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Effects of Fiscal Decentralization on Garbage Classifications

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China has been promoting garbage classification in its rural areas, yet it lacks financial appropriation and fiscal decentralization to support waste processing projects. Though the existing literature has suggested fiscal decentralization strategies between different local government levels, few of the studies ascertain garbage classification efficiency from a quantitative perspective. To bridge the gap, this study examines the optimal fiscal decentralization strategies for garbage classification. It uses an optimization model while considering decision makers' requirements regarding the fund allocation amounts at different government levels and the classification ratios in villages as constraints and decisions, respectively. A three-stage heuristic algorithm is applied to determine optimal landfill locations and efficient classification ratios for the garbage processing system in rural China, with an analytical discussion on the propositions and properties of the model. Our analytical results suggest that 1) the theoretically optimal solution is conditionally achievable, 2) the applied algorithm can achieve the optimal solution faster when the relationship between governance costs and classification ratios reaches some mathematical conditions, and 3) there is always a potential for increasing the retained funds between different government levels or for reducing the total appropriation from the county government. The numerical experiment on a primary dataset from 12 towns and 143 villages in the Pingyuan county of Guangdong province, China, does not only affirm the qualitative results, but it also provides insights into the difficulties encountered during the implementation of the garbage classification policy in China's rural areas.

Keywords: garbage classification, fiscal decentralization, quantitative analysis, optimization, rural area

INTRODUCTION

Under a typical multilevel governance structure, local governments in China—villages, towns and counties—are always authorized specific rights and responsibilities during a garbage processing project. For instance, the village committee is always responsible for hiring cleaning staff to classify and deliver the garbage from each household to the transfer station in town. The town government then transports the waste from the transfer station in town to further treatment sites such as refuse landfills. Efficient allocations of funds between each of two local government levels—that is, fiscal decentralization—are critical to garbage processing efficiency, as well as ensuring consistency between administrative power and financial rights.

However, due to information asymmetry, it is difficult for the central government to design any efficient fiscal decentralization plan to guide subordinate local government levels under a "top-down" scheme. When the supervision costs between each of two different government levels are abnormally high, the fiscal allocation is inefficient. Previous studies have explored factors critical to the financial sustainability of waste management systems (Bartolacci et al., 2018), conceptually proposed specific fiscal decentralization strategies to solve grassroots problems (Gregorio et al., 2019) and evaluated the application of fiscal decentralization principles in practical contexts (Zegras et al., 2013). However, the quantitative examination of the efficiency of decentralization strategies remains scant in the literature.

Considering that garbage classification at the grassroots government level will have a "bottom-top" impact on the fiscal decentralization strategy of the governments at higher levels, inefficient garbage classification at the village level may cause serious financial efficiency and environmental sustainability problems at the town and county levels. For instance, the deregulated classification may lead to a large number of garbage abuses in a village, which will further undermine the local environmental quality. In contrast, an overly strict requirement[1] may lead to excessively high costs for the entire garbage governance system. It could lead to the community surpassing landfill capacity in a relatively short time. Therefore, we argue that an optimized garbage classification ratio not only improves fiscal decentralization through different government levels but also helps to achieve the sustainability goal.

This study optimizes the fiscal decentralization strategy for processing local garbage taking garbage classification as a decision variable. The whole problem is modeled as a location-allocation network, in which the landfill location is also optimized. The requirements of fund flow in this network through different government levels are treated as constraints for the optimization model. Our key findings show that it is possible to improve the fiscal usage efficiency between government levels. We specifically show the impact of garbage production scale on classification decisions and the impact of such decisions on the size of fiscal appropriations.

The remainder of this paper is structured as follows: *Literature Review* reviews the related literature from three aspects: garbage collection, fiscal decentralization and garbage processing optimization. *Setting* describes the research problem by specifying the authorities and financial constraints through different government levels. Model, analytical discussion and algorithm development are presented in *Modeling and Analysis*. *Numerical Experiment* presents the quantitative experiment and optimization solutions. *Conclusion* concludes the paper.

LITERATURE REVIEW

The study aims to optimize fiscal decentralization efficiency in garbage processing under a multilevel government structure. Three strands of relevant literature—garbage classification, multilevel governance and operational optimization—are reviewed in this section. Then gaps in the existing literature are identified.

Garbage Classification

Previous studies have discussed different garbage classification methods. For instance, Nie et al. (2018) propose a new Decision Support System on a specific classification method in Shanghai, China. Idowu et al. (2019) address an identifiable and comprehensive academic evaluation of the value of landfill sites on garbage classification. Li et al. (2019) carry out field investigations, questionnaire interviews and factor analysis in the rural area of Hangzhou, China, to detect the efficiency of some new garbage classification methods. The authors compare four methods, including a "2 + T" source method (biodegradable waste, other waste and toxic waste) and three types of source classification and resourcing treatment patterns. Garbage classification, as an end-of-pipe (EOP) treatment, always happens before garbage collection at farm households. Yet landfill classification refers to any waste management system that processes waste before discarding it into the environment (Dutt and King, 2014). Dutt and King (2014) conduct an empirical study to test the contribution of EOP treatment to improve the waste reduction process. Using EOP treatment was found to increase information about process problems and hence could help practitioners identify the root cause of insufficient capacity and facilitate the source reduction of processed waste.

Besides proposing garbage classification methods, researchers have also tried to improve classification efficiency. According to Nguyen et al. (2015), trust, personal perception, moral norms, perceived difficulties and reciprocity are critical factors that explain residents' intentions in garbage classification separation. Gundupalli et al. (2017) review the automated sorting techniques, including sensors and actuators, and found their contribution to improving garbage processing efficiency. Boonrod et al. (2015) investigate how to design management mechanisms for increasing garbage classification efficiency, and they identified that an economic incentive mechanism, e.g., the community business mechanism, performed best, as it increased separation efficiency by about 58%. According to our pilot experiment, however, higher garbage classification intensity does not necessarily bring about cost reductions, especially for the whole system, since different levels of garbage separation intensity in villages may cause different governance and transportation costs throughout the fiscal decentralization chain.

Through our investigation in the rural areas of Southern China, we find that local garbage is always recommended to be sorted into four classes: organic perishable garbage, hazardous waste, inert trash and others. Most of these types, in terms of classification method, are sorted at the source instead of treatment patterns. In addition to choosing the appropriate classification method, this study suggests that an efficient fiscal decentralization strategy is a critical factor in the successful implementation of rural domestic waste classification and resource management.

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[1]For instance, like in the metropolitan areas of China, garbage is required to be classified before processing.

Fiscal Decentralization

Gregorio et al. (2019) propose a theoretical framework that combines institutional and policy network approaches to the study of multilevel governance of the climate change problem. These authors provide valuable information with which to identify the institutional framework among different government levels. In line with their framework, which highlights the institutional environment, we focus mostly on fiscal institutions and the efficiency of fiscal decentralization through different government levels. According to Oates (1999), pp. (1120), fiscal decentralization, which is also called fiscal federalism, refers to understanding which functions and instruments are best centralized and which are best placed in the sphere of decentralized levels of government. Fiscal decentralization efficiency and environmental performance are evaluation criteria in rural China. Zhang et al. (2017) point out that fiscal decentralization hurts efficiency (Zhang et al., 2017). Zegras et al. (2013) examine Portugal's metropolitan transportation sector from the fiscal federalist's perspective in light of the country's decentralization efforts and new relevant legislation. Several problems are identified within the local metropolitan transportation system, such as a lack of direct user fees, prices that inadequately reflect costs and a heavy reliance on central government subsidies for public transportation investments and operations. In the rural China, garbage disposal processing is always launched by the higher government level, and undertaken by the subordinates, with structurally spent cost through different levels. However, we found that, based on our spot investigation, the cost may not be entirely come from the higher government levels. The villagers for example, are often charged with the garbage disposal fees.

Optimization in Garbage Processing

Anwar et al. (2018) solve a location problem to identify the configuration of a municipal solid waste (MSW) management system. Balaman and Selim (2014) use mixed-integer programming in the network design model to determine the most appropriate locations for biogas plants and biomass stores. Badran and El-Haggar (2006) use a mixed-integer programming model to solve a waste management problem and discussed the selection strategy for the locations of multiple garbage collection stations at different geographical locations. Tavares et al. (2011) use the spatial multicriteria evaluation method to examine the optimal location of an MSW incineration plant. Since these studies have not considered classification at the endpoint of the garbage processing network, no allocation optimization needs to be implemented. Considering waste transportation and the location problem, Srivastava and Nema (2012) use a fuzzy parametric programming model to address the location-allocation problem for urban waste management. Apart from the studies mentioned above, topics related to the application of multilevel governance in optimization can be found in the operational management literature as well. For instance, Levaggi et al. (2018) construct an N-region network programming model to address a systematic garbage disposal problem. In this model, waste mobility is allowed

between nodes, and its effect on the solution was discussed under both centralized and decentralized decision models. In Ma et al. (2018), the authors also used a network optimization method for waste processing issues. In their study, a case from Louisiana, United States, is used, and monetary constraints are considered through different players in the network.

The literature on garbage classification mostly focuses on the classification methods that may improve operational efficiency, the factors that impact the classification behavior/intention and the mechanism design that may increase the policy efficiency (Gundupalli et al., 2017; Nie et al., 2018; Li et al., 2019). Some existing research has discussed the impact of end-of-pipe treatments, such as landfill, on garbage reduction efficiency through the whole process. A few studies have explored the intrinsic connection between end-of-pipe garbage treatment and fiscal decentralization efficiency, incorporating all decision makers in the modeling process. We provide theoretical decision-making suggestions on fiscal decentralization as well as simulate the outcome of the EOP garbage treatment, rather than addressing ex-post discussions on the EOP impact on the participants' decision quality.

Though some studies have discussed the impact of fiscal decentralization on policy efficiency (Zhang et al., 2017), the regional economy (Gregorio et al., 2019) and some public-service departments (Zegras et al., 2013), few of them, however, have scrutinized the impact of fiscal decentralization efficiency on waste management and garbage processing. The optimization literature usually focuses on the application of related programming or computing methodologies, and few studies integrate the network programming technique with any practical garbage classification problems in specific areas.

We quantitatively optimize fund allocation efficiency through different players within a logistics network. Our study is the first attempt to apply an operational method to a rural garbage processing problem under a multilevel governance mechanism.

SETTING

We consider a multilevel governance framework that consists of the issues of "collection-and-classification in the village, transportation in town and processing in the county" (CAV-TT-PC). To determine an efficient fiscal decentralization strategy that starts from garbage classification within the grassroots government, our study builds a location-allocation optimization network, treating the location of the landfill and classification ratio as the decision variables. To approach the local garbage logistics network, a second-order conic programming model is applied, based on the above two decision variables. To specify the other issues, along with these decision variables and the corresponding constraints on fiscal expenditures at each government level, we make the following assumptions.

Assumptions

(1) The garbage production of each village household and the location of the town's transfer station are known.

(2) Only the classified garbage needs to be processed at the refuse landfill in the county. The rest is assumed to be disposed of by local households.

(3) The governance cost related to the classification work is the function of the classification ratio. Such information will then be specified in the quantitative experiment.

(4) The cost of garbage collection from each farm household and the transfer of garbage to the transfer station is constant.

(5) The number of refuse landfills in the county is predetermined as being equal to one.

(6) None of the government levels will accept a negative flow of funds.

In addition to assumption (2), we actually imply another assumption here that the disposal process of the garbage is indifferent to classified waste types. In the reality, different garbage disposal processes are often placed together, in order to avoid pollution to the villages. Besides, there is limited available location to position the processing site in the rural area. For theoretical discussion, we social researchers are always lack of specific data regarding of the benefits and cost of classifying out different garbage types. Based on the above, the distance from the origin to the processing site is accordingly assumed to be equal to that between the origin to the landfill in the county. That is, the distance will be indifferent to the classification result.

Stoeva and Alriksson (2017) state that policies and legislation and people's attitudes could be important factors that affect garbage processing efficiency. In our paper, however, these conditions are implicitly assumed to be satisfied. The local farm households in our area of investigation are always found to have good intentions regarding garbage classification and to follow the guidance of the local government. Thus, in this paper, the implementation quality is assumed to be guaranteed by the incentive mechanism from local governance and the household's behavior. Although we find from the citations from Dutt and King (2014) that many authors approached the garbage governance problem from the perspective of process quality management, we are mostly interested in process efficiency. In the following subsection, to-be-decided variables that are determined by the authorities at each government level are specified under a CAV-TT-PC framework.

Decision Units and the Variables to be Decided
Village Committee
(1) Classification ratio

The village committee determines the classification ratio during garbage collection.

(2) Amount of retained funds

In addition to the funds used for classifying and collecting domestic garbage, the village committee has to decide on the amount of funds to be retained from the amount allotted by the town government level.

Town Government
(1) Funds allocated to villages

These funds are used by the town government to support the garbage classification and processing work and to cover the governance cost in villages.

(2) Amount of retained funds

The town government has to decide on the amount to be retained from the amount allocated by the county government.

County Government
The county government should choose the refuse landfill location while making a plan for the appropriations budget. These two aspects, in practice, jointly influence the total costs of the garbage processing network and the strategies for fund allocation through to subordinate levels. In other words, the county government must consider the location problem that would be created by different landfill locations, as well as the size of the appropriation that comes from the higher government level. The appropriation will always be treated as both an incentive/authority and a constraint/responsibility for the local government during a garbage processing project. Although the total amount of the allocated appropriation from the central government is closely related to the specific authorities and affairs in the subordinate government levels, few studies have explored the potential of improving fund allocation efficiency within grassroots governance.
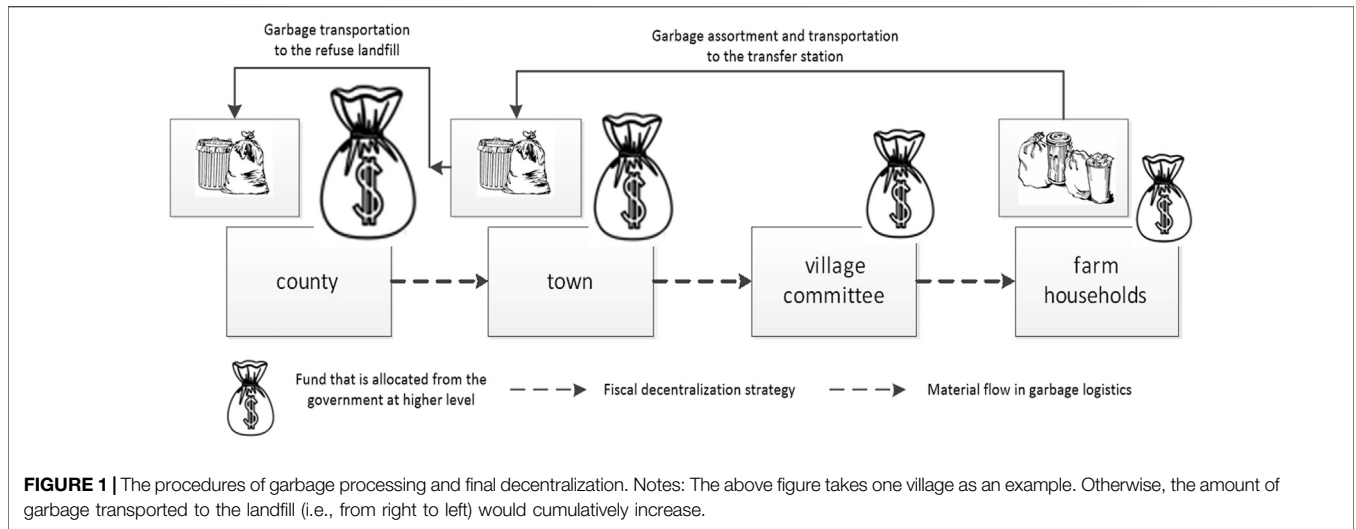
Following the implementation of a location strategy, waste transportation routes from the transfer stations to the landfill site will also be optimized. This change, as stated in Peri et al. (2018), will then mitigate the total logistics cost of the whole system. Further modification of the network will be carried out by optimizing the classification of the garbage from each village.

We do not address the location problem for the transfer station in town for two reasons. First, the delivery cost from each farm household to the transfer station is independent of the station's location, since the salary paid to the cleaning staff is only dependent on the weight of the delivered garbage. Second, the distances from farm households to the transfer station are much smaller than the distance from a transfer station to the landfill in the county. Thus, the transportation cost between farm households to transfer stations has little impact on the total cost. In the following subsection, the requirements of the fund allocation strategy at each government level, superior and subordinate, are specified.

Financial Requirements of Decision Units
Based on the discussion in *Decision units and the variables to be decided*, the following specifies the requirements from different government levels that can be used as the constraints in programming:

From the village committee's perspective, its net fiscal revenue from processing rural garbage is equal to the difference between the garbage processing cost and the funds received from the town government. The processing cost in the equation equals the sum of the collection costs and

FIGURE 1 | The procedures of garbage processing and final decentralization. Notes: The above figure takes one village as an example. Otherwise, the amount of garbage transported to the landfill (i.e., from right to left) would cumulatively increase.

classification-related governance costs. Collection costs are usually paid to the local cleaning staff, while officers always undertake the classification related governance costs at the grassroots government level.

net fiscal revenue of village committee in garbage processing

  = allocated funding from town − garbage collection cost

    − governance cost . . . . . . (1)

In equation **Eq. 1**, the cost is generally specified by the village committee itself. The correlation of the garbage processing expenditure, classification-related governance cost and processed garbage volume mainly reflect the fiscal decentralization efficiency between the local and the superior government levels.

Similarly, the net fiscal revenue of the town government—consisting of the funds allocated by the county government, the allocations to village committees and the expenditures for garbage transportation—is listed by equation **Eq. 2** as follows:

net fiscal revenue of town government in garbage processing

  = allocated funds from county − funding allocation to villages

    − transportation cost . . .

(2)

The net fiscal revenue of the county government is derived by subtracting the allocation funds and transportation costs that occur in the town from the funds received from the central government level. Accordingly, the following equation **Eq. 3** is derived:

net fiscal revenue of county government in garbage processing

  = allocated funds from the central government

    − allocation to town − transportation cost . . .

(3)

According to assumption (6), the net fiscal revenue for the county, town and village governments should be nonnegative. If each local government level has a requirement on the minimum funds to be retained, the lower bound should be considered in the constraint as well.

Integrating *Decision units and the variables to be decided* and *Financial requirements of decision units*, the following argument is proposed. Although the operational analysis of the garbage processing system is derived from a bottom-up approach, the optimized location of the landfill site in the county and the classification ratio in the village are conducted within the fiscal decentralization strategy that is implemented under a top-down approach. This statement can be graphically depicted in **Figure 1**, in which the size of the money bag represents the amount of the allocated funds received by the local government. In contrast, the variation in the size represents the outcome of fiscal decentralization through different government levels. For instance, the town's money bag is bigger than the village's, since the town government needs to use a part of the funds to transport the garbage from the transfer station to the landfill site before the funds are allocated to the village committee. The reduced size of the garbage bags, in the direction opposite to that of the fiscal decentralization, denotes the outcome of garbage classification. That is, for example, why the town holds less garbage than the household does.

MODELING AND ANALYSIS

Based on the above discussion, we first build an operational optimization model, then derive the analytical properties and, after that, put forward some propositions for the model.

Notations
All the relevant parameters and variables discussed in this study are listed as follows:

Index

i	Index for the village such that $i = \{1, 2, \ldots, n_j\}$, where n_j denotes the largest indexed village in town j
j	Index for the town such that $j = \{1, 2, \ldots, m\}$, where m denotes the largest indexed town

Decision variables

α_{ij}	Ratio of garbage classification in household j in town i
V_{ij}	Funds allocated by town j to village i
H_{ij}	Funds retained in village i of town j
W_j	Funds allocated by county to town j
M_j	Funds retained in town j from W_j
$\boldsymbol{R}$	Location of the to-build refuse landfill, such that $\boldsymbol{R} = \{R_1, R_2\}$, where the two elements represent the latitude and longitude, respectively[2]

Parameters

s	Unit wage of the cleaning staff in the village
h_{ij}	Garbage production in village i in town j
r_j	Coordinate of the transfer station in town j
n_{ij}	Population of village i in town j
$\boldsymbol{T}_j$	Location of a transfer station in town j, which is already known
u	Marginal cost of transportation from the town to the refuse landfill
A	Financial budget fixed by the county government
γ	Coefficient that associates the governance cost with the assorted garbage volume
C	Annual garbage processing capacity of the landfill in the county

Modeling — **The programming model, which is denoted by (QP), is shown as follows:**

$\min\limits_{\boldsymbol{r} \in \boldsymbol{L}} G(\boldsymbol{r}, \alpha_{ij}) = u \sum\limits_{j=1}^{m} D_j \sum\limits_{i=1}^{n_j} \alpha_{ij} h_{ij}$ Subject to

Capacity constraint	$C \geq \sum\limits_{j=1}^{m} \sum\limits_{i=1}^{n_j} \alpha_{ij} h_{ij}$	(1)
Fund flow constraint1	$W_j - M_j - \sum\limits_{i=1}^{n_j} V_{ij} \geq u D_j \sum\limits_{i=1}^{n_j} \alpha_{ij} h_{ij}$, $i = \{1, 2, \ldots, n_j\}$, $j = \{1, 2, \ldots, m\}$	(2)
Fund flow constraint2	$V_{ij} - H_{ij} \geq s \alpha_{ij} h_{ij} + f(\alpha_{ij}, h_{ij})$, $i = \{1, 2, \ldots, n_j\}$, $j = \{1, 2, \ldots, m\}$	(3)
Appropriation constraint	$A \geq \sum\limits_{j=1}^{m} W_j$	(4)
Coefficient constraint	$0 \leq \alpha_0 < \alpha_{ij} \leq \overline{\alpha} < 1$	(5)
Variable constraint and nonnegativity constraint	$\boldsymbol{R} \in \mathcal{L}$; $V_{ij}, H_{ij}, M_j, W_j \geq 0$	(6)

The objective function minimizes the total cost, which is the sum of the product between the distance and the assorted garbage from each village. D_j denotes the distance from the landfill position in the county to the transfer station in the town. Mathematically, we have $D_j = \|r_j - \boldsymbol{R}_2\|$ where $\|\cdot\|$ denotes the norm, with its subscript denoting the degree. Constraint (1) ensures the delivered garbage will not exceed the annual processing capacity (*capacity* for abbreviation) of the landfill; constraints (2) and (3) guarantee the fund flows through the town government and village committees are nonnegative, respectively. Note that the right term of (2) is a ton-kilometer cost that follows the pricing convention of the logistics industry, taking the product of the marginal transportation rate with the product of weight and distance. In the right first term of constraint (3), the collection cost of the cleaning staff relates to the assorted volume of the household garbage. In the second, the **function** between the garbage classification and the corresponding governance cost is described as a **general form** of the decision variable α_{ij}, as well as the parameter h_{ij}. The generalization of this function will have

little impact on our analytical discussion. The specific form will be later addressed in the numerical experiment section. Constraint (4) says that the total planned funds over all the towns cannot exceed the appropriation from the county government, and the salary for the cleaning staff in the village is not lower than a lower bound. Such a lower bound always comes from the requirement of the local government or the labor law. The classification ratio is limited by constraint (5), in which α_0 and $\overline{\alpha}$ are the lower and upper bounds, respectively. The two boundaries, naturally, are to be restrained between zero and one to comply with reality. We use $\leq$ after 0 since we consider the extreme case that no garbage is transported from the household; constraint (6) makes sure that all the decision variables are nonnegative.

Remark 1

In the objective, α_{ij} is used as a classification variable that can be determined by the grassroots government level. Then the problem can be solved through a location-allocation algorithm scheme that was proposed by Cooper (1963) and extended by Wu et al. (2015) and Ma et al. (2018). Related pseudocodes are

listed in Algorithm 1 in **Supplementary Appendix A**. Our version in the current paper is closer to that used by Cooper (1963) and Wu et al. (2015), since Ma et al. (2018) considered a multiobjective scenario.

Proposition 1

The problem equals a location-allocation problem.

Proof of Proposition 1

The proof is evident since we can treat $\alpha_{ij}h_{ij}$ as a decision variable, e.g., v_{ij} that concerns the delivered garbage value from village j of town i, determined by the decision of the classification ratio. Then (QP) can be reformulated to $\sum_{j=1}^{m} D_j Q_j$ where $Q_j = \sum_{i=1}^{n_j} v_{ij}$ that represents a total delivered garbage volume from town j. So far, a standard location-allocation problem is constructed, and the proposition is proved. ∎

Proposition 2

Following the scheme that requires D_j and α to be alternately determined, (QP) is convex programming during each iteration round, given $f(\alpha_{ij}, h_{ij})$ is convex.

Proof of Proposition 2

Based on **Proposition 1**, the objective is convex to α given a fixed r—since the function is of a linear form, and convex to r given a fixed α_{ij}—because the function is of a second-order conic form. Then we need to prove that all the constraints are convex: constraint (1) is convex due to its linearity; according to the algorithm scheme, constraint (2) is convex; if $f(\alpha_{ij}, h_{ij})$ is convex, then constraint (3) is convex. Thus, the proposition can be proved. ∎

Remark 2

It can be found from the above that, given that the other conditions are unchanged, the relationship between the governance cost and garbage classification ratio affects the algorithm's effectiveness and efficiency. Exploration of the specific form of such a relationship and its impact on optimization analysis can be left as an interesting problem for future research.

Proposition 3

The three-stage heuristic algorithm by Cooper (1963), Wu et al. (2015) or Ma et al. (2018) is valid in the current problem for searching the locally optimal solution for programming (QP) in terms of both its decision variables r and α_{ij}.

Proof of Proposition 3

To prove this proposition, we have to prove that $G(r^{t+2}, \alpha_{ij}^{t+1}) \leq G(r^t, \alpha_{ij}^{t+1})$ and $G(r^{t+1}, \alpha_{ij}^{t+2}) \leq G(r^{t+1}, \alpha_{ij}^t)$, $0 \leq t \leq t_{\max}$, where t and $t_{\max}$ denote the iteration and predetermined maximum iteration times.

Since $G(r^{t+2}, \alpha_{ij}^{t+1})$ is optimized based on the solution of $G(r^t, \alpha_{ij}^{t+1})$ by using α_{ij}^{t+1} as a constant, and in turn $G(r^{t+2}, \alpha_{ij}^{t+3})$ is optimized by using r^{t+2} as a constant in $G(r^{t+2}, \alpha_{ij}^{t+1})$, we have $G(r^{t+2}, \alpha_{ij}^{t+1}) \leq G(r^t, \alpha_{ij}^{t+1})$ and $G(r^{t+2}, \alpha_{ij}^{t+3}) \leq G(r^{t+2}, \alpha_{ij}^{t+1})$ due to the convexity of each programming. Slightly adjusting the superscripts in the latter inequality, the proposition is proved. ∎

Remark 3

In other words, **Proposition 3** says that whether we start the iteration from the landfill location or garbage classification, the algorithm makes the objective non-increasing.

Looking into the specific constraints, we have the following proposition:

Proposition

The non-increasing monotonicity of the lower bound of constraint (2) is sufficient, but not necessary, to the improvement of the objective.

Proof of Proposition 4

It can be found that for each index j, the lower found of constraint (2) denotes the total transportation cost for each town. If this cost is non-increasing through the algorithm, the summation of the total cost for all the towns is non-increasing. This causal relationship, however, is irreversible. Thus the proposition can be proved. ∎

Remark 4

The reason behind **Proposition 4** can be described as follows: the objective function focuses on the total ton-kilometer cost of the whole county, whereas constraint (2) provides a limit to the solution by considering the ton-kilometer cost from each village to the landfill in the county. Therefore, if the component-wise cost is smaller, the total cost will undoubtedly be smaller. But a smaller total cost does not necessarily mean a small component-wise cost.

With further discussion on the constraints, we have the following property:

Property 1

If $f(\alpha_{ij}, h_{ij})$ is non-increasing with α_{ij}, the optimal solution α_{ij}^* is always equal to its lower bound α_0, and the optimal solution r^* can be found by at most two iteration times.

Proof of Property 1

If the iteration begins with an arbitrarily initiated location site, α_{ij}^* can be solved as equal to its lower bound, due to the minimization scenario and non-increasing monotonicity of constraint (3). Then r^* can be found, given a fixed α_{ij}^*, during the first iteration, which is essentially a location optimization problem. If the iteration, on the contrary, begins with an initiated α_{ij}, α_{ij}^* can be found for the first iteration and r^* can be found for the second. Thus, the property can be proved.

Considering the practical application, α_{ij} can be set as a general standard for the whole county, e.g., α. For this, we have the following discussion:

Remark 5

Although a scalar variable, which can be denoted as α rather than a matrix (vector) that has been denoted by α_{ij} in the modeling, does not violate any of the above propositions and properties; it may cause an intractability problem as we use an equality constraint as (2). Subject to such an equality constraint, intractability may also be caused by not only the inappropriate settings of the total budget A but also the landfill capacity C and the initial landfill location. For instance, an increase of the lower bound of constraint (2) may violate this constraint, although (4) is active. Furthermore, we find that satisfying constraint (2) and (3) are not only necessary but also sufficient to a solvable problem. The above observations indicate

FIGURE 2 | Study area.
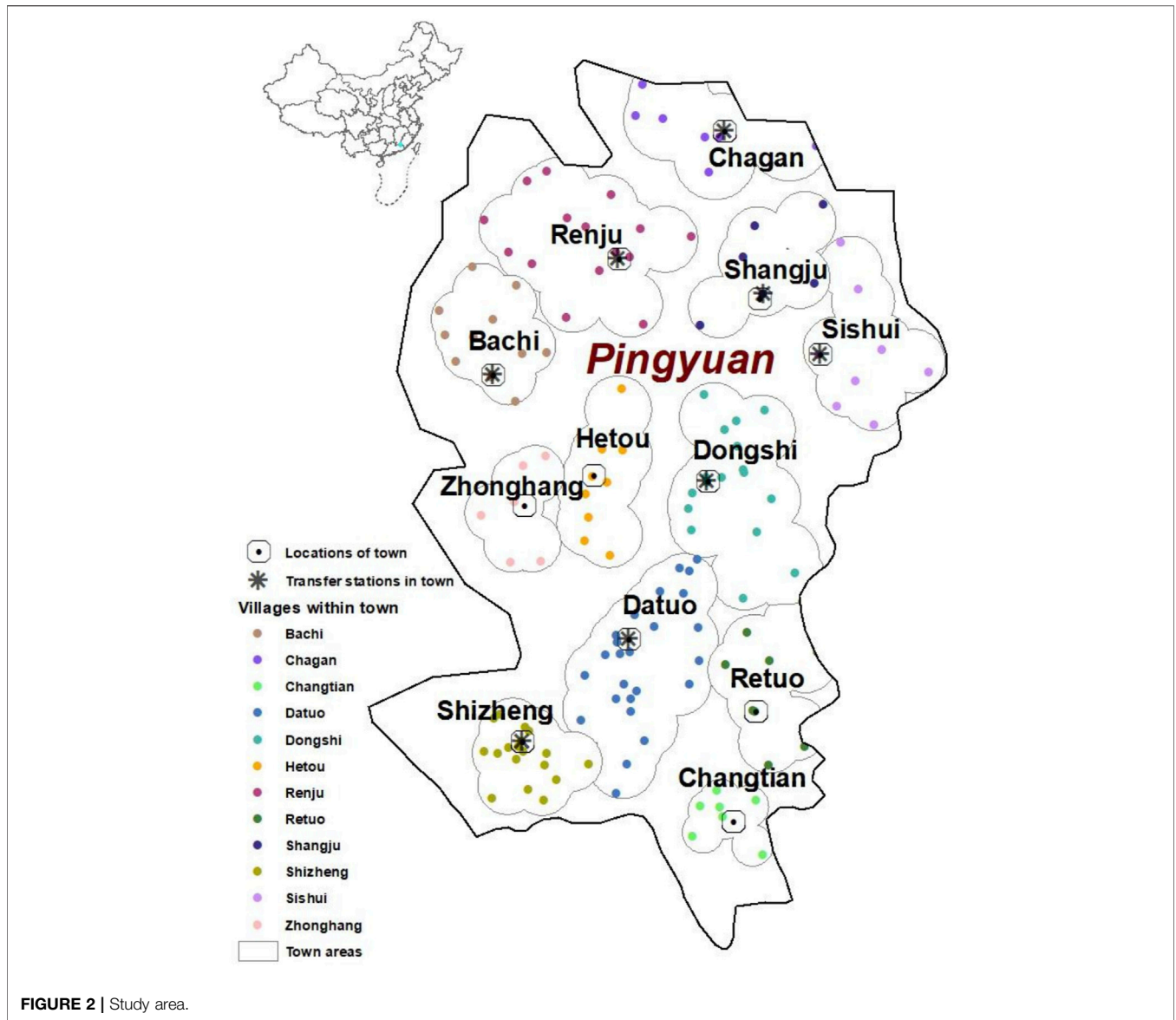
that, in practice, the appropriation size and local operational work have a mutual impact on each other. For instance, a too-small appropriation amount may cause an undesirable location decision for the landfill, in terms of environmental quality. A lack of financial support may also bring about a household's negative motivation regarding garbage classification, or worse, a negative motivation regarding the implementation of the whole system.

NUMERICAL EXPERIMENT

Data

The numerical experiment was conducted on a real case from Pingyuan county, China (**Figure 2**).

There are a total of 12 towns and 143 villages in the county. The specific corresponding relationship between the village

names and indices i in practice is reported in **Table B-1a** in **Supplementary Appendix B**. Their coordinates are reported in **Table B-1b**. The entire garbage production from all the villages reached 30,529.25 tons in 2018, which cost 5.44 million RMB[3] to pay the cleaning staff. The transfer expenditure undertaken by the town government was 3.16 million RMB. More detailed information derived from the surveyed information, such as the village coordinates, population garbage production for each village and the location of the transfer station in each town, etc., are reported in **Tables B-1b, B-1c and B-1c**. This information can be used later as a benchmark for comparison with the optimized solution.

To facilitate the analysis, we simplify $f(\alpha_{ij}, h_{ij})$ into a linear form, e.g., $f(\alpha_{ij}, h_{ij}) = \gamma\alpha_{ij}h_{ij}$, in which γ denotes the marginal

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[3]US$1 = 6.99 RMB (as of 7/20/2020).

governance cost of the classified garbage volume. Here, we denote $\gamma = 58.5$ RMB per ton according to the following calculation.

Governance Cost in Villages

Average garbage production per village equals 213.5 tons per year and that the annual salary for the village officer is about 36,000 RMB, according to the provincial standard. Based on our survey of the county, we find about one-quarter of the working time is spent on inspection and the officer usually goes for inspection for twice a time (using 0.5 in the denominator).[4] So marginal governance cost is calculated as:

$$marginal\ governance\ cost = \frac{36000 \times 0.25 \times (250/360)}{213.50 \times 0.5} \approx 58.5\,(RMB/ton)$$

That is to say, to manage the garbage classification work, the village committee needs to pay 58.5 RMB of compensation per ton of garbage to the village officials.

In reality, however, there is no such expenditure paid to village officials. Thus this paper will also contribute to the optimization of a village officer's salary in terms of fiscal decentralization efficiency.[5]

Marginal Transportation Cost From Town to County

For the transportation cost, we use 6.18 and 16.10 RMB per ton as the lower and upper bounds. The average distance from the transfer station of a town in Pingyuan county to the landfill site is equal to 7.3 km. Considering that the allocated funds for garbage transportation in that town equal to 340.9 thousand RMB and that the local garbage production equals 4,717 tons, the marginal cost is 9.9 RMB per ton-kilometer, if we only consider using the funds on transporting the garbage. Given the contract value is of 212.7 thousand RMB between that town and the commercial company, the cost equals 6.18 RMB per ton-kilometer. Taking the higher price 16.10 quoted by other companies as reference, we use the smaller value, i.e., 6.18 RMB, as the lower bound, and the sum, i.e., 16.10 RMB, as the upper bound in setting the related parameter. For the numerical experiment, we start from the lower bound to check the result and vary this value from 6.18 to 16.10 RMB in the extension case to see the impact of such a variation on the optimized cost.

Landfill Location

We use the real location of the landfill in Pingyuan County as the initial point to start the algorithm and the benchmark case to compare our results.

Optimized Result

In the numerical experiment, first, we report the result by using **Eq. 3** as an inequality constraint with 35,000 tons as the capacity. The actual production of garbage in the study area is 30,529.25 tons per year. Later we vary constraint parametrically up to a constraint of

8,000 tons. We use MATLAB (2010b) to solve the optimization problem.

Result With Inequality Constraint

The specific result with the inequality constraint is listed in **Table 1**, in which the total classified (outbound) volume is equal to 6,052.33 tons. There is always a gap between the optimized retained amount and the calculated number at either the town government or the village committee. The optimized total appropriation size is also found to be smaller than the predetermined budget C. The classification ratio for all villages reaches the lower bound, i.e., 0.2.

Result With Equality Constraint and Reduced Capacity

We reduce the capacity to 8,000 tons and replaced constraint (2) to equality in the optimization model. The results listed in **Table 2** show that the total transportation cost increases from 640,390.66 to 648,446.40 RMB.

Also, the funds from the county to towns, the optimized amount retained in villages, as well as the gap of the retained amount in villages, are larger than those in the previous case, where the inequality constraint is used, and a capacity of 35,000 tons is assumed. The main reason can be attributed to the increased garbage volume delivered. Due to the increment of the garbage processing task, however, we suggest that the retained funds be increased as well. As shown in **Figures 3A,B**, most of the towns have higher retained funds in the result with an equality constraint and a considerably more amount of delivered garbage than in the result with an equality constraint and a smaller amount of delivered garbage. This is mainly because that more delivered garbage requires larger amount of funds to support, which will, according to our modeling logic, lead to larger amount of retained funds.

For the location result, it reaches the same position as Datuo town, i.e., (115.9072, 24.5829), despite the variation of the targeted processed garbage, as well as of the appropriation size. This is because no matter how much garbage is transported to the landfill, such a location point will lead to the minimum transportation cost.

For the classification strategy, we find that larger ratios always come from the villages in Datuo town, because it has the most substantial amount of garbage production. We also find that the larger the production the village has, the smaller the classification ratio it has suggested be implemented. Such a finding is graphically depicted in **Figures 4A,B**. To more clearly display the ratios among different villages, we multiplied the data by 10,000 in **Figure 4B**. We find it exists in $\alpha_{ij}h_{ij}$ of constraint (2)—a small (large) classification ratio is always expected to be accompanied by large (small) garbage volume to reduce the product size.

This result can also be found in the actual situation of our surveyed area, where the classification work is more efficient in villages where garbage production volume is small. For a fiscal decentralization strategy, the numerical result confirms the qualitative analysis.

Sensitivity Analysis

Although some result can be qualitatively derived and numerically testified, e.g., larger garbage production in one

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[4]Assume the effective working days in China equal 250, due to weekends and legal holidays.

[5]As we use 58.5 as a constant in (QP), the optimized salary for each village officer would not be 36,000 RMB per year;

TABLE 1 | Optimization results given **inequality (3)** and **capacity** ≤ 35,000 tons for constraint (1).

Initial location	(115.9483; 24.5557)		Optimized location	(115.9098; 24.6200)
Capacity (ton)	35,000		Delivery (tons)	6,052.33
Salary (RMB)	176.8		Funds from county to towns (in RMB)	4,590,507.55
Constraint (1)	Inequality		Gap of CART(in RMB)	823,764.00
Total cost (RMB)	640,390.66		Optimized amount retained in town (in RMB)	924,682.74

Optimized FTV(RMB)

Town	Datuo	Renju	Dongshi	Shizheng	Bachi	Chagan
Fund	793,657.80	339,301.98	512,991.65	534,459.50	272,212.32	174,684.67
Town	Shangju	Sishui	Changtian	Retuo	Zhonghang	Hetou
Fund	184,921.10	183,232.70	175,396.01	229,808.93	150,475.93	215,600.94

Optimized expenditure in villages (in RMB)

Town	Datuo	Renju	Dongshi	Shizheng	Bachi	Chagan
Fund	488,079.69	145,390.73	332,321.68	329,963.86	107,594.59	75,165.74
Town	Shangju	Sishui	Changtian	Retuo	Zhonghang	Hetou
Fund	41303.24	61267.66	76208.39	109004.54	59893.26	91184.67

Optimized ARV(in RMB)

Town	Datuo	Renju	Dongshi	Shizheng	Bachi	Chagan
Fund	152,789.05	96,955.62	90,334.99	102,247.82	82,308.87	49,759.46
Town	Shangju	Sishui	Changtian	Retuo	Zhonghang	Hetou
Fund	71,808.93	60,982.52	49,593.81	60,402.19	45,291.34	62,208.14

CARV (in RMB)

Town	Datuo	Renju	Dongshi	Shizheng	Bachi	Chagan
Fund	305,578.10	193,911.25	180,669.98	204,495.64	164,617.73	99,518.93
Town	Shangju	Sishui	Changtian	Retuo	Zhonghang	Hetou
Fund	143,617.86	121,965.04	99,187.62	120,804.39	90,582.67	124,416.27

Distance (km)

Town	Datuo	Renju	Dongshi	Shizheng	Bachi	Chagan
Fund	4.13	21.58	8.58	13.75	17.18	30.99
Town	Shangju	Sishui	Changtian	Retuo	Zhonghang	Hetou
Fund	21.51	20.58	22.09	12.88	9.41	7.53

Notes: FCT, funds from the county to towns; ART, amount retained in town; CART, amount retained in town that is calculated by subtracting the optimized cost in town from the optimized allocated amounts from county to town; FTV, funds from towns to villages. ARV, amount retained in village; CARV, the amount of ARV that is derived by the similar formulation used for CART; "Distance" refers to the landfill site to each town.

town along with shorter distance from the landfill to that town will suggest the result locate landfill near the town etc., we still had some trails, including varying the garbage stock for different towns in order to check the variation of the positioning result, vary the classification techniques (i.e., the bounds of the classification constraints) to check the impact on the solution, and change the marginal transportation cost in order to check the sensitivity of the total cost to the variation etc.

Varied Parameters to Location Result

As we vary some parameters like the appropriation funds amount, transportation marginal cost, as well as collection cost from the village etc., location result is affected little. As we, however, arbitrarily increase the garbage amount of one town in the sensitivity analysis, the result to our expectation shows the variation from Datuo to that town, for instance Dongshi where the position is (115.9600, 24.6786). This makes sense, since no

matter how we changed the parameters other than the logistics cost, i.e., the town-kilometer, the location result would not be changed due to the minimization objective of the system. On the contrary, as long as we change that key factor, e.g., the distance from the garbage source to the destination, or the weight of the garbage production, the result would be changed accordingly. In terms of the sensitivity of the model, we claim that the location result is robust to the environment variation of the system.

Impact of Classification Techniques on the Solution

To identify the impact of classification techniques (i.e., the lower and upper bounds of a classification decision) on the solution, we solve the model at different values of α_{ij}, with the other predetermined parameters fixed. The result is reported given $C = 12500$ tons and $A = 400$ million RMB. In the garbage processing practice, the classification ratio is restricted by the

TABLE 2 | Optimization result given **equality (3)** and **capacity = 8,000** tons for constraint (1).

Initial location	(115.9072; 24.5829)		Optimized location		(115.9098; 24.6200)
Capacity(ton)	8,000.00		Delivery (ton)		8,000.00
Salary(RMB)	176.8		FCTs (in RMB)		5,693,646.37
Constraint (1)	*Equality*		Gap of CART (in RMB)		970,832.15
Total cost(RMB)	648,446.40		Optimized ART (in RMB)		1,155,279.96

Optimized FTV (RMB)

Town	Datuo	Renju	Dongshi	Shizheng	Bachi	Chagan
Fund	1,491,023.58	397,246.21	621,426.13	603,192.44	312,078.83	194,061.21
Town	Shangju	Sishui	Changtian	Retuo	Zhonghang	Hetou
Fund	160,190.43	203,493.21	194,930.49	258,952.32	164,788.22	243,576.84

Optimized expenditure in villages (in RMB)

Town	Datuo	Renju	Dongshi	Shizheng	Bachi	Chagan
Fund	1,105,101.61	145,390.73	332,321.68	329,963.86	107,594.59	75,165.74
Town	Shangju	Sishui	Changtian	Retuo	Zhonghang	Hetou
Fund	41,303.24	61,267.66	76,208.39	109,004.54	59,893.26	91,184.67

Optimized ARV(in RMB)

Town	Datuo	Renju	Dongshi	Shizheng	Bachi	Chagan
Fund	192,960.98	125,927.74	144,552.23	136,614.29	102,242.12	59,447.73
Town	Shangju	Sishui	Changtian	Retuo	Zhonghang	Hetou
Fund	59,443.59	71,112.77	59,361.05	74,973.89	52,447.48	76,196.08

CARV(in RMB)

Town	Datuo	Renju	Dongshi	Shizheng	Bachi	Chagan
Fund	385,921.96	251,855.48	289,104.45	273,228.58	204,484.23	118,895.47
Town	Shangju	Sishui	Changtian	Retuo	Zhonghang	Hetou
Fund	118,887.19	142,225.54	118,722.09	149,947.78	104,894.97	152,392.17

Distance (km)

Town	Datuo	Renju	Dongshi	Shizheng	Bachi	Chagan
Fund	0.00	25.69	12.16	10.49	20.48	35.08
Town	Shangju	Sishui	Changtian	Retuo	Zhonghang	Hetou
Fund	25.37	23.94	26.18	10.67	11.89	1.38

Notes: *FCT, funds from the county to towns; ART, amount retained in town; CART, amount retained in town that is calculated by subtracting the optimized cost in town from the optimized allocated amounts from county to town; FTV, funds from towns to villages; ARV, amount retained in village; CARV, the amount of ARV that is derived by the similar formulation used for CART; "Distance" refers to the landfill site to each town.*
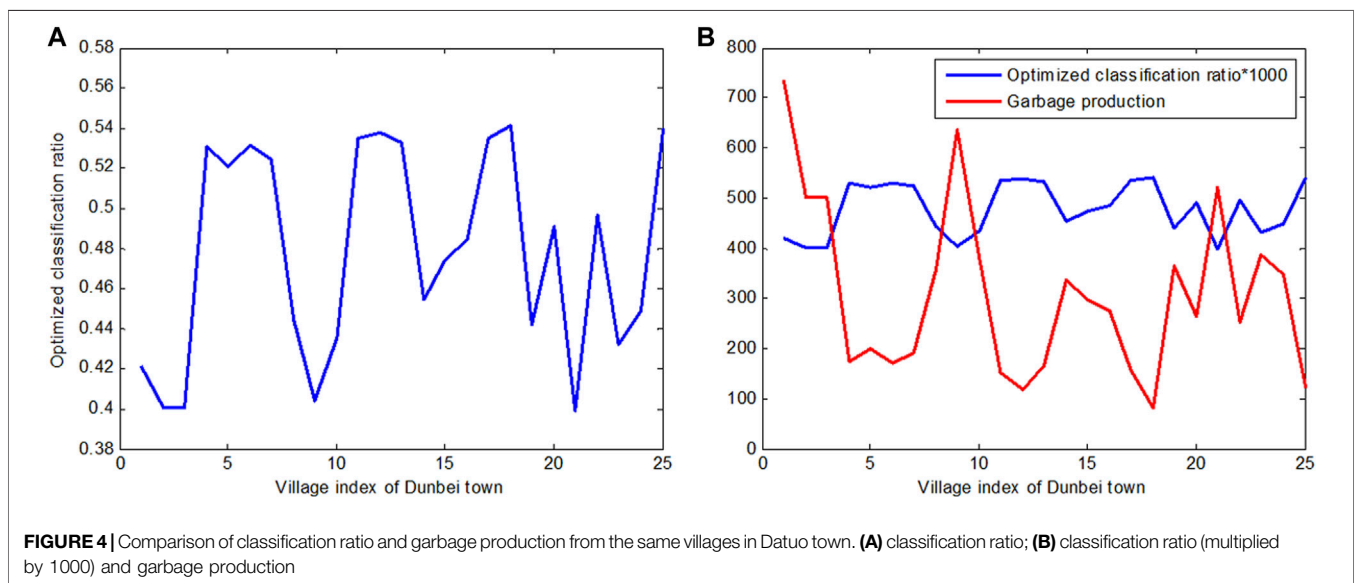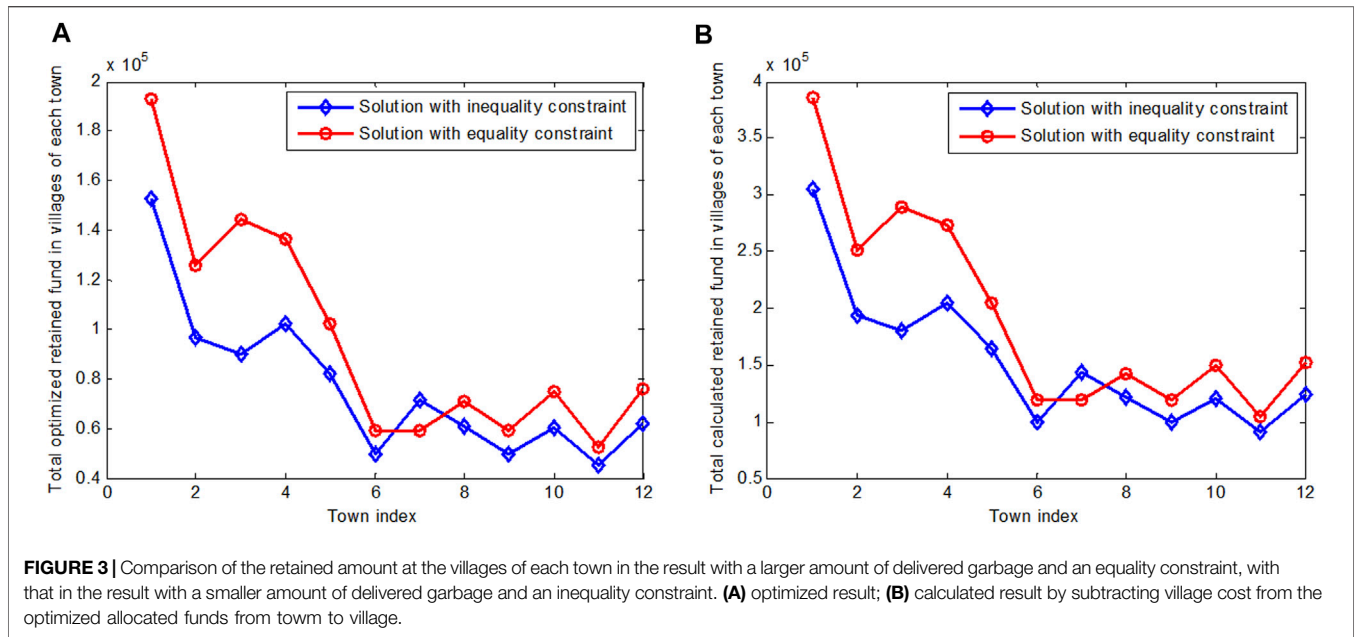
real situation, or techniques, at town and county levels. Thus, we address the following analysis to simulate the reality.

We change the lower bound of the classification from 0.0 to 0.1, given the upper bound equals 0.8. Results show that the total transportation cost under such a scenario is lower than that under the scenario in which the lower bound is 0.2. Tapping into the specific allocation solution, we find the garbage following $\alpha_{ij} = 0$ is mainly transported from the four closer towns (Datuo, Shizheng, Retuo, and Hetou).

As we use 0.1 as the lower bound, garbage still mainly comes from three out of the four towns; the exception is Hetou, whose ratio decreases to 0.1. That is because the volume that should have been undertaken by Hetou is distributed to the other towns.

As we change the upper bound of the classification from 0.8 to 0.7, given the lower bound equals 0.2, the result shows that the total cost increases from 815,906.23 RMB (in the benchmark case) to 886,563.37 RMB and the allocated funds from the county

to town increases from 80,603,456.25 to 130,656,102.66 RMB. That is because more garbage should be collected from the farther towns, as the classification technique in the closer towns is limited. Thus the ton-kilometer cost increases. For the allocation strategy, only Datuo and Shizheng are advised to send out more garbage, but the other towns are advised to keep the ratio equal to the lower bound. As we then decrease the lower bound from 0.7 to 0.6, the transportation cost increases to 963,000.77 tons, and the allocated funds increase to 256,774,139.17 RMB. Three more towns, Retuo, Hetou and Zhonghang, in addition to the above two, are advised to deliver more garbage than the others. Zhonghang town has the fifth nearest distance to the landfill. When the upper bound ratio decreases from 0.6 to 0.5, there are six major supplying towns, including Datuo, Dongshi, Shinzheng, Retuo, Zhonghang and Hetou. Although the transportation cost increases again, to 1,055,076 16 RMB, the allocated funds decrease sharply from 256,774,139.17 to 5,892,470.16 RMB.

FIGURE 3 | Comparison of the retained amount at the villages of each town in the result with a larger amount of delivered garbage and an equality constraint, with that in the result with a smaller amount of delivered garbage and an inequality constraint. **(A)** optimized result; **(B)** calculated result by subtracting village cost from the optimized allocated funds from town to village.

FIGURE 4 | Comparison of classification ratio and garbage production from the same villages in Datuo town. **(A)** classification ratio; **(B)** classification ratio (multiplied by 1000) and garbage production

Form a practical perspective, the above solutions indicate that stricter classification requirements (lower bound ratio) result in higher transportation costs but do not necessarily lead to a larger appropriation size. A lower classification technique (upper bound ratio) also results in higher transportation costs but does not lead to lower total appropriations. In summary, the impact of varied classification ratios' constraints on the fiscal decentralization strategy has less clear direction than the capacity constraints and budget restrictions. Also, it is not

very practical to impose strict garbage classification standards from the very beginning, or set up different waste classification ratios for different towns and villages in the same county. Since it will bring us with higher management and government cost. For more efficiently using the government funds, the result implies to further refine government's waste management categories. so that more specific number regarding the funds retain and allocation can be determined in advance. Based on the variation of funds decentralization against garbage

Trans cost	6.38	6.58	6.78	6.98	7.18	7.38	7.58	7.98
Total cost	669,431.72	690,417.04	711,402.36	Non-convex	753,373.00	774,358.32	795,343.64	816,328.96

classification rate, a more effective and efficient rate can be found, in order to unify the requirement on each farm household.

About the Convexity

As we find the optimal result, the convexity is found sensitive to some factors, for instance the marginal cost for collecting the garbage in the village, and the transportation cost. For instance, as we increase or decrease the collecting cost around the original data, by a large magnitude as 35 and 85 etc., the objective function will be not convex, and will affect the iteration process of the algorithm; also as we increase the marginal transportation cost, non-convexity can be still found during the iteration. The following table shoes the sensitivity of the objective value, i.e., the total cost of the system, to the variation of the marginal transportation cost. We can tell from the table that the total cost varies a lot due to the small change of the transportation cost.

CONCLUSION

Governments around the world have been promoting garbage classification due to the public's increased awareness of environmental problems. China started sorting garbage in rural areas, but it suffers from low efficiency in the multilevel governance structure and the fiscal decentralization strategy.

We addressed the fiscal decentralization problem from a quantitative optimization perspective, and we modeled the local garbage processing system into a logistics network. The classification ratio for each village, as well as the location of the landfill for the county, were treated as decision variables in the model. Fund requirements from different government levels are formulated as constraints to characterize the programming and the mechanism by which the governance cost of garbage classification affects the overall system cost was analyzed. The analytical results helped to identify the sufficiency of the constraints to the optimality of the objective. It also helped to derive the classification solution from a qualitative point of view and depict the iteration process in terms of the algorithm's accessibility to the globally optimal solution. Additionally, we also qualitatively proved that there is always a gap between the optimized funds and calculated expenditures at each government level. If the model is extended, it can also be used in other applied researches, for example, when considering how to build three-level rural logistics network nodes such as the county and rural areas, and how the government supports the development of strategic emerging industries affected by location factors.

The numerical experiment on real cases from the county in rural China shows that larger classification ratios are always placed on smaller, productive villages when the capacity does not exceed some threshold. This result follows the reality that classification is usually easier to implement in the villages with lower garbage production. The extended experiment on varied parameters also shows that strict constraints on garbage classification in a village may result in a prohibitively large appropriation size if such a constraint is required to follow the landfill capacity in the county. However, direct modification of the classification requirement, regardless of the capacity variation, may neither raise the potential of retaining the funds at each government level nor necessarily lead to reductions in total transportation costs in the garbage processing system. The sensitivity analysis based on the numerical result shows that the convexity of the model is impacted a lot by some factors, such as the garbage collecting cost in the village and the marginal transportation cost from town to county etc. Also, we found the total cost is sensitive to the marginal transportation cost.

For future research, specific issues impeding efficiency at each government level throughout the garbage processing system should be identified. Identification of these issues should help to formulate all necessary constraints to build a better cost-minimizing model that captures the effects of fiscal decentralization on garbage sorting.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

FUNDING

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2021.686561/full#supplementary-material

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