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Urban Construction Waste Recycling Path: Robust Optimization

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Abstract: The world produces a huge amount of urban construction waste each year. Scientific planning of the construction waste recycling path is urgently needed to improve the recycling of construction waste. Existing construction waste recycling models do not pay sufficient attention to the uncertainty of the recycling quantity, which limits their ability to provide support for solving practical problems. The purpose of this paper is to solve the problem of uncertain recycling quantities in optimizing the urban construction waste recycling path. Thus, this paper first builds a recycling model for a deterministic environment with the economic objective as the decision criterion and the transportation flow, construction waste treatment capacity and capability, and environmental and social impact as the constraints. Then, a robust optimization method is adopted to optimize the deterministic model for the uncertainty of the recycling quantity. The data of this paper are from Nanjing, China. The validity of the model and the evolution of the recycling path are tested based on the data of Nanjing. The findings of this paper are as follows: Firstly, the robust model is cost-effective in the face of uncertainty in supply. Secondly, the robust model has greater total treatment capacity. Even in the worst-case scenario, it can guarantee a higher treatment capacity. Thirdly, both models follow the proximity principle which reduces the transportation costs and only slowly increases the total cost of the robust model. This paper provides a scientific and convenient tool to plan the recycling path of construction waste in large cities.

Keywords: construction waste; recycling path; uncertainty; robust optimization

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1. Introduction

The world produces a huge amount of urban construction waste each year. The Asia-Pacific region accounts for 23% of global construction waste generation, and China is the largest producer of construction waste in the East Asian region [1]. As in many other countries around the world, the construction industry is a pillar of China's economy, but it also places a heavy burden on the environment [2,3]. The urbanization rate in China has increased by approximately 30% in the last two decades, which results in an enormous amount of construction waste. Approximately 30–40% of the world's annual construction waste is reportedly generated in China [4]. This situation will likely become even more critical with the rapid growth of the construction industry and increasing levels of urbanization [5]. Therefore, how to scientifically dispose of the massive amount of construction waste generated in the city and improve its reutilization rate has become an urgent problem to be solved in the construction industry. Implementing a comprehensive conservation strategy, promoting the economical and intensive use of all types of resources, and accelerating the construction of a waste recycling system are important measures to accelerate the transformation of China's green development.

The study of the existing construction waste recycling system shows that China has basically reduced construction waste, but the reutilization rate of construction waste remains low [6]. At present, the construction waste reutilization technology of China is relatively mature [7,8], so to improve the construction waste recycling efficiency is to solve the problem of low reutilization rate of construction waste. The low recycling efficiency is due to various reasons, among which the most critical problem is the difficulty of recycling raw materials due to unreasonable transport path planning [9,10]. Construction waste recycling has multiple links, and high complexity and uncertainty in the recycling environment [11]. Therefore, construction waste recycling path planning is a strategic decision and the first task of construction waste management.

The purpose of this paper is to solve the problem of uncertain recycling quantities in optimizing urban construction waste recycling path. There are many scholars working on construction waste recycling, but there are very few studies on the optimization of construction waste recycling path considering uncertainties [12]. And existing research on the optimization of construction waste recycling path in uncertain environments has obvious shortcomings in model design and optimization, which limits its ability to provide decision support for solving practical problems. Referring to previous literature [13], the hypotheses of this paper were developed with the following in mind: (1) disregarding the illegal part; (2) transport without loss and at the same speed; (3) costs are linearly related to distance and quantities; (4) no difference in technology, but treatment capacity and capability are limited; (5) no direct landfill [14]. Based on previous research, this study investigates four aspects of construction waste recycling: (1) the method to ensure that the majority of construction waste is recycled; (2) the impact of uncertainties in waste recycling; (3) the characterization of the impact of uncertainties on the transport path; (4) the optimization of the transport path considering the uncertainties.

This paper investigates the robust optimization of construction waste recycling in an uncertain environment and explores the influence of uncertainty on the total cost and recycling path selection. Based on the reality in China, this paper first builds a recycling model in a deterministic environment with the economic objective as the decision criterion and the transportation flow, construction waste treatment capacity and capability, and environmental and social impact as the constraints. Then, the model is optimized by a robust optimization method to solve the uncertainty of the recycling quantity in the construction waste recycling path model. Finally, the validity of the model and evolution of the recycling path are examined in terms of total cost and treatment capacity.

2. Literature Review

2.1. Design of the Construction Waste Recycling Path in a Deterministic Environment

Without considering the uncertainty of the recycling environment, the design of the recycling path for construction waste mainly considers two aspects: (1) the flow among supply sites, treatment plants, and landfill sites, and the waste treatment capacity and capability of all sites; (2) the demands of construction waste recycling stakeholders [15,16]. Stakeholders in construction waste recycling include the construction side (supply side), treatment plant (demand side), and local government, all of which have different interests. The construction side needs lower costs to dispose construction waste; treatment plants need more raw materials for production. However, because of the high cost of disposal, the construction sides are often reluctant to send construction waste to treatment plants, which are located very far away from them. Instead, they choose to dispose the waste in landfill sites, which causes a shortage of raw materials for treatment plants. Therefore, the main objective in the design of the construction waste recycling path is the economic objective of the stakeholders [17]. In addition, the government will intervene in the construction waste recycling as necessary based on environmental and social objectives [18]. Based on these considerations, scholars have mostly used transportation flow, and construction waste treatment capacity and capability as the main constraints.

Most scholars use economic, social, and environmental criteria as the decision criteria of the construction waste recycling path model in a deterministic environment, but there are some differences in the combination of decision criteria. For example, Pan considered the conflict between the objectives of different stakeholders and the dynamic decision-making environment of the construction industry, and they developed a multi-period multi-objective mixed-integer linear programming model using economic criteria such as the profit and cost as the decision criteria [19]. Galan used the total cost and environmental impact as decision criteria and used optimization models to determine the corresponding allocation paths [20]. Li constructed an optimization model for regional construction waste reduction and logistics recycling using economic, environmental, and social criteria as decision criteria [21]. There is currently an imbalance in these three main decision criteria (economic, social, and environmental) [22]. Economic criteria are the key criteria that are commonly considered in the design of the construction waste recycling path and the main objective of the recycling model. Referring to the regulatory documents on construction waste disposal issued by various cities in China, the government requires that construction waste recycling does not exceed a certain limit in terms of environmental and social objectives instead of pursuing the lowest environmental and social impact. Therefore, this paper argues that economic criteria should be used as the decision criterion, and environmental and social impact should be the limiting constraints to construct the model.

2.2. Optimizing Construction Waste Recycling Path in an Uncertain Environment

In practice, there are many uncertainties in the construction waste recycling environment, so some scholars have examined the optimization of the construction waste recycling path in uncertain environments. Barros developed a two-stage model for the problem of increasing the supply of sand from construction waste and used a heuristic algorithm to optimize it [23]. Shi considered the uncertainty of waste yield and proposed a multi-objective model that combined the genetic algorithm and probabilistic robust optimization [24]. Hiete studied the optimization of construction waste recycling paths based on the uncertainty of construction waste landfill costs [25]. Rahimi studied the uncertainty of recycling demand and developed a multi-objective multi-period mixed-integer programming model [26]. Trochu considered the uncertainty in the quality of recovery and used scenario analysis to assess the impact of uncertainty on the recovery pathway [27]. The current research results on the optimization of the construction waste recycling path in uncertain environments mainly focus on the uncertainty of the recycling quantity, quality, and demand. However, this paper only considers the uncertainty of the quantity based on the following considerations: (1) as long as the quality of reutilization products reach the required standards, they are not different from the products supplied by general material suppliers; (2) a large quantity of materials is used in new construction, renovation and expansion, and decoration and renovation projects in China, and the reutilization products produced by treatment plants only account for a small proportion; (3) reutilization products are supported by government subsidies and policies, so the uncertainty in demand for reutilization products has less impact on the construction waste recycling path. Therefore, the uncertainty of the recycling quantity is key to the optimization of the construction waste recycling path.

2.3. Optimization Methods

Some researchers assume that the probability distribution of uncertain parameters on the supply side of construction waste is known and use stochastic programming to solve it [28]. However, in practice, the quantity of recycled construction waste is influenced by the front-end and a combination of disposal charging mechanisms and systems for reduction, reutilization, and landfill. In the real world, it is difficult to obtain sufficient information on uncertain parameters and variables. As a result, the probability distribution of construction waste generation is often difficult to accurately estimate in advance. Another group of researchers has argued that the probability distribution of uncertain parameters on the supply side of construction waste is unknown, and a sensitivity analysis can be used to test the immunity of facility siting to changes in parameters and to assess the corresponding changes in costs [23]. In addition, if the model has multiple parameters of uncertainty, the study can use a scenario analysis to compare and select the optimal decision behavior in a set of contexts [25]. However, to find an optimal solution, the proposed methods must rely on at least a given set of parameters. Furthermore, the sensitivity analysis and scenario analysis are post-optimization methods that do not address the effects of uncertainty in the planning phase. To overcome these limitations, Gabrel and Alumur introduced robust optimization in solving the uncertainty problem, where they argued that the robust solution had better worst-case performance than the solution of the deterministic model [29,30]. The advantages of robust optimization are that the distribution of uncertain parameters does not need to be estimated, and bounds on the uncertainty set can be derived from coarse historical data [31]. This method can improve the robustness of the model and reduce the worst cost or regret value of parameter variation. Some scholars have introduced robust optimization methods to explore the problem of optimizing the construction waste recycling path in uncertain environments, but the relevant research results are relatively few and not sufficiently in-depth.

3. Materials and Methods

3.1. Case City Overview

In this paper, Nanjing is selected to test the model. Nanjing is the core city of the Yangtze River Delta economic zone in China, with 11 districts and a large population (9,343,400 inhabitants at the end of 2022). The urbanization rate has increased by nearly 10% in the last 10 years, and the rate of urban expansion has increased, which results in a large amount of construction waste. According to the Nanjing Municipal Construction Committee, in 2021, Nanjing received 2.08 million tons of construction waste and release 1.95 million tons with a reutilization rate of 94%. In 2022, the Ministry of Ecology and Environment of China issued the "Work Plan for the Construction of Waste-free Cities in the 14th Five-Year Plan Period", and Nanjing was included in the list of Waste-free Cities in the 14th Five-Year Plan Period. How to improve the level of reutilization of construction waste is an urgent issue for Nanjing's urban construction waste management. At present, there are 19 candidate sites for treatment plants in Nanjing (all sites are taken from the 14th Five-Year Plan for Harmless Treatment of Domestic Waste in Nanjing) and 5 landfill sites (all sites are outside Nanjing and selected by government). To facilitate the calculation, the center of each district is assumed to be the supply site, and Figure 1 shows the locations of the supply sites, treatment plant candidate sites, and landfill sites.

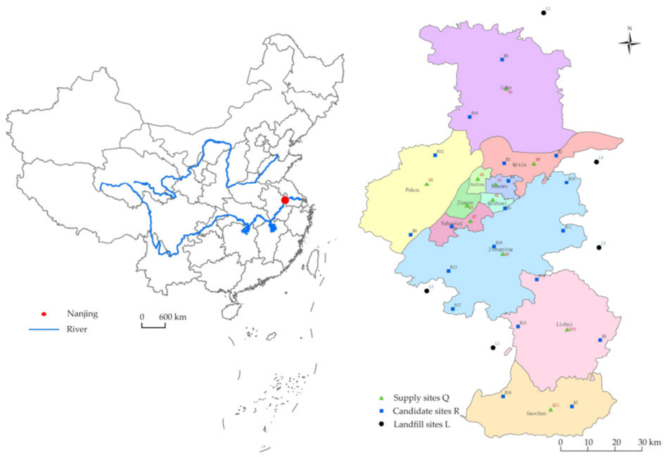

Figure 1. Location of construction waste disposal facilities in Nanjing.

3.2. Model Parameters and Data Sources

The robust optimization model for the construction waste recycling path involves 11 parameters. Table 1 shows the sources of the relevant parameters.

Table 1. Data sources.

Symbols	Meaning	Data Sources
i	Supply sites	The data are from the map of Nanjing, selected from the center of each administrative district [32].
j	Candidate sites for treatment plants	The data are from the "14th Five-Year Plan for Harmless Treatment of Domestic Waste in Nanjing" [33].
q_i	Supply of construction waste at point i	Urban construction waste supply (tons/year) = number of inhabitants or households in the city or region × number of people or households per unit construction waste generation base (0.5–1.0 t/year). The data are from Nanjing Statistical Yearbook 2021 [34], with a value of 0.5 t per capita construction waste generation.
r c_2 c_3 c_4	Rate of residue Unit transportation costs Unit treatment cost Unit landfill costs	The rate of residue is 10%, the unit transportation cost is CNY 1/t, the unit treatment cost at the treatment plant is CNY 15/t and the unit landfill cost at the landfill site is CNY 150/t. The data are from the January 2022 investigation.
m V_m	Landfill sites Maximum capacity of the landfill at point m	The data are from the public information on disposal sites published by the Nanjing Municipal Bureau of Urban Management [35].
c_1 G_j	Construction costs of the treatment plant at point j Design capacity of treatment plant at point j	The data are from the environmental impact reports of various construction waste reutilization projects [36].
d_{ij} d_{jm}	Distance from point i to point j Distance from point j to point m	The data are from Google Maps [37].

3.3. Single-Objective Planning Model in a Deterministic Environment

In reality, there is a high degree of uncertainty in the quantity of construction waste to recycle. To improve the reliability and operational efficiency of construction waste recycling in an uncertain environment, this paper develops a robust optimization model for an unknown probability distribution of the construction waste recycling quantity. In the first stage, a single-objective planning model is developed for a deterministic environment to minimize the total cost (including the construction cost of building a construction waste treatment plant, treatment cost, transportation cost, and landfill cost) by reasonably planning the location of construction waste treatment facilities and allocating the transport paths of construction waste. In the second stage, the model is transformed into a robust optimization model using a robust optimization method.

3.3.1. Underlying Hypotheses of the Model

In order to facilitate the building of the model, a simplification of the real environment is made in this paper. It includes recycling process, transportation speed, treatment technology, treatment site capacity, treatment site volume, and cost. The following 10 hypotheses are made in this paper.

Hypothesis 1. *Illegal landfills and long-term stockpiling of construction waste are excluded.*

Hypothesis 2. *There is no loss of total construction waste during recycling, disposal, and landfill after generation.*

Hypothesis 3. *The speed is fixed for all vehicles during transport.*

Hypothesis 4. *Treatment plants have treatment costs, which are linearly related to the volume of construction waste.*

Hypothesis 5. *Transportation costs are linearly related to the quantity and distance; the cost per unit distance transported per unit mass of construction waste is known and does not change over a period of time.*

Hypothesis 6. *Landfill costs are linearly related to the volume of construction waste.*

Hypothesis 7. *Construction waste treatment facilities and landfill sites have capacity constraints.*

Hypothesis 8. *The total treatment capacity of plants can satisfy the maximum generated amount of construction waste.*

Hypothesis 9. *Treatment plants use the same treatment technology.*

Hypothesis 10. *All generated construction waste is transported to a treatment plant before being sent to a landfill.*

Table 2 shows the symbols and meanings of the relevant parameters of the model.

Table 2. Parameter symbols and meanings.

Symbols		Meanings
Collection	I	Set of potential construction waste supply sites; each element of the set is denoted by i
	J	Set of potential construction waste treatment plants; each element of the set is denoted by j
	M	Set of potential landfill sites; each element of the set is denoted by m
Parameter	q_i	Amount of construction waste supplied at site i
	c_1	Construction cost of treatment plant j
	G_j	Design treatment capacity at treatment plant j
	r	Rate of construction waste treatment residue
	c_2	Unit transportation cost; the transportation cost per unit mass of waste is proportional to the distance traveled
	c_3	Unit treatment cost of treatment plant j
	c_4	Unit landfill cost of landfill m
	V_m	Maximum capacity of landfill m
	d_{ij}	Distance from i to j
	d_{jm}	Distance from j to m
	$u_{ij}{}'$	Transport capacity of construction waste from i to treatment plant j
	u_{ij}	Actual amount of construction waste transported from i to treatment plant j
	$u_{jm}{}'$	Transport capacity of construction waste from j to landfill m
	u_{jm}	Actual quantity of construction waste transported from j to landfill m
Decision variable	X_j	1 if the treatment plant is established at j; 0 otherwise
	T_{ij}	1 if supply site i is assigned to j; 0 otherwise
	Y_{jm}	1 if the treatment plant is assigned to m; 0 otherwise

3.3.2. Objective Function of the Model

(a) Facility construction costs

Because off-site sorting facilities and landfills are not considered, the construction costs of the facilities are specifically the construction costs of treatment plants.

$$\text{Facility construction costs} = \sum_{j}^{J} X_j * c_1 \quad (1)$$

(b) Transportation costs

Transportation costs include the transportation cost of construction waste and transportation cost of residues, and the transportation cost of reutilization products is not considered. The transportation cost of construction waste is the transportation cost per unit weight of each type of construction waste from path *i* to *j* multiplied by the quantity of waste. The transportation cost of residues is the transportation cost per unit weight of residues from path *j* to *m* multiplied by the quantity of residues.

$$\text{Transportation costs} = \sum_{i}^{I}\sum_{j}^{J} q_i * c_2 * d_{ij} * T_{ij} + \sum_{i}^{I}\sum_{j}^{J}\sum_{m}^{M} u_{ij} * c_2 * d_{jm} * r * Y_{jm} \tag{2}$$

(c) Treatment costs

Treatment costs include the cost of construction waste disposal and final landfill of residues. The model does not account for the cost of storage of construction waste in logistics facilities.

$$\text{Treatment costs} = \sum_{i}^{I}\sum_{j}^{J} q_i * c_3 * T_{ij} + \sum_{i}^{I}\sum_{j}^{J}\sum_{m}^{M} u_{ij} * c_4 * r * Y_{jm} \tag{3}$$

(d) Total cost

The total cost includes the construction cost of plants, transportation costs, and treatment costs, so the total cost is calculated as the sum of Equations (1)–(3). The objective of the model is to minimize the total cost, and the objective function is as follows.

$$\begin{aligned} &min\ \text{Total cost} = min(\sum_{j}^{J} X_j * c_1 + \sum_{i}^{I}\sum_{j}^{J} q_i * c_2 * d_{ij} * T_{ij} \\ &+\sum_{i}^{I}\sum_{j}^{J} q_i * c_3 * T_{ij} + \sum_{i}^{I}\sum_{j}^{J}\sum_{m}^{M} u_{ij} * c_2 * d_{jm} * r * Y_{jm} + \sum_{i}^{I}\sum_{j}^{J}\sum_{m}^{M} u_{ij} * c_4 * r * Y_{jm}) \end{aligned} \tag{4}$$

3.3.3. Constraints of the Model

(a) Flow balance constraint

$$\sum_{i}^{I} q_i * T_{ij} = \sum_{i}^{I} u_{ij} \tag{5}$$

$$r * \sum_{i}^{I} u_{ij} = \sum_{m}^{M} u_{jm} \tag{6}$$

Constraint (5) ensures that the amount of construction waste sent from supply point *i* to treatment plant *j* is balanced with the amount of generated construction waste. Constraint (6) ensures that the amount of residues sent to landfill *m* from treatment plant *j* is balanced with the amount of residues generated by treatment plant *j*.

(b) Capacity and capability constraints

$$u_{ij} \leqslant u_{ij}^{'} \tag{7}$$

$$\sum_{i}^{I} u_{ij} \leqslant G_j \tag{8}$$

$$\sum_{m}^{M} u_{jm} \leqslant r * G_j \tag{9}$$

$$u_{jm} \leqslant u_{jm}^{'} \tag{10}$$

$$\sum_{j}^{J} u_{jm} \leqslant V_m \tag{11}$$

Constraint (7) ensures that the quantity transported from i to j does not exceed the transport capacity from i to j. Constraint (8) ensures that the quantity transported from i to j does not exceed the design capacity of treatment plant j. Constraint (9) ensures that the amount of waste transported from j to m does not exceed the quantity of residues generated at the design capacity of treatment plant j. Constraint (10) ensures that the actual quantity transported from j to m does not exceed the transport capacity from j to m. Constraint (11) ensures that the actual quantity transported to m does not exceed the capacity of landfill m.

(c) Environmental and social impact constraints

$$\sum_{i}^{I} q_i * 10\% \geqslant \sum_{j}^{J} \sum_{m}^{M} u_{jm} \tag{12}$$

$$\sum_{i}^{I} \frac{u_{ij}}{20,000} * 0.0021 \leqslant 4.61 * 8 * 365 \tag{13}$$

Constraint (12) ensures that more than 90% of construction waste is recycled. Constraint (13) ensures that NOx emissions do not exceed the specified limit. For every 20,000 tons of construction waste processed, approximately 0.0021 tons of NOx are generated, and the permitted emission standard is 4.61 kg/h, assuming an 8 h day and 365 days of operation. The annual emission levels of treatment plants must be less than the maximum allowable emission level.

$$T_{ij}, X_j, Y_{jm} \in \{0, 1\} \tag{14}$$

$$u_{ij}, u_{jm} \geqslant 0, \forall j \in J, \forall i \in I, \forall m \in M \tag{15}$$

In addition to these three main components, it is necessary to ensure that the transport time avoids peak traffic hours. For example, in the case city of Nanjing, the transport time is set between 22:00 and 6:00 the next day. The transport path should be determined by the local construction waste authority in conjunction with the traffic management department and should generally avoid the main roads of the city. A receipt must be issued to the landfill site for inspection by the construction waste authority.

3.4. Robust Optimization Model in Uncertain Environments

Robust optimization is a minimization problem, where the idea is to consider the worst-case optimization of uncertain parameters in a model. The most important thing to consider in robust optimization is the problem of inscribing the uncertainty set into the corresponding robust inequality. Robust optimization is semi-infinite and generally difficult to directly solve, so the original model must be transformed into a robust optimization model that can be solved in polynomial time. In this paper, we choose the interval robust optimization method proposed by Soyster [38] to solve the problem.

Equations (16)–(25) are templates for robust optimization. The linear programming problem considered by Soyster is as follows:

$$min cx + d \tag{16}$$

$$s.t. Ax \leqslant b \tag{17}$$

$$1 \leqslant x \leqslant u \tag{18}$$

Assume that the uncertain parameters occur only in matrix A and the uncertainty does not affect the elements of the columns in matrix A. Consider a coefficient matrix A where row i is subject to uncertainty perturbation and the uncertainty parameter is in column j. Assume that the uncertain parameters vary in a particular bounded closed space, $u_{Box} = \left\{ \left| \widetilde{a}_{ij} - a_{ij} \right| \leqslant \hat{a}_{ij} \right\}$. $\widetilde{a}_{ij}$ is the uncertain parameter in row i and column j, a_{ij} is the regular value unaffected by the perturbation, $\hat{a}_{ij}$ is the fluctuation range, and $\hat{a}_{ij} = \rho a_{ij}$.$\rho \in [0, 1]$ is the level of uncertainty. When $\rho = 0$, $\hat{a}_{ij} = 0$, there is no range of fluctuation. When $\rho \in (0, 1]$, the uncertainty parameter $\widetilde{a}_{ij} \in \left[(1-\rho)a_{ij}, (1+\rho)a_{ij} \right]$, where the relative deviation of $\widetilde{a}_{ij}$ from a_{ij} is ρ. Let $\eta_{ij} = \frac{\left(\widetilde{a}_{ij} - a_{ij} \right)}{\hat{a}_{ij}}$ be a [−1,1] symmetrically distributed random variable with a robust reciprocal model as follows:

$$min c_j * x_j \tag{19}$$

$$s.t. \sum_{j}^{J} a_{ij} * x_j + \sum_{j}^{J} \hat{a}_{ij} * y_j \leqslant b_i, \forall i \tag{20}$$

$$-y_j \leqslant x_j \leqslant y_j, \forall j \tag{21}$$

$$1 \leqslant x \leqslant u \tag{22}$$

$$y_j \geqslant 0, \forall j \tag{23}$$

Suppose that x^* is an optimal solution to the problem. When the optimal solution is obtained, $y_j = |x_j^*|$; then,

$$s.t. \sum_{j}^{J} a_{ij} * x_j + \sum_{j}^{J} \hat{a}_{ij} * \left| x_j \right| \leqslant b_i, \forall i \tag{24}$$

For any real value of the uncertain parameter $\widetilde{a}_{ij}$, the optimal solution is a feasible solution as follows.

$$\sum_{j}^{J} \widetilde{a}_{ij} * x_j = \sum_{j}^{J} a_{ij} x_j + \sum_{j}^{J} \eta_{ij} \hat{a}_{ij} x_j \leqslant \sum_{j}^{J} a_{ij} x_j + \sum_{j}^{J} \hat{a}_{ij} \left| x_j \right| \leqslant b_i \tag{25}$$

Thus, through the transformation of the robust correspondence inequality, there is sufficient redundancy immune to uncertain perturbations between b_i and $\sum_{j}^{J} a_{ij} x_j$ to provide complete protection against them. In addition, the above equation shows a significant gap between $\sum_{j}^{J} \widetilde{a}_{ij} x_j$ and b_i, which makes the objective function too large and the results too conservative for the minimization problem. However, construction waste recycling is unique in that when recycling activities cannot continue, the accumulation of construction waste can lead to greater losses, so it is necessary to ensure that recycling activities can be maintained even in the worst case. Therefore, the conservatism of Soyster's method becomes an advantage for construction waste recycling, so this paper chooses to use Soyster's robust optimization method.

Based on the above discussion, as shown in Equation (26), this paper obtains a new Constraint (27) by defining a new variable Z and introducing the objective function into the constraint. For the uncertain parameters in Constraint (5), the model transforms the equation constraint into a set of inequality constraints (28). This transformation has no effect on the formation of the feasible domain. Thus, the model in Section 2.1 can be rewritten in the following form:

$$minZ \tag{26}$$

$$\begin{aligned} Z \geqslant \sum_{j}^{J} X_j * c_1 + \sum_{i}^{I}\sum_{j}^{J} q_i * c_2 * T_{ij} + \sum_{i}^{I}\sum_{j}^{J} q_i * c_3 * T_{ij} \\ + \sum_{i}^{I}\sum_{j}^{J}\sum_{m}^{M} u_{ij} * c_2 * r * Y_{jm} + \sum_{i}^{I}\sum_{j}^{J}\sum_{m}^{M} u_{ij} * c_4 * r * Y_{jm} \end{aligned} \tag{27}$$

$$\sum_{i}^{I} q_i T_{ij} \leqslant \sum_{i}^{I} u_{ij} \tag{28}$$

Next, a robust correspondence inequality is developed for constraints with uncertain parameters using Soyster's robust optimization techniques. This model can be rewritten as follows:

$$\begin{aligned} Z \geqslant \sum_{j}^{J} X_j * c_1 + \sum_{i}^{I}\sum_{j}^{J} q_i * (c_2 + c_3) * T_{ij} + \sum_{i}^{I}\sum_{j}^{J} \hat{q}_i * (c_2 + c_3) * y_{ij} \\ + \sum_{i}^{I}\sum_{j}^{J}\sum_{m}^{M} u_{ij} * c_2 * r * Y_{jm} + \sum_{i}^{I}\sum_{j}^{J}\sum_{m}^{M} u_{ij} * c_4 * r * Y_{jm} \end{aligned} \tag{29}$$

$$-y_{ij} \leqslant T_{ij} \leqslant y_{ij} \tag{30}$$

$$\sum_{i}^{I} q_i T_{ij} + \sum_{i}^{I} \hat{q}_i y_{ij} \leqslant \sum_{i}^{I} u_{ij} \tag{31}$$

In this paper, the amount of generated construction waste in each urban area is defined as an uncertainty parameter, which is assumed to vary in a specific bounded closed space; $u_{Box} = \left\{ \left| \widetilde{q}_i - q_i \right| \leqslant \hat{q}_i \right\}$.$q_i$ is the conventional value unaffected by perturbations, $\hat{q}_i$ is the range of fluctuations, and $\hat{q}_i = \rho q_i$. $\rho \in [0,1]$ is the level of uncertainty. When $\rho = 0$ and $\hat{q}_i = 0$, the model is deterministic. When $\rho \in (0,1]$, uncertainty parameter $\widetilde{q}_i \in [(1-\rho)q_i, (1+\rho)q_i]$.

4. Results and Discussion

This paper examines the effectiveness of the robust optimization model by comparing its performance with that of the deterministic model and investigates the reasons for the effectiveness of the robust optimization model by analyzing the evolution of the recycling path. In line with previous research, the robust optimization model and deterministic model are identical in terms of the setting of parameters and decision variables but have some differences in decision objective and constraints [39]. In the deterministic model, uncertainty level ρ of parameter q (supply) in the decision objective and constraints is 0. The deterministic model is transformed into the robust optimization model when $\rho \neq 0$. In this paper, the three uncertainty levels of 0.3, 0.6, and 0.9 are selected for the comparison [24]. In addition, the hypotheses of the robust model and deterministic model are the same [40]. Due to the capacity and treatment capacity hypothesis and the cost linearity hypothesis, the robust model may have more treatment plants, greater total treatment capacity, and greater total cost than the deterministic model [41]. This is basically consistent with previous studies, but different results may occur for different cases that are calculated in a different way.

For example, Tsai et al. used the fuzzy comprehension evaluation method to calculate their results [42]. Bavaghar used Qazvin, Iran as the case city [43]. Compared with them, this paper selects Nanjing as the case city and calculates results by using the robust optimization method. Based on the data sources of the parameters in Table 1, the CPLEX12.10.0 (a software, International Business Machines Corporation, Armonk, NY, USA) toolbox in

MATLAB 2023 Edition (an acronym for "MATrix LABoratory", MathWorks, Natick, MA, USA) was used to calculate Equations (4)–(31) to obtain the objective function values for different uncertainty levels of supply quantity q, results of the selection of the treatment plant, and results of the residue allocation [41]. Due to the use of a different case and a different calculation method, special results are obtained in this paper. Based on the results, the performance of the two models is compared, and the evolution of the recycling path is analyzed.

4.1. Performance Comparison

In the following, the performance of the robust optimization model constructed in this paper for an uncertain environment is compared with that of the model for a deterministic environment. The differences between the models are mainly compared in terms of total cost and treatment capacity.

4.1.1. Total Cost Comparison

This paper compares the total cost based on the results of the objective function values. The objective function values of the total cost for different uncertainty levels of the supply quantity q were obtained using MATLAB. Figure 2 shows the total cost of construction waste recycling. When $\rho = 0$, the generated quantity of construction waste is fixed, and the total cost of construction waste treatment is fixed at this time. When $\rho \neq 0$, the model changes from deterministic to uncertain, and the objective function value rapidly increases.

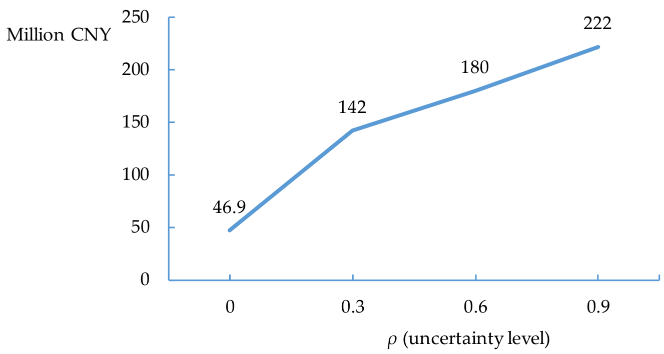

Figure 2. Total cost of construction waste recycling.

According to Figure 2, the difference in cost between the deterministic model and the robust optimization model is relatively large; in particular, the total cost increases rapidly when moving from deterministic to uncertainty. This change indicates that the model is designed to ensure the sustainability of the recycling process in the face of environmental uncertainty at the expense of cost. The total cost of construction waste recycling increases when uncertainty increases, but the total cost increases at a slower rate. Thus, the robust optimization model outperforms the deterministic model in terms of cost savings.

4.1.2. Comparison of Treatment Capacity

This paper compares the treatment capacity based on the treatment quantity of each treatment plant and the total treatment quantity. Figure 3 compares the total treatment capacity of the models based on the results of treatment plant selection output from MATLAB. The top horizontal coordinate is the total annual treatment capacity of the two models, and the sum of the annual treatment capacity of each selected site is the total annual treatment capacity of the models.

According to Figure 3, the total annual treatment capacity of construction waste for the deterministic model is 5,274,650 tons, while the robust optimization model achieves an annual treatment capacity of 7,804,650 tons. The maximum treatment capacity of construction waste in the city increases after robust optimization. The vertical coordinates are the annual treatment capacity of the candidate sites; the lower horizontal coordinates indicate candidate sites 1–19, where a candidate site with a treatment capacity of 0 indicates that the point is not selected. The graph shows that the deterministic model has 14 treatment plants, whereas the robust optimization model has 18 treatment plants. The increase in maximum amount of construction waste disposal in the city is due to the choice of opening more treatment plants, which optimizes the recycling path.

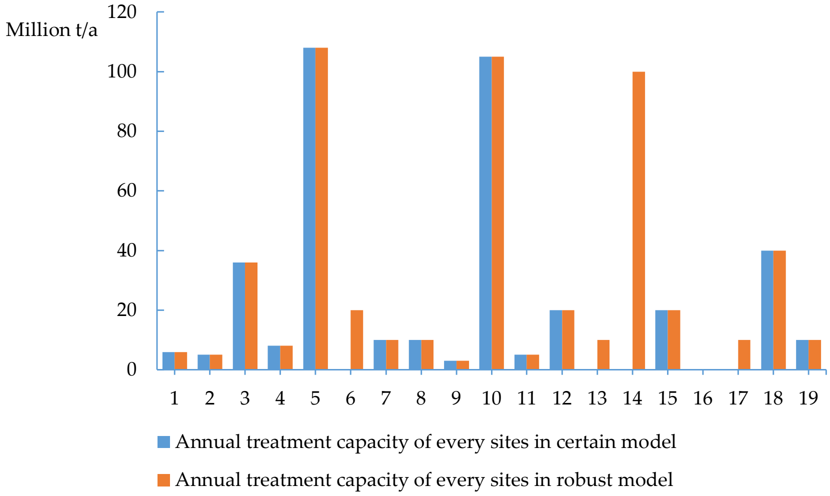

Figure 3. Comparison of the total model throughput. Note: X-axis represents treatment plants 1–19, measurement unit of Y-axis is million tons per year.

4.2. Analysis of the Evolution of the Recycling Path

In the following, the recycling path of the robust optimization model constructed in this paper for an uncertain environment is compared with that of the model for a deterministic environment. The differences between the models are mainly compared in terms of evolution of the recycling path.

4.2.1. MATLAB Calculation Results

In this paper, the evolutionary analysis of the recycling path is based on the allocation results of the treatment plant and allocation results of the landfill. Tables 3 and 4 show the results of opening and closing the construction waste treatment plants and the allocation results of the landfill output by MATLAB. In Table 3, $Q_i(R_j)$ indicates that the construction waste generated at Q_i is transported to the treatment plant at R_j. In Table 4, $R_j(L_m)$ indicates that the resource treatment plant at R_j is opened, and the residue at R_j is sent to landfill L_m.

The data in Tables 3 and 4 were processed by ArcGIS 22.0 and plotted against four levels of uncertainty in the supply of construction waste to obtain the changes in location of treatment plants and allocation of transport paths, as shown in Figure 4.

Table 3. The paths from supply sites to treatment plants under different levels of uncertainty ρ.

Uncertainty ρ	$Q_i(R_j)$
0	$Q_1(R_1R_4R_{11})Q_2(R_{17})Q_3(R_1)Q_4(R_8R_{13})Q_5(R_8R_{12})Q_6(R_2R_4R_{19})Q_7(R_1R_{13}R_{17})Q_8(R_{17}R_{18})Q_9(R_9R_{12})Q_{10}(R_7)Q_{11}(R_7)$
0.3	$Q_1(R_1R_2R_4R_8R_9R_{11}R_{17}R_{19})Q_2(R_1R_2R_4R_6R_{11}R_{12}R_{15}R_{18}R_{19})Q_3(R_1R_8R_{11}R_{13}R_{17})Q_4(R_3R_4R_6R_{11}R_{15}R_{18})$ $Q_5(R_5R_8R_{10}R_{12}R_{18})Q_6(R_2R_3R_4R_6R_{18}R_{19})Q_7(R_1R_4R_8R_{11}R_{13}R_{17}R_{18}R_{19})Q_8(R_5R_{14}R_{18})Q_9(R_1R_2R_3R_4R_8R_9R_{12}R_{18}R_{19})$ $Q_{10}(R_1R_2R_4R_6R_7R_8R_9R_{11}R_{12}R_{13}R_{15}R_{19})Q_{11}(R_1R_2R_4R_6R_7R_8R_9R_{11}R_{13}R_{15}R_{17}R_{19})$
0.6	$Q_1(R_1R_2R_4R_7R_8R_9R_{11}R_{12}R_{19})Q_2(R_2R_3R_4R_6R_7R_9R_{11}R_{12}R_{15}R_{18}R_{19})Q_3(R_1R_2R_4R_8R_{11}R_{13}R_{15}R_{17})Q_4(R_3R_4R_6R_{11}R_{13}R_{15}R_{17}R_{18})$ $Q_5(R_5R_8R_{10}R_{12}R_{14}R_{18})Q_6(R_2R_3R_4R_6R_{11}R_{12}R_{15}R_{18}R_{19})Q_7(R_1R_2R_4R_8R_{11}R_{13}R_{15}R_{17}R_{18}R_{19})Q_8(R_5R_{14}R_{18})$ $Q_9(R_1R_2R_3R_4R_8R_9R_{10}R_{12}R_{18}R_{19})Q_{10}(R_1R_2R_4R_6R_7R_8R_9R_{11}R_{12}R_{13}R_{15}R_{19})Q_{11}(R_1R_2R_4R_6R_7R_8R_9R_{11}R_{13}R_{15}R_{17}R_{19})$
0.9	$Q_1(R_1R_2R_4R_8R_9R_{11}R_{12}R_{17}R_{18}R_{19})Q_2(R_2R_3R_4R_6R_{11}R_{12}R_{15}R_{18}R_{19})Q_3(R_1R_2R_4R_8R_{11}R_{13}R_{15}R_{17})Q_4(R_3R_4R_{11}R_{12}R_{13}R_{14}R_{18})$ $Q_5(R_5R_8R_{10}R_{12}R_{14}R_{18})Q_6(R_2R_3R_4R_{12}R_{14}R_{18}R_{19})Q_7(R_1R_2R_4R_8R_{11}R_{13}R_{17}R_{18}R_{19})Q_8(R_5R_{14}R_{18})$ $Q_9(R_1R_2R_3R_4R_8R_9R_{10}R_{12}R_{18}R_{19})Q_{10}(R_1R_2R_4R_6R_7R_8R_9R_{11}R_{12}R_{13}R_{15}R_{18}R_{19})Q_{11}(R_1R_2R_4R_6R_7R_8R_9R_{11}R_{13}R_{15}R_{17}R_{19})$

Table 4. The paths from treatment plants to landfill sites under different levels of uncertainty ρ.

Uncertainty ρ	$R_j(L_m)$
0	$R_1(L_3)R_2(L_4)R_3(L_4)R_4(L_4)R_5(L_5)R_7(L_1)R_8(L_3)R_9(L_2)R_{10}(L_1)R_{11}(L_4)R_{12}(L_2)R_{15}(L_1)R_{18}(L_3)R_{19}(L_4)$
0.3	$R_1(L_3)R_2(L_4L_5)R_3(L_4)R_4(L_4L_5)R_5(L_3L_5)R_6(L_1L_5)R_7(L_1L_3L_4)R_8(L_1L_3)R_9(L_2)R_{10}(L_1L_2)R_{11}(L_4L_5)R_{12}(L_2)R_{13}(L_1L_3)$ $R_{14}(L_4L_5)R_{15}(L_1L_3)R_{17}(L_1L_3)R_{18}(L_3L_5)R_{19}(L_4L_5)$
0.6	$R_1(L_3L_5)R_2(L_4L_5)R_3(L_4L_5)R_4(L_4L_5)R_5(L_3L_5)R_6(L_1L_5)R_7(L_1L_5)R_8(L_1L_3L_4)R_9(L_1L_3)R_{10}(L_1L_2)R_{11}(L_4L_5)R_{12}(L_2L_3)$ $R_{13}(L_1L_3)R_{14}(L_4L_5)R_{15}(L_1L_3)R_{17}(L_1L_3)R_{18}(L_3L_5)R_{19}(L_4L_5)$
0.9	$R_1(L_3)R_2(L_4)R_3(L_4)R_4(L_4)R_5(L_3L_5)R_6(L_1L_5)R_7(L_1L_3L_4)R_8(L_3)R_9(L_2)R_{10}(L_1L_2)R_{11}(L_4)R_{12}(L_2)R_{13}(L_1L_3)R_{14}(L_4L_5)$ $R_{15}(L_1L_3)R_{17}(L_1L_3)R_{18}(L_3)R_{19}(L_4L_5)$

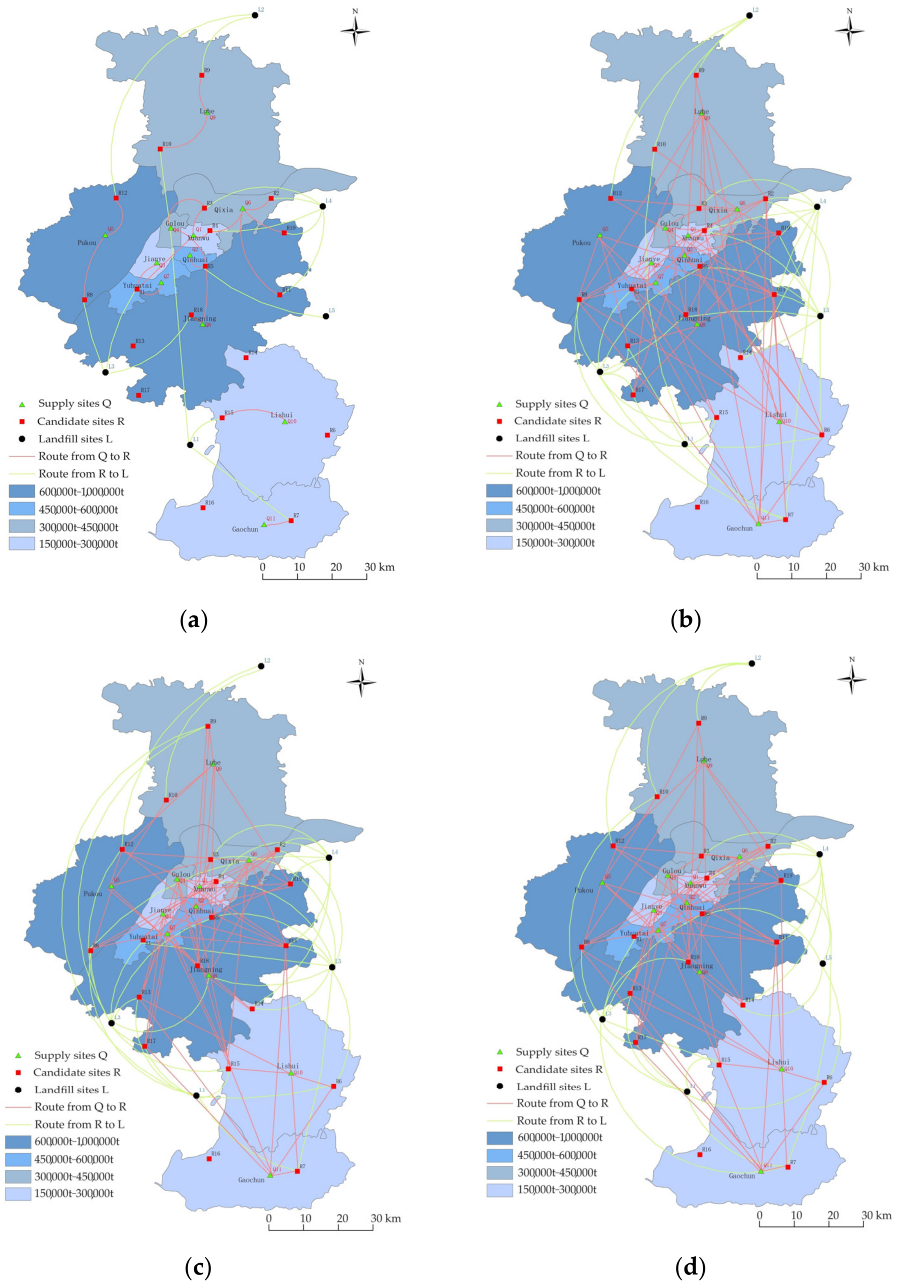

Figure 4. Location of treatment plants and allocation of transport paths under different levels of uncertainty ρ: (**a**) ρ = 0; (**b**) ρ = 0.3; (**c**) ρ = 0.6; (**d**) ρ = 0.9.

Figure 4a–d present the results for uncertainty levels ρ = 0, 0.3, 0.6, and 0.9, respectively. ρ = 0 implies no fluctuation in the amount of construction waste generated per year, and

$\rho > 0$ implies fluctuation in the amount of construction waste generated per year. A higher uncertainty level makes it more expensive to maintain the recycling operation.

4.2.2. Analysis of Results

The following is a comparative analysis of the differences in construction waste recycling under different levels of uncertainty in terms of the location of treatment plants and allocation of transport paths.

(1) Comparison of treatment plant sites under different levels of uncertainty

A comparison of Figure 4a–d shows that the deterministic model is cheaper to build than the robust optimization model due to fewer treatment plants. Therefore, in the face of supply uncertainty, the robust optimization model is immune to supply uncertainty at the cost of building additional treatment plants. When the level of uncertainty increases, Figure 4b–d show no change in the construction of treatment plants, which slows the growth of costs.

(2) Comparison of transport paths under different levels of uncertainty

In terms of transport paths, Figure 4a–d follow the approach of transporting and landfilling near the site, while a few consider long-distance transport. The transport paths in Figure 4b–d are more complex than those in Figure 4a because more treatment plants have been opened, and more proximity sites are available. The lower transportation costs of following the proximity principle enable more costs to be spent on the construction and treatment of the treatment plant, which results in higher treated volumes, higher reutilization rates, and a slower increase in total costs.

From the above analysis, the following basic conclusions can be drawn: Compared to the deterministic model, the robust optimization model accounts for the uncertainty of the generated amount of construction waste on the supply side in real environments. The generation of construction waste in China's large cities has been increasing due to the high population absorption capacity. The advantage of the robust optimization model is that it considers the worst case. Thus, even in the worst-case scenario, the recycling system can guarantee a higher treatment capacity and a higher reutilization rate while ensuring a lower growth rate of the total cost.

5. Conclusions

Scientific planning of construction waste recycling path is a priority for improving the reutilization rate of construction waste. The existing construction waste recycling models do not pay sufficient attention to the uncertainty of construction waste recycling quantity, which limits their ability to provide support for solving practical problems. In this paper, a robust optimization model for the construction waste recycling path was developed by taking into account the uncertainty of the construction waste recycling quantity. This paper first used the economic objective as the decision criterion, and the transportation flow, construction waste treatment capacity and capability, environment impact, and social impact were the constraints to build the recycling model in a deterministic environment. Then, a robust optimization method was adopted to optimize the deterministic model, and a robust optimization model was built to solve the uncertainty of the recycling quantity. Then, the validity of the model was examined in terms of total cost and treatment capacity. The evolution of the recycling path under supply uncertainty was analyzed to investigate the reasons for model optimization. The main conclusions of this paper are as follows:

1. This paper built a deterministic model and robust model considering the reality of Nanjing. The reality is generally consistent with our hypotheses. Hypotheses 1–3 hold. The robust model has a better total cost. From the deterministic model to the robust model, the total cost increases rapidly. And the total cost increases at a slower rate when uncertainty increases. Costs are linearly related to distance and quantities, so the robust model has a greater total cost than the deterministic model. Hypotheses 4–6 hold. The robust model is cost-effective in the face of uncertainty in supply.

2. The robust model has better treatment capacity. From the deterministic model to the robust model, the total treatment capacity increases rapidly due to opening more treatment plants. There is no difference in technology among the treatment plants, but treatment capacity and capability are limited. The robust model has more treatment plants, so it has greater total treatment capacity. Hypotheses 7–9 hold. The robust model is immune to supply uncertainty at the cost of building additional treatment plants. Thus, even in the worst-case scenario, it can guarantee a higher treatment capacity.
3. Both models follow the proximity principle, transporting and landfilling near the supply and treatment site, while a few other models consider long-distance transportation. This is consistent with the hypothesis that there is no direct landfill. Construction waste should be transported to treatment plants before landfilling. Hypothesis 10 holds. Compared with the deterministic model, the robust model has longer total transportation distances. However, the total cost increases very slowly, because the proximity principle significantly reduces the transportation costs and to some extent offsets the construction and treatment costs of the treatment plants, and ultimately achieves the optimization objective of the model.

The robust optimization model constructed in this paper is more in line with Chinese reality and takes into account the uncertainty of construction waste supply; therefore, the model can be used as a scientific tool for construction waste recycling path planning in large cities similar to Nanjing. At the same time, the model has the advantage of being easy to use. For the management of construction waste in other large cities, the model parameters can be modified to match and optimize the local waste transport path. This paper only investigates the uncertainty of the recycling quantity. For the subsequent study of the robust optimization of the construction waste recycling path, the uncertainty parameter can be increased to make the model more compatible with the actual situation.

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References

1. Qiao, X.; Lee, H.; Shen, Q.; Li, Y.C. Research on the Tripartite Evolutionary Game of Zero-Waste City Construction in China. *Sustainability* **2023**, *15*, 10507. [CrossRef]
2. Hu, R.; Chen, K.; Fang, W.; Zheng, L.; Xu, J. The technology-environment relationship revisited: Evidence from the impact of prefabrication on reducing construction waste. *J. Clean. Prod.* **2022**, *341*, 130883. [CrossRef]
3. Tam, V.W.Y.; Hao, J.J.L. Prefabrication as a mean of minimizing construction waste on site. *Int. J. Constr. Manag.* **2014**, *14*, 113–121. [CrossRef]
4. Jin, R.; Li, B.; Zhou, T.; Wanatowski, D.; Piroozfar, P. An empirical study of perceptions towards construction and demolition waste recycling and reuse in China. *Resour. Conserv. Recycl.* **2017**, *126*, 86–98. [CrossRef]
5. Aslam, M.S.; Huang, B.; Cui, L. Review of construction and demolition waste management in China and USA. *J. Environ. Manag.* **2020**, *264*, 110445. [CrossRef] [PubMed]

6. Wang, L.; Lv, Y.; Huang, S.; Liu, Y.; Li, X. The Evolution of Research on C&D Waste and Sustainable Development of Resources: A Bibliometric Study. *Sustainability* **2023**, *15*, 9141. [CrossRef]
7. Han, S.; Zhao, S.; Lu, D.; Wang, D. Performance Improvement of Recycled Concrete Aggregates and Their Potential Applications in Infrastructure: A Review. *Buildings* **2023**, *13*, 1411. [CrossRef]
8. Zeng, M.; Huang, H.; Zhang, X. Experiment on the Performance of Recycled Powder of Construction Waste on Adobe Materials. *Buildings* **2023**, *13*, 1358. [CrossRef]
9. Abarca-Guerrero, L.; Lobo-Ugalde, S.; Méndez-Carpio, N.; Rodríguez-Leandro, R.; Rudin-Vega, V. Zero Waste Systems: Barriers and Measures to Recycling of Construction and Demolition Waste. *Sustainability* **2022**, *14*, 15265. [CrossRef]
10. Wang, Y.; Li, H.; Xue, L.; Gou, W. The Evolution of the Construction Waste Recycling System and the Willingness to Use Recycled Products in China. *Sustainability* **2022**, *14*, 12541. [CrossRef]
11. Qun, Z.; Rong, W.L. Progress of Research on Reverse Logistics Network Design. *Chin. J. Manag. Sci.* **2016**, *24*, 165–176. [CrossRef]
12. Bao, Z.; Lee, W.M.W.; Lu, W. Implementing on-site construction waste recycling in Hong Kong: Barriers and facilitators. *Sci. Total Environ.* **2020**, *747*, 141091. [CrossRef] [PubMed]
13. Aydin, N. Designing reverse logistics network of end-of-life-buildings as preparedness to disasters under uncertainty. *J. Clean. Prod.* **2020**, *256*, 120341. [CrossRef]
14. Ma, M.; Tam, V.W.Y.; Le, K.N.; Li, W. Challenges in current construction and demolition waste recycling: A China study. *Waste Manag.* **2020**, *118*, 610–625. [CrossRef] [PubMed]
15. Lin, Z.; Xie, Q.; Feng, Y.; Zhang, P.; Yao, P. Towards a robust facility location model for construction and demolition waste transfer stations under uncertain environment: The case of Chongqing. *Waste Manag.* **2020**, *105*, 73–83. [CrossRef] [PubMed]
16. Bouzon, M.; Govindan, K.; Rodriguez, C.M.T. Evaluating barriers for reverse logistics implementation under a multiple stakeholders' perspective analysis using grey decision making approach. *Resour. Conserv. Recycl.* **2018**, *128*, 315–335. [CrossRef]
17. Hammes, G.; De Souza, E.D.; Taboada Rodriguez, C.M.; Rojas Millan, R.H.; Mojica Herazo, J.C. Evaluation of the reverse logistics performance in civil construction. *J. Clean. Prod.* **2020**, *248*, 119212. [CrossRef]
18. Chileshe, N.; Rameezdeen, R.; Hosseini, M.R.; Martek, I.; Li, H.X.; Panjehbashi-Aghdam, P. Factors driving the implementation of reverse logistics: A quantified model for the construction industry. *Waste Manag.* **2018**, *79*, 48–57. [CrossRef] [PubMed]
19. Pan, X.; Xie, Q.; Feng, Y. Designing recycling networks for construction and demolition waste based on reserve logistics research field. *J. Clean. Prod.* **2020**, *260*, 120841. [CrossRef]
20. Galan, B.; Dosal, E.; Andrés, A.; Viguri, J. Optimisation of the construction and demolition waste management facilities location in Cantabria (Spain) under economical and environmental criteria. *Waste Biomass Valori.* **2013**, *4*, 797–808. [CrossRef]
21. Li, X.; Dong, C.; Chunxiang, G.; Xinyi, S. Logistics Network Design for Construction Waste Reduction System under Multidimensional Perspective. *Syst. Eng. Theory Pract.* **2019**, *39*, 2842–2854. [CrossRef]
22. Balancing the Pillars for Sustainable Development. Available online: https://www.un.org/en/development/desa/news/sustainable/sustainable-development-pillars.html (accessed on 31 March 2023).
23. Barros, A.I.; Dekker, R.; Scholten, V. A two-level network for recycling sand: A case study. *Eur. J. Oper. Res.* **1998**, *110*, 199–214. [CrossRef]
24. Shi, Q.; Ren, H.; Ma, X.; Xiao, Y. Site selection of construction waste recycling plant. *J. Clean. Prod.* **2019**, *227*, 532–542. [CrossRef]
25. Michael, H.; Julian, S.; Jens, L. Matching construction and demolition waste supply to recycling demand: A regional management chain model. *Build. Res. Inf.* **2011**, *39*, 333–351. [CrossRef]
26. Rahimi, M.; Ghezavati, V. Sustainable multi-period reverse logistics network design and planning under uncertainty utilizing conditional value at risk (CVaR) for recycling construction and demolition waste. *J. Clean. Prod.* **2018**, *172*, 1567–1581. [CrossRef]
27. Trochu, J.; Chaabane, A.; Ouhimmou, M. A carbon-constrained stochastic model for eco-efficient reverse logistics network design under environmental regulations in the CRD industry. *J. Clean. Prod.* **2020**, *245*, 118818. [CrossRef]
28. Listeş, O.; Dekker, R. A stochastic approach to a case study for product recovery network design. *Eur. J. Oper. Res.* **2005**, *160*, 268–287. [CrossRef]
29. Gabrel, V.; Murat, C.; Thiele, A. Recent advances in robust optimization: An overview. *Eur. J. Oper. Res.* **2014**, *235*, 471–483. [CrossRef]
30. Alumur, S.A.; Nickel, S.; Saldanha-da-Gama, F. Hub location under uncertainty. *Transp. Res. Part B Methodol.* **2012**, *46*, 529–543. [CrossRef]
31. Hu, C.; Liu, X.; Lu, J. A bi-objective two-stage robust location model for waste-to-energy facilities under uncertainty. *Decis. Support Syst.* **2017**, *99*, 37–50. [CrossRef]
32. Nanjing City Map. Available online: http://zrzy.jiangsu.gov.cn/jsbzdt/index.html#mao4 (accessed on 31 March 2023).
33. Notice of the General Office of the Municipal Government on the Issuance of the 'Thirteenth Five-Year Plan' for the Harmless Treatment of Domestic Waste in Nanjing. Available online: https://www.nanjing.gov.cn/index.html (accessed on 31 March 2023).
34. Nanjing Statistical Yearbook 2021. Available online: http://tjj.nanjing.gov.cn/material/njnj_2021/index.htm (accessed on 31 March 2023).
35. Disposal Site Public Notice. Available online: http://cgj.nanjing.gov.cn/ (accessed on 31 March 2023).
36. Construction Waste Reutilization Project Environmental Impact Report. Available online: http://ghj.nanjing.gov.cn/ (accessed on 31 March 2023).
37. Google Maps. Available online: https://www.google.com.hk/maps/?hl=zh-CN (accessed on 31 March 2023).

38. Soyster, A.L. Technical Note—A Duality Theory for Convex Programming with Set-Inclusive Constraints. *Oper. Res.* **1974**, *22*, 892–898. [CrossRef]
39. Ahmed, R.R.; Zhang, X. Multi-stage network-based two-type cost minimization for the reverse logistics management of inert construction waste. *Waste Manag.* **2021**, *120*, 805–819. [CrossRef] [PubMed]
40. Lu, S.; Zhu, L.; Wang, Y.; Xie, L.; Su, H. Integrated forward and reverse logistics network design for a hybrid assembly-recycling system under uncertain return and waste flows: A fuzzy multi-objective programming. *J. Clean. Prod.* **2020**, *243*, 118591. [CrossRef]
41. Yang, C.; Chen, J. Robust design for a multi-echelon regional construction and demolition waste reverse logistics network based on decision Maker's conservative attitude. *J. Clean. Prod.* **2020**, *273*, 122909. [CrossRef]
42. Tsai, F.M.; Bui, T.; Tseng, M.; Wu, K. A causal municipal solid waste management model for sustainable cities in Vietnam under uncertainty: A comparison. *Resour. Conserv. Recycl.* **2020**, *154*, 104599. [CrossRef]
43. Bavaghar Zaeimi, M.; Abbas Rassafi, A. Designing an integrated municipal solid waste management system using a fuzzy chance-constrained programming model considering economic and environmental aspects under uncertainty. *Waste Manag.* **2021**, *125*, 268–279. [CrossRef] [PubMed]