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Optimization and GIS-based combined approach for the determination of sites and size of biogas plants for a whole region

Ouyang Sanchuan, *Zhu* Hongguang*, *Chen* Junjie, *Zhao* minqi,

Modern Agricultural Science & Engineering, Institute of Biomass Energy Research Centre, Tongji University, Shanghai 200092, China

Abstract. To make better use of agricultural residues and solve the problem of residues pollution, it is necessary to carry out regional management, which means spatial planning of the entire region is essential. This study developed a methodology based on GIS for determining the suitable locations, optimal sizes and number of biogas plants for the entire region while meeting the conditions that all biomass can be collected. Based on the optimization of transportation distance, the nearest facility model and the modified location allocation model were used to obtain the correspondence between plants and supply points, the transportation path and the plants' capacity under different numbers of plants. Based on economic optimization, the economic model was constructed to calculate the total cost of different numbers of biogas plants and the optimal number was obtained after comparing. The cross path was adjusted for the selected plan to ensure that there was no crossover in the plants' collection area. This approach was applied (as a case study) in Funan County, Anhui Province. Based on the existing results, the optimal construction number of biogas plants in the region was 9.

1 Introduction

Anaerobic digestion technology is an environmental engineering technology that can process organic waste and produce clean energy, biogas. It has received more and more attention in the world [1]. China is vigorously supporting the development of biogas industry. The county-based manure treatment and agricultural waste resource utilization are the current development directions of the industry, and its market prospect is very broad [2].

In 2016, the Ministry of Agriculture investigated the construction and operation of rural biogas in China. The results show that China's biogas project is developing rapidly, but the existing biogas project is not effective, and the idle phenomenon is more serious. The root cause is that there is no reasonable site space layout planning before the new construction. Blind construction projects have led to problems in most projects soon after they are put into use. In order to promote the treatment of manure, promote the smooth transformation and upgrading of biogas projects and comply the utilization of agricultural waste in the whole region, relevant spatial layout planning and design is indispensable.

Among the traditional spatial layout methods, there are many methods such as expert selection method, simulation method and analytical method [3]. There are two main types of location analysis based on geographic information systems: suitability analysis [4] and optimality analysis [5]. Perpiña et al [6], Silva et al [7], Franco et al [8] combined geographic information system (GIS) with multicriteria assessment making for biogas plant site selection, while Sultana et al [10], Sahoo et al [11] Ng et al [12], Zhang et al [13] used multicriteria assessment to determine the suitability of land parcels and determine candidate sites for bioenergy facilities. The optimality analysis usually has a service area model [14] and a location allocation model. The location allocation model used in most of the articles is mainly based on the Network Analyst analysis module provided by ArcGIS, which minimizes the weighted distance [10,11,15,16]. The mathematical planning method is applied in the site selection of biomass-based facilities based on the biomass supply chain design and management methods, covering the strategic level, tactical level and operational level, including plant site selection, logistics planning, inventory management, etc. [17]. The model usually targets supply chain profit maximization or cost minimization [13,18-21], or builds an economic and environmental multi-objective model [22-24], in addition, calculates supply chain energy considering the minimization of the input energy [12,25,26]. Most of the constructed models are mixed integer linear programming (MILP) models involving many equations and parameters, sometimes requiring some pre-processing and long solution times [27].

Simple suitability analysis often fails to meet the site selection requirements. Most of the studies used the location allocation models which were simple and only considered a single resource. With supply chain analysis,

* Zhu Hongguang: zhuhg@tongji.edu.cn

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although there were many planning contents available, the establishment and solving of the model itself was complicated. Meanwhile most of the models were not well integrated with GIS and the results obtained were likely to have crossovers of the transport path. Few studies mentioned the need to achieve full coverage of the site radiation range within the planned area. Cheng [28] studied the spatial layout optimization of biogas stations in Funan County, Anhui Province. By a supply and demand model and an environmental constraint model and based on the principle of maximizing coverage and social resources and road accessibility, 12 sites were planned to cover all administrative villages in addition to the existing 3 biogas sites in the county and all sites had the same production capacity. The program was adopted by *the Funan County Agricultural Waste Biogas and Biological Natural Gas Open Utilization Plan (2016-2030)*. However, all plants in the program had the same capacities, and no further consideration of how to plan more economically when the plant capacity could be changed.

The aim of this study was to develop methods in GIS environment to locate biomethane plants, based on the research of Cheng [28], through integration of modified location-allocation model and logistics cost model. Under the condition that the capacity of each plant can be different, the number of plants, capacities and location were optimized. It covered the entire region and handled different kinds of agricultural biomass. The specific objectives were:

-To develop a model to allocate optimally all biomass sources to biogas plants with transportation distance minimization and compute plants' specific production capacities.

-To develop a model to compute the minimum cost of biogas plants considering different parts of biomass supply chain.

-To develop a methodology to ensure the collection area of each biogas plant without crossover.

This approach was finally applied to a case study for Funan County, Anhui Province.

2 Material and methods

This study comprised site suitability analysis of candidate biogas plants and determination of plants production capacity, spatially optimized biomass collection areas and transportation distances as well as the number of plants by minimum the cost. (Fig. 1). All spatial related tasks were performed using ArcGIS version 10.2 software and its associated extensions such as the Spatial Analyst and Network Analyst. The modified location-allocation model was solved using the LINGO version 12.0 software. The site selection method and results developed by Cheng [28] was used directly to determine candidate plant sites. For details, see section 3.2.

2.1 Case Study

In this study, we selected Funan County, Anhui Province as a primary study region. The major breeds in Funan are pigs, beef cattle, sheep, laying hens, etc and there were about 930,000 standard animal equivalents of large-scale farming (2016). Corn, rice, soybeans and wheat are the four major crops cultivated in Funan and nearly 1 million tons per year straws could be collected (2016).

The data used in this study was mainly collected through literature review, field research and other forms. A database was established in GIS to provide data support. Considering that the amount of straw was much larger than manure and to ensure the operation of biogas plants, the amount of straw was collected in a certain proportion in the case of all collection of manure. Therefore, the following analysis was mainly based on livestock manure.

2.2 Road network modification and supply point selection

The amount of resources in the region was counted by the administrative village as a unit and was also collected and transported by the unit. Therefore, when calculating transportation distances, each village was the supply point. Each village simplified from a surface to a point that was the centroid of village. Road network was modified appropriately to ensure good accessibility of the roads and to enable each supply point to be on the road.

2.3 Determination of plants' collection areas, production capacity and biomass transportation distances

The location–allocation analysis was performed with the road network data layer of the study area to deliver biomass to the plant with the minimum transportation distance and by allocating all biomass of all supply point to the facilities. The plant's production capacity could also be computed. Before computing, the closest-facility model was used to get the transportation distance from the station to each supply point along the road network, which was the basic data. In this approach, the Spatial Analyst-Network Analyst- Closest Facility Model in ArcGIS 10.2 software was used. The location-allocation model was calculated using the LINGO12.0 software.

$$\mathrm{Min} \sum_{i=1}^{M} \sum_{j=1}^{N} x_{ij} \cdot d_{ij} \quad (1)$$

$$\text{s.t} \quad \sum_{j=1}^{N} x_{ij} = 1, \quad \forall i,\ i=1 \text{ to } M \quad (2)$$

$$(1+\alpha\%) y_{j1} Q_{j1} \le \sum_{i=1}^{M} x_{ij} \cdot q_{ij} \le (1+\beta\%) y_{j1} Q_{j1},$$
$$\forall l,\ l=1 \text{ to } S \ \&\forall j,\ j=1 \text{ to } N \quad (3)$$

$$x_{ij} \cdot d_{ij} \le D_{max}, \quad \forall i\&j \quad (4)$$

$$\sum_{i=1}^{M} \sum_{j=1}^{N} x_{ij} = M \quad (5)$$

$$\sum_{l=1}^{S} y_{j1} \le 1 \quad (6)$$

$$\sum_{l=1}^{S} \sum_{j=1}^{N} y_{ij} = P \quad (7)$$

$$\sum_{l=1}^{S} \sum_{j=1}^{N} Q_{j1} = Q_{max} \quad (8)$$

$$x_{ij}, y_{j1} \in \{0,1\}, \quad i \in M \ \&\ j \in N \ \&\ 1 \in S \quad (9)$$

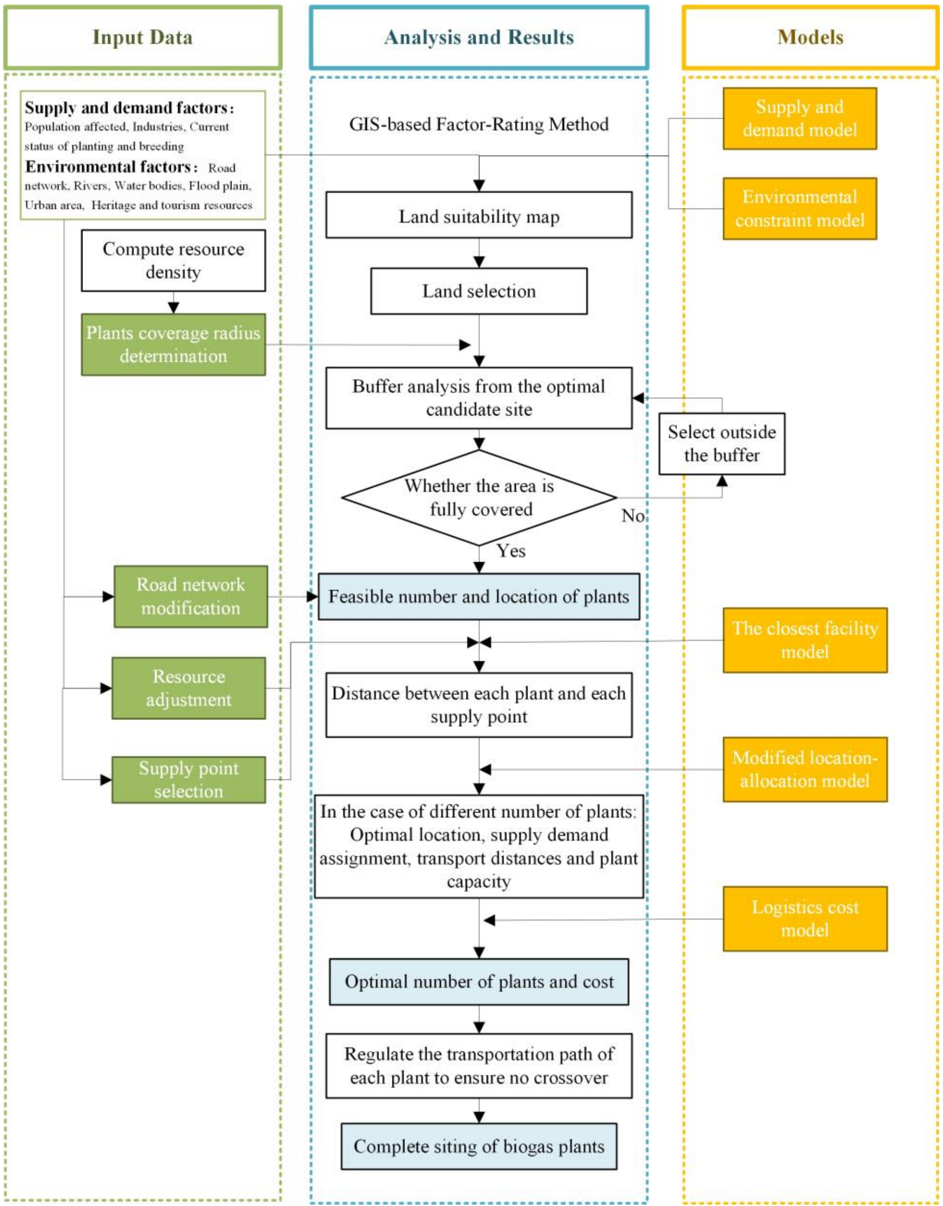

Fig. 1. Flow chart of an integrated approach to optimal siting of plants

Equation (1) minimizes sum of transport distances(d_{ij}) of biomass(q_{ij}) between supply points(i=1 to N) and demands plants (j=1 to N) by selecting 'P' number of plants of capacity (Q_{jl})(l means capacity level, l=1 to S). It was assumed that a supply point should supply biomass to only one plant (equation (2)), i.e., there is no splitting of delivered biomass between selected plants. Equation (3) ensures that the quantity of delivered biomass should be less or more than the capacity of each plant in some extent and that supply point will only be assigned to a plant location selected in the optimum solution. The maximum transport distance (D_{max}) limit was maintained by equation (4) All supply points should be computed ensured by equation (5). Equation (6) ensures a plant only can choose one capacity level. The number of selected plant locations should be equal to 'P' as shown in equation (7) and the sum of capacities of all selected plants should be equal to 'Q_{max}' as shown in equation (6),which means the total capacity remains constant. Equation (9) defines x_{ij} and y_{jl} as binary decision variables (1/0, means selected/not selected).

It is worth noting that only the transport distances were used in this study, not the weighted transport distances. This is because when weighted distances were used (most studies used biomass as weight values), the near-transport principle was weakened, causing some of the transport paths to cross, which was particularly evident when covering the entire region. The maximum transport distance was set similarly. In addition, the level was set when the plant production capacity was calculated, so that the production capacity of the biogas plants in the region can be different, which can also meet the actual engineering. The upper and lower limits were also set for the production capacity for the same reason.

Selecting different numbers of plants for calculations formed multiple situations. In each situation, the shortest route network distances were computed for delivering and allocating biomass to the plants with capacity determined, which provided calculation data for the following economic models.

2.4 Determination of the optimal number of plants

To determine the number of biogas plants, an economic model was used for comparative analysis. The economic model consists mainly of two parts – cost and income. The main objective function of economic analysis was to maximize the weighted benefit of the global waste biogas site, ie equation (10).

$$\text{Max Profit} = \text{Total Revenue} - \text{Total Cost} = (\omega_1 \cdot R_g + \omega_2 \cdot R_f) - (\omega_3 \cdot C_z + \omega_4 \cdot C_t + \omega_5 \cdot C_o + \omega_6 \cdot C_g) \quad (10)$$

$$C_z = C_b \cdot (1-\varepsilon)/y \quad (11)$$

$$C_t = (a + 2b \textstyle\sum d) \cdot Q \quad (12)$$

Where

R_g- Total sales revenue of biogas

R_f- Total sales revenue of organic fertilizer

C_z- Annual depreciation of fixed assets of biogas plants

C_b- Total construction cost of biogas plants

C_t- Total cost of transportation

C_o-Total operating cost of biogas plants,

C_g-Total cost of biogas transmission construction,

ω_i- Income/cost weighted index, i =1~6

ε - Estimated net residual value rate, generally 3%-5%

y-Project lifecycle, year

a -Fixed cost related to loading and unloading of biomass, cost per dry ton

b- Variable cost related to distance traveled, cost per ton km

d -Transportation distances between supply points and plants, km

Q-Total biomass at one supply point, ton

According to the objective function, revenue was divided into fertilizer revenue and biogas revenue, including biogas direct sales and electricity generation. The cost was composed of construction cost, operation cost, transportation cost and biogas transmission cost. Transportation costs, including biomass transportation and organic fertilizer transportation, were calculated according to equation (12). The construction cost included infrastructure cost and equipment cost. This part was the fixed assets of the biogas plants, and its proportion was far greater than other parts of the cost. Therefore, the annual depreciation amount was taken according to the equation (11). Operating costs included biomass acquisition costs, labor costs, electricity costs, etc. The cost estimate of construction and operation was based primarily on an economic analysis of existing biogas projects. In the actual project construction, in order to facilitate project management and operation, the construction scale of biogas plant is basically fixed or scaled. Considering the local conditions and field investigation results of Funan County and referring to the existing biogas plants projects, the plant production capacities selected in this study were 6000m^3, 12000m^3, 18000m^3, 24000m^3, and 30000m^3, which equal to the capacity of anaerobic fermentation tanks. The results of the economic analysis are shown in Figure 2.

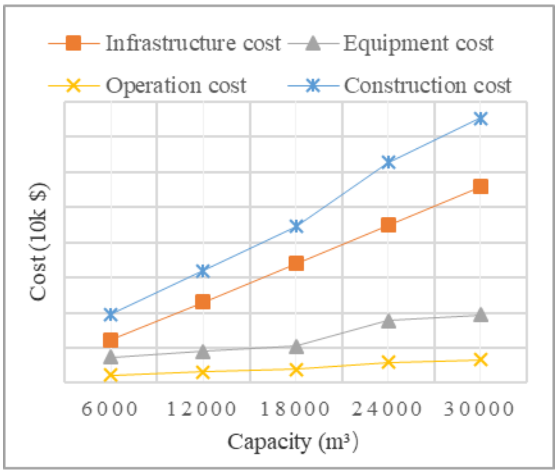

Fig. 2. Relationship between project scale and investment and operating expenses of biogas plants.

2.5 Determination of no crossover in plants' collection area

The economic models determined the number of biogas plants. From the location-allocation model, the corresponding relationship between each plant and the supply point was obtained, that was the plant's collection area, and the capacity of each plant was also determined. Since the model covered all the supply points and limited the plant production capacity, it was unavoidable to cross some of the collection areas most of the time, which was inconsistent with the actual situation. Therefore, when using ArcGIS software to generate a plants' coverage map, it's necessary to manually adjust the correspondence between the plant and the supply point to ensure that there was no crossover among collection areas.

3 Results and discussion

3.1 Biomass and biomethane resources

The amount of potential biomass in Funan County, Anhui Province was estimated to be manure186 tons dry weight per day and crop residues 2978 per day, according to the data of the third survey of livestock production in Funan County at the end of 2016 and the *Comprehensive Utilization Plan of Crop Straw in Funan County (2016-2020)*. The amount of manure and crop residues in 28 townships were shown in Table 1 (321 villages' detail data were omitted).

Considering the crop residues cannot be 100% collected during the collection process and 80% of the residues was currently used in other resources, in this study, the amount of crop residues collected was approximately double the amount of manure in total dry

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weight. From this, the total capacity of all biogas plants was calculated to be 150,000 m^3.

Table 1. Summary of biomass in each town in Funan.

No.	Name	Standard animal equivalent	Total amount of straw t/y	Dry matter quality of manure t/d	Dry matter quality of manure t/d	No.	Name	Standard animal equivalent	Total amount of straw t/y	Dry matter quality of manure t/d	Dry matter quality of manure t/d
1	Lucheng	53878	41720	11	97	15	Honghe	44578	93530	9	218
2	Fangji	38358	21387	8	50	16	Dicheng	44907	36574	9	85
3	Zhonggang	46533	28427	9	66	17	Wangji	19479	18132	4	42
4	Chaiji	27287	53458	5	124	18	Wanghua	51169	32467	10	76
5	Xincun	10173	47588	2	111	19	Caoji	24936	40806	5	95
6	Zhuzhai	31093	57748	6	134	20	Huilong	26197	24036	5	56
7	Liugou	23296	36397	5	85	21	Wangdian	27760	47914	6	112
8	Zhaoji	28462	41465	6	97	22	Xutang	26797	49569	5	115
9	Tianji	21420	45942	4	107	23	Duanying	42377	52531	8	122
10	Miaoji	43015	51233	9	119	24	Gongqiao	34242	89694	7	209
11	Huanggang	29761	39729	6	93	25	Longwang	36993	31251	7	73
12	Jiaopo	40549	50491	8	118	26	Yuji	23035	57140	5	133
13	Zhangzhai	42018	42029	8	98	27	Laoguan	27239	41132	5	96
14	Wangyan	39317	44502	8	104	28	Gaotai	26051	61910	5	144
	Total	930920	1278803	186	2978	Design total pool capacity m³				1500000	

3.2 Candidate plant site selection

Cheng [28] selected four basic influencing factors, two supply and demand factors and six environmental factors to develop a supply and demand model and an environmental constraint model. GIS-based factor-rating method was used to determine the score of each factor. Then land suitability map of the region was got. Through further selecting, 287 areas were suitable for biogas plants. Through local research, it was known that Longwang, Zhonggang and Gongqiao were actively constructing biogas plant, so plant site selection must be based on the existing three sites.

The buffer analysis was started at the highest score in 287 plots. Through multiple loop buffer analysis, 12 sites were selected to cover all administrative villages in the county, except for the existing 3 biogas sites. Site location and rating levels are shown in Table 2.

Through the analysis of the service-area in GIS, the spatial layout of the 15 sites was reasonable, so it was used as candidates for the biogas plants.

3.3 Transportation distance analysis and economic analysis

3.3.1 Total distance and plants capacity change under different number of plants

From the above analysis, it was known that 15 sites had been initially selected, of which 3 were existed. Using the closest-facility model in ArcGIS 10.2 software, the distances between each plant and 321 supply points were sequentially exported and organized into a two-dimensional matrix. According to equations (1)-(9), LINGO12.0 software was used to calculate the allocation of 321 supply points under the number of 5-15 plants, where the plants' production capacity level was 5 (6000, 12000, 18000, 24000, 30000m^3), the upper and lower limits 'α%, β%' were taken 5%, the total pool capacity was maintained at 150,000 m^3, and the longest transport distance was 24 km.

With the increase in the number of biogas plants, the total transportation distance was decreasing, and the trend was gradually stable. As shown in Figure 3. The corresponding plant capacity of each site was shown in Table 3. It can be seen from the table that the Honghe Shitai site could be easily replaced, followed by the Chaiji jinghu site and the Wanghua Dahu site, which indicates that the selected candidate plant sites were not optimized in spatial layout. The most suitable combination with the existing three sites was the Jiaopo Yanmiao site and the Wangyan Malou site.

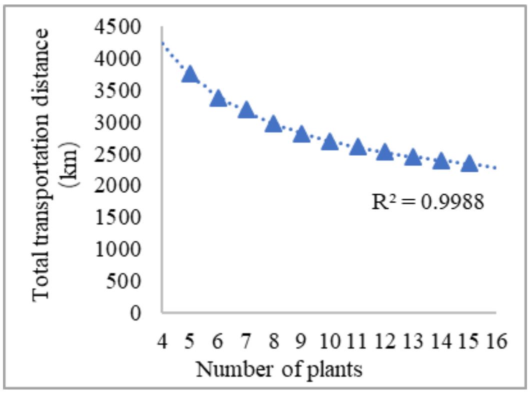

Fig. 3. Variation of transportation distance with different amount of plants in Funan County

3.3.2 Cost analysis of different numbers of sites

In this case, considering that no matter how many biogas sites were built, the total pool capacity was consistent, which meant the total amount of biomass processed was consistent. The amount of biogas and the amount of fertilizer produced could be approximated as being

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constant, ie, the income was constant, so it could be simplified to compare the cost of different numbers of plants. The gas project had achieved global penetration. The number and location of biogas plants had little impact on the project. The cost of this part was regarded as constant or not included in the calculation. The cost of biomass purchases was also certain and not included.

Under different amount of biogas plants, the results obtained from the location allocation model were used to calculate the site construction cost (converted to the annual depreciation amount (equation (11)), the residual value was 5%, the depreciation period was 20 years), the site operation cost and the transportation cost, which were shown in Figure 4. From the figure, with increase in number of plants, the site construction cost was increasing smoothly as it was converted to be depreciation amount. The site operation cost was increased rapidly after the number of 9 biogas plant while the transportation cost continued to decrease. In addition, the cost of these three parts was in the same grade, which meant the additivity was available, when other constant costs mentioned above were not calculated. In this case all weight values were taken as 1 respectively. The total conversion costs for different numbers of plants were shown in Figure 5. As can be seen from the figure, both the total cost of all plants and the cost of per unit volume are optimal for the number of 9 plants.

Table 2. Statistical Table of Biogas Plants Sites in Funan County, Anhui Province

No.	Village	Town	Rank	No.	Village	Town	Rank	No.	Village	Town	Rank
1	Hanying	Longwang	Exist	6	Malou	Wangyan	10	11	Shitai	Honghe	9
2	Changan	Zhonggang	Exist	7	Zhaolao	Tianji	10	12	Wujing	Zhuzhai	8
3	Mengzhai	Gongqiao	Exist	8	Shizhai	Wangdian	9	13	Wuyue	Wangdian	8
4	Xiangji	Lucheng	16	9	Baozhuang	Laoguan	9	14	Jinghu	Caoji	8
5	Dahu	Wanghua	11	10	Yanmiao	Jiaopo	9	15	Caotai	Gaotai	7

Table 3. Variation of each plant capacity with different amount of plants in Funan County (m^3)

Plant Info.			**Number of plants**										
No.	**Village**	**Town**	**15**	**14**	**13**	**12**	**11**	**10**	**9**	**8**	**7**	**6**	**5**
1	Xiangji	Lucheng	12000	12000	12000	12000	12000	12000	18000	18000	0	0	0
2	Dahu	Wanghua	12000	12000	12000	0	0	0	0	0	0	0	0
3	Malou	Wangyan	18000	18000	18000	12000	18000	18000	18000	18000	18000	18000	0
4	Laozhao	Tianji	6000	6000	6000	12000	6000	12000	0	0	0	0	0
5	Shizhai	Wangdian	6000	6000	6000	12000	6000	0	0	0	18000	24000	30000
6	Baozhuang	Laoguan	6000	12000	12000	12000	12000	18000	18000	0	0	0	0
7	Yanmiao	Jiaopo	12000	12000	12000	12000	18000	18000	18000	18000	18000	24000	30000
8	Shitai	Honghe	6000	0	0	0	0	0	0	0	0	0	0
9	Wujing	Zhuzhai	6000	6000	6000	12000	0	0	0	0	0	0	0
10	Wuyue	Wangdian	6000	6000	6000	12000	6000	12000	12000	12000	0	0	0
11	Jinghu	Caoji	12000	6000	0	0	0	0	0	0	0	0	0
12	Caoji	Gaotai	6000	6000	12000	12000	12000	12000	12000	18000	12000	0	0
13	Changan	Zhonggang	18000	18000	18000	12000	18000	18000	18000	24000	30000	30000	30000
14	Hanying	Longwang	12000	18000	18000	18000	18000	18000	18000	30000	30000	30000	30000
15	Mengzhai	Gongqiao	12000	12000	12000	12000	12000	12000	18000	18000	24000	24000	30000

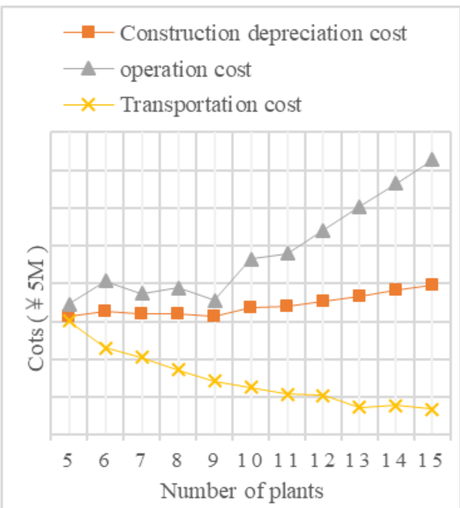

Fig. 4. Variation of construction/ operation/ transportation cost with different amount of plants in Funan County

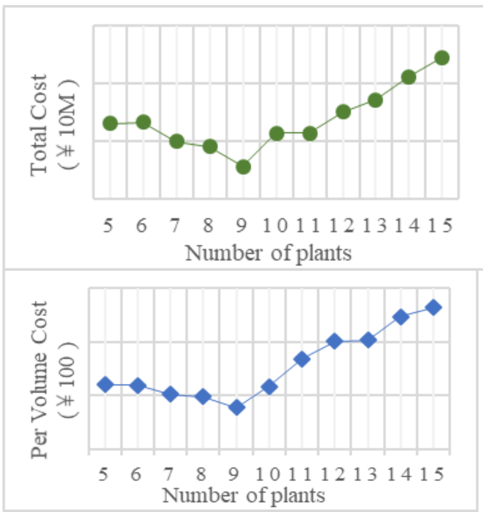

Fig. 5. Variation of total cost and per volume cost with different amount of plants in Funan County

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3.5 Modification of plants' collection area

According to the above analysis results, it was most economical to plan 9 biogas plants in Funan County, Anhui Province, including the existing 3 plants, Zhonggang Changan, Longwang Hanying, Gongqiao Mengzhai, and other 6 plants, Lucheng Xiangji, Wangyan Malou, Laoguan Baozhuang, Jiaopo Yanmiao, Wangdian Wuyue and Gaotai Caotai.

The 9 sites were imported into ArcGIS. Each supply point was connected by the corresponding plants and some of the connecting line crossed. In order to better meet the actual operation situation, the cross-path was manually adjusted and the coverage of each plant was generated, as shown in Figure 6. The information of each plant after adjustment is shown in Table 4. Most plants' production capacity were18,000 m3, and only two were 12,000. The crop residues collection power of each plant in the collection area was less than 20%, which was consistent with the actual situation.

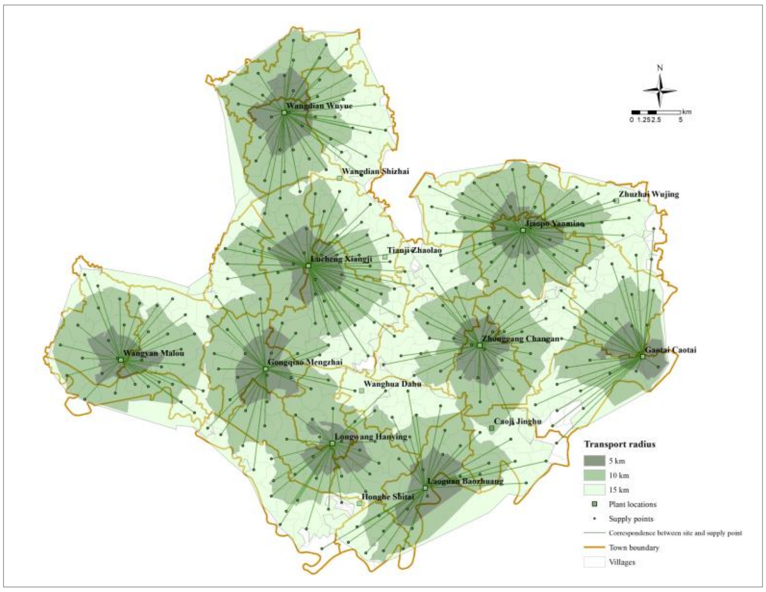

Fig. 6. 9 biogas plants coverage map and correspondence with 321 supply points in Funan County

Table 4. Biogas plant basic information under optimal cost

No.	Plan Info. Village	Town	Number of collected villages	Total transport distance km	Total crop residue dry weight t/d	Total manure dry weight t/d	Dry weight of collected crop residue t/d	Crop residue collection coefficient	Plant production cacibility m3
1	Xiangji	Lucheng	52	465	328	23	51	15.6%	18000
2	Dahu	Wanghua	0	0	0	0	0	0.0%	0
3	Malou	Wangyan	32	265	266	24	52	19.5%	18000
4	Laozhao	Tianji	0	0	0	0	0	0.0%	0
5	Shizhai	Wangdian	0	0	0	0	0	0.0%	0
6	Baozhuang	Laoguan	30	269	274	21	47	17.2%	18000
7	Yanmiao	Jiaopo	49	421	402	23	50	12.4%	18000
8	Shitai	Honghe	0	0	0	0	0	0.0%	0
9	Wujing	Zhuzhai	0	0	0	0	0	0.0%	0
10	Wuyue	Wangdian	40	335	368	14	31	8.5%	12000
11	Jinghu	Caoji	0	0	0	0	0	0.0%	0
12	Caoji	Gaotai	28	308	269	14	32	11.7%	12000
13	Changan	Zhonggang	34	281	299	24	52	17.4%	18000
14	Hanying	Longwang	27	232	351	22	48	13.5%	18000
15	Mengzhai	Gongqiao	29	232	421	21	47	11.2%	18000
Total			321	2808	2978	186	410	13.8%	150000

4 Conclusions

A method was developed in GIS environment to analyse suitable locations of biomass-based facilities, their optimal capacities and number of plants considering local road network for the entire region. The method optimized the location-allocation model and ranked plant production capacity in the calculation, which achieved full collection of the entire region without cross paths. The method also considered the cost of each link of the biomass supply chain and ranked the construction and operation costs. In addition, the method simplified the existing supply chain model and made the planned transportation route more reasonable in combination with ArcGIS.

This approach was applied (as a case study) in Funan County, Anhui Province. Based on the biogas plant sites identified by Cheng [28], optimal capacities and number of plants and collection area of each plant were determined by a modified location-allocation model and a logistics cost model. The location–allocation model results was that the transportation distance reduced rapidly with increase in number of plants, which was similar with the changes of transportation cost. While the costs of construction and operation were increasing. By comparing the total cost of 5-15 plants, based on the existing 3 plant locations, building 6 more plants was optimal for the region. Among them, 2 plants' capacity was 12,000 m^3 and others was 18,000 m^3.

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