AN OPTIMAL C&D WASTE LOGISTICS NETWORK DESIGN FROM CONTRACTORS' PERSPECTIVE

Zhuangqin Lin,[3] Qiu Xie,[1,2]* Yingbin Feng,[4] Peng Zhang, Yu Yang[3]

ABSTRACT

The construction industry is one of the major producers of municipal solid waste. Although there are many studies in municipal solid waste management, the research on the recovery of recyclable building material from construction sites remains limited. This paper addresses the optimal design issue of the construction and demolition (C&D) waste logistics network based on the features of the construction industry from the contractors' perspective. The purpose of this paper is to provide an optimal C&D waste recycling network decision (RND) model considering the change of construction sites location over time. A multi-period and multi-objective mixed-integer linear programming model was developed to minimize the cost of C&D waste disposal for contractors, and to minimize the carbon emissions from C&D waste transportation. An application study was conducted to assess the performance of the RND model. Through some sensitivity analysis experiments based on an immune genetic algorithm, the influences of environmental policies and carbon tax policy on improving the recycling rate of C&D waste and reduce the carbon emission were explored. The findings of this research suggest that: (1) a RND model with the feature of the construction industry developed in this paper can effectively optimize the C&D waste logistics network; (2) government policies and laws are valid political instruments to improve the recycling rate of C&D waste; (3) the carbon-tax analyses demonstrate that a carbon tax policy can effectively reduce carbon emissions.

KEYWORDS

C&D waste, logistics network decision, the contractors' perspective, construction sites

1. INTRODUCTION

Construction and demolition (C&D) waste is one of the largest solid waste streams around the world. In China, with rapid urbanization and urban transformation, C&D waste has reached

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30–40% of the total municipal solid waste output (Zhao et al., 2010), as well as 70%, 50%, 44%, 36%, and 30% of the total waste in Spain, United Kingdom, Australia, Japan and Italy, respectively (Poon et al., 2013). At present, simple landfill is the main waste disposal method in many countries, even including illegal dumping (Wolfsberger et al., 2016). Simple landfill or unreasonable disposal for C&D waste may result in serious environment pollution and threaten the environment (Poon et al., 2004). Recycling of C&D waste is considered as one of the most effective and environmentally friendly waste disposal methods. The adverse impacts on the environment can be mitigated and recyclable materials can be recovered through the recycling system of C&D waste.

As an important part of the recycling system, a well-designed reverse logistics network (RLN) plays a major role in improving the recycling rate of construction material in the C&D industry (Xu et al., 2018). However, how to determine the optimal location of landfills and treatment plants is a major challenge in RLN design. Moreover, due to the inherent nature of the construction industry, the RLN design for C&D waste is very complex (Trochu et al., 2018). For example, the construction sites where C&D waste is generated vary over time with changes in construction activities. It directly affects the distance and the transportation cost between construction sites and final disposal facilities, and indirectly affects the optimal location strategy of final disposal facilities. The changes in the location of construction sites make the RLN design problem of C&D waste challenging.

Government policies and laws are important drivers for C&D waste disposal and are essential to promote a sustainable waste management systerm (Kylili & Fokaides, 2017). C&D waste recycling policies have led to landfill reductions and a large increase in the C&D waste recycling rate in the United Kingdom and Germany (Esa et al., 2017). Therefore, in order to encourage the recycling of C&D waste, relevant laws and policies, such as landfill fees and penalties for illegal dumping, have been introduced (Ajayi et al., 2015; Fei et al., 2016). As a major stakeholder in the C&D waste management system, the construction contractor is the undertaker and decision-maker of C&D waste collection, transportation and disposal in the construction industry. On the other hand, contractors are the implementers of environmental policies that constrain their disposal decisions of C&D waste. Because most decision-makers in C&D waste management activities in China are profit-oriented, most of C&D waste is disposed based on the principle of cost minimization (Yuan & Wang, 2014). These environmental policies directly or indirectly affect the disposal costs of C&D waste, which in turn affects contractors' decision-making. Therefore, in addition to introduce more comprehensive laws and regulations, it is also necessary to consider the interests of contractors in RLN design to effectively promote the recycling of construction materials from construction sites.

The green economy has attracted worldwide attention due to increasing concerns about environmental problems. A RLN for waste recycling is expected to process all the wastes with minimum financial and environmental impact. In order to incorporate environmental considerations into network design decisions, researchers have used many environmental indicators. Previous studies have used indicators such as carbon emissions, energy use and waste generation to measure the environmental impact of a supply chain (Xu et al., 2018). In this paper, carbon emission that results from the transportation process of C&D waste is considered as an environmental indicator.

This research is inspired by a worldwide concern about C&D waste recycling and carbon emissions reduction. However, previous studies rarely considered the characteristics of the construction industry in addressing the problem of RLN design. The impact of government policies on the recycling rate of C&D waste and carbon emissions from the contractors' perspective is seldom considered in solid wastes management literature as well. Noting the gap that exists in the literature, this research aims to develop a C&D waste recycling network decision (RND) model from the contractors' perspective to improve C&D waste recycling and reduce environmental pollution. The objective is to minimize the cost of C&D waste disposal for contractors and the carbon emissions from C&D waste transportation with environmental policies being regarded as the constraints. The contribution of this work lies in two particularities. Firstly, this model takes into account the characteristic of the construction industry that the location of the construction sites changes over time. Secondly, the impact of government policies on the recycling rate of C&D and carbon emissions from the contractors' perspective is taken into account.

The remainder of this paper is organized as follows. The paper gives a brief overview of RLN in Section 2. In Section 3, a methodology about a RND model is proposed to solve C&D waste logistics network optimal design issues. Section 4 presents a case study along with the insights derived from the results. Finally, the conclusions and future research perspectives are provided in Section 5.

2. LITERATURE REVIEW

The emergence of decision-making tools that support the design and optimization of a RLN goes back to 1998 (Barros et al., 1998). The optimization model is one of the decision-making tools in which the objective function(s) should be minimised or maximised according to a number of constraints. In this section, we review the developed optimisation models for supporting decision-making in RLN.

Much research shows that different types of optimisation models have been developed in this field. These models include linear programing (LP) (Abou Najm et al., 2002), non-linear programing (NLP) (Yadav et al., 2016), mixed-integer linear program (MILP) (Tan et al. 2014) and stochastic programming (Jeihoonian et al., 2016). Munster and Meibom (2011) developed a LP model for identifying the best waste to energy facilities. Achillas et al. (2010) developed a MILP model for the optimization of the local RLN with an existing infrastructure consideration. The majority of those optimization models focus on the economic aspects. Min et al. (2006) proposed a nonlinear mixed integer programming model for determining the locations of centralized return centers to minimize reverse logistics costs. Schultmann et al. (2003) addressed the RLN design problem within the context of the collection and processing of used batteries in Germany. However, the environmental aspects are rarely considered in the developed optimization models. Harijani et al. (2017) developed a multi-objective MILP model to design a sustainable recycling network for municipal solid waste in which the economic, environmental and social dimensions of sustainability are concurrently balanced. Xu et al. (2017) used robust MILP to model a global reverse supply chain with uncertainty in wastes collection rate, currency exchange rate, and the maritime cost under carbon emission constraints.

Government policies and laws are not only intended to provide an economic incentive for contractors and developers to reduce waste but also to encourage reuse and recycling of waste material (Hao et al., 2008). These environmental policies and laws affect the operation of RLN as well. However, the current studies on the influence of policies and laws on contractors' decision-making behavior are mainly qualitative research (Tam et al., 2014; Wang et al., 2019; Yuan et al., 2011), and there are few quantitative research works. Most of the current RLN optimization models are developed from a system optimization perspective (Zarbakhshnia et al., 2019; Xu et al., 2018). The models did not consider the impact of these policies on the behavior of contractors, nor can they guide contractors to reduce landfill and recycle waste by optimizing and designing RML. This makes it difficult to combine the incentive mechanism of these environmental policies with the design of RLN to play a better role in guiding contractors' decision-making behavior, which are identified as the key limitations of previous studies.

We also note that very few papers developed their models considering the characteristics of the construction industry. Kazemi et al. (2018) investigated cases in the fields of both RLN design and closed-loop supply chain network design. The result shows that the majority of the developed models are generic. The decision-making models with industry characteristics mainly addressed the electronics, manufacturing, materials, and automotive sectors. Reverse logistics processes in the construction sector vary from other industries and general logistics network design models; consequently, the existing literature may not work well for the construction industry (Kazemi et al., 2018). Although Sinha and Singh (2009) designed a reverse logistics recovery network based on a stochastic approach in the construction sector, the issue of change in the C&D waste generation sources locations was not addressed. However, the location of C&D waste generation sources is an important element in the construction sector for determining the optimal RLN (Trochu et al., 2018). Therefore, development of an appropriate RLN optimization model for the construction industry to fill this gap is necessary.

In order to alleviate the shortcomings of previous studies in RLN, this paper attempts to present a RND model from the contractors' perspective for the C&D waste recycling problem. The model considers the characteristics of the construction industry and environmental factors, and analyses the economic and environmental effects of environmental policies and laws.

3. METHODOLOGY

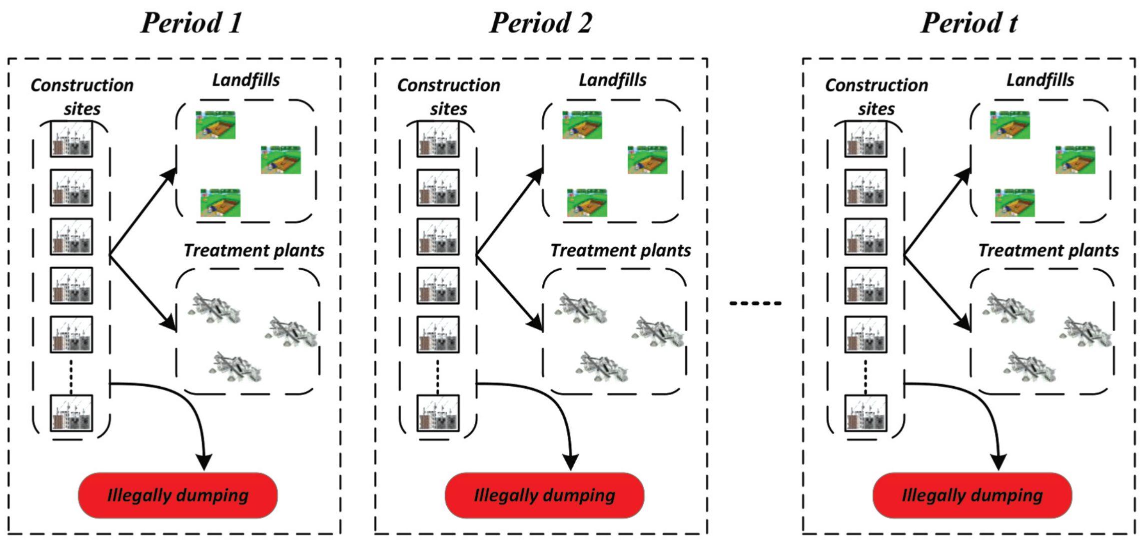
3.1 Superstructure for model development

This study presents a C&D waste logistics network based on the reverse logistics theory and field research, and it consists of multiple C&D disposal centres like landfills and treatment plants. In China, there are two main disposal methods of C&D waste: waste recycling and waste landfilling, but illegal dumping occurs where there is poor supervision (Jia et al., 2017). Previous research assumed that C&D waste generated from construction sites can be allocated to specific disposal facilities. However, in a real situation, the contractors choose the least costly disposal method for C&D waste (Yuan & Wang, 2014). Figure 1 shows the structure of the logistics network for C&D waste, which has the following characteristics.

- The logistics network contains three disposal methods for C&D waste: waste recycling, waste landfilling, and illegal dumping.
- A contractor chooses the C&D waste disposal method according to the principle of minimum disposal cost.
- The cost of each disposal method is subject to environmental policies, such as the landfill fee or the penalty for illegal dumping.
- The location of the construction sites changes over time, which leads to the change in the location of C&D waste generation sources.

To specify the research scope, the assumptions are postulated as given below:

FIGURE 1. Structure of the logistics network for C&D waste from contractors' perspective.



- Assuming that the capacity of the landfills or treatment plants is large enough to handle the C&D waste transported from construction sites.
- The number of C&D waste transport vehicles is not limited but vehicle specifications are consistent.
- The cost of carbon emission in illegal waste dumping process is not taken into account.
- It is also assumed that practitioners in C&D waste management can obtain information on C&D waste landfill cost, recycling costs, and waste dumping costs.

3.2 Development of recycling network decision (RND) model

3.2.1 Notations, parameters, and variables

I: The set of construction sites, indexed by *i*;

J: The set of potential landfills, indexed by *j*;

K: The set of potential treatment plants, indexed by *k*;

T: The set of periods, indexed by *t*;

TC_1: The unit cost of transporting C&D waste from construction sites to the inappropriate areas, CNY/ton;

TC_2: The unit cost of transporting C&D waste from construction sites to landfills, CNY/ (t·km);

TC_3: The unit cost of transporting C&D waste from construction sites to treatment plants, CNY/(t·km);

PN: The penalty imposed on the practitioner who dumped waste at inappropriate areas, CNY/ton;

FC: The unit fee charged for disposing of waste in landfills, CNY/ton;

DC: The unit cost of disposing of waste in treatment plants, CNY/ton;

Q_i^t : The amount of waste generated in construction site "*i*" in "*t*" period;

P: Probability of receiving penalties when contractors dump waste at inappropriate areas;

d_{ij}^t : The distance between construction site "*i*" and landfill "*j*" in "*t*" period;

d_{ik}^t : The distance between construction site "*i*" and treatment plant "*j*" in "*t*" period;

c_0: Unit carbon emission cost;

e_0: Carbon emission coefficient; M_j: Maximum number of landfills established;

O_k: Maximum number of treatment plants established;

$$Y_j^t = \begin{cases} 1, & \text{if potential landfill site "}j\text{" is established in "}t\text{" period, } (j \in \text{J}) \\ 0, & \text{otherwise} \end{cases}$$

$$N_k^t = \begin{cases} 1, & \text{if potential treatment plant site "}k\text{" is established in "}t\text{" period, } (k \in K) \\ 0, & \text{otherwise} \end{cases}$$

$$H_i^t = \begin{cases} 1, & \text{if waste generated in construction site "}i\text{" are dumped illegally in "}t\text{" period, } (i \in I) \\ 0, & \text{otherwise} \end{cases}$$

$$Z_{ij}^t = \begin{cases} 1, & \text{if construction site "}i\text{" allocated to landfill "}j\text{" in "}t\text{" period, } (i \in I, j \in J, t \in T) \\ 0, & \text{otherwise} \end{cases}$$

$$L_{ik}^t = \begin{cases} 1, & \text{if construction site "}i\text{" allocated to treatment plant "}k\text{" in "}t\text{" period, } (i \in I, k \in K, t \in T) \\ 0, & \text{otherwise} \end{cases}$$

3.2.2 Objective function

(1) According to Section 3.1, the current methods of disposing C&D waste mainly include: illegal dumping, waste landfilling and waste recycling. When contractors choose how to dispose of C&D waste, they trade off between different disposal methods in order to minimize the total disposal cost. Therefore, the first objective function tries to minimize the total cost of C&D waste disposal for contractors, which consists of the costs of three disposal methods: the cost of illegal waste dumping (C_1), landfilling costs (C_2) and recycling costs (C_3).

$$\text{Min } C = \sum_{t \in T} \sum_{i \in I} C_i^t = \sum_{t \in T} \sum_{i \in I} C_1 + C_2 + C_3 \tag{1}$$

- The cost of violation of regulations (illegal waste dumping) includes transportation costs and fines:

$$C_1 = \left(TC_1 + PN\right) \bullet Q_i^t \bullet P \bullet H_i^t \tag{2}$$

- The cost of C&D waste landfilling includes transportation costs and landfill costs:

$$C_2 = \sum_{j \in J} \left(TC_2 \bullet d_{ij}^t \bullet Q_i^t + FC \bullet Q_i^t \right) \bullet Y_j^t \bullet Z_{ij}^t \tag{3}$$

The cost of C&D waste recycling includes transportation costs and disposal costs:

$$C_3 = \sum_{k \in K} \left(TC_3 \bullet d_{ik}^t \bullet Q_i^t + DC \bullet Q_i^t \right) \bullet N_k^t \bullet L_{ik}^t \tag{4}$$

(2) The carbon emissions generated from inter-node transportation are mainly the direct and indirect carbon dioxide emissions caused by the consumption of various energy and materials in the logistics process. This paper mainly calculates carbon emissions based on the amount of fuel consumption during transportation. Xiao et al. (2012) formulate fuel consumption rate (FCR)—fuel consumption per unit of distance—as a linear function dependent on load Q_1 approximately as:

$$\rho(Q_1) = \rho_0 + \frac{\rho^* - \rho_0}{Q} Q_1 \tag{5}$$

where Q is the capacity of the vehicle (the maximal weight the vehicle could carry), Q_1 is the carried load weight, ρ^* is the full-load FCR and ρ_0 is the the no-load FCR.

For any arc {i, j} in RLN, where point j is the next point the vehicle serves after it leaves point i, the carbon emission costs for traveling from i to j can be expressed as:

$$e(Q_1) = c_0 e_0 \rho(Q_1) d_{ij} \tag{6}$$

Where c_0 is unit carbon emission cost (carbon tax), e_0 is carbon emission coefficient, d_{ij} is the distance from i to j.

Therefore, The second objective function is to minimize the carbon emission costs from the transportation of C&D waste from the construction sites to the landfills or treatment plants. It is determined as follows:

$$Min\ \mathrm{E} = \sum_{t \in T} \sum_{i \in I} \sum_{j \in J} c_0 e_0 \rho(Q_i^t) d_{ij}^t Y_j^t Z_{ij}^t + \sum_{t \in T} \sum_{i \in I} \sum_{k \in K} c_0 e_0 \rho(Q_i^t) d_{ik}^t N_k^t L_{ik}^t \tag{7}$$

3.2.3 Constraints

The constraints of the model are as follows.

1. A contractor can only choose one disposal method for C&D waste generated.

$$\sum_{i \in I} H_i^t + \sum_{j \in J} Z_{ij}^t + \sum_{k \in K} L_{ik}^t = 1 \tag{8}$$

2. The total number of established landfills should not exceed a specific limit.

$$0 \le \sum_{j \in J} Y_j \le M_j \tag{9}$$

3. The total number of established treatment plants should not exceed a specific limit.

$$0 \le \sum_{k \in K} N_k \le O_k \tag{10}$$

4. Logistics links only exist between established logistics facilities.

$$\mathrm{Z}_{ij}^{t} \le Y_j^t \tag{11}$$

$$L_{ik}^{t} \le N_k^t \tag{12}$$

5. Constraints (13)–(14) represent range of decision variables.

$$\mathrm{H}_i^t, Y_i^t, N_k^t, Z_{ij}^t, L_{ik}^t \in \{0,1\} \tag{13}$$

$$\forall i \in I, j \in J, k \in K, t \in T \tag{14}$$

3.3 Immune algorithm

The RND model is a multi-object mixed-integer linear programming. The immune algorithm has a strong global searchability for the optimal solution and is suitable for our model. In this paper, the immune algorithm is designed to solve the RND model in the following steps:

Step A. Create an initial population of *n* individuals by generating random binary strings;

Step B. Fitness (the objective function value), concentration and excellence are calculated for each member of the current population, and the individuals are sorted according to their excellence;

Step C. The first *n*/2 individuals are subjected to immunological operations; the last *n*/2 counterparts refreshed by generating random binary strings;

Step D. A new population is generated by combining two subpopulations of step C and sorted according to their excellence, where the best fitness is selected out and recorded;

Step E. If the desired number of generations has elapsed, stop. The fittest individual in the current generation is the best solution found. Otherwise, return back to step C.

Several parameters such as the number of generation and the number of individuals of the population may be adjusted to increase the probability of finding the objective function value.

4. CASE STUDY

4.1 Data collection

Shenzhen, one of the cities with the fastest urbanization process in China, produces a large volume of C&D waste every year. It is one of the first Chinese cities implementing comprehensive C&D waste management. Shenzhen covers an area of 51997.30 square kilometres with ten administrative regions and has a permanent population of 11,378,700 in 2015. The data in this study are mainly from the following sources: the 2015 Statistical Yearbook in Shenzhen, governmental documents, authoritative websites and previous literature (Jia et al., 2017; Tam et al., 2014; Yuan & Wang, 2014). With an average of 0.6 tons of C&D waste generated per person per year, the average amount of C&D waste generated in Shenzhen city approached 6.83 million tons per year in 2015. Trochu et al. (2018) developed a method to estimate the number of generation sources in different areas. Since there is no historical data on the exact number and location of C&D sites, the total amount of waste generated is divided into 46 construction sites considering the population density of each region. Table 1 gives more details about the characteristics and the geographical configuration of the different regions. According to the dynamic and life cycle of the construction project, this paper divides three periods ($T= \{T_1, T_2, T_3\}$) to describe the dynamics of construction sites location. It is assumed that the location of the construction sites remains the same during each period, and the location of the construction sites may be different between different periods. It is assumed that there are 7 potential treatment plants and 7 potential landfills in Shenzhen and all of the potential treatment plants and landfills are obtained after site investigation and assessment. The location coordinates of the construction sites and all potential final disposal facilities in this paper were obtained from Google Maps. Because the distance between the construction sites and the final disposal facilities in the simulation is expressed as the Euclidean distance, the location coordinates obtained from Google Maps are converted to rectangular coordinates vis MAPGIS software. The rectangular coordinates of these locations will be used to calculate the distance between network nodes. Considering that China has not introduced a relevant carbon tax policy, the initial value of the carbon tax was set to 0. More detailed information of the main variables are shown in Table 2.

All computations were run using an immune algorithm accessed via MTLAB 2016a on a PC with Windows 10 (Professional 64), Intel Core i3 binuclear and 2 GB memory of RAM at 1600 MHz.

TABLE 1. Annual estimated C&D waste generation by administrative region in Shenzhen, China.

Administrative region	1	2	3	4	5	6
Population (10 000 persons)	1440.6	975.6	221.2	1291.2	2863.3	2052.4
C&D waste generated (K-tons)	864.36	585.36	132.72	774.72	1717.98	1231.44
Number of C&D sites per region	6	4	1	5	10	8
Administrative region	**7**	**8**	**9**	**10**		**Total**
Population (10 000 persons)	531.2	356.1	1511.5	135.6		11378.7
C&D waste generated (K-tons)	318.72	213.66	906.9	81.36		6827.22
Number of C&D sites per region	2	2	6	2		46

TABLE 2. Input data of RND model.

Variables	Value
Landfill fee	40 CNY/ton
Penalty for illegal dumping	100 CNY/ton
Unit cost of recycling C&D waste	18 CNY/ton
Waste transported to inappropriate areas	10 CNY/ton
Waste transported to landfills	2.56 CNY/ (t·km)
Waste transported to treatment plants	2.56 CNY/ (t·km)
Probability of receiving penalties	0.5
carbon emission coefficient (e_0)	2.61(kg/l)
Full-load fuel consumption rate (ρ^*)	2 (l/kg)
No-load fuel consumption rate (ρ_0)	1 (l/kg)

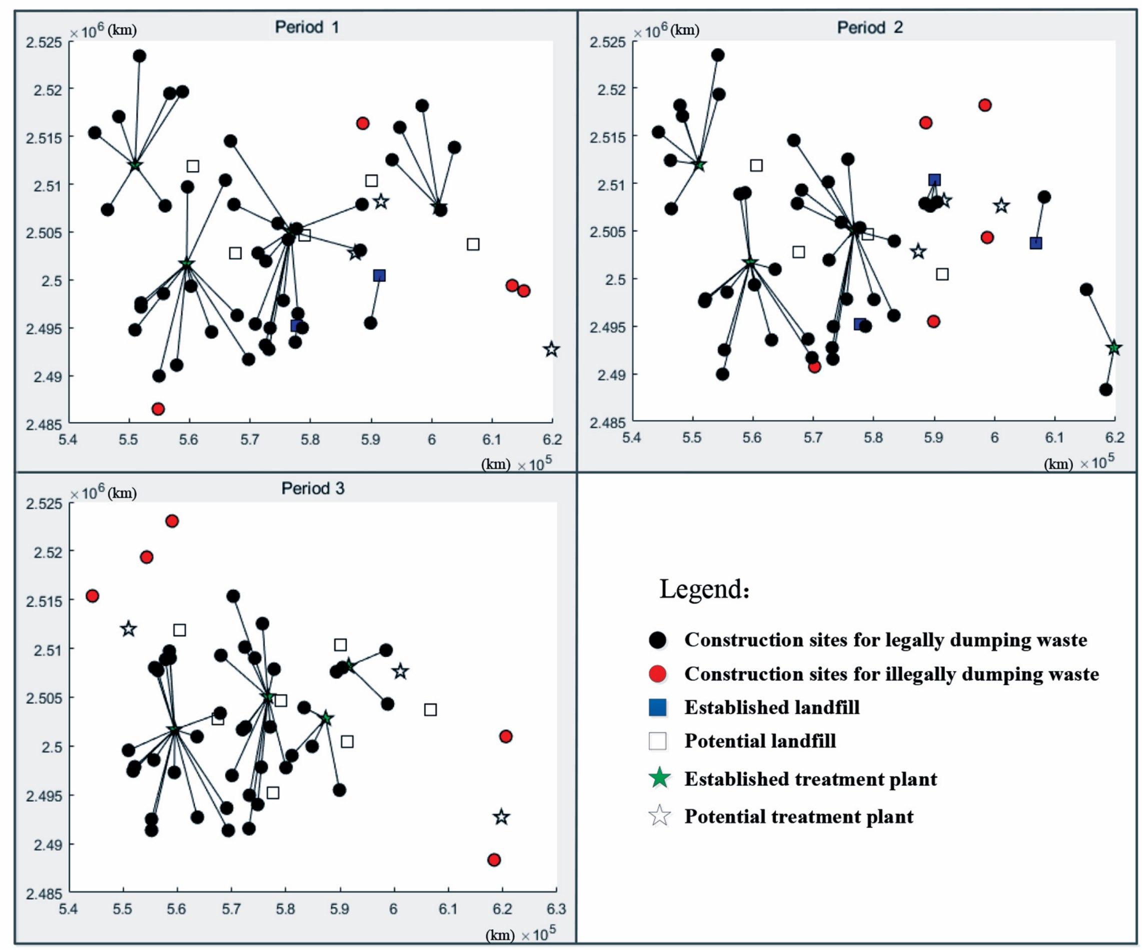
4.2 Computational results

Table 3 and Figure 2 show the best location and number of landfills and treatment plants in every period of the RND model, in which the activated facilities are illustrated with "Y". With the change in the location of the construction sites where C&D waste is generated, the optimal location strategy for the landfills and the treatment plants is continuously adjusted in order to

TABLE 3. Facilities location in every period of RND model.

		Period 1	Period 2	Period 3
Landfill	1			
	2			
	3	**Y**	**Y**	
	4			
	5		**Y**	
	6	**Y**		
	7		**Y**	
Treatment plant	1	**Y**	**Y**	
	2	**Y**	**Y**	**Y**
	3	**Y**	**Y**	**Y**
	4			**Y**
	5			**Y**
	6	**Y**		
	7		**Y**	

FIGURE 2. Optimal C&D waste logistics network under environmental policies.



reduce the contractors' transportion costs by keeping these final disposal facilities closer to the construction sites. In addition to the two legal disposal methods of landfill and recycling, the phenomenon of illegal dumping also exists and the construction sites with behavior of illegal dumping are far from the final disposal facilities, as shown in Figure 2. It can be concluded that high transportation cost may be the main reason for illegal dumping of C&D waste.

Environmental policies affect not only the total disposal costs of C&D waste for contractors, but also the number of landfills and treatment plants. When the cost of landfilling waste is higher than the cost of recycling waste, the contractors are more willing to transport C&D waste to the treatment plants, which will lead to a reduction in the number of landfills. This is why no landfill is built in period 3, as shown in Table 3. Under the constraints of environmental policies, C&D waste recycled accounted for 86.65% of the total amount of C&D waste generated in construction sites, which is much higher than the amount of C&D waste being landfilled and illegally dumped, as shown in Table 4. This means that good environmental policies have a positive guiding effect on the contractor's decision to dispose of C&D waste.

TABLE 4. Proportion of C&D waste with different disposal methods and the total disposal cost for contractor.

	Illegal dumped waste	Waste landfilled	Waste recycled	The total disposal cost (CNY)
Proportion	8.07%	5.57%	**86.36%**	**8.257E+08**

4.3 Sensitivity analysis

As the main influencing factor of C&D waste management, government policies and regulations not only influence the contractors cost structure in the C&D waste disposal process, but also could improve the recycling rate of C&D waste. Environmental policies and carbon tax policy are the main policies that affect the C&D waste recycling rate and carbon emission, and it is necessary to further explore the process of their impact on contractors' choice of waste disposal methods and carbon emissions. Sensitivity analysis is the test of any parameter that has a significant impact on the model results after changing the parameter values (Baroni & Tarantola, 2014). In order to investigate the influence of environmental policies and carbon tax policy on C&D waste management and environment, a sensitivity analysis was carried out on the penalty for illegal dumping, landfill fee and carbon tax to test how they affect the recycling rate of C&D waste and carbon emission. The main results are summarized as following.

4.3.1 Penalty policy

Penalty policy plays an important role in reducing the amount of C&D waste illegally dumped by increasing the cost of violation of the regulation. In order to learn how the penalty could affect C&D waste disposal methods, we increased the penalty from 0 to 100 CNY/ton with fixed values for landfilling fee (landfilling fee = 5 CNY/ton). Figure 3 shows the main results: (1) Penalty policy can vastly diminish the proportion of illegally dumping waste and increase the proportion of waste landfilling and recycling. The results are consistent with the real-world situation in Shenzhen. (2) As the penalty increases, the quantity of waste landfilled increases significantly, while the proportion of waste recycling increase less. The main reason may be that landfill costs are lower than the cost of recycling. (3) When the penalty is increased up to 70 or more, although the increase in the proportion of waste landfilled is not obvious, the amount of C&D waste recycled continues to grow at a higher rate.

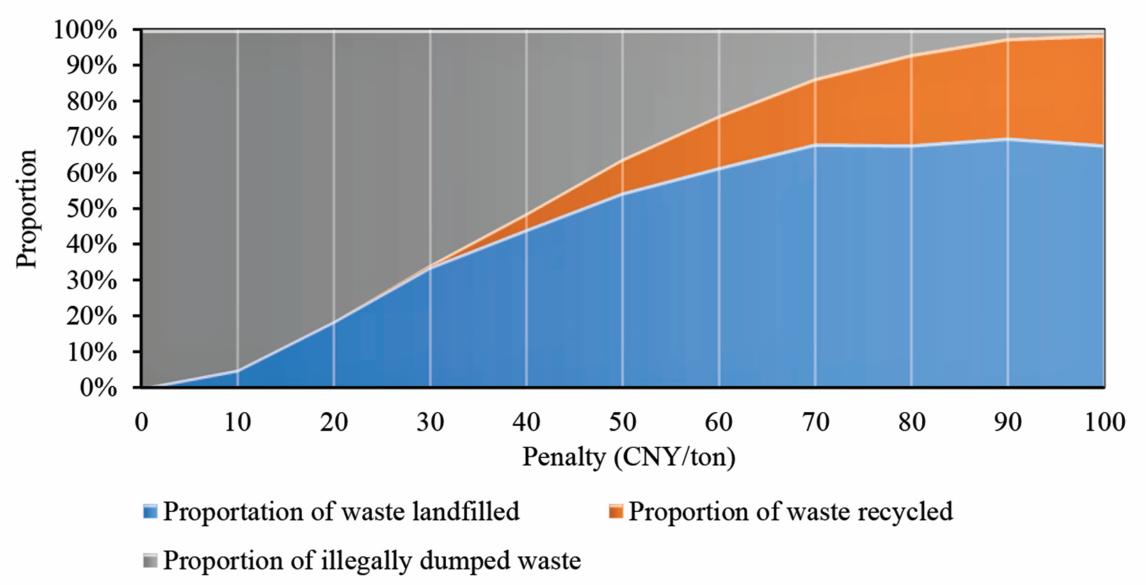
4.3.2 Landfill charging policy

Landfill charges must be determined based on local conditions and the interests of the stakeholders involved. With the increase of landfill fee from 5 CNY/ton to 60 CNY/ton under the penalty of 80 CNY/ton, the main results of C&D waste management are shown in Figure 4. It is concluded that increasing the landfill fee is conducive to the recycling of C&D waste, but the proportion of illegal dumping also increases. This shows that simply increasing the cost of waste landfilling will trigger illegal dumping and increase environmental costs.

4.3.3 Combination policy

From the above discussion, it could be found that there are some limitations in the single policy of the penalty and the landfill fee for increasing the recycling rate of C&D waste. It is necessary to take into account the combination policy since it may have double efficacy and possesses

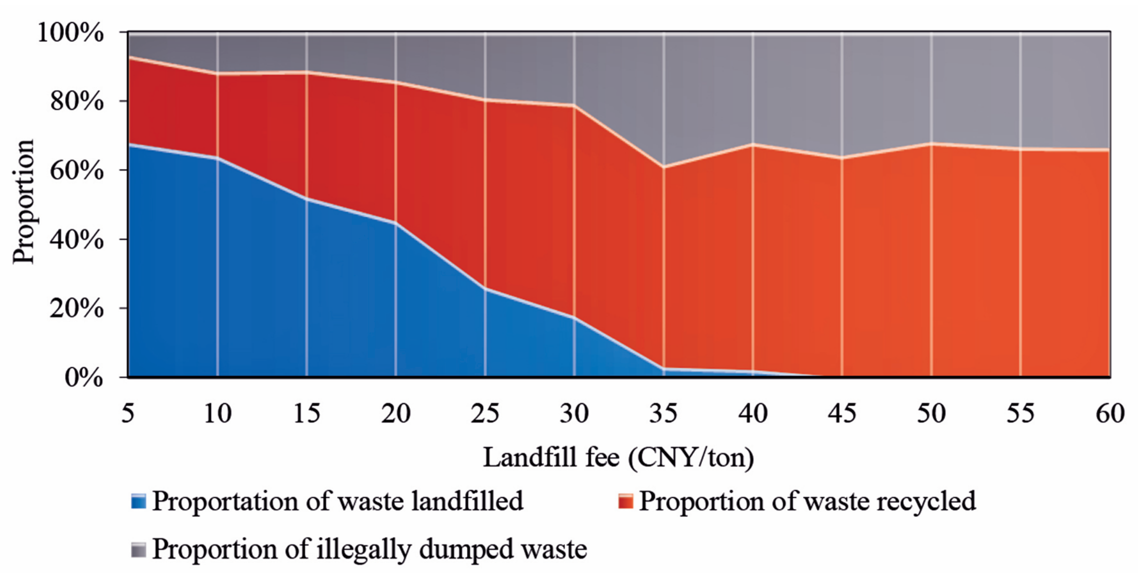
FIGURE 3. Influence of different penalty polices on C&D waste management.



practical potential. In order to examine the influence of different combination policies on the C&D waste management, we increase the value of landfill fee from 5 CNY/ton to 60 CNY/ton under five scenarios with different penalty values.

- As shown in Figure 5(a), the proportion of waste recycled increases with the increase of landfill fee. Meanwhile, with the increase of penalty the proportion of C&D waste recycled increases as well. However, The proportion of waste recycled increases slowly once the landfill fee exceeds 40 CNY/ton. When the penalty in Figure 5(a) ranges from

FIGURE 4. Influence of different landfill fee on the C&D waste management.



90–100 CNY/ton, the effect of increasing the proportion of waste recycled through penalty is not obvious. Therefore, the landfill charge should not surpass 40 CNY/ton and the value of penalty should fall within the range of 90–100 CNY/ton.

- With the active promotion of the combined policies, the amount of waste landfilled is reduced and the trend of all the curves tend to be consistent in Figure 5(b).
- Figure 5(c) shows that although all the curves are on the rise with the increase of landfill fee, the penalty can effectively curb the increase in illegal dumping waste.

4.3.4 Carbon tax policy

Yang et al. (2012) stated that the scope of the carbon tax being studied by the National Development and Reform Commission is 0.01–0.10 CNY/kg CO_{2eq} in China. Based on the expected policy, the carbon tax is adjusted from 0.01 to 0.10 CNY/kg. Figure 6 shows the influence of the carbon tax policy on carbon emission and C&D waste management.

- As can be seen, carbon emission decreases with a rise in the carbon tax in Figure 6. In other words, a carbon tax policy has a positive impact on reducing carbon emissions, which indicates that the environment can be protected through the introduction of carbon tax.

FIGURE 5. Influence of different combination policy on the C&D waste management. (a) Proportion of waste recycled; (b) Proportion of waste landfilled; (c) Proportion of illegally dumped waste.

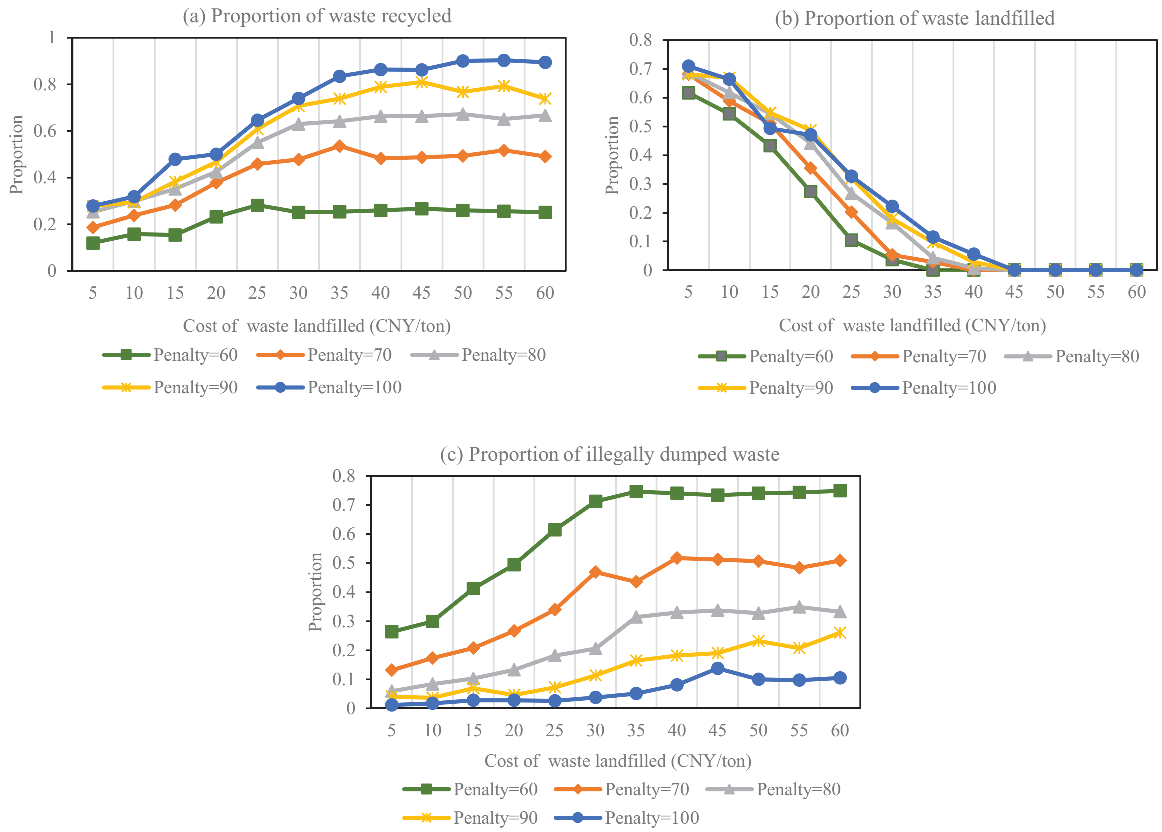
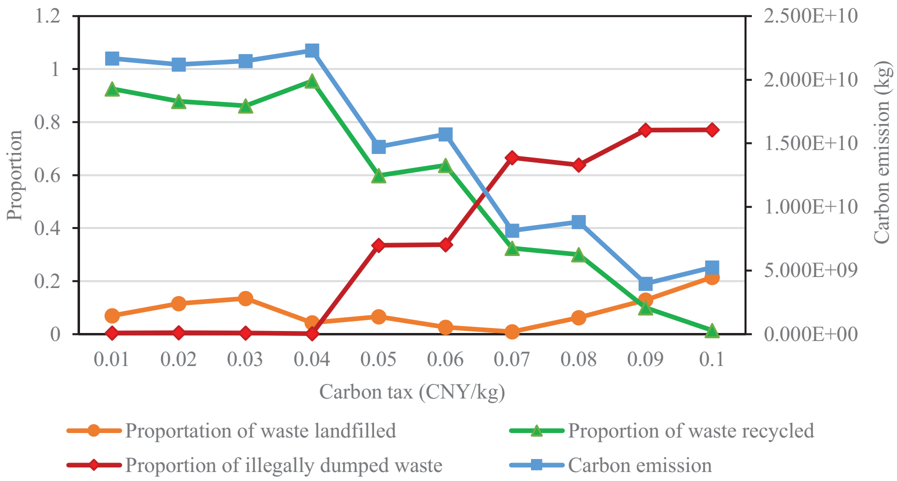


FIGURE 6. Carbon emission and the C&D waste management under different carbon tax policies.



- Carbon tax has diverse influences on the different disposal methods for C&D waste. On the one hand, the recycling rate of C&D waste decreases with an increase in the carbon tax, while the proportion of C&D waste landfilled grows slowly. On the other hand, the amount of illegal dumping C&D waste rises with the increase of carbon tax. The main reason may be that the carbon tax policy increases the cost of legal disposal of C&D waste, leading to contractors' tendency of illegally dumping C&D waste generated on construction sites.

5. CONCLUSIONS

The pressure of environmental protection and resource conservation has led countries and regions to pay more attention to C&D waste management; however, there is a dearth of literature exploration and models on logistics network design that take into account the features of the construction industry. In this paper, a methodology, considering the features of the construction industry has been presented to provide a logical framework for municipal officials and researchers to develop a C&D waste logistics network from the contractors' perspective. Based on this methodology, we developed an RND model to produced an optimum C&D waste logistics network design including best location and number of landfills and treatment plants.

In order to evaluate the impact of environmental policies and carbon tax policy on the recycling rate of C&D waste and carbon emissions, we selected three important parameters in the model for sensitivity analysis. The results showed that the combination policy including penalty and landfill fee has double efficacy on increasing the recycling rate of C&D waste. On the other hand, the carbon-tax analysis demonstrates that the carbon tax policy can effectively reduce carbon emissions, but will reduce the recycling rate due to the increase in recycling costs of C&D waste. Based on the particular situations in different regions, governments in different countries can develop different environment policies and carbon tax policies to improve the recycling rate of C&D waste and reduce environmental pollution. Although this paper focuses on a case study of recycling C&D waste in Shenzhen, China, the application of the RND model proposed is not limited to this country. While some specific values of this approach would depend on practical application, the model and the analysis provided here are general enough to be applied to other waste recycling studies to assess their performance in terms of cost and carbon emissions.

This model could be extended to include more environmental policies such as subsidies for recycling of C&D waste, as the recycling cost for C&D waste could be reduced through government support. Moreover, the value appeals of different stakeholders, the carbon emissions from the final disposal facilities and profit from C&D waste remanufactured products should be considered in the future.

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REFERENCE

Abou Najm, M., M. El-Fadel, G. Ayoub, M. El-Taha, and F. Al-Awar. 2002. "An optimisation model for regional integrated solid waste management I. Model formulation," *Waste Management & Research*, 20: 37–45.

Achillas, Ch, Ch Vlachokostas, D. Aidonis, N. Moussiopoulos, E. Iakovou, and G. Banias. 2010. "Optimising reverse logistics network to support policy-making in the case of Electrical and Electronic Equipment," *Waste Management*, 30: 2592–600.

Ajayi, Saheed O., Lukumon O. Oyedele, Muhammad Bilal, Olugbenga O. Akinade, Hafiz A. Alaka, Hakeem A. Owolabi, and Kabir O. Kadiri. 2015. "Waste effectiveness of the construction industry: Understanding the impediments and requisites for improvements," *Resources, Conservation and Recycling*, 102: 101–12.

Baroni, G., and S. Tarantola. 2014. "A General Probabilistic Framework for uncertainty and global sensitivity analysis of deterministic models: A hydrological case study," *Environmental Modelling & Software*, 51: 26–34.

Barros, A. I., R. Dekker, and V. Scholten. 1998. "A two-level network for recycling sand: A case study," *European Journal of Operational Research*, 110: 199–214.

Esa, Mohd Reza, Anthony Halog, and Lucia Rigamonti. 2017. "Strategies for minimizing construction and demolition wastes in Malaysia," *Resources, Conservation and Recycling*, 120: 219–29.

Fei, Fan, Lili Qu, Zongguo Wen, Yanyan Xue, and Huanan Zhang. 2016. "How to integrate the informal recycling system into municipal solid waste management in developing countries: Based on a China's case in Suzhou urban area," *Resources, Conservation and Recycling*, 110: 74–86.

Hao, Jane L., Martin J. Hills, and Vivian W. Y. Tam. 2008. "The effectiveness of Hong Kong's Construction Waste Disposal Charging Scheme," *Waste Management & Research*, 26: 553–58.

Harijani, Ali Mirdar, Saeed Mansour, and Behrooz Karimi. 2017. "A multi-objective model for sustainable recycling of municipal solid waste," *Waste Management & Research*, 35: 387–99.

Jeihoonian, Mohammad, Masoumeh Kazemi Zanjani, and Michel Gendreau. 2016. "Stochastic programming approach for closed-loop supply chain network design under uncertain quality status." In *6th International Conference on Information Systems, Logistics and Supply Chain, ILS 2016, June 1, 2016—June 4, 2016*. Bordeaux, France: International Conference on Information Systems, Logistics and Supply Chain.

Jia, Shuwei, Guangle Yan, Aizhong Shen, and Jun Zheng. 2017. "Dynamic simulation analysis of a construction and demolition waste management model under penalty and subsidy mechanisms," *Journal of Cleaner Production*, 147: 531–45.

Kazemi, Nima, Nikunja Mohan Modak, and Kannan Govindan. 2018. "A review of reverse logistics and closed loop supply chain management studies published in IJPR: a bibliometric and content analysis," *International Journal of Production Research*, 1–24.

Kylili, Angeliki, and Paris A. Fokaides. 2017. "Policy trends for the sustainability assessment of construction materials: A review," *Sustainable Cities and Society*, 35: 280–88.

Min, H., H. J. Ko, and C. S. Ko. 2006. "A genetic algorithm approach to developing the multi-echelon reverse logistics network for product returns," *Omega-International Journal of Management Science*, 34: 56–69.

Munster, Marie, and Peter Meibom. 2011. "Optimization of use of waste in the future energy system," *Energy*, 36: 1612–22.

Poon, C. S., Ann T. W. Yu, and L. Jaillon. 2004. "Reducing building waste at construction sites in Hong Kong," *Construction Management and Economics*, 22: 461–70.

Poon, C. S., Ann T. W. Yu, Agnes Wong, and Robin Yip. 2013. "Quantifying the Impact of Construction Waste Charging Scheme on Construction Waste Management in Hong Kong," *Journal of Construction Engineering and Management*, 139: 466–79.

Schultmann, F., B. Engels, and O. Rentz. 2003. "Closed-loop supply chains for spent batteries," *Interfaces*, 33: 57–71.

Sinha, Vinita, and R Singh. 2009. "Immunological role of hardiness on depression," 31: 39–44.

Tam, Vivian W. Y., Jingru Li, and Hong Cai. 2014. "System dynamic modeling on construction waste management in Shenzhen, China," *Waste Management & Research*, 32: 441–53.

Tan, Sie Ting, Chew Tin Lee, Haslenda Hashim, Wai Shin Ho, and Jeng Shiun Lim. 2014. "Optimal process network for municipal solid waste management in Iskandar Malaysia," *Journal of Cleaner Production*, 71: 48–58.

Trochu, Julien, Amin Chaabane, and Mustapha Ouhimmou. 2018. "Reverse logistics network redesign under uncertainty for wood waste in the CRD industry," *Resources Conservation and Recycling*, 128: 32–47.

Washington, I. D., and C. L. E. Swartz. 2017. "A parallel structure exploiting nonlinear programming algorithm for multiperiod dynamic optimization," *Computers & Chemical Engineering*, 103: 151–64.

Wolfsberger, Tanja, Michael Pinkel, Stephanie Polansek, Renato Sarc, Robert Hermann, and Roland Pomberger. 2016. "Landfill mining: Development of a cost simulation model," *Waste Management & Research*, 34: 356–67.

Xu, Jiuping, Yi Shi, and Siwei Zhao. 2018. "Reverse Logistics Network-Based Multiperiod Optimization for Construction and Demolition Waste Disposal," *Journal of Construction Engineering and Management*, 145.

Xu, Zhitao, Adel Elomri, Shaligram Pokharel, Qin Zhang, X. G. Ming, and Wenjie Liu. 2017. "Global reverse supply chain design for solid waste recycling under uncertainties and carbon emission constraint," *Waste Management*, 64: 358–70.

Yadav, Vinay, Subhankar Karmakar, A. K. Dikshit, and Shivkumar Vanjari. 2016. "A feasibility study for the locations of waste transfer stations in urban centers: a case study on the city of Nashik, India," *Journal of Cleaner Production*, 126: 191–205.

Yuan, H. P., L. Y. Shen, Jane J. L. Hao, and W. S. Lu. 2011. "A model for cost-benefit analysis of construction and demolition waste management throughout the waste chain," *Resources, Conservation and Recycling*, 55: 604–12.

Yuan, Hongping, and Jiayuan Wang. 2014. "A system dynamics model for determining the waste disposal charging fee in construction," *European Journal of Operational Research*, 237: 988–96.

Zarbakhshnia, Navid, Hamed Soleimani, Mark Goh, and Seyyedeh Sara Razavi. 2019. "A novel multi-objective model for green forward and reverse logistics network design," *Journal of Cleaner Production*, 208: 1304–16.

Zhao, W., R. B. Leeftink, and V. S. Rotter. 2010. "Evaluation of the economic feasibility for the recycling of construction and demolition waste in China-The case of Chongqing," *Resources Conservation and Recycling*, 54: 377–89.