apply methods to estimate the debris amounts. Similarly, the U.S. Army Corps of Engineering (USACE) have proposed a guide for estimating the debris amounts during hurricanes [42]. Moreover, Scawthorn et al. [43] have proposed the debris estimation tool that is known as HAZUS-MH. As is presented in the tools, the decision makers can apply those tools for debris estimation. In the second step, the potential facility location of each type is considered. The decision makers should provide the potential facility location along with consideration of the environment, risks, geographic properties, demographic properties and so on [8]. The potential facility location of each type should be located in an area that does not disrupt local business operations or cause dangerous conditions for residents, schools, hospitals and sensitive areas. The decision makers should consider public lands first in order to avoid costly land leases. The TDWCSCs, TDWPRCs, landfill sites and markets that are in close proximity to the affected area are all considered ideal locations. Areas near TDWPRCs and landfill sites need to be evaluated for TDWCSCs. Furthermore, the vacant lots, parks and sports fields that will not incur extensive repair costs should be considered for TDWCSCs as well. According to the consideration of the potential facility location of each type, the decision maker should provide an estimate of the suitable capacity associated with the potential debris amounts that will need to be stored and processed. Finally, the maximum selected location of each type, the debris composition (reduction percentage) and the fixed and variable penalty costs of transportation, RSR processing and disposal can be estimated and determined by the decision makers. In particular, RSR parameters are common knowledge to the experts in the recycling field (many of these may already be in use in the local area for everyday solid waste management) [6]. For the expectation of obtaining that data, the decision makers can use several tools to calculate those figures. Moreover, the historical data can be applied to estimate that data as well. A matrix specifying the cost of transporting debris between each location type can be created using the Euclidian metric method in which the transportation distance is used to calculate the cost of transporting debris based on negotiations with trucking contractors [6]. The scale of each facility location type in this model is proposed for medium- and long-term planning (or annually) in which it is dependent upon the scale of the disaster and the relevant debris volumes. To prepare the suitable input data, the decision makers of each city or region should use suitable tools. After all data are generated, the input data for the proposed model can be presented in Appendix A.4. The system boundary of the proposed model is based on the assumptions that are proposed in Section 3.2. The proposed model can be applied to a strategy that needs to balance between on-site and off-site separation procedures for recyclable materials. Also, the time

condition has not been considered in this model.

To reach a possible solution under a variety of scenarios including an emergency situation or an irregular situation, the proposed model should be used with several varying conditions in order to obtain results that are unique to each situation, such as over-abundance of debris volume, high cost of installing RSR technology, capacity shortage, installing the temporary incinerators, installing additional temporary storage sites, unusable facility location (after disaster hit) and so on. After a disaster occurs, some emergency situations might also occur. Consequently, the post-disaster waste supply chain management (PWSCM) model requires a new model solution based on those emergency situations.

According to the problems associated with the NP-hard system, the solution cannot be found by mathematical programming solution software when a larger problem is presented. In the actual practice, the decision made on the operation for facility location and allocation in the PWSCM problem involves an evaluation of a variety of scenarios including a range of possible data employed to reach an acceptable solution [44,45]. In the model, the computation time involves a lengthy amount of time to reach a solution and this is not desirable in practice. Therefore, we aim to propose a solution algorithm by using a meta-heuristic approach in this study that is represented in next section.

4. Solution algorithm

As mentioned in the introduction, this paper was motivated by the limitations of applying PSO and DE in solving post-disaster waste management problems. Hence, this research study has focused on applying two effective metaheuristics – Particle Swarm Optimization (PSO) and Differential Evolution (DE) – to plan the post-disaster waste management process. The search procedures employed for each algorithm are described in Appendix A.2 in the Supplementary data section. Details of the encoding and decoding schemes, allocation solutions and local searches for PWSCM problems are presented in the following sections.

4.1. Encoding and decoding scheme

4.1.1. Encoding

The encoding procedures used in this study start by providing the range of dimensions that make up the overall dimensions of the maximal number of the selected locations of each location type, the sequence of the location selection process at each location type, and the sequence of the assignment for allocation purposes. The total dimensions can be calculated as $3 + I + 3J + 2K + L$ where I is the number of affected zones, J is the number of TDWCSCs, K is the number of TDWPRCs and L is the number of landfill sites. To more easily understand this, consider an example with two locations within each location type and two RSR technologies. For this example, the number of dimensions is equal to 17. Fig. 2 illustrates an encoding scheme of a random key representation in which each value in a dimension is randomly generated with a uniform random number (RN) between 0 and 1. The dimensions are separated into seven sets as are shown in Fig. 2. Sets 1–4 are used to generate the open/close decision of each location type, while Sets 5–7 are used in the allocation method.

4.1.2. Decoding

To decode the random numbers in a dimension of this problem, a sorting list rule was applied in this study. An example of the decoding method is presented in Fig. 3. Fig. 3(a) presents a decoding example for the maximal number of selected locations in Set 1, while Fig. 3(b) presents a decoding example for the sequence of location selections and the sequence of the assignments for allocations in Sets 2–7.

As is shown in Fig. 3(a), an example of the decisions for the maximal number of selected TDWPRCs is presented. The maximal number of selected locations is identified using a sorting rule with a choice of the

Dimension No. <i>d</i>																	
Dim.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
RN	0.73	0.41	0.48	0.34	0.54	0.71	0.27	0.56	0.20	0.35	0.64	0.98	0.77	0.24	0.85	0.31	0.52
↓																	
Set	Set 1			Set 2	Set 3	Set 4	Set 5	Set 6	Set 7								
Name	The maximal number of selected			Sequence of TDWCSC selection	Sequence of TDWPRC selection	Sequence of landfill site selection	Sequence of affected zone assignment	Sequence of TDWCSC assignment for transferring to TDWPRC	Sequence of TDWCSCs and TDWPRC assignment for transferring to landfill and market								
	TDWCSCs (MJ)	TDWPRCs (MK)	Landfill sites (ML)														
Open/close decision									Allocation decision								

Fig. 2. An encoding scheme for PWSCM system.

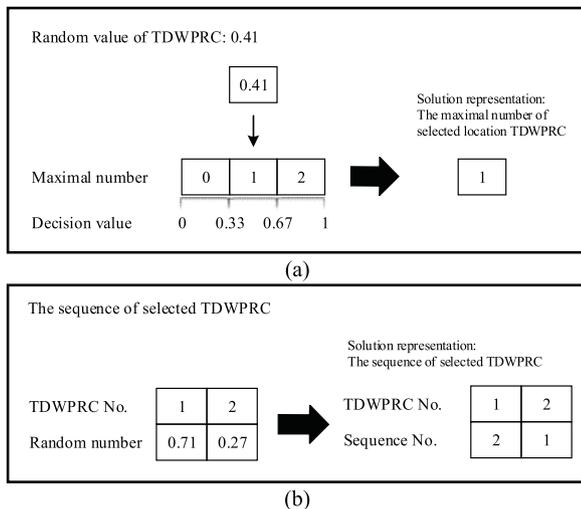


Fig. 3. An example of decoding scheme. (a) A decoding for the maximal number of selected TDWPRC; (b) A decoding for the sequence of TDWPRC selection.

maximal number of selected locations. The choice for the maximal number of selected locations can be determined using the equation $U + 1$, where U is the total number of locations that can be selected from the candidate location. In this example, we assume that the U value is 2 in each location type. Since there are three choices required to make the decision for TDWPRC in this example problem, the three choices are equally ranged under the space between 0 and 1. Thus, each choice can be selected with a probability of 1/3. Accordingly, the random value of the maximal number of selected TDWPRCs in Fig. 2 is 0.41. The random value is taken between 0.33 and 0.67. Therefore, the decoding solution for the maximal number of selected TDWPRCs as provided is 1. The decision on the maximal number of selected TDWCSCs and landfill sites in Set 1 can be decoded in the same way.

To generate the sequencing in Sets 2–7, the decoding example for the sequence of TDWPRC selection (Set 3) is proposed in Fig. 3(b). The sequence is determined according to the order of ascending values in a dimension, in which the sequence is ordered from the minimum random number to the maximum random number. The solution for the example for the sequence of the TDWPRC selection in Fig. 3(b) revealed that TDWPRC 1 is determined as sequence number 2, while TDWPRC 2 is revealed as sequence number 1. The same procedure is applied to decode the sequencing in Sets 2–7. After both decoding approaches are applied to this problem, the summary of all solution representations is presented in Fig. 4.

To identify the open/close decision of each location type, the decoding in Sets 1–4 is employed to make the decision. The decision method in each location type is generated following the sequence of the location selection along with the maximal number of selected locations.

If the sequence number of the facility location is less than or equal to the maximal number of the selected location, that facility location is selected as open. Otherwise, that facility location is indicated as being closed. The solution of open/close decision in this example is represented as shown in Fig. 5. As is illustrated in Fig. 5, the TDWCSC 1, TDWCSC 2, TDWPRC 2, and Landfill site 2 are opened, while the remaining locations are closed. Note that the value 1 is “open” and the value 0 is “closed”.

4.2. Allocation solution

After the decisions on location selection (Open/Close) and the sequence of assignment at each stage is made, the method of allocation of PWSCM is proposed. The structure of method is divided into three main stages: (1) allocating waste for collection and separation; (2) allocating waste for processing and recycling; (3) allocating waste for disposal and sale. At each step in each stage, only one arc is added to the system by selecting an origin location with the highest priority and connecting it to a destination location considering the minimum total cost of transport and operation (LC). The decoding in Sets 5–7 is employed to determine the priority of allocations in which the priority is sequenced from the minimal sequence number to the maximal sequence number. The available locations in each location type are considered following the decoding scheme of the open/close decision. The pseudo code of the allocation method is presented in Fig. 6 and described as follows.

Stage 1. Allocating waste for collection and separation

The allocation algorithm is initiated from this stage. All affected zones are assigned to the location of collection and separation. To consider the separation method of recyclable materials, both on-site and off-site separation are considered at this stage. Materials from some affected zones are separated on-site, while the rest goes to an off-site separation facility. The decoding in Set 5 is employed to determine the priority of allocation at this stage. The pseudo code of this stage is listed in Appendix A.3 Table A2.

Stage 2. Allocating waste for recycling

After the allocation of waste for collection and separation is completed, the process of allocating waste for recycling is then proposed for the next step. This stage operates for processing and recycling by considering RSR technologies. The waste at TDWCSC is allocated to TDWPRC by separating the debris for each RSR technology, while the waste that is separated at off-site (TDWPRCs) is not needed to make the allocation. To complete the sequence of allocation for TDWCSCs, the decoding in Set 6 is applied. The pseudo code of this stage is listed in Appendix A.3 Table A3.

Stage 3. Allocating waste for disposal and sale

Finally, allocation of waste for disposal and sale is proposed. The decoding in Set 7 is applied to determine the priority of TDWCSCs and TDWPRCs allocation at this stage. In this stage, the waste at the

Dim.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Location type	The maximal number of selected			TDWCSC		TDWPRC		Landfill site		Affected zone		TDWCSC		TDWCSC		TDWPRC	
ID No.	MJ	MK	ML	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Decode	2	1	1	1	2	2	1	2	1	1	2	2	1	1	4	2	3

The maximal number of selected location (Set 1)
Sequence of TDWCSC selection (Set 2)
Sequence of TDWPRC Selection (Set 3)
Sequence of landfill site selection (Set 4)
Sequence of affected zone assignment (Set 5)
Sequence of TDWCSC assignment for transferring to TDWPRC (Set 6)
Sequence of TDWCSCs and TDWPRC assignment for transferring to landfill and market (Set 7)

Fig. 4. The summary of decoding scheme for PWSCM system.

Location type	TDWCSC 1	TDWCSC 2	TDWPRC 1	TDWPRC 2	Landfill 1	Landfill 2
Open/Close	1	1	0	1	0	1

Fig. 5. An open/close decision of each location type.

TDWCSCs and TDWPRCs is divided into two portions; disposal and sale. The waste is then assigned to landfill sites and markets, respectively. The pseudo code of this stage is listed in Appendix A.3 Table A4.

4.3. Local search

In general, a local search may be applied to a certain group of vectors or particles in order to enhance the exploitation of the search space. The local search typically attempts to improve the quality of the solution by searching for better solutions around its neighbors. According to the above solution, some facility locations do not need to be opened with full capacity. Therefore, the local search is proposed to improve the quality of the solution by providing the maximum capacity of each location. The encode and decode are presented as Fig. 7. In this study, the TDWCSC and TDWPRC are provided to find the maximum capacity of each location in order to improve the quality of the solution since those factors are able to threaten the next generated stage in finding better or worse solutions.

According to this example, two locations are considered in each location type and two RSR technologies. The dimensions of the local search are set at 6 (J + (K × N)), where J is the number of TDWCSCs, K is the number of TDWPRCs and N is the number of RSR technologies. The encoding value in the dimensions is generated with a uniform random number between [0, 1]. To decode the dimensions of this problem, a sorting list rule is applied to an individual value in order to generate the maximum capacity. Assume that the portion of capacity in this example is separated with a probability of 1/5 and the capacity of each location type and RSR technology type is provided as 10,000. Accordingly, the portion of capacity associated with the decision value and the example of TDWCSC 1 is presented in Fig. 8. In this example, the random number of TDWCSC 1 is 0.73, which falls between 0.6 and 0.8. Hence, the capacity of TDWCSC 1 is adjusted to 8000. The same

procedure is employed to decode the capacity in each location. According to the random number shown in Fig. 7(a), the solution representation of the decoding process is illustrated in Fig. 7(b). After the maximum capacity is provided, the solution is improved using the proposed algorithm. If the fitness value is improved and made better than the previous solution, then the new solution and the new fitness value are updated.

5. Computational experiments

5.1. Parameter setting and test problems

The performance of the metaheuristic algorithms does not only depend on the searching mechanisms and solution representation procedures, but the parameter setting also affects how good the solutions are and how they can be found and converged [46,47]. In this study, two metaheuristic approaches are proposed to solve the PWSCM problem; the Differential Evolution (DE) and Particle Swarm Optimization (PSO). In both algorithms, the function evaluations are set as a fixed value of 300,000, so that sufficient function evaluations are allowed in order to find the best solution. To determine the appropriate parameters of PSO and DE; firstly, the preliminary experiments are conducted with four different values of each parameter. Then, for each parameter, while the values of the other parameters are fixed, the outstanding parameter values out of all other parameter values are identified according to the total cost obtained from the algorithm. The following combinations of the parameter's suitable values are further tested for each size of the specified instance.

A full factorial design is conducted to determine the best parameter setting as is shown in Table 2. The average results obtained from the algorithm are then computed for each parameter setting. The simple decision-making process is considered according to the results and they

<p>I. Allocate waste for collection and separation</p> $LC \leftarrow \min \{ \{Ca_{ij} + O_j^{TDWCSC}, i \in I, j \in J\} \text{ (On-site separation)}$ $\text{or } \{Cb_{ik} + O_{kn}^{TDWPRC}, j \in J, k \in K, n = 1\} \} \text{ (Off-site separation)}$ <p>II. Allocate waste for recycling</p> $LC \leftarrow \min \{Cc_{jk} + O_{kn}^{TDWPRC}, j \in J, k \in K, n = 2 \dots N\}$ <p>III. Allocate waste for disposal and sale</p> <p style="margin-left: 20px;">TDWCSC</p> $\text{Disposal: } LC \leftarrow \min \{Cd_{jl} + O_l^{Landfill}, j \in J, l \in L\}$ $\text{Sale: } LC \leftarrow \min \{Ce_{jm} - \delta_m, j \in J, m \in M\}$ <p style="margin-left: 20px;">TDWPRC</p> $\text{Disposal: } LC \leftarrow \min \{Cf_{kl} + O_l^{Landfill}, k \in K, l \in L\}$ $\text{Sale: } LC \leftarrow \min \{Cg_{km} - \delta_m, k \in K, m \in M\};$ <p>*LC: The lowest cost or minimum total cost</p>

Fig. 6. The pseudo code of allocation method.

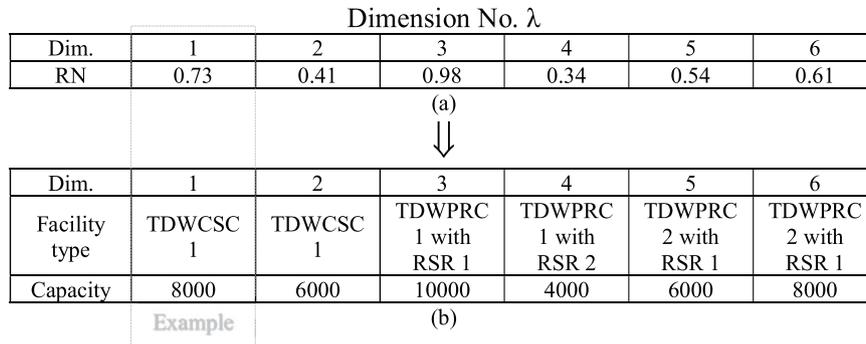


Fig. 7. Example of solution representation of local searches: (a) An encoding scheme, (b) A decoding scheme.

are employed to identify the suitable parameters [48]. The details of parameter experiments are described in Appendix A.5 in the Supplementary data section. The results indicate that the best solution quality is obtained from the parameter setting as is shown in Table 3. Hence, this method will be used in the following computational study.

5.2. Experimental results

The experiments of PWSCM are implemented using C# language of Microsoft Visual Studio 2015. A personal computer with an Intel(R) Xeon(R) X5690 CPU @3.47 GHz with 24 GB RAM is used to execute and verify the algorithms. To determine the performance of PSO and DE, LINGO 16 is proposed to evaluate the algorithm solution. The numerical results obtained from the PSO and DE are compared with an optimal solution and the PSO and DE are compared under the same conditions which are the encoding and decoding schemes. The Gap of the solution (*Gap*) obtained from the PSO or DE versus LINGO software solver and the Relative Improvement (*RI*) of the solution obtained from the PSO versus DE is evaluated according to Eq. (33) and Eq. (34), respectively.

$$Gap = ((Sol_{PSOorDE} - Sol_{LINGO}) / Sol_{LINGO}) \times 100 \tag{33}$$

$$RI = ((Sol_{DE} - Sol_{PSO}) / Sol_{DE}) \times 100 \tag{34}$$

where

Gap: the gap of solution (%) between proposed algorithm solution by using PSO or DE and optimal solution*,

RI: the relative improvement between Sol_{PSO} and Sol_{DE} **

Sol_{PSO} : the solution of proposed algorithm obtained from PSO,

Sol_{DE} : the solution of proposed algorithm obtained from DE,

Sol_{LINGO} : the optimal solution obtained from LINGO software solver.

Note;

*The more negative *Gap* is the superior performance of PSO or DE to the LINGO software solver.

**The more positive *RI* is the superior performance of PSO to the DE.

In this study, twenty PWSCM problems were designed to investigate how the performance of the proposed algorithm works for real cases.

Table 2
Parameter experiments.

PSO	DE
Swarm size: 100, 150, 200	Population size: 100, 150, 200
w : [0.1, 0.5], [0.4, 0.9] (linearly increase)	F : [0.1, 0.5], [0.5, 1] (linearly increase)
c_p : 1, 1.6	C_r : [0.1, 0.5], [0.5, 1] (linearly increase)
c_g : 1, 1.6	

Table 3
Parameter setting.

PSO	DE		
Number of iterations	1500	Number of iterations	2000
Number of particles	200	Number of population	150
Inertia weight, w	[0.4, 0.9]	Amplification factor, F	[0.1, 0.5]
Personal best position, c_p	1	Crossover rate, C_r	[0.5, 1]
Global best position, c_g	1		

Twenty instances are presented in Table 4 including the number of the affected zones (I), TDWCSC (J), TDWPRC (K), landfills (L), markets (M), RSR technology (N), variables and constraints. Twenty instances were divided into four categories consisting of small-size problem (case 1–5), medium-size problem (case 6–10), large- size problem (case 11–15), and very large- size problem (case 16–20). The PWSCM problem was tested with two case groups; without a limit of locations and with a limit of locations. Some data have been generated randomly based on a real-case problem from the work of Fetter and Rakes [6], such as the volume of debris, reduction proportion, proportion of reduced debris from RSR technology saleable as recycled material, cost of RSR technology, disposal cost, and revenue. In order to verify the validity of the proposed model, Instance 1 is employed to investigate which data is presented in Appendix A.4. The results of the example data are provided in Table 5.

Tables 6 and 7 show the results of the PWSCM problem without a limit of locations and with a limit of locations such as the optimal

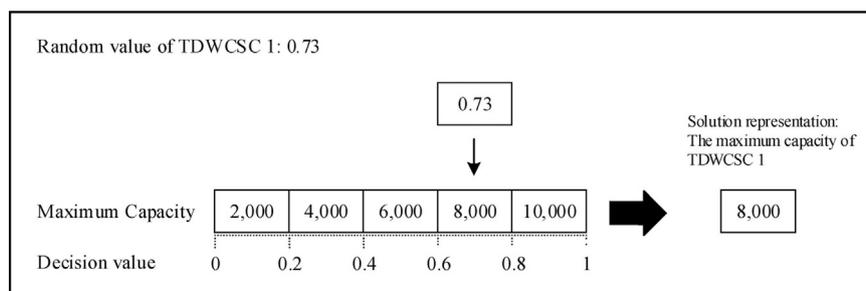


Fig. 8. Decoding example of TDWCSC 1 under the portion of capacity associated with the decision value.

Table 4
Experimental design for various cases.

Case	Test problem						Variables		St.
	I	J	K	L	M	N	Total	Integers	
1	10	2	2	2	2	2	153	70	121
2	15	3	3	2	2	3	320	152	233
3	20	3	4	3	2	2	437	205	291
4	32	4	4	4	3	3	772	368	497
5	40	7	5	5	4	3	1454	700	877
6	50	10	5	5	5	3	2175	1060	1284
7	64	10	8	5	5	3	3240	1579	1846
8	70	15	10	8	6	4	5547	2696	3067
9	80	18	12	9	9	4	7784	3783	4222
10	96	20	15	10	8	3	9958	4830	5286
11	100	20	10	5	10	3	8235	4065	4504
12	123	25	15	10	8	3	13,718	6710	7265
13	208	32	10	10	10	4	21,901	10,848	11,685
14	325	40	18	13	12	3	45,169	22,351	23,460
15	427	47	20	18	15	4	69,490	34,385	35,885
16	500	50	30	20	20	3	95,775	47,290	48,899
17	632	60	30	30	30	4	139,445	68,820	70,933
18	785	65	25	30	27	4	165,010	81,750	84,484
19	890	78	32	36	30	5	235,895	116,794	119,821
20	1000	100	50	45	30	5	373,375	184,445	188,104

Table 5
The result of example problem.

Global optimal solution found			
Total cost (\$):	2,248,082	Operation cost (\$):	493,925
Fixed cost (\$):	72,500	Revenue (\$):	180,125
Transport cost (\$):	1,469,164	Penalty cost (\$):	392,617
Selected TDWCSC:	TDWCSC 2		
Selected TDWPRC:	TDWPRC 1, TDWPRC 2		
Selected Landfill site:	Landfill 1, Landfill 2		
Cpu time(s):	0.21		

(feasible) solution within the computational time limit, the best, average and standard deviations of the total cost of PWSCM from ten runs of each algorithm for each case, the gap of the solution and the *RI* of the best and average solutions obtained from the PSO and DE. Moreover, a comparison of the total cost in the supply chain between LINGO software solver, PSO, DE and *RI* between PSO and DE is illustrated in Figs. 9 and 10, respectively.

According to the results from Tables 6 and 7, the differences between the global optimum figures of the LINGO software and the proposed algorithm using PSO and DE are sufficiently small. When the results of the PWSCM problem without a limit of locations are reviewed as is shown in Table 6 and Fig. 9(a), the maximum gap of 2.36%, as the difference from the global optimum, is admissible in persuading the acceptability of the proposed algorithms' performance. While LINGO software could not find the solution within a reasonable computing time (12 hrs.), as the problem size increases, PSO and DE showed their potential in solving the larger problems (case 19–20) without difficulties. The performance of the LINGO software overcame the PSO and DE, while in many cases it took more time than the proposed algorithm that used PSO and DE. In the very large-size problem (case 16–20), the proposed algorithm using PSO and DE found a preferred solution to what the LINGO software was able to find. The average gap of the very large-sized problem from PSO was -4.80, while the DE was -4.69.

In the results of the PWSCM problem with the limit of locations, as is shown in Table 7 and Fig. 9(b), the maximum error of both algorithms obtained from the global optimum was 2.22% and 2.77%, respectively. In this case, the LINGO software was able to find the optimal solution in small- and medium-sized problems (except in case 7). In the large-sized problem, the LINGO software was still able to find the solution, but it

was not an optimal solution within reasonable computing time (12 hrs.). However, the LINGO software also yielded a better solution than the proposed algorithms using PSO and DE in which the average gap of the PSO was 0.64%, while the gap of the DE was 1.25%. When the very large-sized problems are tested, the results of the very large-sized problem using the LINGO software generated worse solutions than the proposed algorithm, in which case 16 could outperform the others at 0.43% by PSO and 0.28% by DE. From case 17 to case 20, the LINGO software could not find a solution to the problem, while the proposed algorithm using PSO and DE was able to generate a solution easily in a relatively short period of time. According to the two case groups, we found that the solution of the PWSCM problem with a limit of facility location is quite a bit harder to reach than the PWSCM problem without a limit of facility location. This is because there would be a longer computation time needed when the problem is solved using LINGO software.

To compare the degree of performance of PSO and DE, the results of the *RI* are shown in Fig. 10. Fig. 10(a) presents the computational results without the limit of location, while Fig. 10(b) shows the computational results with the limit of location. Notably, the more positive *RI* is the superior performance of PSO to the DE. As is shown in Fig. 10(a), the DE was able to find the best solution and better average solution than the PSO in some cases. However, the PSO also displays the outstanding performance of the DE when compared with all of the cases. In terms of the problem with the limit of location that is shown in Fig. 10(b), the proposed algorithm using PSO produced outstanding results when compared to the DE. There were just two cases of the *RI* for which the average displayed a lower level of performance than DE (Cases 6 and 11). A summation of each problem group produces a positive value, which means that the PSO performed far better when compared to the DE.

The proposed algorithm also has produced an error in the optimal solution (feasible solution), but that error is admissible and can still confirm the acceptability of the proposed algorithm's performance. With regard to the employment of metaheuristics, both PSO and DE were considered efficient algorithms to solve the problem in this study, wherein which each algorithm serves a different purpose. Though the DE utilized a shorter runtime than the PSO and outperformed the PSO in some cases, the PSO generally yielded outstanding results when compared to the DE because the overall results of the PSO could generate the final solution better than the DE, especially in the instances of "with limit location" that are shown in Fig. 10(b). However, both PSO and DE could be applied to this problem efficiently.

5.3. Numerical tests for PWSCM improvement

In this section, we aim to represent the benefits of PWSCM improvement under integrated decisions for the on-site and off-site separation of recyclable materials. Although the superior performance of the mixed model has been confirmed in many studies and has been achieved in many real cases [13], we also desire to present the advantages of this model from an economic perspective and an environmental perspective with respect to our proposed model. In this numerical test, Case 9 is used to show the performance of the proposed model. The proposed model is compared with the on-site and off-site separation models in the handling of recyclable materials with respect to our system. The proposed model is reformulated for on-site separation and off-site separation. To formulate the on-site separation model, the proposed model in Section 3 is reformulated by adding Eq. (35). While the off-site separation model is formulated by adding Eq. (36). The numerical tests are solved without the limit of location. The solution results of the three models are tabulated in Table 8 and are shown in Fig. 11.

$$\sum_k \xi b_{ik} = 0 \quad \forall i \tag{35}$$

Table 7
Experimental results of total costs in supply chain network on a set of generated problems for PWSCM problem with a limit of facility location.

Case	LINGO			PSO			Time(s)			DE			Time(s)			Gap			RI PSO V.S. DE				
	Time(\$)	Best	Avg.	%SD $\frac{SD}{\bar{x}}$	Max	Avg.	Gap	Best	Avg.	%SD $\frac{SD}{\bar{x}}$	Max	Avg.	Best	Avg.	%SD $\frac{SD}{\bar{x}}$	Max	Avg.	Best	Avg.	%SD $\frac{SD}{\bar{x}}$	Max	Avg.	
1	2,287,871	2,287,871	2,287,871	0.00	8.36	7.02	0.00	2,287,871	2,287,871	0.00	5.27	5.08	0.00	0.00	0.00	5.27	5.08	0.00	0.00	0.00	0.00	5.27	5.08
2	4,248,466	4,248,466	4,261,580	0.15	13.43	10.12	0.00	4,248,466	4,262,005	0.14	7.75	6.39	0.00	0.00	0.00	7.75	6.39	0.00	0.00	0.010	0.00	7.75	6.39
3	4,778,515	4,781,516	4,869,678	1.18	14.96	11.43	0.06	4,906,223	4,914,580	0.06	6.99	6.77	2.67	2.67	2.67	6.99	6.77	2.67	2.608	0.922	0.922	6.99	6.77
4	8,261,991	8,320,360	8,411,137	1.36	21.23	18.87	0.71	8,381,368	8,466,295	0.84	10.98	9.77	1.44	1.44	1.44	10.98	9.77	1.44	0.733	0.656	0.656	10.98	9.77
5	9,855,092	10,005,681	10,116,301	0.82	19.62	19.21	1.53	10,127,872	10,504,335	1.94	10.98	9.19	2.77	2.77	2.77	10.98	9.19	2.77	1.221	3.836	3.836	10.98	9.19
6	11,463,659	11,718,222	11,798,881	0.77	40.45	36.64	2.22	11,718,222	11,721,883	0.05	21.42	16.82	2.22	2.22	2.22	21.42	16.82	2.22	4.563	5.424	5.424	21.42	16.82
7	15,467,488	15,467,545	15,528,214	0.29	62.04	58.04	0.00	15,484,260	15,541,952	0.24	38.14	34.54	0.11	0.11	0.11	38.14	34.54	0.11	0.108	0.088	0.088	38.14	34.54
8	16,249,516	16,360,544	16,519,496	0.84	39.79	31.50	0.68	16,378,618	16,627,432	0.77	20.26	19.07	0.79	0.79	0.79	20.26	19.07	0.79	0.110	0.653	0.653	20.26	19.07
9	17,904,998	18,085,518	18,278,828	0.48	53.95	49.05	1.01	18,231,508	18,571,328	1.47	23.71	17.70	1.82	1.82	1.82	23.71	17.70	1.82	0.807	1.600	1.600	23.71	17.70
10	20,917,017	21,314,826	21,500,924	0.50	84.88	69.80	1.90	21,385,088	21,547,541	0.96	45.07	33.80	2.24	2.24	2.24	45.07	33.80	2.24	0.330	0.217	0.217	45.07	33.80
11	23,440,007	23,668,575	23,797,760	0.45	120.29	118.75	0.98	23,699,489	23,785,861	0.40	75.93	67.64	1.11	1.11	1.11	75.93	67.64	1.11	1.355	1.906	1.906	75.93	67.64
12	26,398,570	26,728,440	27,022,953	0.90	80.40	65.06	1.25	26,890,925	27,376,307	1.03	39.79	26.38	1.87	1.87	1.87	39.79	26.38	1.87	0.608	1.308	1.308	39.79	26.38
13	50,450,854	50,115,669	50,656,224	0.51	109.71	89.03	-0.66	50,985,276	51,854,275	1.18	38.97	24.38	1.06	1.06	1.06	38.97	24.38	1.06	1.735	2.365	2.365	38.97	24.38
14	54,039,564	54,365,664	54,666,788	0.30	758.13	719.99	0.60	54,502,530	54,885,033	0.44	423.19	342.99	0.86	0.86	0.86	423.19	342.99	0.86	0.252	0.399	0.399	423.19	342.99
15	77,029,993	77,817,591	78,120,094	0.15	1622.43	1449.33	1.02	78,060,828	78,428,764	0.17	596.84	527.80	1.34	1.34	1.34	596.84	527.80	1.34	0.313	0.395	0.395	596.84	527.80
16	85,378,377	85,015,474	85,215,109	0.19	858.74	722.76	-0.43	85,135,823	86,117,567	1.23	691.52	626.78	-0.28	-0.28	-0.28	691.52	626.78	-0.28	0.142	1.059	1.059	691.52	626.78
17	N/A	113,711,350	113,977,700	0.14	2631.92	2543.34	N/A	114,064,853	114,389,559	0.20	1595.46	1215.63	N/A	N/A	N/A	1595.46	1215.63	N/A	0.311	0.361	0.361	1595.46	1215.63
18	N/A	144,412,521	144,582,565	0.09	2848.63	2651.79	N/A	144,601,319	145,158,103	0.16	2354.22	1883.26	N/A	N/A	N/A	2354.22	1883.26	N/A	0.131	0.398	0.398	2354.22	1883.26
19	N/A	172,408,347	172,692,499	0.11	4119.55	3655.57	N/A	172,622,228	173,407,216	0.18	5024.26	2622.45	N/A	N/A	N/A	5024.26	2622.45	N/A	0.124	0.414	0.414	5024.26	2622.45
20	N/A	183,205,084	183,769,445	0.11	10,167.94	9138.07	N/A	183,915,996	184,679,456	0.15	7965.27	5776.45	N/A	N/A	N/A	7965.27	5776.45	N/A	0.388	0.495	0.495	7965.27	5776.45
							-0.43												1.095	2.728	2.728		

^a indicates that the best solution was found in 12 h (43,200 s), while the optimal solution was not available.

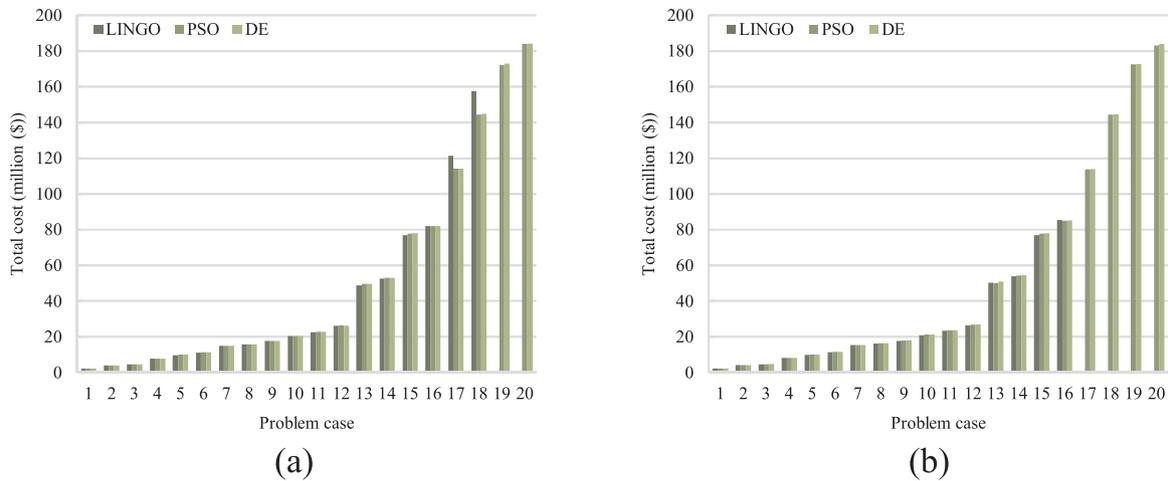


Fig. 9. The total cost comparison of each solution between LINGO, PSO, and DE; (a) without the limit of location, (b) with the limit of location.

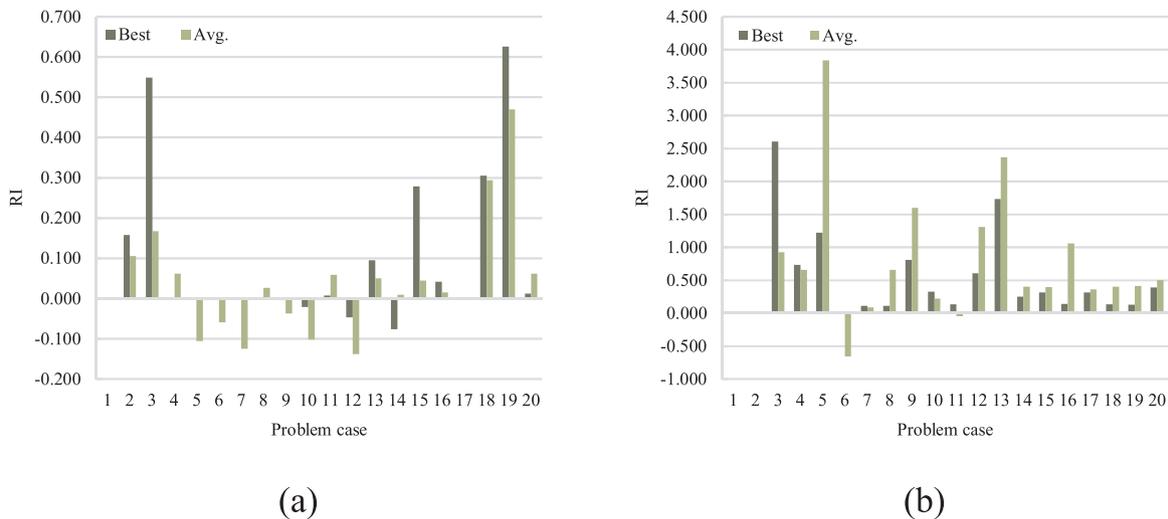


Fig. 10. The RI of each solution between PSO and DE; (a) without the limit of location, (b) with the limit of location.

Table 8

The results of on-site, off-site, and mixed model separation for recyclable material in terms of cost (cost unit: \$).

	On-site	Off-site	Mixed model	% of changing	
Total cost (Z)	17,853,049	18,589,503	17,838,077	4.04%	(-)
Fixed cost (FC)	333,500	368,500	338,500	8.14%	(-)
Transport cost (TC)	11,599,307	12,113,922	1,580,392	4.40%	(-)
Operation cost (OC)	4,466,163	4,514,490	4,468,004	1.03%	(-)
Revenue (R)	1,759,015	1,733,091	1,758,498	1.47%	(+)
Penalty cost (PC)	3,213,094	3,325,682	3,209,679	3.49%	(-)

Note: The percentage of change is based on the worst value of the three models; the more negative value of Z, FC, TC, OC, and PC is the superior performance of the worst value; the more positive value of R is the superior performance of worst value.

$$\sum_j \xi a_{ij} = 0 \quad \forall i \tag{36}$$

From the solution results in Table 8, we can see that the mixed separation model employed for handling recyclable materials could overcome the results of the on-site and the off-site separation models in terms of both an economic perspective and an environmental perspective. The mixed separation model could reduce the total costs at 4.04% from the total cost of the off-site separation model and 0.08% from the total cost of the on-site separation model. Based on the worst

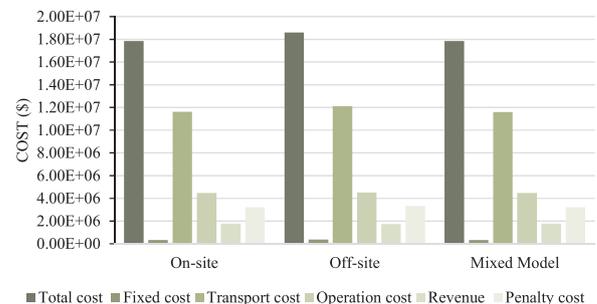


Fig. 11. The graphical model for cost comparison of on-site, off-site and mixed separation models.

values of each cost, the mixed separation model with respect to our proposed model was able to increase the level of performance with regard to costs in which all the worst values were obtained from off-site separation model. The superior performance based on the worst values is tabulated in the final column of Table 8. Based on a comparison between the on-site and the mixed separation models, the mixed separation model was able to overcome the on-site separation model in terms of total costs, transport costs, and penalty costs at 0.08%, 0.16%, and 0.11%, respectively. Whereas, the on-site separation model could overcome the mixed separation model in terms of fixed costs, operational costs, and revenue yields at 1.50%, 0.04%, and 0.03%,

respectively. Although some costs in the on-site separation model were preferred over the mixed separation model, the mixed separation model was still considered to be superior to the on-site separation model in terms of the overall costs. From an environmental perspective, based on penalty costs, the mixed separation model could overcome the on-site and off-site separation at 0.11% and 3.49%, respectively. In other words, the mixed separation model could reduce the negative effects on the environment and humans. Fig. 11 reveals that the mixed separation model could not overcome all costs in both the on-site and off-site separation models simultaneously, but the mixed separation model could balance the costs of both models. Ultimately, the mixed separation model was able to minimize the total costs, as it was able to overcome both the on-site and off-site separation models.

As is stated in the above analysis, we have determined that our proposed model is capable of down system performance deficiencies in a post-disaster waste supply chain management context. This provided the empirical insight into how change is improved with regard to post-disaster waste supply chain management systems. With PWSCM improvement, this is a choice that can be a benefit for the government in designing or planning the sustainable PWSCM strategy in the future.

6. Conclusion

This research studied the problem of post-disaster waste supply chain management with respect to a minimization of total costs in the supply chain. The facility location and allocation problems were applied in this study. To achieve the sustainable post disaster waste management system, this research aims to employ an economic perspective and an environmental perspective simultaneously. The objective function was to minimize the financial totals of the fixed costs and the variable costs as well as the penalty costs that are associated with the negative environmental and human effects of post-disaster waste and to maximize the potential revenue incurred from the sellable waste. The network structure of the proposed mixed-integer linear programming model was composed of the debris collection and separation sites, the processing and recycling sites, the disposal sites and the market sites with decision-making for locating the suitable temporary debris collection sites, processing sites and landfills and was used to facilitate the debris flow decision-making process. Furthermore, this model determined the separation of recyclable materials where debris is separated on-site or off-site and also determined the RSR technologies in this study as well. Since the problem is NP-hard, this paper proposes employing two metaheuristic approaches with the encoding and decoding schemes to solve this problem. The performance values of the proposed algorithm by PSO and DE were evaluated using the set of generated cases and were compared with the results obtained from the exact solution method using LINGO software solver. The experimental results showed that the proposed algorithm produced an error in the optimal solution (feasible solution), but that error is considered admissible in terms of the acceptability of the proposed algorithm's performance. Both the PSO and DE could be used as an efficient alternative approach for solving the post-disaster debris supply chain management problem. However, the PSO displayed outstanding performance of the DE since it was able to find an effective quality solution even if the runtime was longer than the DE. Finally, we have also proposed the numerical tests in order to determine the performance of the proposed model.

A key advantage of this research was to analyze the entire supply chain with regard to the post-disaster debris problem and to balance the advantages and disadvantages of the on-site and off-site separation processes of recyclable materials. The proposed model could be employed to serve emergency management purposes in the preparation stage and the recovery stage. Also, our proposed algorithms can be applied in the actual practice in decision-making in the operation for the purposes of facility location and distribution in the PWSCM problem. This can evaluate in a variety of scenarios with a variety of possible data in order to reach an acceptable solution by using the short

computation time to reach a desired solution for the model. Due to the fact that substantial disasters will likely occur in the future as either natural disasters or man-made disasters, it is believed that the proposed algorithm can be employed to address this challenge. Nevertheless, this research still has some limitations. The proposed model in this study was based on a constant parameter and deterministic model, which may not represent the uncertainty of different parameters and scenarios. Thus, the mathematical model needs to be modified for real-world situations. This can be handled via several ways such as by employing the stochastic model, the robust model and the dynamic model [49]. Since this study employs a theoretical application, further studies should be applied in practical or real case applications that might be more reasonable and practical. This proposed model is suitable for a strategy that needs to balance between on-site and off-site separation for recyclable materials. In scenarios like this, the decision makers must consider all aspects of the situation carefully in order to select the appropriate strategy. To apply the real-world problem, the decision makers should prepare potential data carefully, with regard to the volume of the disaster debris. Some techniques should be used to forecast or predict relevant data. To apply to the special case or special area such as highly populated cities, rural cities, coastal areas, mountainous areas and so on, the proposed model should be revised and some conditions should be added in order to solve the problem efficiently. However, all procedures depend on the decision of the policymakers and the specific situation they find themselves in.

Further studies are recommended that should include other constraints in order to make addressing the problem more practical such as with regard to road closures or traffic congestion, different modes of transportation, operation times or time schedules, the uncertainty of disasters, resources, and in other such examples. Finally, the researchers have continued to investigate ways to improve the algorithm performance with a wider range of post-disaster debris management problems.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.ijdr.2018.07.003](https://doi.org/10.1016/j.ijdr.2018.07.003).

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