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Research on the recycling of sharing bikes based on time dynamics series, individual regrets and group efficiency

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ABSTRACT

Sharing bicycle has attracted the most sharply increased attention throughout the world in recent years. Its rapid development has increased transportation convenience. However, abandoned bicycles have caused a waste of resources and environmental damage. Additionally, the negative effects will exceed the positive impact that sharing bicycle creates if these abandoned bicycles are handled improperly. This paper proposes a two-stage method to study the recycling of abandoned bicycles, including the selection of the third-party logistics suppliers (3 PLs) and the recycling network design. In the first stage, interval type-2 fuzzy sets (IT2FSs) and Vlse Kriterjumska Optimizacija I Kompromisno Resenje (VIKOR) are used to select the 3 PLs. The dynamic time series, individual regrets, and group efficiency are all taken into account. In the second stage, From the perspective of maximizing overall benefits, a mathematical model considering the purchase cost of raw materials, transportation costs, recovery costs, and environmental benefits is established to design a recycling network. Finally, the applicability of the proposed method is numerically demonstrated by solving a real case, and key conclusions are that the recycling mode with the participation of the 3 PLs in sharing bicycle system is the most reasonable and feasible. However, in this mode, the selection criteria of the 3 PLs are different from other industries, which need to be given enough attention by the sharing bicycle operators. Additionally, in the recycling network design, considering the maximum overall interests of the three parties, the factory, the 3 PLs, and the operators, must coincide with the social philosophy of sustainable development. The results are of great guiding significance to the recycling of sharing bicycles.

1. Introduction

Sharing bicycle is an important component of a city's slow traffic system. Bikes are popular and have a broad market prospect due to the characteristics of convenience and flexibility. To meet the huge market demand and occupy a larger market share, operators of sharing bicycles are racing to bring bikes to the market. According to the statistics data of the National Bureau, in the first quarter of 2017, more than three million bikes were placed into circulation, and the estimated annual number may reach 20 million (Hbspca, 2017), which directly caused the problem of overcapacity for sharing bicycles. In the next one or two years, the number of bikes that have been destroyed and need to be scrapped will increase rapidly, and many abandoned bikes will cause serious environmental damage. A bicycle is made up of more than 100 components, including the cushion, frame, wheels and so on. When 20 million sharing bicycles are scrapped, approximately 300 thousand tons of steel are generated, which is equivalent to the weight of the structural steel of five aircraft carriers (Xinhuanet, 2017). If this discarded steel cannot be effectively recycled, serious waste of resources will result (Zhang et al., 2015).

Due to the high cost of recycling and narrow profit margin, most companies choose to ignore abandoned sharing bicycles and do nothing to dispose of them properly (Ministry of commerce of the People's Republic of China Department of Circulation Industry Development, 2017). In view of this situation, it is necessary to introduce third-party logistics suppliers (3 PLs) for recycling,

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specifically, the sharing bicycles' operators and the 3 PLs enter into a contract, which stipulates that the 3 PLs are responsible for recycling the abandoned sharing bicycles, and the operators also pay the corresponding remunerations to the 3 PLs (Aguezzoul, 2014; Govindan et al., 2015). Organizations have widely adopted this approach because of its high efficiency (Tuğba et al., 2008). Meanwhile, there is no doubt that the importance of the 3 PLs in improving service quality and operational performance (Liu and Lyons, 2011; Guarnieri et al., 2015). However, the scientific selection and evaluation of the 3 PLs is a complex group decision making (GDM) problem, which involves decision-making criteria and experts (Zarbakhshnia et al., 2018). Its complexity is reflected in the following aspects. First, in the decision-making process, experts can be influenced by others who they believe are important in this group. When their opinions are less acceptable, they will change their views to reach a consensus. It will not only produce regrettable results but has an adverse influence on the final decision-making (Chen et al., 2016). Second, according to relevant research results, due to the environment changes and the improvement of expert knowledge, the same expert may hold two different opinions on the same issue at different time periods. Therefore, inviting experts to evaluate the same issue multiple times with in different time periods is an effective measure to solve this problem (Jin et al., 2013). Third, in GDM, individual opinions must be aggregated to form a common opinion of the decision-making team. The efficiency of the decision-making team's expert collaboration also influences the decision-making result (Opricovic and Tzeng, 2004). Therefore, dynamic time series, personal regret, and team efficiency should all be considered in the decision-making process.

In this paper, two stages of research are carried out based on the recycling of sharing bicycles, namely the selection of the optimum 3 PLs and the design of recycling network. In the first stage, firstly, the relevant evaluation criteria of 3 PLs are determined by reviewing the existing research. Then, interval type-2 fuzzy sets (IT2FSs) are used as the evaluation language and Vlse Kriterjumska Optimizacija I Kompromisno Resenje (VIKOR) is used as the evaluation method to evaluate these criteria. In addition, in order to make the evaluation results more scientific, the effects of time dynamics series, individual regrets and group efficiency on the decision results are also considered comprehensively. In this paper, we mainly consider the three major subjects involved in the recycling activities, enterprises, factories and 3 PLs. Therefore, in the second stage, the recycling path model based on the maximization of overall economic and environmental benefits is established. Maximizing economic benefits means maximizing the common economic benefits and minimizing costs for companies, factories and 3 PLs. Among them, for the company, both the purchase cost and the transportation cost of raw material are considered into the model. For the factory, the cost of production is mainly considered into the model. The recovery cost and transportation cost of recovery material are mainly considered as for the 3 PLs. Maximizing environmental benefits means minimizing the total carbon emissions in the recovery process. The carbon emissions come from production, transportation and recycling, which are also determined on the basis of the three main bodies associated with the recycling process. Next, the Genetic Simulated Annealing Algorithm (GA-SA) algorithm is used to solve the recycling path model and complete the design of recycling network. What's more, in the comparative analysis, we compare the GA-SA algorithm with the GA algorithm to highlight the superiority of the algorithm chosen in this paper. In the sensitivity analysis, the impact on the recycling plans is analyzed by changing the total amount of components on the sharing bicycles. Fig. 1 clearly shows the main structure of this paper. Before conducting further research, the operation and recycling modes should be described, as the important research premise. Sharing bicycles are a kind of green transportation. Customers obtain sharing bicycles at stations, and then use the bicycles to travel to bus or subway stations and transfer to destinations using public transportation. In the process, customers pay the corresponding fees to the sharing bicycles' operators through the mobile terminal. Then, they obtain the usage rights for a certain period. In the recycling mode, the sharing bicycles' operators play a connecting role. They commission factories to produce the bikes, and they commission the 3 PLs to recycle the abandoned sharing bicycles, here, abandoned sharing bicycles can usually be obtained anywhere at stations or on the side of the road. The raw materials purchased by the operator and the materials recovered by the 3 PLs are delivered to the factories for the production of bicycles. As a result, operators, the 3 PLs, and the factories form a recycling mode similar to a closed-loop supply chain. Operation and recycling modes for sharing bicycles are shown in Fig. 2.

This paper is structured as follows. Section 2 provides a detailed literature review of the existing research on the 3 PLs.The theory of Vlse Kriterjumska Optimizacija I Kompromisno Resenje (VIKOR), IT2FSs and other theories are briefly introduced in section 3. Section 4 presents the process of the recycling model establishment based on the principle of maximizing the overall benefits. A numerical example is given in section 5. Here, we change the relevant variables and observe the extent of their impact on the outcome to determine the importance of these variables. Finally, the conclusions, the direction of future research, and the inadequacies are discussed in section 6.

2. Literature review

This paper is developed based on the recycling activities of sharing bicycles and explores two stages, which are the choice of the 3 PLs based on GDM and the design of recovery network based on the cost and environmental benefits. Therefore, in order to have a more comprehensive understanding of these research statuses in the related fields and carry out innovative research, the literature is reviewed on three related topics: sharing bicycles, 3 PLs and the GDM problem, which is shown in Table 1.

Sharing bicycle has received significant attention recently due to its convenience and environmental benefits. With the increase in sharing bicycles, it is particularly important to solve the problem of abandoned sharing bicycles. However, the research results in this area are scarce. In fact, the current research on sharing bicycles mainly includes the following two aspects: (1) qualitative research: analysis the development of sharing bicycles, their advantages and disadvantages (Guo et al., 2017b; Pelechrinis et al., 2017); (2) quantitative research is mainly concentrated in two aspects, which are the station layout problem (Chen et al., 2016; Frade and Ribeiro, 2015) and bike repositioning problem on sharing bicycles (Chen et al., 2018; Faghih-Imani et al., 2017; Ghosh et al., 2017). As people gradually realize the importance of non-motorized traffic models, sharing bicycle is attracting attention. Guo et al. (2017b) established a binary probabilistic model to explore the factors that affect the using rate and satisfaction of sharing bicycles. The result showed that the user's gender, station locations, and family income are three important influencing factors. Pelechrinis et al. (2017) studied the positive impact of sharing bicycles on people's health, air quality and road traffic by quantitative analysis. Besides, this research also analyzed the data of the Pittsburgh real estate market and found that sharing bicycles can even produce a shadow of housing rental and selling prices in the region. Finally, the study proposed two related public policies to guide the further development of urban sharing bicycles. Chen et al. (2016) studied the layout and quantity of sharing bicycle stations in the region. In this paper, the mathematical modeling was established considering the

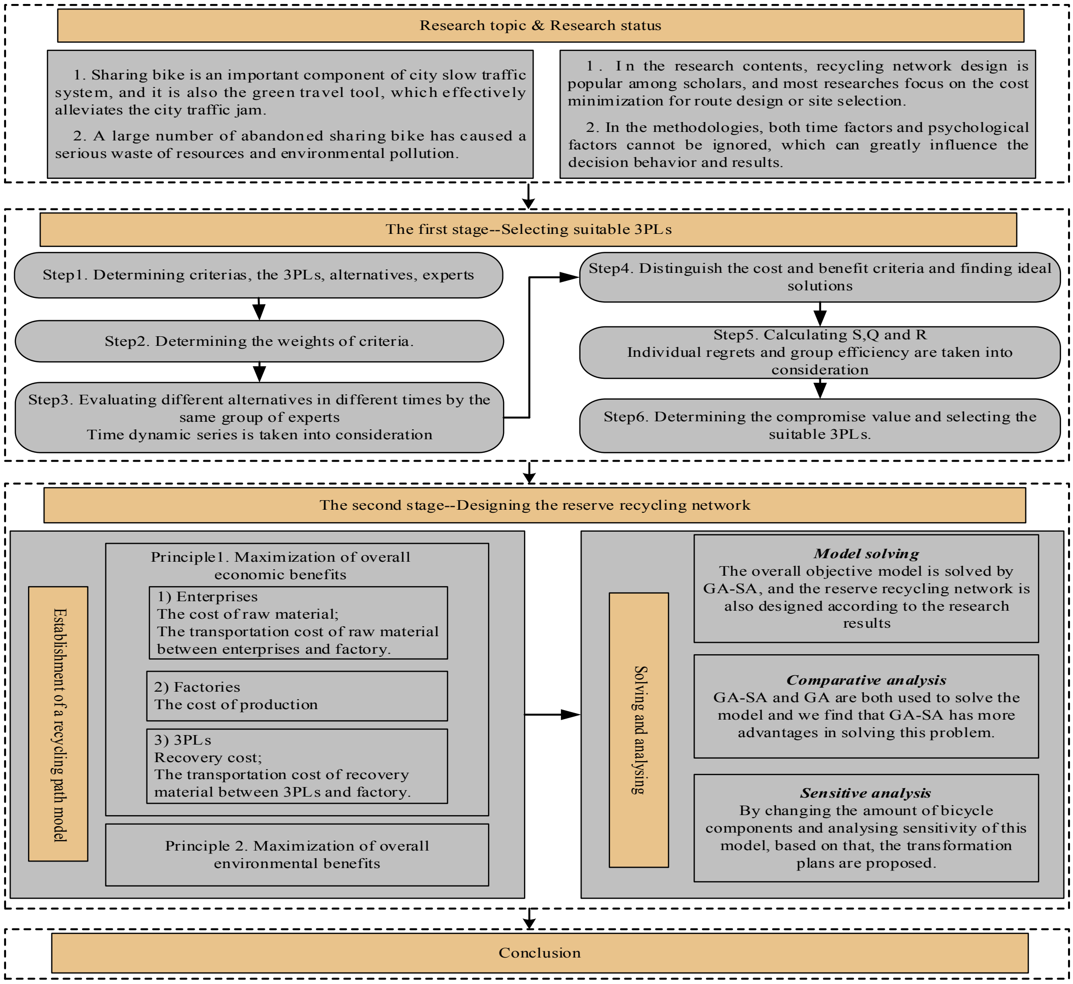

Fig. 1. The main structure of this paper.

minimum total time and cost to maximize the satisfaction of the customer. Finally, the model was solved by LINGO and the feasibility was also verified based on the real case. Sharing bicycle is becoming more and more popular because of its sustainable development. Frade and Ribeiro (2015) focused on the social impact of sharing bicycles and designed the sharing bicycle system by using optimization methods. The system mainly consisted of three parts, namely, the best location of sharing bicycle stations, the number of sharing bicycles at stations and the capacity of stations. Chen et al. (2018) established a mathematical planning model based on maximizing demand satisfaction and studied the bike repositioning problem on sharing bicycles. The validity of the model was demonstrated using a correlation calculation. Faghih-Imani et al. (2017) conducted three stages of research on the rebalancing problem of sharing bicycles. In the first stage, the impact of these factors such as the number of stations and the characteristics of the population distribution on the flow of sharing bicycles was analyzed using a hybrid linear model. In the second stage, a binary logit model was established to identify the rebalancing period and determine the rebalancing amount. In the third stage, the data from Barcelona and Seville, Spain, were used for verification analysis. Station selection is a critical issue in the design of sharing bicycles systems. It has a significant impact on the performance and efficiency of the system. The parking of sharing bicycles is often not restricted by location, which often causes imbalance between supply and demand of bicycles between regions. Ghosh et al. (2017) studied the repositioning problem of sharing bicycles through optimization method. Meanwhile, this method also took into account the design and optimization of sharing bicycle rescheduling routes. Finally, the effectiveness of the method was evaluated by real data.

Reverse logistics is a new research topic that has attracted the attention of scholars at home and abroad since it was proposed. We will review the relevant researches from two perspectives, research contents and research methodologies. In the aspect of the research contents, most studies on the 3 PLs focused on facility location (Kilic et al., 2015; Afshari et al., 2016), resource allocation (Liu et al., 2014) and network design (Alshamsi and Diabat, 2015; Altekin et al., 2014; Hatefi and Jolai, 2014; Bing et al., 2014). Kilic et al. (2015) designed an electronic reverse logistics system for Turkey. In this paper, a mixed integer linear programming model was adopted to identify the most suitable locations for storage and recycling facilities. Liu et al. (2014) proposed a multi-objective scheduling model which considered the joint cost between two adjacent activities and two successive activities. According to the actual size of the initial investment, Alshamsi and Diabat (2015) considered the choice of site optimization, the capacities of test centers and remanufacturing facilities, and used mixed integer linear programming (MILP) to design a transportation network for a reverse logistics (RL) system to allocate resources. In the study of the methodologies, scholars proposed mathematical programming models (Govindan et al., 2016; Ayhan and Kilic, 2015; Yeh and

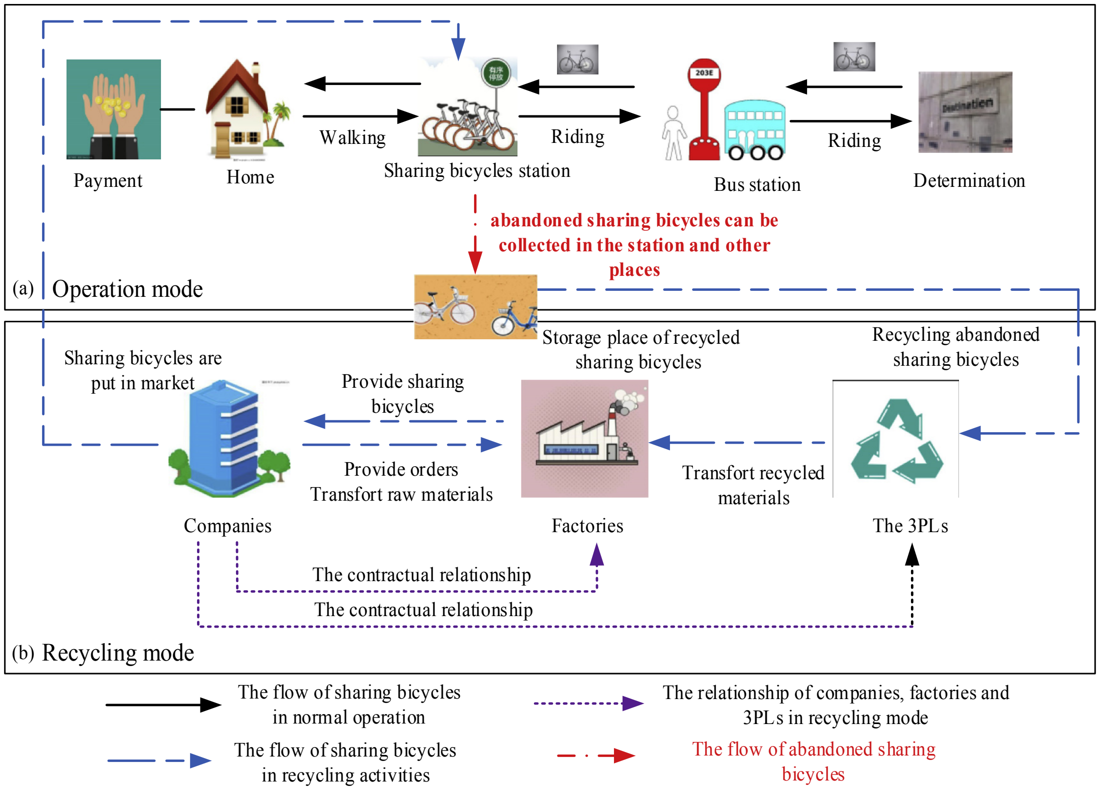

Fig. 2. Operation and recycling modes for sharing bicycles.

Table 1
Literature review.

Review works	Classified	Literatures
Sharing bicycles	**Qualitative research:** analysis the development of sharing bicycles, their advantages and disadvantages **Quantitative research:** station layout problem; bike repositioning problem	Guo et al., 2017b; Pelechrinis et al., 2017; Chen et al., 2016; Fishman et al., 2015; Zhang et al., 2015 Chen et al., 2018; Ghosh et al., 2017; Faghih-Imani et al., 2017; Alvarez-Valdes et al., 2016; Schuijbroek et al., 2016; Cruz et al., 2016; Chen et al., 2016; Erdogan et al., 2015; Forma et al., 2015; Frade and Ribeiro, 2015; Dell'Amico et al., 2014; Ho and Szeto, 2014; Chemla et al., 2013; Raviv et al., 2013; Lin et al., 2013; García-Palomares et al., 2012.
Reverse logistics	**Research contents:** facility location; resource allocation; network design **Methodologies:** mathematical programming models; multi criteria decision making approaches; artificial intelligence approaches	Afshari et al., 2016; Kilic et al., 2015; Alshamsi and Diabat, 2015; Liu et al., 2014; Altekin et al., 2014; Hatefi and Jolai, 2014; Bing et al., 2014. Guo et al., 2017a; Prakash and Barua, 2017; Govindan et al., 2016; Ayhan and Kilic, 2015; Zhou et al., 2015; Jayant et al., 2014; Senthil et al., 2014; Dai and Wang, 2014; Dobos and Vörösmarty, 2014; Diabat et al., 2013; Amin and Zhang, 2012; Diego et al., 2012; Pishvaee et al., 2012; Yeh and Chuang, 2011.
Group decision making problem	Determining the weights of the experts; Determining attribute weights	Ren et al., 2017; Wu et al., 2016; You et al., 2015; Rezaie et al., 2014; Snežana et al., 2014; Sanayei et al., 2010.

Chuang, 2011; Amin and Zhang, 2012; Diabat et al., 2013; Guo et al., 2017a), multi criteria decision making (MCDM) approaches (Dobos and Vörösmarty, 2014; Pishvaee et al., 2012; Jayant et al., 2014; Senthil et al., 2014; Prakash and Barua, 2017; Diego et al., 2012) as well as artificial intelligence approaches (Dai and Wang, 2014; Zhou et al., 2015) to study the 3 PLs. Govindan et al. (2016) designed a reverse logistics network based on minimizing costs and maximizing environmental benefits, and the multi-objective particle swarm optimization (MOPSO) algorithm was proposed to solve the model. Amin and Zhang (2012) proposed a two-stage integrated model that includes manufacturers, refurbishment and disposal sites. In the first stage, a criteria framework for 3 PLs selection was designed, and in the second stage, a multi-objective MILP model was established to determine the most suitable 3 PL and the optimal number of parts and products in the closed-loop supply chain network. Pishvaee et al. (2012) proposed a fuzzy mathematical programming model based on double objective reliability for the design of green logistics network and strategic resource allocation in uncertain environment. The objective of this model was to minimize the environmental impact of CO_2 equivalent index and to provide a sensible balance between the total costs of network construction. Prakash and Barua (2017) proposed a fuzzy analytic hierarchy process (FAHP) and a flexible method for explaining the sorting process to evaluate the factors that affected the adoption rate of RL. Diego et al. (2012) proposed a multi-criteria evaluation model to evaluate 3 PLs using analytic hierarchy process (AHP), data envelopment analysis (DEA) and linear programming. The model overcomes the limitations of AHP because it combined expert's instructions with objective judgments that were derived from historical data analysis. Zhou et al. (2015) used particle swarm optimization algorithm (PSOA) and genetic algorithms (GA), and other intelligent algorithms to solve the Cournot-Nash problem that the smooth objective function was not differentiable. Their research resolved the flow path for each product in the supply chain. To sum up, in the research contents, recycling network design is popular among scholars, and most researches focus on the cost minimization for route design or site selection. What's more, most researches are developed on the basis of the company's perspectives and pursue the maximum economic benefits. In the methodologies, the above research results could solve some practical problems and achieved good results. However, in the rapidly changing modern market environment, time and psychological factors cannot be ignored, which can greatly influence the decision behavior as well as the results.

Due to the complexity of the decision-making environment, a single decision-maker is unable to consider all aspects of the problem. However, group decision-making can synthesize more information, viewpoints, and suggestions to make the decision-making result more rational and objective (Wan et al., 2016). The process of multi-criteria group decision-making consists of constructing an evaluation index system, determining attribute weights, determining attribute values, standardizing the decision matrix, and comprehensive sequencing. Among these, existing researches mainly focus on the following topics: (1) Determining the weights of the experts. Due to differences in the status, power, prestige, knowledge experience, and preferences of experts, their decisions may conflict. Therefore, in the process of synthesizing different expert opinions, how to judge the importance of the experts has become an important research topic (Snežana et al., 2014; Wu et al., 2016); (2) Determining attribute weights in multi-attribute group decision-making. Because multi-attribute decision-making is the basis of group decision-making, the weight of each attribute must be determined first in group decision-making. The methods for determining the weight of each attribute include the subjective method, objective method, subjective and objective comprehensive weighting method, etc. (Sanayei et al., 2010; Ren et al., 2017); (3) Determination and selection of decision methods in multi-attribute group decision making (Rezaie et al., 2014; You et al., 2015). With the development of intelligent and automated information systems in the information age, the demand for more efficient decision-making methods is also increasing. Shemshadi et al. (2011) combined VIKOR with trapezoidal fuzzy numbers to study supplier selection. First, the experts were invited to use fuzzy language terminology to evaluate the supplier selection criteria. Then the VIKOR method was used to determine the most suitable supplier. Finally, the scientific validity of the proposed method was verified through related experiments. Lourenzutti and Krohling (2016) conducted innovative research on Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) and developed the Group Modular Random TOPSIS (GM-RTOPSIS) method to study multi-criteria group decision-making problems in a dynamic environment. The method processed different types of decision information, such as clear, fuzzy, or intermittent information, so that each decision maker could fully express their own ideas. Meanwhile, each decision maker evaluated the plan in the way they consider. Then, based on the importance of the decision makers, the evaluation results were summarized and the most appropriate solution was selected. Finally, the validity of the method was verified using three cases. High efficiency and low carbon sustainability are the basic requirements for urban logistics. Snežana et al. (2014) proposed an evaluation method for selecting the most suitable city logistics mode. Since urban logistics involves different participants and stakeholders, different participants often have conflicting evaluation criteria because of different goals and interests. Based on this, the author defines a large number of filtered standards for urban logistics concept assessment. Additionally, a mixed MCDM model combining the fuzzy decision-making trial and evaluation laboratory (DEMATEL), fuzzy analysis network processing (ANP) and fuzzy VIKOR methods was developed to evaluate the criteria and select the most suitable city logistics mode. Recently, determining the most suitable supplier in the supply chain has become an important issue in enterprise development. However, the supplier's choice is a complex multi-criteria group decision problem. The supplier's evaluation criteria often involve many qualitative or quantitative factors. There may be conflicts between these factors, which further increases the complexity of the problem. The VIKOR method is an effective tool for solving contradictory multi-criteria decision-making problems. Therefore, Sanayei et al. (2010) combined the VIKOR method with fuzzy set theory to address the issue of supplier selection in supply chain systems. Triangular fuzzy language was used to evaluate the importance of different standards, and the VIKOR method was used to determine the most suitable supplier. Finally, the validity of the method was verified using relevant numerical examples. In summary, the current research on multi-attribute group decision making is very beneficial. Therefore, based on the existing research, this paper considers the time dynamics series, individual regrets, and group efficiency in the group decision-making problem to make the decision-making result more scientific.

Based on previous studies, the following improvements are proposed in this paper: (1) the existing researches on sharing bicycles focus on delivery paths and delivery point arrangements, but with little attention to the bicycle recycling (Raviv et al., 2013; Schuijbroek et al., 2011; Nair and Miller-Hooks, 2014), therefore, this paper focuses on the design of recycling network by inheriting scholars' research contents; (2) Changing the one-sided research perspective. In this paper, the research is not limited to selecting the optimal 3 PLs. Based on the principle of maximizing the overall benefit for the closed reserve recycling network. The optimal recycling routes are designed including companies of sharing bicycles, the 3 PLs and factories; (3) In this paper, two methods are used to study two sub problems. First, 3 PLs are selected using a fuzzy evaluation method; second, a mathematical model is established to design the recycling network; (4) IT2FSs is combined with VIKOR, considering individual regret, dynamic time and group efficiency.

3. The method of selecting the 3 PLs

The selection of 3 PLs is influenced by various factors, and the entire process involves transportation, logistics, scrap handling and several departments. Therefore, it is difficult to identify the most appropriate 3 PLs that meet all of criteria. In this section, the method for selecting the 3 PLs is introduced in detail including factors that affect the determination, such as dynamic time factors and individual regret that are both considered in the group decision.

3.1. Relevant criteria on the selection of 3 PLs of sharing bicycles

3.1.1. Green image

Thousands of abandoned bicycles have led to the waste of resources and environmental pollution. Performing the recycling activities of sharing bicycles is imperative. It is a positive response to the construction of low-carbon cities and a strategic choice for sharing bicycles' operators under the guidance of sustainable development. Based on this, 3 PLs must also have a strong sense of environmental protection and a green business philosophy. Additionally, ISO14000 certification is an important measure for Chinese companies to integrate into the international market. The green image should be selected as a criterion for evaluating 3 PLs (Kafa et al., 2015; Ji et al., 2014; Cohen and Muñoz, 2016).

3.1.2. Financial ability

Recycling activities of sharing bicycles involve many links, such as, search, transportation, disassemble, machining and so on. These activities require a large investment, which needs to invest a lot of manpower and money. If there is not sufficient funding as a guarantee, the recycling activities will be difficult to continue carry on perform. Therefore, sufficient funds must be provided as a basic guarantee. For companies, maintaining a stable cash flow is necessary. Financial ability is composed of financial management ability, financial activity ability, financial relationship ability and financial performance ability. Weak financial ability makes it difficult for companies to ensure that they can gain a competitive advantage. Therefore, financial ability is also an important criterion to be considered in the selection of 3 PLs on sharing bicycles (Kafa et al., 2015; Senthil et al., 2014).

3.1.3. Recovery capacity

This paper focuses on recycling activities of sharing bicycles. As the name suggests, recovery capacity is an important index for evaluating and selecting of 3 PLs on sharing bicycles. It includes the total number of bikes, the amount of recovery per time unit, the rate of recovery (ratio of quantity to the actual number of recovered) and specialized infrastructures. The total recovery rate reflects the size of the 3 PLs, unit time recovery amount and the rate of recovery are a reflection of its recovery level, and the construction of a professional infrastructure is a manifestation of the 3 PLs' technological ability (Aguezzoul, 2014; Ayhan and Kilic, 2015; Mafakheria and Nasirib, 2013).

3.1.4. Pollution and emission

The purpose of performing recycling activities is to reduce the adverse impact of abandoned bikes on the environment, and the introduction of the 3 PLs improves the recycling efficiency. However, if the 3 PLs cause serious damage to the environment during the recycling process that exceeds the destruction of the abandoned bicycles, it will be counterproductive. Pollution and emission are important criteria for evaluating the capacity of environmental protection. They can be measured using the volume of pollutants (waste water, waste gas, etc.) produced in a unit of time (Sasikumar and Noorul, 2001; Chen et al., 2013; Tsai and Hung, 2009; Abdulrahman et al., 2014; Xu et al., 2017).

3.1.5. Searching ability

Based on the actual situation, the abandoned sharing bicycles may need to be located. The convenience of sharing bicycles is reflected in the fact that customers can pick up and drop off bikes at any time and place. Thus, abandoned bicycles are not always parked at the station and are usually scattered in every corner of the city. Therefore, the 3 PLs need to have a strong ability to search for abandoned bicycles in the recycling activities. The search ability is an important index for evaluating 3 PLs (Zhang et al., 2015).

3.2. Fundamentals of IT2FSs

IT2FSs is developed form the theory of type-2 fuzzy sets (T2FSs), which effectively solves the linguistic ambiguity of the T2FSs and the data noise problem, and has greater freedom and precision in dealing with the uncertainty problem. From the algebraic perspective, when the secondary membership values of the T2FSs are equal to one, then the T2FSs can be transferred into the IT2FSs (Chen and Kuo, 2017). From a geometric point of view, the expression of the IT2FSs can finally be transformed into the representation of the upper and lower boundaries of the footprint of uncertainty (FOU), which means that the upper and lower boundaries of the FOU can uniquely determine the FOU and further determine the corresponding IT2FSs (Wu and Mendel, 2007). At present, IT2FSs mostly are used in the research of MCDM problems with their superior expressiveness to fuzzy things. In the first stage of this paper, experts are required to evaluate relevant criteria, but the attitude of experts is often vague, so it is very suitable to use IT2FSs to quantitatively describe the evaluation results of experts. In this section, we present some basic definitions of IT2FSs.

Definition1. IT2FSs

X is the universe of $\tilde{A}$, and $\mu_{\tilde{A}}\in[0,1]$ is the membership function of $\tilde{A}$. When $\mu_{\tilde{A}}(x,u)=1$, $\forall x\in X$, $\tilde{A}=\int x\in X\int u\in I_x 1/(x,u)dudx$ and $\tilde{A}$ is the IT2FSs. Corresponding to X, u is also the membership function, which is similar to $I_x\in[0,1]$.

$$\tilde{A}=\left\{\left((x,u),\mu_{\tilde{A}}(x,u)\right)\middle|\forall x\in X,\ \forall u\in I_x\subseteq[0,1],0\le\mu_{\tilde{A}}(x,u)\le 1\right\}$$
$$=\int x\in X\int u\in I_x\mu_{\tilde{A}}(x,u)/(x,u)dudx \tag{1}$$

Definition2. IT2FN

When the upper and lower bounds of the IT2FSs are trapezoidal fuzzy numbers, the $\tilde{A}_i$ is a trapezoidal internal type 2 fuzzy number (IT2FN), as shown in Fig. 3 $H_1(\tilde{A}_i^U)$ and $H_2(\tilde{A}_i^U)$ are the memberships of $\tilde{A}_i^U$. $H_1(\tilde{A}_i^L)$ and $H_2(\tilde{A}_i^L)$ are the memberships of (see Fig. 4) $\tilde{A}_i^L$.

$$\tilde{A}_i=\left(\tilde{A}_i^U,\tilde{A}_i^L\right)=\left(\left(a_{i1}^U,a_{i2}^U,a_{i3}^U,a_{i4}^U;H_1\left(\tilde{A}_i^U\right),H_2\left(\tilde{A}_i^U\right)\right),\left(a_{i1}^L,a_{i2}^L,a_{i3}^L,a_{i4}^L;H_1\left(\tilde{A}_i^L\right),H_2\left(\tilde{A}_i^L\right)\right)\right) \tag{2}$$

Definition3. Basic operation

$$\begin{aligned}\tilde{A}_1&=\left(\tilde{A}_1^U,\tilde{A}_1^L\right)=\left(\left(a_{11}^U,a_{12}^U,a_{13}^U,a_{14}^U;H_1\left(\tilde{A}_1^U\right),H_2\left(\tilde{A}_1^U\right)\right),\left(a_{11}^L,a_{12}^L,a_{13}^L,a_{14}^L;H_1\left(\tilde{A}_1^L\right),H_2\left(\tilde{A}_1^L\right)\right)\right)\\ \tilde{A}_2&=\left(\tilde{A}_2^U,\tilde{A}_2^L\right)=\left(\left(a_{21}^U,a_{22}^U,a_{23}^U,a_{24}^U;H_1\left(\tilde{A}_2^U\right),H_2\left(\tilde{A}_2^U\right)\right),\left(a_{21}^L,a_{22}^L,a_{23}^L,a_{24}^L;H_1\left(\tilde{A}_2^L\right),H_2\left(\tilde{A}_2^L\right)\right)\right)\end{aligned} \tag{3}$$

$$\begin{aligned}\tilde{A}_1 \oplus \tilde{A}_2 &= \left(\tilde{A}_1^U, \tilde{A}_1^L\right) \oplus \left(\tilde{A}_2^U, \tilde{A}_2^L\right) \\ &= \left(\left(a_{11}^U + a_{21}^U, a_{12}^U + a_{22}^U, a_{13}^U + a_{23}^U, a_{14}^U + a_{24}^U; min\left(H_1\left(\tilde{A}_1^U\right), H_1\left(\tilde{A}_2^U\right)\right), min\left(H_2\left(\tilde{A}_1^U\right), H_2\left(\tilde{A}_2^U\right)\right)\right),\right. \\ &\left.\left(a_{11}^L + a_{21}^L, a_{12}^L + a_{22}^L, a_{13}^L + a_{23}^L, a_{14}^L + a_{24}^L; min\left(H_1\left(\tilde{A}_1^L\right), H_1\left(\tilde{A}_2^L\right)\right), min\left(H_2\left(\tilde{A}_1^L\right), H_2\left(\tilde{A}_2^L\right)\right)\right)\right)\end{aligned} \tag{4}$$

$$\begin{aligned}\tilde{A}_1 \Theta \tilde{A}_2 &= \left(\tilde{A}_1^U, \tilde{A}_1^L\right) \Theta \left(\tilde{A}_2^U, \tilde{A}_2^L\right) \\ &= \left(\left(a_{11}^U - a_{24}^U, a_{12}^U - a_{23}^U, a_{13}^U - a_{22}^U, a_{14}^U - a_{21}^U; min\left(H_1\left(\tilde{A}_1^U\right), H_1\left(\tilde{A}_2^U\right)\right), min\left(H_2\left(\tilde{A}_1^U\right), H_2\left(\tilde{A}_2^U\right)\right)\right),\right. \\ &\left.\left(a_{11}^L - a_{24}^L, a_{12}^L - a_{23}^L, a_{13}^L - a_{22}^L, a_{14}^L - a_{21}^L; min\left(H_1\left(\tilde{A}_1^L\right), H_1\left(\tilde{A}_2^L\right)\right), min\left(H_2\left(\tilde{A}_1^L\right), H_2\left(\tilde{A}_2^L\right)\right)\right)\right)\end{aligned} \tag{5}$$

$$\begin{aligned} def\tilde{A}_i &= \frac{1}{2}\left[\frac{a_{i1}^U + \left(1 + H_1\left(\tilde{A}_i^U\right)\right)a_{i2}^U + \left(1 + H_2\left(\tilde{A}_i^U\right)\right)a_{i3}^U + a_{i4}^U}{4 + H_1\left(\tilde{A}_i^U\right) + H_2\left(\tilde{A}_i^U\right)}\right] + \\ &= \frac{1}{2}\left[\frac{a_{i1}^L + \left(1 + H_1\left(\tilde{A}_i^L\right)\right)a_{i2}^L + \left(1 + H_2\left(\tilde{A}_i^L\right)\right)a_{i3}^L + a_{i4}^L}{4 + H_1\left(\tilde{A}_i^L\right) + H_2\left(\tilde{A}_i^L\right)}\right]\end{aligned} \tag{6}$$

3.3. IT2FN-VIKOR

The MCDM approach is mostly used to solve problems where criteria are conflicting and difficult to compared (Yang et al., 2013). For the choice of 3 PLs, it is influenced by various factors that belong to the MCDM problem. As we know, MCDM problem usually cannot find the optimal solution that satisfies all the criteria at the same time. Therefore, it is necessary to find a compromise solution instead of the optimal solution to complete the final decision. In MCDM, VIKOR and TOPSIS can achieve this goal. However, Opricovic and Tzeng (2004) showed that TOPSIS failed to consider the relative importance of positive and negative ideal solutions in the ranking process. Therefore, the VIKOR method was proposed, which is a decision-making method that can replace TOPSIS (Opricovic and Tzeng, 2007; Opricovic and Tzeng, 2004). The VIKOR is an effective MCDM method, which evaluates each alternative according to each evaluation dimension. As for VIKOR, the optimal value of each evaluation dimension consists of an ideal solution and the worst value consists of a negative ideal solution. The ranking of the overall alternatives is determined according to the relative distance between the actual solution and the ideal solution. The "compromise solution" based on VIKOR should satisfy that the distance from the positive ideal solution as close as possible and the distance from the negative ideal solution as far as possible. More importantly, for the VIKOR method, the establishment of the compromise function takes into account the maximization of the overall utility level and the minimization of individual regrets, which can effectively improve the scientificity of the decision results. Additionally, trapezoidal IT2FN expresses the attitudes of the decision makers. The specific combination is as followings: there are L alternatives $B = \{B_1, B_2, \cdots, B_L\}$ and P criteria $C = \{C_1, C_2, \cdots,$

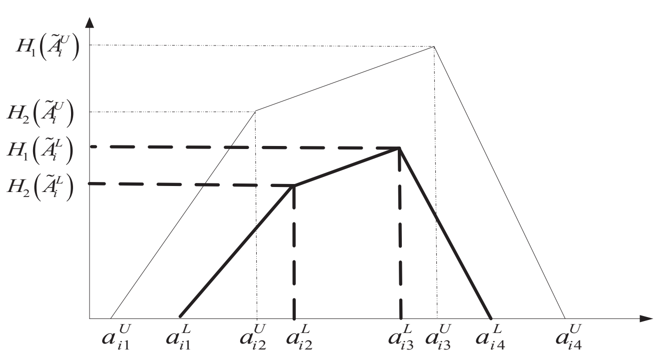

Fig. 3. The trapezoidal IT2FN.

Table 2
Linguistic terms and their relevant IT2FNs.

Linguistic terms	IT2FNs
Very Low (VL)	((0,0,0,0.1; 1,1), (0,0,0,0.05; 0.9,0.9))
Low (L)	((0,0.1,0.15,0.3; 1,1), (0.05,0.1,0.15,0.2; 0.9,0.9))
Medium Low (ML)	((0.1,0.3,0.35,0.5; 1,1), (0.2,0.3,0.35,0.4; 0.9,0.9))
Medium (M)	((0.3,0.5,0.55,0.7; 1,1), (0.4,0.5,0.55,0.6; 0.9,0.9))
Medium High (MH)	((0.5,0.7,0.75,0.9; 1,1), (0.6,0.7,0.75,0.8; 0.9,0.9))
High (H)	((0.7,0.85,0.9,1; 1,1), (0.8,0.85, 0.9,0.95; 0.9,0.9))
Very High (VH)	((0.9,1,1,1; 1,1), (0.95,1,1,1; 0.9,0.9))

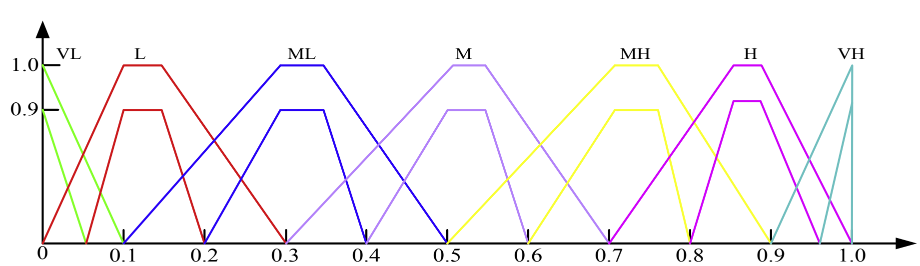

Fig. 4. Membership functions of IT2FSs linguistic terms.

$C_P\}$. B_l means the lth alternative, and C_p is the pth criteria.

Step1. A group of experts are invited to evaluate the criteria. $D = \{D_1, D_2, \cdots, D_D\}$ represents a group of experts, and D_d is the dth expert. Table 2 shows the linguistic variables used to evaluate the variables. Different IT2FNs are used to correspond with them.

Step2. $\tilde{E} = (\tilde{e}_{pl})_{P\times L}$ represents the evaluation matrix that shows the satisfaction degree of criteria as for the relevant alternatives made by a group of experts. And $\tilde{E}^d = (\tilde{e}^d_{pl})_{P\times L}$ is the result evaluated by the dth experts where $\tilde{e}_{pl}$ and $\tilde{e}^d_{pl}$ are IT2FNs, as shown in the definition 2.

$$\tilde{E} = \begin{array}{c} \\ B_1 \\ B_2 \\ \vdots \\ B_L \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_P \end{array} \\ \begin{bmatrix} \tilde{e}_{11} & \tilde{e}_{12} & \cdots & \tilde{e}_{1P} \\ \tilde{e}_{21} & \tilde{e}_{22} & \cdots & \tilde{e}_{2P} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{e}_{L1} & \tilde{e}_{L2} & \cdots & \tilde{e}_{LP} \end{bmatrix} \end{array} \tag{7}$$

$$\tilde{E}^d = \begin{array}{c} \\ B_1 \\ B_2 \\ \vdots \\ B_L \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_P \end{array} \\ \begin{bmatrix} \tilde{e}^d_{11} & \tilde{e}^d_{12} & \cdots & \tilde{e}^d_{1P} \\ \tilde{e}^d_{21} & \tilde{e}^d_{22} & \cdots & \tilde{e}^d_{2P} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{e}^d_{L1} & \tilde{e}^d_{L2} & \cdots & \tilde{e}^d_{LP} \end{bmatrix} \end{array} \tag{8}$$

$$\tilde{E} = \frac{\tilde{E}^1 \oplus \tilde{E}^2 \oplus \cdots \oplus \tilde{E}^D}{D} \tag{9}$$

$d = 1, 2, \cdots, D; p = 1, 2, \cdots, P; l = 1, 2, \cdots, L$

Step3. Identify the benefit criteria $C^{benefit}$ and cost criteria C^{cost}, and find different ideal solutions $\tilde{I}^+_p$ and $\tilde{I}^-_p$.

$$\tilde{I}^+_p = \max_l \tilde{e}_{lp}, \tilde{I}^-_p = \min_l \tilde{e}_{lp}, \text{for } C_p \in C^{benefit} \tag{10}$$

$$\tilde{I}^+_p = \min_l \tilde{e}_{lp}, \tilde{I}^-_p = \max_l \tilde{e}_{lp}, \text{for } C_p \in C^{cost} \tag{11}$$

$p = 1, 2, \cdots, P; l = 1, 2, \cdots, L$

Step4. Calculate the $\tilde{S}_l$, $\tilde{R}_l$ and $\tilde{Q}_l$. $\tilde{\omega}_p$, $p = 1, 2, \cdots, P$ is the weight of different criteria, θ is the compromise coefficient.

$$\tilde{S}_l = \sum_{p=1}^{P} \left(\tilde{\omega}_p \times \frac{\tilde{I}^+_p - \tilde{e}_{lp}}{\tilde{I}^+_p - \tilde{I}^-_p} \right), l = 1, 2, \cdots, L; p = 1, 2, \cdots, P \tag{12}$$

$$\tilde{R}_l = \underset{p}{MAX} \left(\tilde{\omega}_p \times \frac{\tilde{I}^+_p - \tilde{e}_{lp}}{\tilde{I}^+_p - \tilde{I}^-_p} \right), l = 1, 2, \cdots, L; p = 1, 2, \cdots, P \tag{13}$$

$$\tilde{Q}_l = \theta \left(\frac{\tilde{S}_l - \min_l \tilde{S}_l}{\max_l \tilde{S}_l - \min_l \tilde{S}_l} \right) + (1-\theta) \left(\frac{\tilde{R}_l - \min_l \tilde{R}_l}{\max_l \tilde{R}_l - \min_l \tilde{R}_l} \right), l = 1, 2, \cdots, L \tag{14}$$

Here, θ is the compromise coefficient.

Step5. Compromise solution.

First, defuzzify $\tilde{S}_l$, $\tilde{R}_l$ and $\tilde{Q}_l$, and rank these values in descending order.

Second, discuss the following two conditions and determine the compromise solution with the best-ranked alternative. Before the alternative supplier $B^{(1)}$ with the first position in the $\tilde{Q}$ ranking is proposed as the compromise solution, the following two conditions should be satisfied.

Condition1. Acceptable advantage.

$$\tilde{Q}\left(B^{(2)}\right) - \tilde{Q}\left(B^{(1)}\right) \geq 1/(L-1) \tag{15}$$

Where, $B^{(2)}$ is the alternative with the second position in the $\tilde{Q}$ ranking list, and L is the number of alternative suppliers.

Condition2. The alternative $B^{(1)}$ must also be the best in the $\tilde{S}$ or $\tilde{R}$ ranking list.

If the two conditions are both satisfied, the alternative is the best solution. However, when Condition 1 is not satisfied, $B^{(com)}$ is determined using the following formula:

$$\tilde{Q}\left(B^{(com)}\right) - \tilde{Q}\left(B^{(1)}\right) < 1/(L-1) \tag{16}$$

3.4. IT2FN-VIKOR considering the time dynamic series, individual regrets and team effectiveness

3.4.1. Time dynamic factors

Time is the factor that affects the evaluation result, and it is very normal to make totally different decision in different periods. Given that, we divide the processes of evaluation into T periods, and the interval of each period is one month. $\tilde{E}^d_t = (\tilde{e}^d_{tlp})_{L\times P}$ shows the evaluation result of the alternatives by the dth expert at time t (Jin et al., 2013).

To make the evaluation results more scientific, we set $\chi_t (t = 1, 2, \cdots, T)$, which is the weight of time t, which has an important influence on the result and has attracted the attention of many scholars (Xu, 2005; Sadiq and Tesfamariam, 2007). Based on the relevant research, we use the BUM (basic unit-interval monotonic function) method to determine time weights in this paper (Xu and Yager, 2008; Yager, 2004). The specific steps are as follows.

Step1. BA is the basic unit-interval monotonic function, and $BA(0) = 0$, $BA(1) = 1$ and $BA(x) \geq BA(y)$, if $x > y$.

$$\chi_t = BA\left(\frac{t}{T}\right) - BA\left(\frac{t-1}{T}\right), t = 1, 2, \cdots, T \tag{17}$$

Step2. r is the coefficient, and it can affect the time weights. If the $BA(x) = x^r, r > 0$, we obtain the following formula and there are some conditions about r.

$$\chi_t = BA\left(\frac{t}{T}\right)^r - BA\left(\frac{t-1}{T}\right)^r, t = 1,2,\cdots,T \tag{18}$$

Co.1. If $r>1$, then $\chi_{t+1} - \chi_t = \frac{2}{T^r}; t = 1,2,\cdots,T-1$;
Co.2. If $r = 1$, then $\chi_t = \frac{1}{T}; t = 1,2,\cdots,T$;
Co.3. If $0<r<1$, then $\chi_{t+1} < \chi_t$; $t = 1,2,\cdots,T-1$.

3.4.2. Individual regret and team effectiveness

Given that participants are often a group of experts and scholars in MCDM problems, they need to form a team and research criteria many times. Therefore, the efficiency of the team will affect the evaluation. Meanwhile, the team members interact with each other. Therefore, some team members' thoughts will be affected by the more prestigious or supportive decision makers. Thus, their decision may have regrets. Therefore, the degree of individual regret and team effectiveness should be considered in VIKOR, where *EFFI* represents the utility value of the alternative and *REG* indicates the degree of regret of the individual (Chen et al., 2016; Opricovic and Tzeng, 2004).

$$EFFI_l = def\sum_{p=1}^{P}\left(\tilde{\omega}_p \times \frac{defd\left(\tilde{I}_p^+ - \tilde{e}_{lp}\right)}{def\left(\tilde{I}_p^+ - \tilde{I}_p^-\right)}\right), l = 1,2,\cdots,L; p = 1,2,\cdots,P \tag{19}$$

$$REG_l = def\underset{p}{MAX}\left(\tilde{\omega}_p \times \frac{defd\left(\tilde{I}_p^+ - \tilde{e}_{lp}\right)}{def\left(\tilde{I}_p^+ - \tilde{I}_p^-\right)}\right), l = 1,2,\cdots,L; p = 1,2,\cdots,P \tag{20}$$

$$\zeta_l = \theta\left(\frac{EFFI_l - \min_l EFFI_l}{\max_l EFFI_l - \min_l EFFI_l}\right) + (1-\theta)\left(\frac{REG_l - \min_l REG_l}{\max_l REG_l - \min_l REG_l}\right), l = 1,2,\cdots,L \tag{21}$$

When $\theta>0.5$, experts tend to make decisions according to the maximize group utility. When $\theta<0.5$, it suggests that decision makers tend to make decisions with the greatest degree of regret. When $\theta = 0.5$, it shows that policy-makers adopted a compromise value to make the decision.

3.4.3. IT2FWA operator

The solution for an MCDM problem often requires many experts together to discuss, sometimes, to make the decision-making more scientific, experts are invited to evaluate the same criteria or alternatives in different periods. Thus, the fuzzy evaluation matrix requires the integration of different experts in different periods of the evaluation results. Therefore, the total fuzzy evaluation matrix is the result of the integration of evaluation matrixes, which are constructed by different experts in different periods. Under the circumstance, the IT2F-fuzzy weighted aggregation operator (IT2FWA operator) is introduced into group decision making. It has been widely applied (Qin et al., 2017; Zhang et al., 2012).

Suppose that $\chi_t(t = 1,2,\cdots,T, \sum_{t=1}^{T}\chi_t = 1)$ is the weight of different periods, $\tilde{T}E^t = (\tilde{t}e_{lp}^t)_{L\times P}$ is the evaluation results made in time t by a group of experts, and the total evaluation result $\tilde{T}E = (\tilde{t}e_{lp})_{L\times P}$ can be integrated using the IT2FWA operator. The detailed operation is as follows.

$$\tilde{T}E^t = \left(\tilde{t}e_{lp}^t\right)_{L\times P} = \begin{pmatrix} \tilde{t}e_{11}^t & \tilde{t}e_{12}^t & \cdots & \tilde{t}e_{1P}^t \\ \tilde{t}e_{21}^t & \tilde{t}e_{22}^t & \cdots & \tilde{t}e_{2P}^t \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{t}e_{L1}^t & \tilde{t}e_{L2}^t & \cdots & \tilde{t}e_{LP}^t \end{pmatrix} \tag{22}$$

$$\tilde{T}E = \left(\tilde{t}e_{lp}\right)_{L\times P} = \begin{pmatrix} \tilde{t}e_{11} & \tilde{t}e_{12} & \cdots & \tilde{t}e_{1P} \\ \tilde{t}e_{21} & \tilde{t}e_{22} & \cdots & \tilde{t}e_{2P} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{t}e_{L1} & \tilde{t}e_{L2} & \cdots & \tilde{t}e_{LP} \end{pmatrix} \tag{23}$$

$$\begin{aligned}\tilde{t}e_{lp}^t &= \left(\tilde{t}e_{lp}^{tU}, \tilde{t}e_{lp}^{tL}\right) \\ &= \left(\alpha_{lp1}^{tU}, \alpha_{lp2}^{tU}, \alpha_{lp3}^{tU}, \alpha_{lp4}^{tU}; H_1\left(\tilde{t}e_{lp}^{tU}\right), H_2\left(\tilde{t}e_{lp}^{tU}\right)\right), \\ &\quad \left(\alpha_{lp1}^{tL}, \alpha_{lp2}^{tL}, \alpha_{lp3}^{tL}, \alpha_{lp4}^{tL}; H_1\left(\tilde{t}e_{lp}^{L}\right), H_2\left(\tilde{t}e_{lp}^{L}\right)\right)\end{aligned}$$

$$\begin{aligned}\tilde{t}e_{lp} &= \left(\tilde{t}e_{lp}^{U}, \tilde{t}e_{lp}^{L}\right) \\ &= \left(\beta_{lp1}^{U}, \beta_{lp2}^{U}, \beta_{lp3}^{U}, \beta_{lp4}^{U}; H_1\left(\tilde{t}e_{lp}^{U}\right), H_2\left(\tilde{t}e_{lp}^{U}\right)\right), \\ &\quad \left(\beta_{lp1}^{L}, \beta_{lp2}^{L}, \beta_{lp3}^{L}, \beta_{lp4}^{L}; H_1\left(\tilde{t}e_{lp}^{L}\right), H_2\left(\tilde{t}e_{lp}^{L}\right)\right)\end{aligned}$$

$$\left(\tilde{t}e_{lp}\right) = IT2FWA\chi_t\left(\tilde{t}e_{lp}^t\right) = \left[\begin{array}{l}\left(\sum_{t=1}^{T}\chi_t\alpha_{lp1}^{tU}, \sum_{t=1}^{T}\chi_t\alpha_{lp2}^{tU}, \sum_{t=1}^{T}\chi_t\alpha_{lp3}^{tU}, \sum_{t=1}^{T}\chi_t\alpha_{lp4}^{tU}; 1-\prod_{t=1}^{T}\left(1-H_1\left(\tilde{t}e_{lp}^{tU}\right)\right), 1-\prod_{t=1}^{T}\left(1-H_2\left(\tilde{t}e_{lp}^{tU}\right)\right)\right) \\ \left(\sum_{t=1}^{T}\chi_t\alpha_{lp1}^{tL}, \sum_{t=1}^{T}\chi_t\alpha_{lp2}^{tL}, \sum_{t=1}^{T}\chi_t\alpha_{lp3}^{tL}, \sum_{t=1}^{T}\chi_t\alpha_{lp4}^{tL}; 1-\prod_{t=1}^{T}\left(1-H_1\left(\tilde{t}e_{lp}^{L}\right)\right), 1-\prod_{t=1}^{T}\left(1-H_2\left(\tilde{t}e_{lp}^{L}\right)\right)\right)\end{array}\right] \tag{24}$$

4. Establishing of a recycling path model

The companies of sharing bicycles, the 3 PLs, and factories form a closed recovery chain for the abandoned sharing bicycles. Based on the principle of maximizing the overall economic and environmental benefits, the recycling path is planned.

4.1. Assumptions

(1) A company only works with a factory and a 3 PL, but a 3 PL and a factory can provide service for multiple companies.

(2) The company purchases raw materials on demand, so the amount of raw materials that each company sends to a factory is its purchase amount.
(3) The 3 PL recycles materials on demand, so the amount of material transported by each 3 PL to a factory is the recycling amount.
(4) The factory is engaged in the assembly of components. Therefore, in the process of production, the loss rate of materials is low and can be ignored.
(5) The specifications of all sharing bicycles required by all companies are exactly the same, so the types of materials required are exactly the same for different companies.
(6) The company n can complete the transportation of all the materials at one time, and the 3 PL k can also complete the transportation of the order coming from the company n at one time.
(7) The total number of components required for each bicycle is the same.
(8) There is no difference in components. The unit price of all newly purchased components is equal among the companies. Similarly, for 3 PLs, the unit price of all recycled components is equal.
(9) The freight rate refers to the unit price of transportation, which is determined by the transportation distance and the transportation amount. The company's freight rate depends on the company's operating capacity during the transport. Different companies' freight rates are different.
(10) The maximum recovery capacity refers to the recovery without considering the companies' orders, or the maximum number of components recycled by the 3PLk. Similarly, the maximum production capacity refers to the maximum number of bicycles that can be produced by the factory m.
(11) Companies and 3 PLs use large trucks to transport materials. The truck's rated load is 4-8t.

4.2. Model formulation

Sets and indices:

Co_n: Company n $(n = 1, 2, \cdots, N)$
F_m: Factory m $(m = 1, 2, \cdots, M)$
R_k The 3 PL k $(k = 1, 2, \cdots, K)$

Parameters:

$\Re$: The total amount of raw material needed for each bike. It is a certain amount.
∂: The number of companies that cooperate with factory m.
$\wp$: The number of companies that cooperate with the 3 PL.
ACM_n: The price of purchasing a unit of raw materials by company n.
ARP_k: The price per unit of materials recycled by the 3 PL k (RMB/kilogram)
APC_m: The cost of producing per unit bicycle in factory m.
CF_{nm}: The transportation distance from company n to factory m.
FCR_n: The freight rate of company n. (RMB/kilogram kilometer)
FRF_k: The freight rate of the 3 PL k. (RMB/kilogram kilometer)
MCF_m: The maximum production capacity of factory m. (kilogram/day)
MCR_k: The maximum recycling capacity of the 3 PL k. (kilogram/day)
$RN_{mn} = RN_n$: The quality of bicycles produced by factory m based on the order of company n.
RN_n: The order quantity of the company n on sharing bicycles.
RN_{mn}: The number of bicycles produced by factory m based on company n's order.
RF_{km}: The transportation distance from the 3 PLs to factory m.
$TNR_{kn}^m = TNR_{kn}$: The number of materials that the 3 PL k recycles based on the company n's orders, which are transported to factory m in cooperation with company n.
$unit \quad carbon_m$: The carbons emissions released by factory m producing one unit bicycle. (gram/unit)
$unit \quad carbon_n$: The carbon emissions that company n purchased a unit of material. (gram/kilogram)
$unit \quad carbon^{freight}$: The carbon emissions from 1-km transport of truck. (gram/kilometer)
$unit \quad carbon_k$: The carbon emissions that are released from a unit of recycled materials by the 3 PL k. (gram/kilogram)
w_1: The proportion of cost minimization goal in the total objective function
w_2: The proportion of carbon emission minimization objectives in the total objective function

Decision variables:

$CF_n^{freight}$: The one-way transportation costs of company n.
$carbon_n$: The total carbon emissions of company n.
$carbon_{mn}$: When company n's order is completed by factory m, the total carbon emissions released by factory m.
$carbon_{kn}$: The carbon emissions that are released by 3 PL k while completing the company n's order.
$carbon_n^{freight}$: The carbon emissions of company n from transporting raw materials to factory m
$carbon_{kn}^{mfreight}$: The carbon emissions of the 3 PL k from transporting recycled materials to factory m, which cooperates with company n.
MC_n: The cost of purchasing raw materials by company n
$RF_{kn}^{freight}$: The total cost for the 3 PL k that completes the transportation task of company n.
TMP_n: The amount of raw material purchased by the company n.
TRC_{kn}: The total cost of materials recycled by the 3 PL k based on company n's order.
TPC_{nm}: The production cost for factory m to complete the company n's order.

4.3. Detailed model

Assuming that there is a cooperative relationship between company n, factory m, and the 3 PL k, the overall objective model is as follows.

Formula (25) is the recycling path model. The cost and environmental benefits are considered in the model. Specially, in this model, the total cost of the material, transportation cost, recovery cost and production cost are mainly taken into account in terms of the total economic cost. The environmental benefits are mainly measured by carbon emissions, mainly including the carbon emissions in transportation, production and recovery.

$$\begin{aligned} &\min F = \min(w_1 F_1 + w_2 F_2) \\ &s.t. F_1 = \left(MC_n + CF_n^{freight} + TRC_{kn} + RF_{kn}^{freight} + TPC_{nm}\right) \\ &F_2 = \left(carbon_{mn} + carbon_n + carbon_n^{freight} + carbon_{kn}^{mfreight} + carbon_{kn}\right) \end{aligned} \tag{25}$$

Formula (26) is the cost of raw material purchased by company n, which is mainly influenced by the unit price and amount of raw material.

$$MC_n = ACM_n * TMP_n \tag{26}$$

Formula (27) is the total amount of raw materials purchased by company n. We assume that each bike consists of a specific number and type of components, which is consistent with actual production.

$$TMP_n = RN_n * \Re \tag{27}$$

Formula (28) represents the total recycling cost of 3 PLs k.

$$TRC_{kn} = ARP_k * TNR_{kn} \tag{28}$$

Formula (29) calculates the total production cost of the factory, which includes the labor cost, management fee, equipment use fee and so on.

$$TPC_{nm} = APC_m * RN_{mn} \tag{29}$$

Formula (30) shows the one-way transportation costs between company n and factory m. The freight rate depends on the company's operating capacity in the transport. The freight rates of different companies are not equal.

$$CF_n^{freight} = CF_{nm} * TMP_n * FCR_n \tag{30}$$

Formula (31) is the total cost of the 3 PL k that completes the transportation task of company n. With the increase of transport distance, freight volume and freight rate, the transportation cost is also increasing.

$$CF_n^{freight} = CF_{nm} * TMP_n * FCR_n \tag{31}$$

Formula (32) represents the total carbon emissions released by factory m when the company n's order is completed by factory m.

$$carbon_{mn} = unit \quad carbon_m * RN_{mn} \tag{32}$$

Formula (33) is the total carbon emissions of company n.

$$carbon_n = unit\ carbon_n * TMP_n \tag{33}$$

Formula (34) shows that the carbon emissions of company n in the process of transporting raw materials to factory m.

$$carbon_n^{freight} = unit\ carbon^{freight} * CF_{nm} \tag{34}$$

Formula (35) means that the carbon emissions of the 3 PL k in the process of transporting recycled materials to the factory m, which cooperates with company n.

$$carbon_{km}^{freight} = unit\ carbon^{freight} * RF_{km} \tag{35}$$

Formula (36) represents the carbon emissions that are released by the 3 PL k while completing company n's order.

$$carbon_{kn} = unit\ carbon_k * TNR_{kn} \tag{36}$$

Contains:

(1) The factory produces within its maximum range of production.
(2) The 3 PL performs recycling activities within its maximum recovery capacity.
(3) The quantity of new materials purchased by the enterprise and the amount of recycled materials provided by the 3 PLs meets the production requirements of the factory.

$$\sum_{n=1}^{\partial} RN_n \le MCF_m, m \in [1, M], 0 \le \partial \le N \tag{37}$$

Where the ∂ is a positive integer.

$$\sum_{n=1}^{\wp} TNR_{kn} \le MCR_k, k \in [1, K], 0 \le \wp \le N \tag{38}$$

Where the $\wp$ is a positive integer.

$$TMP_n + TNR_{kn} = \Re * RN_n, n = 1, 2, \cdots, N; k = 1, 2, \cdots, K \tag{39}$$

5. An illustrative example

Recently, with the development of the sharing economy, the market of sharing bicycle boomed, which has become one of the new four great inventions in China. Sharing bicycle supports a healthy life style and low-carbon emissions while meeting the requirements for the current stage of economic development. It also opens up the city traffic “last mile”, provides convenience for the general public to travel, and has broad market prospects. Under the circumstance, the operators of sharing bicycles have seized the market shares and put many bicycles on the market, so that the number of sharing bicycles is a lot and very rich in species. This phenomenon has resulted in excess bicycles on the market. However, every coin has two sides, many operators always ignore the bicycle management, and a large number of abandoned bicycles created “bicycle graveyards”, which results in resources waste and serious environmental damage. This waste offsets the positive impact of sharing bicycles. In this paper, based on the objective reality, we focus on the treatment of abandoned bicycles and propose reasonable and effective measures to solve the problem through the introduction of the 3 PLs.

5.1. Problem description

There are 15the 3 PLs ($R_1, R_2, R_3, \cdots, R_{15}$), 40 companies of sharing bicycles ($Co_1, Co_2, Co_3, \cdots, Co_{40}$) and 20 factories ($F_1, F_2, F_3, \cdots, F_{20}$) in region A.

In the first stage, we should evaluate these 3 PLs and select the suitable 3 PLs on the basis of the research contents in this paper. First of all, by reviewing existing research, five related factors (C_1: Green image; C_2: Financial ability; C_3: Recovery capacity; C_4: Pollution and emission; C_5: Searching ability) are selected to evaluate these 3 PLs (as shown in section 3.1). Secondly, five experts (D_1, D_2, D_3, D_4, D_5) are invited to evaluate these criteria three times ($t = 1, 2, 3$). Each evaluation is a week apart by using IT2F-linguistic variables, as shown in Table 2. In the end, the top five 3 PLs are selected, and these 3 PLs have capacity to provide recovery service for the abandoned bicycles for 40 companies in the area.

In the second stage, the recycle network should be designed by solving the recycling path model, as shown in formula (25). However, data acquisition is of vital importance before conducting research. So, we obtained first-hand data in the area through field research, such as: fright rate, demand of sharing bicycle and so on, specially, Tables 3–5 show the relevant data of companies, factories and 3 PLs. What's more, we also consider the carbon emissions in our model, which refer to the average emissions of greenhouse gases during the processes of production, transportation, recycling

Table 3
The relevant company data.

Companies	Coordinate	Freight Unit Price (RMB/kilogram kilometer)	Demand of sharing bike (kilogram)	Unit price of new materials purchased (RMB/kilogram)
1	(3238,3280)	1.35	2462	12.32
2	(3394,6453)	1.51	3630	13.11
3	(3240,3130)	1.22	2857	10.34
4	(5061,2366)	1.59	2904	15.07
5	(2359,2317)	1.09	2699	17.23
6	(3626,2212)	1.39	4876	14.11
7	(6332,2712)	1.78	1986	12.00
8	(9788,1532)	2.25	3502	12.54
9	(6659, 2695)	1.84	2998	10.87
10	(3229, 7439)	1.53	3724	12.09
11	(7179,4545)	2.17	2905	17.00
12	(9790, 2908)	1.44	3954	15.06
13	(8715,2136)	1.45	2820	13.45
14	(4029, 7412)	1.70	3119	12.11
15	(8932, 1587)	1.90	3706	11.98
16	(2412,1618)	2.49	2012	12.00
17	(5569,6238)	1.28	2148	12.98
18	(3602, 1234)	2.11	3661	13.99
19	(4231,1413)	2.77	2849	13.09
20	(4560, 8591)	2.31	3341	11.67
21	(9023, 4612)	1.29	2724	16.09
22	(8228, 3210)	1.46	4577	13.90
23	(6968,5260)	1.23	3011	12.11
24	(6012,2289)	2.01	2789	13.32
25	(3316,7123)	1.00	3123	14.21
26	(1987, 123)	2.06	3354	12.67
27	(4403,6517)	1.80	3009	11.90
28	(7347,8123)	2.22	3462	12.22
29	(4029,4123)	2.42	2342	15.34
30	(2214,3148)	2.19	4242	13.78
31	(2458,1243)	1.90	3425	11.90
32	(1325,8254)	1.45	3897	10.00
33	(546,4560)	1.78	3674	13.09
34	(6521, 1132)	1.90	2565	15.63
35	(7821, 5123)	1.89	3243	15.00
36	(7810,3456)	2.45	3453	16.90
37	(3241,987)	2.11	3654	12.67
38	(6679,1234)	2.39	2009	13.23
39	(9087,5678)	1.70	4235	10.46
40	(1190,3210)	2.05	3420	11.76

Table 4
The relevant factory data.

Factories	Coordinate	Average unit production cost (RMB/kilogram)	Maximum capacity (kilogram)
1	(8361,4628)	8.7	61507
2	(6144,6841)	9.96	49839
3	(5640,6991)	6.15	52186
4	(5927, 9781)	7.44	74404
5	(7253,9547)	7.52	98467
6	(3486,5079)	5.21	93203
7	(2462,6287)	7.10	71036
8	(6051,9988)	8.66	83906
9	(7376,4948)	8.00	68554
10	(6947,9703)	6.04	75239
11	(2527,2799)	9.21	61680
12	(7001,6170)	7.00	71642
13	(7982,5741)	9.11	64353
14	(4373,7322)	8.01	74404
15	(1919,8894)	7.59	92130
16	(9393,5375)	8.22	64284
17	(2652, 9393)	6.39	90003
18	(1796,9649)	8.01	88060
19	(4647,9311)	7.24	66425
20	(2671,8283)	8.00	78472

activities and others. For the company, carbon emissions mainly include two aspects. One is the carbon emissions of raw materials purchased in the production process, that is to say, carbon emissions from purchasing one unit of materials can be measured by the carbon emissions of producing one unit materials. And most of bicycle materials are made of steel, and it can be speculated that carbon emission of one unit of materials is 125 g. On the other hand, the carbon emissions are released during the process of transportation. For the large trucks with a 4-8t rated load, the estimated value of carbon emissions is 514.03 g/km (Ministry of Industry and Information Technology of the People's Republic of China, 2011). The production of the bicycles consists of assembling components and parts. For factories, the estimated value of the carbon emissions is 45 g per bike (China Institute of Information and Communications, 2018). Two parts should be considered in evaluating the carbon emissions of the 3 PLs. The first is the carbon emissions in the process of collecting the abandoned bicycle. The second is the carbon emissions in the process of processing scrap bikes. Thus, the carbon emissions for one unit recycled materials is 67 g (Hiselius and Åse, 2017; Singh and Dasgupta, 2016; Fukuta et al., 2014; Gupta and Dasgupta, 2014; Zhang et al., 2013; Tian et al., 2011).

Moreover, there must be a serious description of the following two aspects. First, due to the difficulty of obtaining the data and the time limit of the survey, we convert the monthly data obtained in this region to the daily data on the basis of ensuring a certain scientific. The reason is that we find that the daily data is not always equal in a month and there are high and low peaks in a month. Therefore, we can't guarantee that the selected day is representative, so we can only use the current month's data divided by the number of days as the daily data to reduce the impact of the error on the research results. Second, we found that the average weight of each sharing bicycles is about 15 kg through survey. What's more, the averaged monthly data doesn't be guaranteed to be integers, especially the daily demand for sharing bicycles, the amount of daily recycling and other data. Therefore, we measure them by weight to ensure unit uniformity during the research process.

5.2. The evaluation steps of 3 PLs

Step1. A group of experts D_1, D_2, D_3, D_4, D_5 are invited to evaluate the criteria weights $\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$, according to the formulas (6) and (9). The evaluation results can be obtained, as shown in the Table 6.

$$\tilde{\lambda}_1 = ((0.50, 0.68, 0.73, 0.86; 1, 1), (0.60, 0.68, 0.73, 0.78; 0.9, 0.9))$$
$$\tilde{\lambda}_2 = ((0.12, 0.30, 0.35, 0.50; 1, 1), (0.21, 0.30, 0.35, 0.40; 0.9, 0.9))$$
$$\tilde{\lambda}_3 = ((0.58, 0.76, 0.81, 0.94; 1, 1), (0.68, 0.76, 0.81, 0.86; 0.9, 0.9))$$
$$\tilde{\lambda}_4 = ((0.28, 0.46, 0.51, 0.66; 1, 1), (0.37, 0.46, 0.51, 0.56; 0.9, 0.9))$$
$$\tilde{\lambda}_5 = ((0.08, 0.22, 0.27, 0.42; 1, 1), (0.15, 0.22, 0.27, 0.32; 0.9, 0.9))$$

$$\lambda_1 = 0.6866, \lambda_2 = 0.3138, \lambda_3 = 0.7653, \lambda_4 = 0.4711, \lambda_5 = 0.2401$$

Step2. According to the formulas (17) and (18), we can obtain the three evaluations, $\chi_1 = \frac{1}{6}$, $\chi_2 = \frac{2}{6}, \chi_3 = \frac{3}{6}$. Based on these weights, the group of experts evaluates the criteria and alternatives. The results evaluated by the five experts at different times can be obtained by A1-A3, and then the total evaluation result aggregated by the IT2FWA operator is shown in formula (24) and Tables 7 and 8.

Step3. Distinguishing the benefit and cost criteria. C_1: Green image; C_2: Financial ability; C_3: Recovery capacity; C_5: Searching ability are the benefit criteria, and if the 3 PL has very strong characteristics in these criteria and it will has a better competitive advantage than the other 3 PLs was discussed. However, if the 3 PL

Table 5
The relevant 3PLsdata.

3PLs	Coordinate	Freight Unit Price (RMB/kilogram kilometer)	Unit cost of recycling components (RMB/kilogram)	Maximum recovery capacity (kilogram)
1	(5224,2766)	1.11	11.86	11040
2	(7922,6462)	1.89	10.98	16640
3	(8594,1584)	2.43	9.96	22490
4	(6652,5348)	2.05	9.01	21300
5	(3088,3428)	1.90	10.75	27800

Table 6
Criteria evaluation results.

	D_1	D_2	D_3	D_4	D_5
C_1	H	MH	M	M	H
C_2	ML	ML	L	M	ML
C_3	MH	H	MH	MH	H
C_4	H	MH	M	M	M
C_5	L	ML	M	L	L

C_1: Green image; C_2: Financial ability; C_3: Recovery capacity; C_4: Pollution and emission; C_5: Searching ability.

releases more carbon dioxide in the recycling activities and it is uncompetitive in terms of environmental protection. Based on that, C_4: Pollution and emission is the cost criteria. Next, the different ideal solutions can be obtained on the basis of formulas (10) and (11) (as shown in Table 9), which lays the foundation for calculating $\tilde{S}_l$, $\tilde{R}_l$ and $\tilde{Q}_l$ according to the IT2FN-VIKOR method.

Step4. After considering the time dynamic factors, individual regrets and group efficiency are added to the evaluation, which is shown in formulas (19) and (20). Table 10 shows the evaluation results.

Step5. Determine the compromise solution.

According to formulas (15) and (16) and the two conditions for determining the best alternatives, $R_{11}^{(1)}$ and $R_4^{(2)}$ rank first and second, respectively by ζ, however, they don't have the same ranks using *EFFI* and *REG*. Therefore, the compromise solutions should be determined by the following formula (16), finally, we select $R_2, R_4, R_7, R_8, R_{11}$ as the most suitable objectives and use them to design the reverse logistics supply network. To express the research results, we set the values as follows:

$$3PL1 = R_2, 3PL2 = R_4, 3PL3 = R_7, 3PL4 = R_8, 3PL5 = R_{11}$$

5.3. The design of the reverse logistics recovery network

According to the overall objective function, w_1 and w_2 represent the weight of the cost and environment, respectively. Through our field research, we found that economic benefits are the fundamental driving force for the recycling of sharing bicycles. However, with the increasingly serious environmental problems and the development of relevant environmental protection regulations, environmental benefits have become an important factor, moreover, as far as sharing bicycle recycling is concerned, it is a matter of environmental significance. Therefore, we should take into account the pursuit of economic benefits while paying attention to the realization of environmental benefits. Based on that, we set $w_1 = 0.6; w_2 = 0.4$ and the GA-SA is used to design the reverse logistics network.

The Windows 7.0 operating system and MATLAB are used as tools for calculation. The population size is 100, the number of iterations is 200, and the crossover probability is 0.8. The overall objective function is calculated using the GA-SA. Figs. 5–8 show the model's results by using the GA-SA, which is the reverse logistics network design. Among that, the yellow marks represent 20 factories, the green marks represent five 3 PLs, and the red marks

Table 7
The total evaluation results.

	C_1	C_2	C_3	C_4	C_5
R_1	((0.14,0.31,0.36,0.51; 1,1), (0.23,0.31,0.36,0.41; 0.9,0.9))	((0.46,0.65,0.70,0.84; 1,1), (0.56,0.65,0.70,0.75; 0.9,0.9))	((0.62,0.79,0.84,0.96; 1,1), (0.72 ,0.79,0.84,0.89; 0.9,0.9))	((0.30,0.49,0.54,0.68; 1,1), (0.40 ,0.49,0.54,0.59; 0.9,0.9))	((0.53,0.70,0.75,0.88; 1,1), (0.63,0.70,0.75,0.80; 0.9,0.9))
R_2	((0.55,0.72,0.76,0.88; 1,1), (0.64,0.72,0.76,0.81; 0.9,0.9))	((0.54,0.71,0.76,0.88; 1,1), (0.64,0.71,0.76,0.81; 0.9,0.9))	((0.74,0.88,0.92,1.00; 1,1), (0.83,0.88,0.92,0.96; 0.9,0.9))	((0.46,0.64,0.69,0.82; 1,1), (0.56,0.64,0.69,0.74; 0.9,0.9))	((0.57,0.74,0.78,0.89; 1,1), (0.66,0.74,0.78,0.82; 0.9,0.9))
R_3	((0.28,0.48,0.53,0.67; 1,1), (0.38,0.48,0.53,0.58; 0.9,0.9))	((0.50,0.68,0.73,0.86; 1,1), (0.60,0.68,0.73, 0.78; 0.9,0.9))	((0.42,0.62,0.67,0.82; 1,1), (0.52,0.62,0.67,0.72; 0.9,0.9))	((0.42,0.61,0.66,0.80; 1,1), (0.52,0.61,0.66,0.71; 0.9,0.9))	((0.26,0.45,0.50,0.65; 1,1), (0.36,0.45,0.50,0.55; 0.9,0.9))
R_4	((0.42,0.60,0.65,0.78; 1,1), (0.52,0.60,0.65,0.70; 0.9,0.9))	((0.46, 0.64,0.69,0.81; 1,1), (0.56, 0.64,0.69,0.74; 0.9,0.9))	((0.70,0.85,0.90,1.00; 1,1), (0.80,0.85,0.90,0.95; 0.9,0.9))	((0.38,0.57,0.62,0.76; 1,1), (0.48,0.57,0.62,0.67; 0.9,0.9))	((0.50,0.67,0.71,0.82; 1,1), (0.59,0.67,0.71,0.75; 0.9,0.9))
R_5	((0.27,0.44,0.49,0.64; 1,1), (0.36,0.44,0.49,0.54; 0.9,0.9))	((0.59,0.76,0.81,0.93; 1,1), (0.69,0.76,0.81,0.86; 0.9,0.9))	((0.62,0.77,0.80,0.88; 1,1), (0.70,0.77,0.80,0.83; 0.9,0.9))	((0.30,0.50,0.55,0.70; 1,1), (0.40,0.50,0.55,0.60; 0.9,0.9))	((0.27,0.47,0.52,0.67; 1,1) ,(0.37,0.47,0.52,0.57; 0.9,0.9))
R_6	((0.34,0.53,0.58,0.72; 1,1), (0.44,0.53,0.58,0.63; 0.9,0.9))	((0.26,0.46,0.51,0.66; 1,1), (0.36,0.46,0.51,0.56; 0.9,0.9))	((0.62,0.79,0.84,0.96; 1,1), (0.72,0.79,0.84,0.89; 0.9,0.9))	((0.34,0.54,0.59,0.74; 1,1), (0.44,0.54,0.59,0.64; 0.9,0.9))	((0.66,0.82,0.87,0.97; 1,1), (0.76,0.82,0.87,0.91; 0.9,0.9))
R_7	((0.44,0.59,0.64,0.76; 1,1), (0.53,0.59,0.64,0.69; 0.9,0.9))	((0.62,0.78,0.83,0.94; 1,1), (0.72,0.78,0.83,0.88; 0.9,0.9))	((0.66,0.82,0.86,0.96; 1,1), (0.75,0.82,0.86,0.90; 0.9,0.9))	((0.26,0.46,0.51,0.66; 1,1), (0.36,0.46,0.51,0.56; 0.9,0.9))	((0.50,0.67,0.72,0.84; 1,1), (0.60,0.67,0.72,0.77; 0.9,0.9))
R_8	((0.50,0.69,0.74,0.88; 1,1) ,(0.60,0.69,0.74,0.79; 0.9,0.9))	((0.54,0.71,0.76,0.88; 1,1), (0.64,0.71,0.76,0.81; 0.9,0.9))	((0.62,0.78,0.83,0.94; 1,1), (0.72,0.78,0.83,0.88; 0.9,0.9))	((0.34,0.54,0.59,0.74; 1,1), (0.44,0.54,0.59,0.64; 0.9,0.9))	((0.50,0.67,0.72,0.84; 1,1), (0.60 ,0.67,0.72,0.77; 0.9,0.9))
R_9	((0.26,0.46,0.51,0.65; 1,1), (0.36,0.46,0.51,0.56; 0.9,0.9))	((0.58,0.75,0.80,0.92; 1,1), (0.68,0.75,0.80,0.85; 0.9,0.9))	((0.42, 0.61,0.66,0.80; 1,1), (0.52, 0.61,0.66,0.71; 0.9,0.9))	((0.38,0.58,0.63,0.78; 1,1), (0.48,0.58,0.63,0.68; 0.9,0.9))	((0.58,0.74,0.77,0.86; 1,1), (0.66,0.74,0.77,0.80; 0.9,0.9))
R_{10}	((0.30,0.50,0.55,0.70; 1,1) ,(0.40,0.50,0.55,0.60; 0.9,0.9))	((0.38,0.57,0.62,0.76; 1,1), (0.48,0.57,0.62,0.67; 0.9,0.9))	((0.66,0.81,0.85,0.94; 1,1), (0.75,0.81,0.85,0.89; 0.9,0.9))	((0.26,0.46,0.51,0.66; 1,1), (0.36,0.46,0.51,0.56; 0.9,0.9))	((0.54,0.71,0.76,0.82; 1,1), (0.64,0.71,0.76,0.81; 0.9,0.9))
R_{11}	((0.50,0.70,0.75,0.90; 1,1) ,(0.60,0.70,0.75,0.80; 0.9,0.9))	((0.38,0.56,0.61,0.74; 1,1), (0.48,0.56,0.61,0.66; 0.9,0.9))	((0.66,0.81,0.85,0.94; 1,1), (0.75,0.81,0.85,0.89; 0.9,0.9))	((0.22,0.42,0.47,0.62; 1,1), (0.32,0.42,0.47,0.52; 0.9,0.9))	((0.50,0.69,0.74,0.88; 1,1), (0.60,0.69,0.74,0.79; 0.9,0.9))
R_{12}	((0.26,0.42,0.47,0.62; 1,1) ,(0.34,0.42,0.47,0.52; 0.9,0.9))	((0.49,0.66,0.71,0.83; 1,1), (0.59,0.66,0.71,0.76; 0.9,0.9))	((0.66,0.81,0.85,0.94; 1,1), (0.75,0.81,0.85,0.89; 0.9,0.9))	((0.50,0.69,0.74,0.88; 1,1), (0.60,0.69,0.74,0.79; 0.9,0.9))	((0.40,0.64,0.68,0.70; 1,1), (0.55,0.64,0.68,0.72; 0.9,0.9))
R_{13}	((0.46,0.64,0.69,0.82; 1,1), (0.56,0.64,0.69,0.74; 0.9,0.9))	((0.38,0.56,0.61,0.74; 1,1), (0.48,0.56,0.61,0.66; 0.9,0.9))	((0.58,0.75,0.80,0.92; 1,1), (0.68,0.75,0.80,0.85; 0.9,0.9))	((0.38,0.58,0.63,0.78; 1,1), (0.48,0.58,0.63,0.68; 0.9,0.9))	((0.54,0.71,0.76,0.88; 1,1), (0.64,0.71,0.76,0.81; 0.9,0.9))
R_{14}	((0.18,0.38,0.43,0.58; 1,1), (0.28,0.38,0.43,0.48; 0.9,0.9))	((0.34,0.53,0.58,0.72; 1,1), (0.44,0.53,0.58,0.63; 0.9,0.9))	((0.70,0.85,0.89,0.98; 1,1), (0.79,0.85,0.89,0.93; 0.9,0.9))	((0.26,0.45,0.50,0.64; 1,1), (0.36,0.45,0.50,0.55; 0.9,0.9))	((0.34,0.54,0.59,0.74; 1,1), (0.44,0.54,0.59,0.64; 0.9,0.9))
R_{15}	((0.22,0.42,0.47,0.62; 1,1) ,(0.32,0.42,0.47,0.52; 0.9,0.9))	((0.46,0.64,0.69,0.82; 1,1), (0.56,0.64,0.69,0.74; 0.9,0.9))	((0.50,0.68,0.73,0.86; 1,1), (0.60,0.68,0.73,0.78; 0.9,0.9))	((0.38,0.58,0.63,0.78; 1,1), (0.48,0.58,0.63,0.68; 0.9,0.9))	((0.62,0.78,0.83,0.94; 1,1), (0.72,0.78,0.83,0.88; 0.9,0.9))

Table 8
The total evaluation results after defuzzification.

	C_1	C_2	C_3	C_4	C_5
R_1	0.3277	0.6563	0.7956	0.4989	0.7098
R_2	0.7198	0.7169	0.8792	0.6473	0.7382
R_3	0.4838	0.6866	0.6259	0.6169	0.4626
R_4	0.6079	0.6443	0.8563	0.5776	0.6702
R_5	0.4550	0.7664	0.7628	0.5079	0.4751
R_6	0.5383	0.4686	0.7956	0.5473	0.8222
R_7	0.6014	0.7866	0.8185	0.4686	0.6776
R_8	0.6956	0.7169	0.7866	0.5473	0.6776
R_9	0.4656	0.7563	0.6169	0.5866	0.7324
R_{10}	0.5079	0.5776	0.8095	0.4686	0.7119
R_{11}	0.7046	0.5686	0.8095	0.4293	0.6956
R_{12}	0.4343	0.6645	0.8095	0.6956	0.6265
R_{13}	0.6473	0.5686	0.7563	0.5866	0.7169
R_{14}	0.3899	0.5383	0.8488	0.4596	0.5473
R_{15}	0.4293	0.6473	0.6866	0.5866	0.7866

Table 9
Ideal solutions.

	C_1	C_2	C_3	C_4	C_5
I^+	0.7198	0.7866	0.8792	0.4293	0.8222
I^-	0.3277	0.4686	0.6169	0.6956	0.4626

Table 10
Results considering the individual regrets and group efficiency.

	$EFFI_l$	REG_l	ζ_l
R_1	1.2574	0.6866	0.7154
R_2	0.5107	0.3856	0.1666
R_3	1.8230	0.7390	0.9769
R_4	0.7672	0.1959	0.0977
R_5	1.1943	0.4637	0.4956
R_6	1.0844	0.3179	0.3257
R_7	0.5505	0.2073	0.0252
R_8	0.6867	0.2702	0.1323
R_9	1.5785	0.7653	0.9068
R_{10}	0.9238	0.3710	0.3112
R_{11}	0.5295	0.2151	0.0240
R_{12}	1.4257	0.5000	0.6157
R_{13}	1.0493	0.3587	0.3482
R_{14}	1.1486	0.5777	0.5783
R_{15}	1.5103	0.5620	0.7023

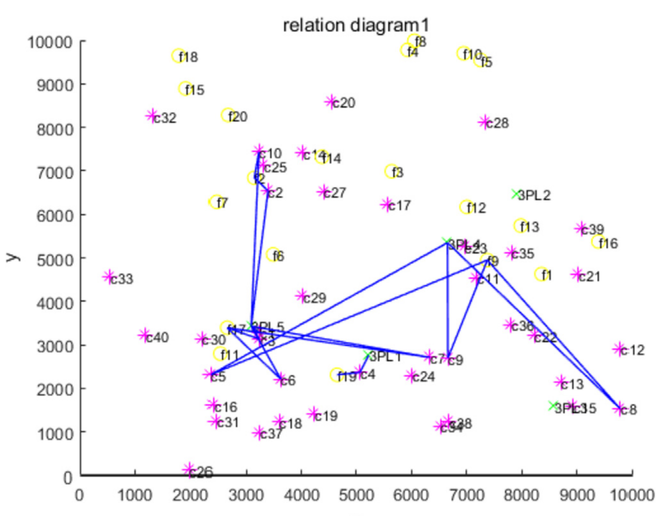

Fig. 5. The sub graph of the reverse logistics network using GA-SA ($Co_1 - Co_{10}$).

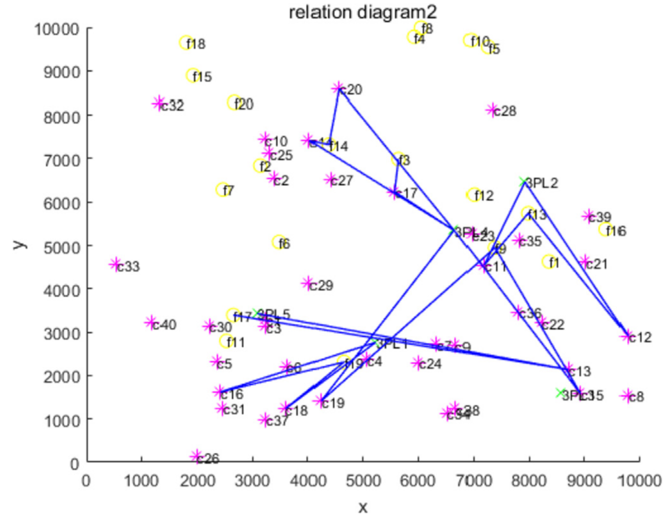

Fig. 6. The sub graph of the reverse logistics network using GA-SA ($Co_{11} - Co_{20}$).

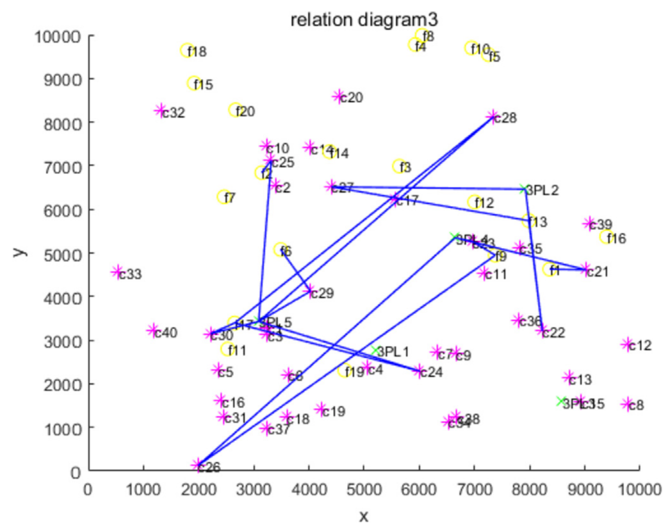

Fig. 7. The sub graph of the reverse logistics network using GA-SA ($Co_{21} - Co_{30}$).

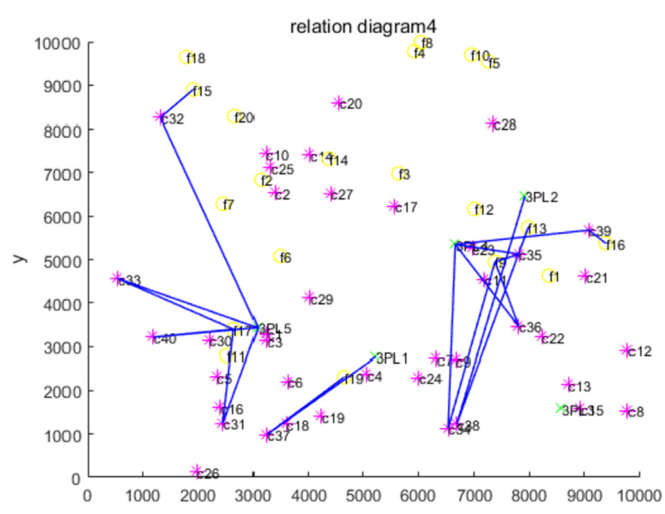

Fig. 8. The sub graph of the reverse logistics network using GA-SA ($Co_{31} - Co_{40}$).

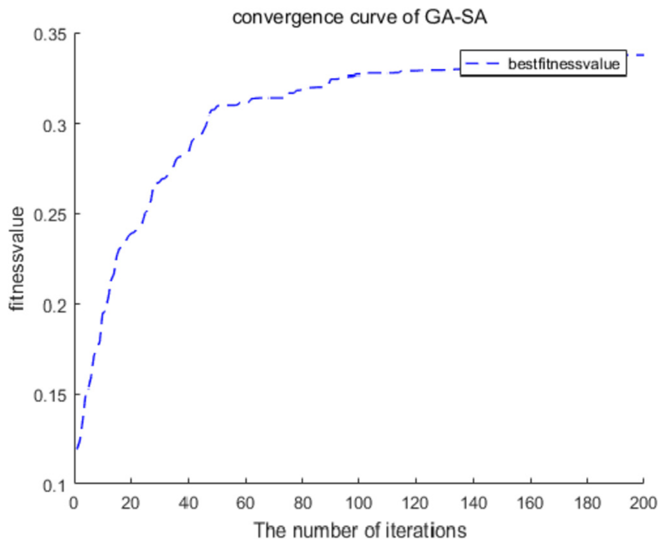

Fig. 9. Convergence curve of GA-SA.

represent 40 companies. The network structure consisting of blue lines represents the reverse logistics recovery network composed of companies, factories and 3 PLs. For the results to be clearly displayed, we divided the 40 companies into four groups ($Co_1 - Co_{10}$, $Co_{11} - Co_{20}$, $Co_{21} - Co_{30}$, $Co_{31} - Co_{40}$), and the corresponding total recycling network also be divided into four parts. Fig. 5 shows the recycling network related companies $Co_1 - Co_{10}$, 20 factories and five 3 PLs; Fig. 6 shows the recycling network related companies $Co_{11} - Co_{20}$, 20 factories and five 3 PLs; Fig. 7 represents the recycling network related companies$Co_{21} - Co_{30}$, 20 factories and five 3 PLs; Fig. 8 is the recycling network related companies $Co_{31} - Co_{40}$, 20 factories and five 3 PLs. Fig. 9 is the fitness curve. When iterating 100 times, the GA-SA algorithm begins to converge and the fitness value is about 0.325. To more clearly show the cooperation relations between the factories, companies and the 3 PLs, we summarized these in Table 11. Every row of this table represents a partnership between factories, companies and the 3 PLs.

Table 11
The design of recycling network—GA-SA.

Companies	The 3 PLs	The factories
(3238,3280)	(3088,3428)	(2652,3393)
(3394,6453)	(3088,3428)	(3144,6841)
(3240,3130)	(3088,3428)	(2652,3393)
(5061,2366)	(5224,2766)	(4647,2311)
(2359,2317)	(6652,5348)	(7376,4948)
(3626,2212)	(3088,3428)	(2652,3393)
(6332,2712)	(3088,3428)	(2652,3393)
(9788,1532)	(6652,5348)	(7376,4948)
(6659, 2695)	(6652,5348)	(7376,4948)
(3229, 7439)	(3088,3428)	(3144,6841)
(7179,4545)	(7922,6462)	(7982,5741)
(9790, 2908)	(7922,6462)	(7982,5741)
(8715,2136)	(3088,3428)	(2652,3393)
(4029, 7412)	(6652,5348)	(4373,7322)
(8932, 1587)	(6652,5348)	(7376,4948)
(2412,1618)	(5224,2766)	(4647,2311)
(5569,6238)	(6652,5348)	(5640,6991)
(3602, 1234)	(5224,2766)	(4647,2311)
(4231,1413)	(6652,5348)	(7376,4948)
(4560, 8591)	(6652,5348)	(4373,7322)
(9023, 4612)	(6652,5348)	(8361,4628)
(8228, 3210)	(7922,6462)	(7982,5741)
(6968,5260)	(6652,5348)	(7376,4948)
(6012,2289)	(3088,3428)	(2652,3393)
(3316,7123)	(3088,3428)	(3144,6841)
(1987, 123)	(6652,5348)	(7376,4948)
(4403,6517)	(7922,6462)	(7982,5741)
(7347,8123)	(3088,3428)	(2652,3393)
(4029,4123)	(3088,3428)	(3486,5079)
(2214,3148)	(3088,3428)	(2652,3393)
(2458,1243)	(3088,3428)	(2652,3393)
(1325,8254)	(3088,3428)	(1919,8894)
(546,4560)	(3088,3428)	(2652,3393)
(6521, 1132)	(6652,5348)	(7376,4948)
(7821, 5123)	(6652,5348)	(7376,4948)
(7810,3456)	(6652,5348)	(7376,4948)
(3241,987)	(5224,2766)	(4647,2311)
(6679,1234)	(7922,6462)	(7982,5741)
(9087,5678)	(6652,5348)	(9393,5375)
(1190,3210)	(3088,3428)	(2652,3393)

5.4. Comparative analyses

We make comparative analyses from two perspectives. The first perspective is the selection of the 3 PLs. The second perspective is the design of the reverse logistics recovery network. The specific processes are as follows.

5.4.1. Comparative analysis1.TOPSIS, ANP

From the comparative results of Table 12, we can see that the evaluation results of ANP and IT2FN-VIKOR are exactly the same. However, TOPSIS is slightly different. Thus, we can obtain the conclusion that the method proposed in this paper is efficient and stable.

Table 12
Comparative results.

methods	Evaluation results
TOPSIS	$R_1, R_3, R_7, R_8, R_{11}$
ANP	$R_2, R_4, R_7, R_8, R_{11}$
IT2FN-VIKOR	$R_2, R_4, R_7, R_8, R_{11}$

5.4.2. Comparative analysis2.GA

We use GA to solve the overall objective function. Figs. 10–13 show the design of recycling network, which has the same meaning as expressed in Figs. 5–8. That is to say, Fig. 10 is the recycling network related companies $Co_1 - Co_{10}$, 20 factories and five 3 PLs; Fig. 11 shows the recycling network related companies $Co_{11} - Co_{20}$, 20 factories and five 3 PLs; Fig. 12 represents the recycling network related companies $Co_{21} - Co_{30}$, 20 factories and five 3 PLs; Fig. 13 dedicates the recycling network related companies $Co_{31} - Co_{40}$, 20 factories and five 3 PLs. Similarly, Table 13 are provided to clearly show the cooperation relations between the factories, companies and the 3 PLs. Fig. 14 shows the fitness curves. According to the legend, the red line represents the fitness curve of the GA algorithm and the blue line represents the fitness curve of the GA-SA algorithm. We can see that the fitness value of GA-SA is significantly higher than that of GA. Additionally, the GA-SA of convergence appears after 140 iterations. However, GA has no sign of convergence at that moment. In conclusion, the GA-SA has more advantages in solving the problem.

5.5. Sensitive analyses

5.5.1. Comparative analysis1.Components

It is obviously that there is a great impact on the speed of installation and production costs. According to the survey that the bicycle has approximately 100 components, therefore, we want to discuss that whether a higher economy goal could be achieved by reducing the number of components. Since this is a new study, we

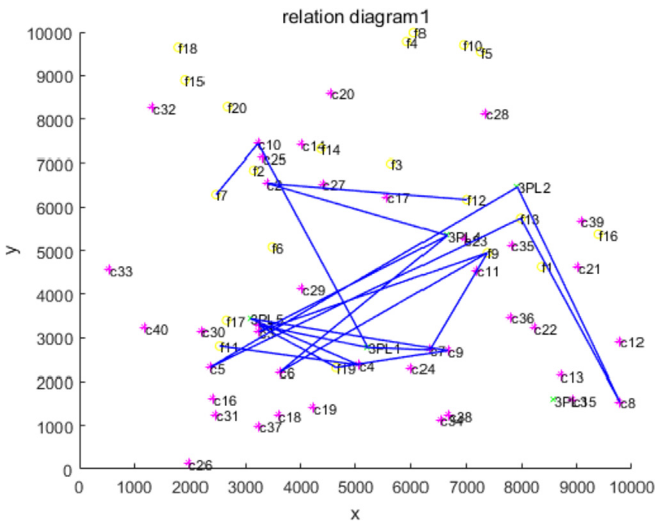

Fig. 10. The subgraph of the reverse logistics network by GA ($Co_1 - Co_{10}$).

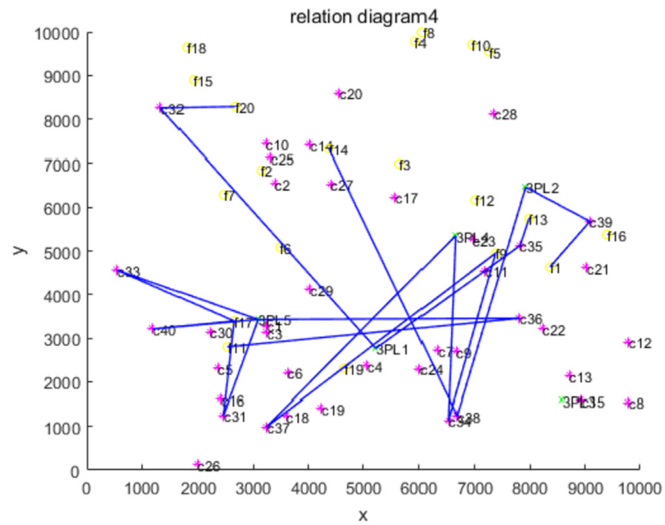

Fig. 13. The subgraph of the reverse logistics network by GA ($Co_{31} - Co_{40}$).

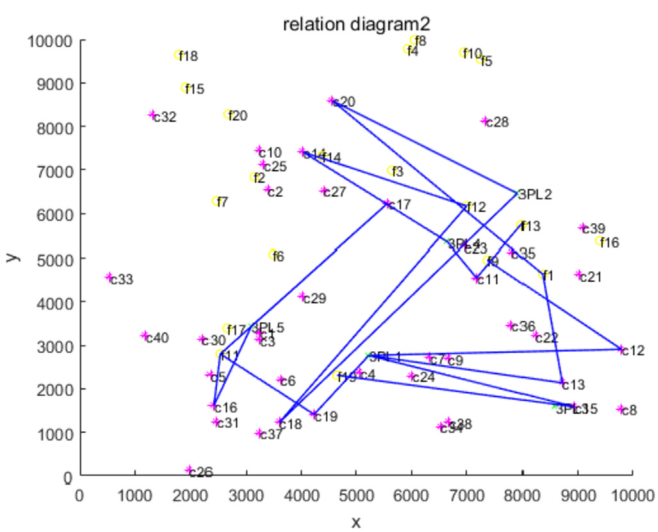

Fig. 11. The subgraph of the reverse logistics network by GA ($Co_{11} - Co_{20}$).

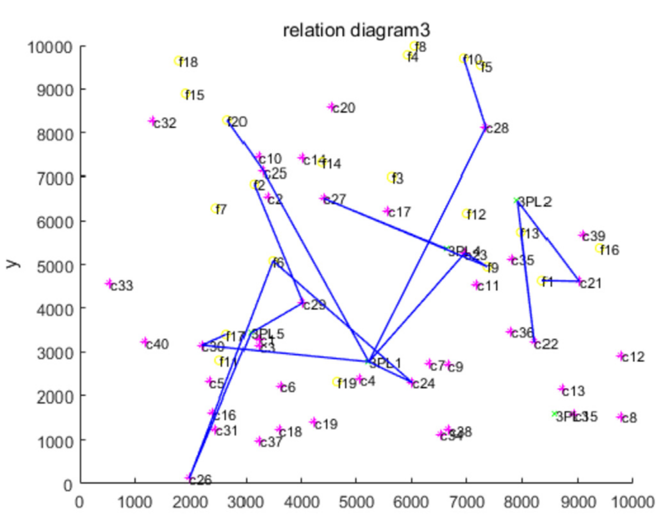

Fig. 12. The subgraph of the reverse logistics network by GA ($Co_{21} - Co_{30}$).

have not found relevant references to testify our parameter settings. Moreover, the focus of this analysis is to illustrate our assumption that the number of components will affect the benefits of recycling activities, rather than determining the optimal number

Table 13
The design of recycling network–GA.

Companies	The 3 PLs	The factories
(3238,3280)	(5224,2766)	(4647,2311)
(3394,6453)	(6652,5348)	(7001,6170)
(3240,3130)	(6652,5348)	(7376,4948)
(5061,2366)	(3088,3428)	(2527,2799)
(2359,2317)	(7922,6462)	(7982,5741)
(3626,2212)	(6652,5348)	(7376,4948)
(6332,2712)	(5224,2766)	(7376,4948)
(9788,1532)	(7922,6462)	(7982,5741)
(6659, 2695)	(3088,3428)	(4647,2311)
(3229, 7439)	(5224,2766)	(2462,6287)
(7179,4545)	(6652,5348)	(7982,5741)
(9790, 2908)	(5224,2766)	(7376,4948)
(8715,2136)	(5224,2766)	(8361,4628)
(4029, 7412)	(6652,5348)	(7001,6170)
(8932, 1587)	(5224,2766)	(4647,2311)
(2412,1618)	(3088,3428)	(2527,2799)
(5569,6238)	(3088,3428)	(2527,2799)
(3602, 1234)	(7922,6462)	(7001,6170)
(4231,1413)	(5224,2766)	(2527,2799)
(4560, 8591)	(7922,6462)	(8361,4628)
(9023, 4612)	(7922,6462)	(8361,4628)
(8228, 3210)	(7922,6462)	(7982,5741)
(6968,5260)	(5224,2766)	(7376,4948)
(6012,2289)	(5224,2766)	(3486,5079)
(3316,7123)	(5224,2766)	(2671,8283)
(1987, 123)	(3088,3428)	(3486,5079)
(4403,6517)	(6652,5348)	(7376,4948)
(7347,8123)	(5224,2766)	(6947,9703)
(4029,4123)	(3088,3428)	(3144,6841)
(2214,3148)	(5224,2766)	(2652,3393)
(2458,1243)	(3088,3428)	(2652,3393)
(1325,8254)	(5224,2766)	(2671,8283)
(546,4560)	(3088,3428)	(2652,3393)
(6521, 1132)	(6652,5348)	(7376,4948)
(7821, 5123)	(5224,2766)	(7982,5741)
(7810,3456)	(3088,3428)	(2527,2799)
(3241,987)	(6652,5348)	(7376,4948)
(6679,1234)	(7922,6462)	(4373,7322)
(9087,5678)	(7922,6462)	(8361,4628)
(1190,3210)	(3088,3428)	(2652,3393)

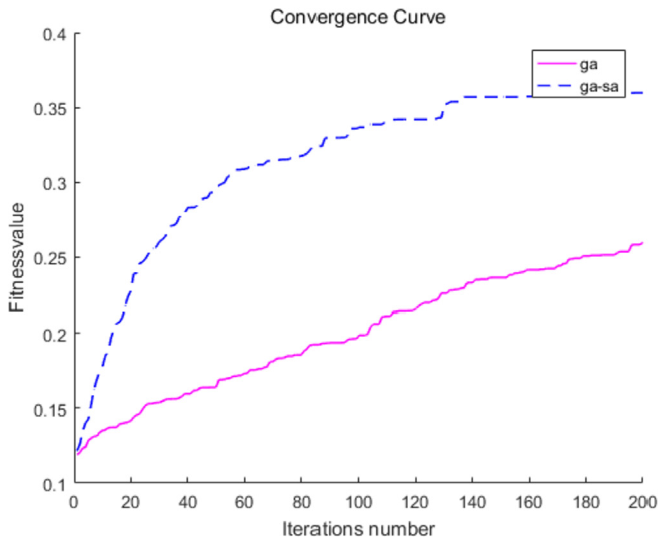

Fig. 14. The convergence curve of GA-SA and GA.

of components. Therefore, the specific number of components has little scientific impact on the experimental results. Even so, we try to make it adversely affect the results of the research. In order to be as close to reality as possible, we set up $\Re = 90$, $\Re = 120$ and the corresponding cost of renovation to validate our assumption. The results are shown in the Table 14.

Table 14 analyzes the influence from two perspectives. One is economic benefits and the other is the environmental benefits. According to the general objective model established in this paper, economic benefits and environmental benefits refer to the total costs and carbon emissions, which are both cost criteria. Comparing with the $\Re = 100$, when $\Re = 90$, in terms of the costs, it is higher than $\Re = 100$, which is 1.737%, and as for the carbon emissions, it is higher than $\Re = 100$, which is more than 1.401%; when $\Re = 120$, in terms of the costs, it is higher than $\Re = 100$, which is 1.340%, and as for the carbon emissions, it is higher than $\Re = 100$, which is more than 6.936%. In conclusion, when $\Re = 100$, the maximum economic and environmental benefits can be obtained.

When the bicycle has fewer components, it reduces the assembly cost in the production process, and also greatly reduces the cost of disassembly in the recycling process. Therefore, reducing the number of components is a direct and effective measure to reduce the production and recovery costs. This provides guidance for improving the economic benefits for the operators of sharing bicycle and for the social environment. However, for the bicycles, fewer components require technical personnel to redesign the bike, which will greatly increase the development cost. What's more, when the cost is too high, the operators will abandon the redesign of the bicycles. Coupled with the current level of technology, the number of components cannot be reduced indefinitely and just reach a certain optimal solution.

5.5.2. Comparative analysis2.Weights

The recycling path model is a weighted combination of cost and environmental benefits, as shown in formula (25). Therefore, the determination of weights has an impact on the research results. What needs to be highlighted before the discussion is that we only select nine discrete points with a gradient of 0.1 because the weight deviation of the two decimals has little effect on the research results. Based on $0 \le w_1, w_2 \le 1$, there are nine sets of weight combinations, $w_1 = 0.1, w_2 = 0.9$; $w_1 = 0.2, w_2 = 0.8$; $w_1 = 0.3, w_2 = 0.7$; $w_1 = 0.4, w_2 = 0.6$; $w_1 = 0.5, w_2 = 0.5$; $w_1 = 0.6, w_2 = 0.4$; $w_1 = 0.7, w_2 = 0.3$; $w_1 = 0.8, w_2 = 0.2$; $w_1 = 0.9, w_2 = 0.1$.

Fig. 15 shows the fitness curve under nine weight combinations. Among that, Fig. 15 (a) shows that the GA-SA algorithm begins to converge after 100 iterations and the fitness value ranges from 0.8 to 0.9 when $w_1 = 0.1, w_2 = 0.9$. Fig. 15 (b) represents that the GA-SA algorithm begins to converge after 120 iterations and the fitness value ranges from 0.6 to 0.65 when $w_1 = 0.2, w_2 = 0.8$. Fig. 15 (c) denotes that the GA-SA algorithm begins to converge after 140 iterations and the fitness value ranges from 0.5 to 0.55 when $w_1 = 0.3, w_2 = 0.7$. Fig. 15(d) shows that the GA-SA algorithm begins to converge after 160 iterations and the fitness value ranges from 0.45 to 0.5 when $w_1 = 0.4, w_2 = 0.6$. Fig. 15(e) shows that the GA-SA algorithm begins to converge after 120 iterations and the fitness value ranges from 0.35 to 0.4 when $w_1 = 0.5, w_2 = 0.5$. Fig. 15(f) shows that the GA-SA algorithm begins to converge after 100 iterations and the fitness value ranges from 0.3 to 0.35 when $w_1 = 0.6, w_2 = 0.4$. Fig. 15(g) denotes that the GA-SA algorithm begins to converge after 120 iterations and the fitness value ranges from 0.3 to 0.35 when $w_1 = 0.7, w_2 = 0.3$. Fig. 15(h) shows that the GA-SA algorithm begins to converge after 110 iterations and the fitness value ranges from 0.25 to 0.3 when $w_1 = 0.8, w_2 = 0.2$. Fig. 15(i) represents that the GA-SA algorithm begins to converge after 160 iterations and the fitness value ranges from 0.24 to 0.26 when $w_1 = 0.9, w_2 = 0.1$. In order to more intuitively reflect difference between the nine sets of fitness curves, we select their fitness values after convergence and draw discounted charts to show their trends, as shown in Fig. 16. Among that, Fig. 16(a) and (b) show the statistical results of fitness values and iterations, respectively. As far as the fitness value is concerned, it shows a downward trend as the value of w_1 increases or the value of w_2 decreases. Among them, When $w_1 = 0.1, w_2 = 0.9$ and $w_1 = 0.9, w_2 = 0.1$, there are two extreme appearances of maximum fitness value and minimum fitness value. In terms of the number of iterations, when $w_1 = 0.1$, $w_2 = 0.9$ and $w_1 = 0.6, w_2 = 0.4$, GA-SA algorithm has the fastest convergence, on the contrary, GA-SA algorithm has the slowest convergence, when $w_1 = 0.4, w_2 = 0.6$ and $w_1 = 0.9, w_2 = 0.1$.

Based on the above results, we will analyze how to determine w_1, w_2 from three aspects. On the one hand, based on the stability of the fitness value, the three sets of fitness values $w_1 = 0.6, w_2 = 0.4$; $w_1 = 0.7, w_2 = 0.3$ and $w_1 = 0.8, w_2 = 0.2$ have the smallest slope of the polyline, that is, the fitness value has the smallest change with the weight, and the fitness value gradually becomes stable. Therefore, we have reason to lock the choice of weights in these three sets. On the other hand, based on the fitness value, $fitnessvalue(w_1 = 0.6, w_2 = 0.4) > fitnessvalue(w_1 = 0.8, w_2 = 0.2)$; $fitnessvalue(w_1 = 0.7, w_2 = 0.3) > fitnessvalue(w_1 = 0.8, w_2 = 0.2)$ and begin with $w_1 = 0.8, w_2 = 0.2$, the fitness value starts to show a downward trend. Therefore, we have reason to exclude $w_1 = 0.8$,

Table 14
The different economic and environmental benefits with different numbers of components.

The amount of components	The cost of transformation activity	The overall economic benefits	General environmental benefit
$\Re = 90$	RMB 210,0000	442207159.09	97627229.01
$\Re = 100$	RMB 100,0000	434665852.91	96278573.36
$\Re = 120$	RMB 90,0000	492925353.56	102859952.30

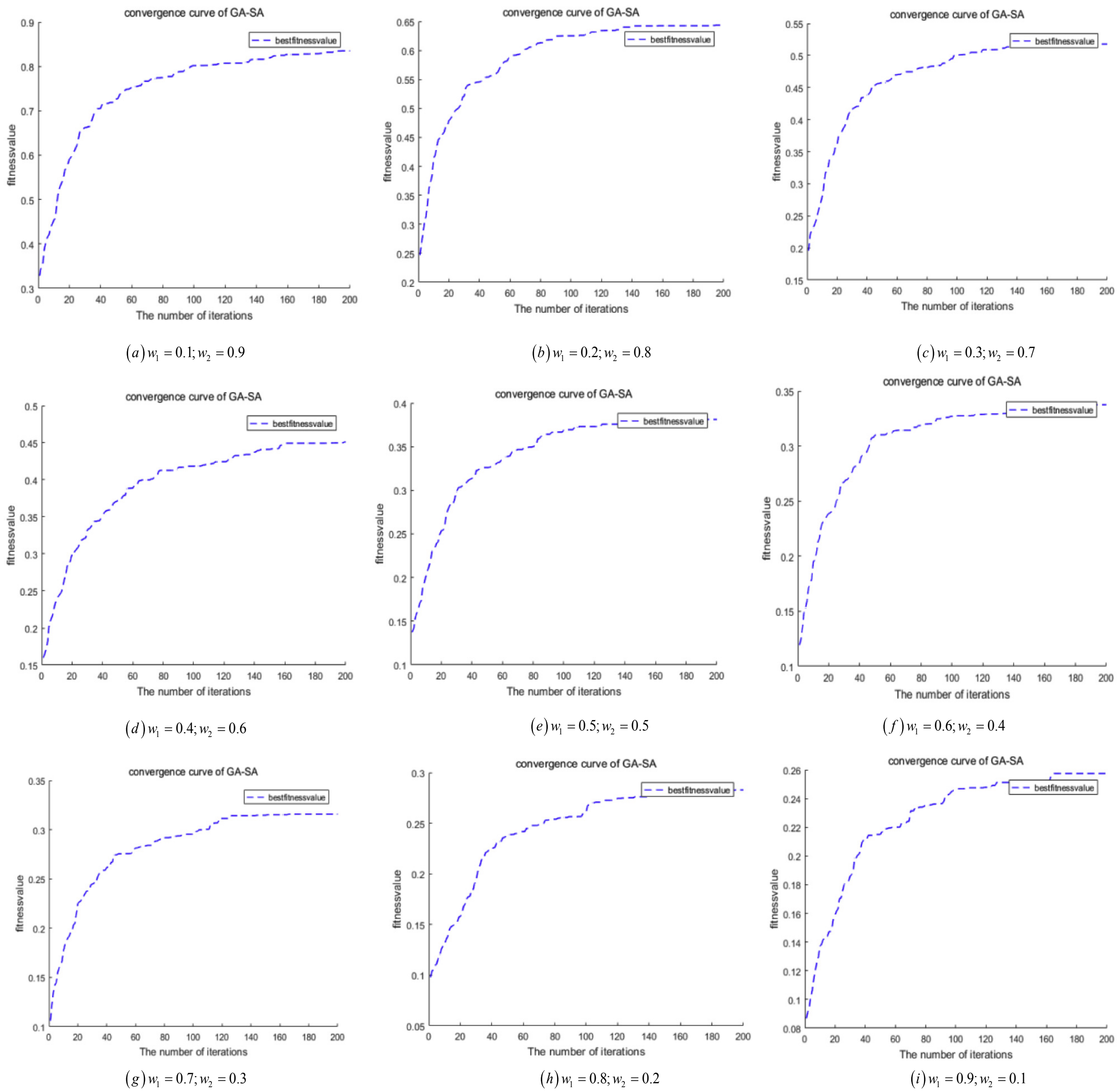

Fig. 15. Fitness curve under different weight combinations.

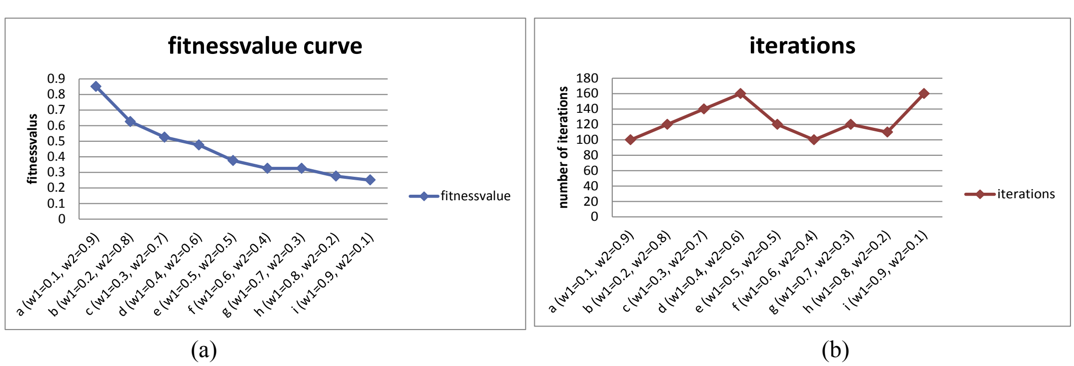

Fig. 16. Statistics charts of fitness value and iteration.

$w_2 = 0.2$ from the scope of our choice. The number of iterations affects the computational speed of the intelligent algorithm, from the experimental results of this paper, $iteration(w_1 = 0.6, w_2 = 0.4) < iteration(w_1 = 0.7, w_2 = 0.3)$, however, the difference is too small to allow us to exclude $w_1 = 0.7, w_2 = 0.3$. Finally, as mentioned earlier, the recycling of abandoned sharing bicycles is an environmentally-friendly activity, but it cannot be denied, the essential driving force is still economic benefits. In order to make the recycle path model more realistic, the impact of cost and environment benefits should be considered simultaneously. Therefore, in order to balance the impact of two factors, we have reason to believe that it is more in line with the requirements of model establishment when $w_1 = 0.6, w_2 = 0.4$ in the case that the fitness values are almost the same. Therefore, this paper chooses it to weight the integration of the recycling path model.

6. Conclusion

In this paper, the recycling of abandoned sharing bicycles is studied in two stages, including the choice of the 3 PLs and the design of the recycling network. Then, some conclusions are drawn regarding recycling management related to the abandoned bicycles.

(1) The recycling mode with the participation of the 3 PLs in sharing bicycles is the most reasonable and feasible. The outsourcing of recycling activities to the 3 PLs improves the recycling efficiency. Additionally, the sharing bicycles' operators only need to supervise the recycling activities and pay the corresponding fees to the 3 PLs, which reduces the operator's costs and enables the operators to invest more capital in the development and operation of the bicycles. Moreover, green image, financial ability, recovery capacity, pollution and emission, and searching ability should be considered in the selection of 3 PLs.

(2) For the recycling of sharing bicycles, it is an environmental activity. Therefore, in the design of recycling network, the cost and environmental benefits are equally important and should be considered. This is also the difference between the recycling mode of sharing bicycles and other recycling modes.

(3) Reducing the number of components is an effective measure to improve the economic and environmental benefits of sharing bicycles' operators. However, the number of components cannot be reduced indefinitely so an optimal solution should be identified.

Finally, through the analysis of the whole paper, there are several shortcomings can be found: For the selection of 3 PLs in the first stage, this paper uses the simple and easy-to-operate VIKOR method, although it can fully obtain the research results required in this paper. However, the scientific improvement of the VIKOR method and the exploration of a more complete and scientific decision-making method are a major research direction in the future. In addition, in the second stage of designing the recycling network, the model is built based on the impact of the two main factors, cost and environment, which ignores the impact of other factors on recycling activities, such as policies, regulations, citizen recycling awareness and so on. Finally, in the sensitivity analysis, we found that the amount of components can affect the recycling efficiency and further affect the recycling activities, but the degree of impact is difficult to be determined in this paper. Moreover, under the current technical level, how many components can be designed to achieve the optimal goal is also the direction that needs to conduct more in-depth research in the future.

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Appendix 1. Evaluation results of the five experts in time 1

	C_1	C_2	C_3	C_4	C_5
R_1	((0.16,0.34, 0.39,0.54; 1,1), (0.25,0.34,0.39,0.44; 0.9,0.9))	((0.46,0.65,0.70,0.84; 1,1), (0.56,0.65,0.70,0.75; 0.9,0.9))	((0.62,0.79,0.84,0.96; 1,1), (0.72,0.79,0.84,0.89; 0.9,0.9))	((0.30,0.49,0.54, 0.68; 1,1), (0.40, 0.49,0.54,0.59; 0.9,0.9))	((0.50,0.68,0.73,0.86; 1,1), (0.60,0.68,0.73,0.78; 0.9,0.9))
R_2	((0.50,0.68,0.73,0.86; 1,1), (0.60, 0.68, 0.73, 0.78; 0.9,0.9))	((0.54,0.71,0.76,0.88; 1,1), (0.64,0.71,0.76,0.81; 0.9,0.9))	((0.74,0.88,0.92,1.00; 1,1), (0.83,0.88,0.92,0.96; 0.9,0.9))	((0.46,0.64,0.69,0.82; 1,1), (0.56,0.64,0.69,0.74; 0.9,0.9))	((0.54,0.71,0.75,0.86; 1,1), (0.63,0.71,0.75,0.79; 0.9,0.9))
R_3	((0.30,0.49,0.54, 0.68; 1,1), (0.40, 0.49,0.54,0.59; 0.9,0.9))	((0.50,0.68,0.73,0.86; 1,1), (0.60,0.68,0.73,0.78; 0.9,0.9))	((0.42,0.62,0.67,0.82; 1,1), (0.52,0.62,0.67,0.72; 0.9,0.9))	((0.42,0.61,0.66,0.80; 1,1), (0.52,0.61,0.66,0.71; 0.9,0.9))	((0.30,0.49,0.54,0.68; 1,1), (0.40,0.49,0.54,0.59; 0.9,0.9))
R_4	((0.42,0.60,0.65,0.78; 1,1), (0.52, 0.60,0.65,0.70; 0.9,0.9))	((0.42,0.60,0.65,0.78; 1,1), (0.52,0.60,0.65,0.70; 0.9,0.9))	((0.70,0.85,0.90,1.00; 1,1), (0.80,0.85,0.90,0.95; 0.9,0.9))	((0.38,0.57,0.62,0.76; 1,1), (0.48,0.57,0.62,0.67; 0.9,0.9))	((0.50,0.67,0.71,0.82; 1,1), (0.59,0.67,0.71,0.75; 0.9,0.9))
R_5	((0.24,0.42,0.47,0.62; 1,1), (0.33,0.42,0.47,0.52; 0.9,0.9))	((0.58,0.75,0.80,0.92; 1,1), (0.68,0.75,0.80,0.85; 0.9,0.9))	((0.62,0.77,0.80,0.88; 1,1), (0.70,0.77,0.80,0.83; 0.9,0.9))	((0.30,0.50,0.55, 0.70; 1,1), (0.40, 0.50,0.55,0.60; 0.9,0.9))	((0.26,0.46,0.51,0.66; 1,1), (0.36,0.46,0.51,0.56; 0.9,0.9))
R_6	((0.34,0.53,0.58,0.72; 1,1), (0.44,0.53,0.58,0.63; 0.9,0.9))	((0.26,0.46,0.51,0.66; 1,1), (0.36,0.46,0.51,0.56; 0.9,0.9))	((0.62,0.79,0.84,0.96; 1,1), (0.72,0.79,0.84,0.89; 0.9,0.9))	((0.34,0.54,0.59,0.74; 1,1), (0.44,0.54,0.59,0.64; 0.9,0.9))	((0.62,0.79,0.84,0.96; 1,1), (0.72,0.79,0.84,0.89; 0.9,0.9))
R_7	((0.44,0.59,0.64,0.76; 1,1), (0.53,0.59,0.64,0.69; 0.9,0.9))	((0.62,0.78,0.83,0.94; 1,1), (0.72,0.78,0.83,0.88; 0.9,0.9))	((0.66,0.82,0.86,0.96; 1,1), (0.75,0.82,0.86,0.90; 0.9,0.9))	((0.26,0.46,0.51,0.66; 1,1) ,(0.36,0.46,0.51,0.56; 0.9,0.9))	((0.50,0.67,0.72,0.84; 1,1), (0.60,0.67,0.72,0.77; 0.9,0.9))
R_8	((0.50,0.69,0.74,0.88; 1,1), (0.60,0.69,0.74,0.79; 0.9,0.9))	((0.54,0.71,0.76,0.88; 1,1), (0.64,0.71,0.76,0.81; 0.9,0.9))	((0.62,0.78,0.83,0.94; 1,1), (0.72,0.78,0.83,0.88; 0.9,0.9))	((0.34,0.54,0.59,0.74; 1,1), (0.44,0.54,0.59,0.64; 0.9,0.9))	((0.50,0.67,0.72,0.84; 1,1), (0.60,0.67,0.72,0.77; 0.9,0.9))
R_9	((0.22,0.42,0.47,0.62; 1,1), (0.32,0.42,0.47,0.52; 0.9,0.9))	((0.58,0.75,0.80,0.92; 1,1), (0.68,0.75,0.80,0.85; 0.9,0.9))	((0.42,0.61,0.66,0.80; 1,1), (0.52,0.61,0.66,0.71; 0.9,0.9))	((0.38,0.58,0.63,0.78; 1,1), (0.48,0.58,0.63,0.68; 0.9,0.9))	((0.58,0.74,0.77,0.86; 1,1) (0.66,0.74,0.77,0.80; 0.9,0.9))
R_{10}	((0.30,0.50,0.55,0.70; 1,1), (0.40,0.50,0.55,0.60; 0.9,0.9))	((0.38,0.57,0.62,0.76; 1,1), (0.48,0.57,0.62,0.67; 0.9,0.9))	((0.66,0.81,0.85,0.94; 1,1), (0.75,0.81,0.85,0.89; 0.9,0.9))	((0.26,0.46,0.51,0.66; 1,1), (0.36,0.46,0.51,0.56; 0.9,0.9))	((0.54,0.71,0.76,0.88; 1,1), (0.64,0.71,0.76,0.81; 0.9,0.9))
R_{11}	((0.50,0.70,0.75,0.90; 1,1), (0.60,0.70,0.75,0.80; 0.9,0.9))	((0.38,0.56,0.61,0.74; 1,1), (0.48,0.56,0.61,0.66; 0.9,0.9))	((0.66,0.81,0.85,0.94; 1,1), (0.75,0.81,0.85,0.89; 0.9,0.9))	((0.22,0.42,0.47,0.62; 1,1), (0.32,0.42,0.47,0.52; 0.9,0.9))	((0.50,0.69,0.74,0.88; 1,1), (0.60,0.69,0.74,0.79; 0.9,0.9))

(*continued*)

	C_1	C_2	C_3	C_4	C_5
R_{12}	((0.26,0.42,0.47,0.62; 1,1), (0.34,0.42,0.47,0.52; 0.9,0.9))	((0.46,0.63,0.68,0.80; 1,1), (0.56,0.63,0.68,0.73; 0.9,0.9))	((0.66,0.81,0.85,0.94; 1,1) ,(0.75,0.81,0.85,0.89; 0.9,0.9))	((0.50,0.69,0.74,0.88; 1,1), (0.60,0.69,0.74,0.79; 0.9,0.9))	((0.40,0.64,0.68,0.80; 1,1), (0.55,0.64,0.68,0.72; 0.9,0.9))
R_{13}	((0.46,0.64,0.69,0.82; 1,1), (0.56,0.64,0.69,0.74; 0.9,0.9))	((0.38,0.56,0.61,0.74; 1,1), (0.48,0.56,0.61,0.66; 0.9,0.9))	((0.58,0.75,0.80,0.92; 1,1), (0.68,0.75,0.80,0.85; 0.9,0.9))	((0.38,0.58,0.63,0.78; 1,1) ,(0.48,0.58,0.63,0.68; 0.9,0.9))	((0.54,0.71,0.76,0.88; 1,1) ,(0.64,0.71,0.76,0.81; 0.9,0.9))
R_{14}	((0.18,0.38,0.43,0.58; 1,1), (0.28,0.38,0.43,0.48; 0.9,0.9))	((0.34,0.53,0.58,0.72; 1,1), (0.44,0.53,0.58,0.63; 0.9,0.9))	((0.70,0.85,0.89,0.98; 1,1), (0.79,0.85,0.89,0.93; 0.9,0.9))	((0.26,0.45,0.50,0.64; 1,1), (0.36,0.45,0.50,0.55; 0.9,0.9))	((0.34,0.54,0.59, 0.74; 1,1), (0.44, 0.54,0.59,0.64; 0.9,0.9))
R_{15}	((0.22,0.42,0.47,0.62; 1,1), (0.32,0.42,0.47,0.52; 0.9,0.9))	((0.46,0.64,0.69,0.82; 1,1) ,(0.56,0.64,0.69,0.74; 0.9,0.9))	((0.50,0.68,0.73,0.86; 1,1), (0.60,0.68,0.73,0.78; 0.9,0.9))	((0.38,0.58,0.63,0.78; 1,1), (0.48,0.58,0.63,0.68; 0.9,0.9))	((0.62,0.78,0.83,0.94; 1,1), (0.72,0.78,0.83,0.88; 0.9,0.9))

Appendix 2. Evaluation results of the five experts in time 2

	C_1	C_2	C_3	C_4	C_5
R_1	((0.10,0.26, 0.31,0.46; 1,1), (0.18,0.26,0.31,0.36; 0.9,0.9))	((0.46,0.65,0.70,0.84; 1,1), (0.56,0.65,0.70,0.75; 0.9,0.9))	((0.62,0.79,0.84,0.96; 1,1), (0.72,0.79,0.84,0.89; 0.9,0.9))	((0.30,0.49,0.54, 0.68; 1,1), (0.40, 0.49,0.54,0.59; 0.9,0.9))	((0.58,0.75,0.80,0.92; 1,1), (0.68,0.75,0.80,0.85; 0.9,0.9))
R_2	((0.46,0.64,0.69,0.82; 1,1), (0.56, 0.64, 0.69, 0.74; 0.9,0.9))	((0.54,0.71,0.76,0.88; 1,1), (0.64,0.71,0.76,0.81; 0.9,0.9))	((0.74,0.88,0.92,1; 1,1), (0.83,0.88,0.92,0.96; 0.9,0.9))	((0.46,0.64,0.69,0.82; 1,1), (0.56,0.64,0.69,0.74; 0.9,0.9))	((0.62,0.79,0.84,0.96; 1,1), (0.72,0.79,0.84,0.89; 0.9,0.9))
R_3	((0.30,0.49,0.54, 0.68; 1,1), (0.40, 0.49,0.54,0.59; 0.9,0.9))	((0.50,0.68,0.73,0.86; 1,1), (0.60,0.68,0.73,0.78; 0.9,0.9))	((0.42,0.62,0.67,0.82; 1,1), (0.52,0.62,0.67,0.72; 0.9,0.9))	((0.42,0.61,0.66,0.80; 1,1), (0.52,0.61,0.66,0.71; 0.9,0.9))	((0.18,0.38,0.43,0.58; 1,1), (0.28,0.38,0.43,0.48; 0.9,0.9))
R_4	((0.42,0.60,0.65,0.78; 1,1), (0.52, 0.60,0.65,0.70; 0.9,0.9))	((054,0.71,0.76,0.88; 1,1), (0.64,0.71,076,0.81; 0.9,0.9))	((0.70,0.85,0.90,1; 1,1), (0.80,0.85,0.90,0.95; 0.9,0.9))	((0.38,0.57,0.62,0.76; 1,1), (0.48,0.57,0.62,0.67; 0.9,0.9))	((0.50,0.67,0.71,0.82; 1,1), (0.59,0.67,0.71,0.75; 0.9,0.9))
R_5	((0.32,0.49,0.54,0.68; 1,1), (0.41,0.49,0.54,0.59; 0.9,0.9))	((0.62,0.78,0.83,0.94; 1,1), (0.72,0.78,0.83,0.88; 0.9,0.9))	((0.62,0.77,0.80,0.88; 1,1), (0.70,0.77,0.80,0.83; 0.9,0.9))	((0.30,0.50,0.55, 0.70; 1,1), (0.40, 0.50,0.55,0.60; 0.9,0.9))	((0.22,0.42,0.47,0.62; 1,1), (0.32,0.42,0.47,0.52; 0.9,0.9))
R_6	((0.34,0.53,0.58,0.72; 1,1), (0.44,0.53,0.58,0.63; 0.9,0.9))	((0.26,0.46,0.51,0.66; 1,1), (0.36,0.46,0.51,0.56; 0.9,0.9))	((0.62,0.79,0.84,0.96; 1,1), (0.72,0.79,0.84,0.89; 0.9,0.9))	((0.34,0.54,0.59,0.74; 1,1), (0.44,0.54,0.59,0.64; 0.9,0.9))	((0.62,0.79,0.84,0.96; 1,1), (0.72,0.79,0.84,0.89; 0.9,0.9))
R_7	((0.44,0.59,0.64,0.76; 1,1), (0.53,0.59,0.64,0.69; 0.9,0.9))	((0.62,0.78,0.83,0.94; 1,1), (0.72,0.78,0.83,0.88; 0.9,0.9))	((0.66,0.82,0.86,0.96; 1,1), (0.75,0.82,0.86,0.90; 0.9,0.9))	((0.26,0.46,0.51,0.66; 1,1), (0.36,0.46,0.51,0.56; 0.9,0.9))	((0.50,0.67,0.72,0.84; 1,1), (0.60,0.67,0.72,0.77; 0.9,0.9))
R_8	((0.50,0.69,0.74,0.88; 1,1), (0.60,0.69,0.74,0.79; 0.9,0.9))	((0.54,0.71,0.76,0.88; 1,1), (0.64,0.71,0.76,0.81; 0.9,0.9))	((0.62,0.78,0.83,0.94; 1,1), (0.72,0.78,0.83,0.88; 0.9,0.9))	((0.34,0.54,0.59,0.74; 1,1), (0.44,0.54,0.59,0.64; 0.9,0.9))	((0.50,0.67,0.72,0.84; 1,1), (0.60,0.67,0.72,0.77; 0.9,0.9))
R_9	((0.34,0.53,0.58,0.72; 1,1), (0.44,0.53,0.58,0.63; 0.9,0.9))	((0.58,0.75,0.80,0.92; 1,1), (0.68,0.75,0.80,0.85; 0.9,0.9))	((0.42,0.61,0.66,0.80; 1,1), (0.52,0.61,0.66,0.71; 0.9,0.9))	((0.38,0.58,0.63,0.78; 1,1), (0.480.58,0.63,0.68; 0.9,0.9))	((0.58,0.74,0.77,0.86; 1,1), (0.66,0.74,0.77,0.80; 0.9,0.9))
R_{10}	((0.30,0.50,0.55,0.70; 1,1), (0.40,0.50,0.55,0.60; 0.9,0.9))	((0.38,0.57,0.62,0.76; 1,1), (0.48,0.57,0.62,0.67; 0.9,0.9))	((0.66,0.81,0.85,0.94; 1,1), (0.75,0.81,0.85,0.89; 0.9,0.9))	((0.26,0.46,0.51,0.66; 1,1), (0.36,0.46,0.51,0.56; 0.9,0.9))	((0.54,0.71,0.76,0.88; 1,1), (0.64,0.71,0.76,0.81; 0.9,0.9))
R_{11}	((0.50,0.70,0.75,0.90; 1,1), (0 .60,0.70,0.75,0.80; 0.9,0.9))	((0.38,0.56,0.61,0.74; 1,1), (0.48,0.56,0.61,0.66; 0.9,0.9))	((0.66,0.81,0.85,0.94; 1,1), (0.75,0.81,0.85,0.89; 0.9,0.9))	((0.22,0.42,0.47,0.62; 1,1), (0.32,0.42,0.47,0.52; 0.9,0.9))	((0.50,0.69,0.74,0.88; 1,1), (0.60,0.69,0.74,0.79; 0.9,0.9))
R_{12}	((0.26,0.42,0.47,0.62; 1,1), (0.34,0.42,0.47,0.52; 0.9,0.9))	((0.54,0.71,0.76,0.88; 1,1), (0.64,0.71,0.76,0.81; 0.9,0.9))	((0.66,0.81,0.85,0.94; 1,1), (0.75,0.81,0.85,0.89; 0.9,0.9))	((0.50,0.69,0.74,0.88; 1,1), (0.60,0.69,0.74,0.79; 0.9,0.9))	((0.40,0.64,0.68,0.80; 1,1), (0.55,0.64,0.68,0.72; 0.9,0.9))
R_{13}	((0.46,0.64,0.69,0.82; 1,1), (0.56,0.64,0.69,0.74; 0.9,0.9))	((0.38,0.56,0.61,0.74; 1,1), (0.48,0.56,0.61,0.66; 0.9,0.9))	((0.58,0.75,0.80,0.92; 1,1), (0.68,0.75,0.80,0.85; 0.9,0.9))	((0.38,0.58,0.63,0.78; 1,1), (0.48,0.58,0.63,0.68; 0.9,0.9))	((0.54,0.71,0.76,0.88; 1,1), (0.64,0.71,0.76,0.81; 0.9,0.9))
R_{14}	((0.18,0.38,0.43,0.58; 1,1), (0.28,0.38,0.43,0.48; 0.9,0.9))	((0.34,0.53,0.58,0.72; 1,1), (0.44,0.53,0.58,0.63; 0.9,0.9))	((0.70,0.85,0.89,0.98; 1,1), (0.79,0.85,0.89,0.93; 0.9,0.9))	((0.26,0.45,0.50,0.64; 1,1), (0.36,0.45,0.50,0.55; 0.9,0.9))	((0.34,0.54,0.59, 0.74; 1,1), (0.44, 0.54,0.59,0.64; 0.9,0.9))
R_{15}	((0.22,0.42,0.47,0.62; 1,1), (0.32,0.42,0.47,0.52; 0.9,0.9))	((0.46,0.64,0.69,0.82; 1,1), (0.56,0.64,0.69,0.74; 0.9,0.9))	((0.50,0.68,0.73,0.86; 1,1), (0.60,0.68,0.73,0.78; 0.9,0.9))	((0.38,0.58,0.63,0.78; 1,1), (0.480.58,0.63,0.68; 0.9,0.9))	((0.62,0.78,0.83,0.94; 1,1), (0.72,0.78,0.83,0.88; 0.9,0.9))

Appendix 3. Evaluation results of the five experts in time 3

	C_1	C_2	C_3	C_4	C_5
R_1	((0.16,0.34, 0.39,0.54; 1,1), (0.25,0.34,0.39,0.44; 0.9,0.9))	((0.46,0.65,0.70,0.84; 1,1), (0.56,0.65,0.70,0.75; 0.9,0.9))	((0.62,0.79,0.84,0.96; 1,1), (0.72,0.79,0.84,0.89; 0.9,0.9))	((0.30,0.49,0.54, 0.68; 1,1), (0.40, 0.49,0.54,0.59; 0.9,0.9))	((0.50,0.68,0.73,0.86; 1,1), (0.60,0.68,0.73,0.78; 0.9,0.9))
R_2	((0.62,0.78,0.82,0.92; 1,1), (0.71,0.78,0.82,0.86; 0.9,0.9))	((0.54,0.71,0.76,0.88; 1,1), (0.64,0.71,0.76,0.81; 0.9,0.9))	((0.74,0.88,0.92,1; 1,1), (0.83,0.88,0.92,0.96; 0.9,0.9))	((0.46,0.64,0.69,0.82; 1,1), (0.56,0.64,0.69,0.74; 0.9,0.9))	((0.54,0.71,0.75,0.86; 1,1), (0.63,0.71,0.75,0.79; 0.9,0.9))
R_3	((0.26,0.46,0.51, 0.66; 1,1), (0.36,0.46,0.51,0.56; 0.9,0.9))	((0.50,0.68,0.73,0.86; 1,1), (0.60,0.68,0.73,0.78; 0.9,0.9))	((0.42,0.62,0.67,0.82; 1,1), (0.52,0.62,0.67,0.72; 0.9,0.9))	((0.42,0.61,0.66,0.80; 1,1), (0.52,0.61,0.66,0.71; 0.9,0.9))	((0.30,0.49,0.54,0.68; 1,1), (0.40,0.49,0.54,0.59; 0.9,0.9))
R_4	((0.42,0.60,0.65,0.78; 1,1), (0.52,0.60,0.65,0.70; 0.9,0.9))	((0.42,0.60,0.65,0.78; 1,1), (0.52,0.60,0.65,0.70; 0.9,0.9))	((0.70,0.85,0.90,1; 1,1), (0.80,0.85,0.90,0.95; 0.9,0.9))	((0.38,0.57,0.62,0.76; 1,1), (0.48,0.57,0.62,0.67; 0.9,0.9))	((0.50,0.67,0.71,0.82; 1,1), (0.59,0.67,0.71,0.75; 0.9,0.9))
R_5	((0.24,0.42,0.47,0.62; 1,1), (0.33,0.42,0.47,0.52; 0.9,0.9))	((0.58,0.75,0.80,0.92; 1,1), (0.68,0.75,0.80,0.85; 0.9,0.9))	((0.62,0.77,0.80,0.88; 1,1), (0.70,0.77,0.80,0.83; 0.9,0.9))	((0.30,0.50,0.55, 0.70; 1,1) ,(0.40, 0.50,0.55,0.60; 0.9,0.9))	((0.30,0.50,0.55,0.70; 1,1), (0.40,0.50,0.55,0.60; 0.9,0.9))
R_6	((0.34,0.53,0.58,0.72; 1,1), (0.44,0.53,0.58,0.63; 0.9,0.9))	((0.26,0.46,0.51,0.66; 1,1), (0.36,0.46,0.51,0.56; 0.9,0.9))	((0.62,0.79,0.84,0.96; 1,1), (0.72,0.79,0.84,0.89; 0.9,0.9))	((0.34,0.54,0.59,0.74; 1,1), (0.44,0.54,0.59,0.64; 0.9,0.9))	((0.70,0.85,0.89,0.98; 1,1), (0.79,0.85,0.89,0.93; 0.9,0.9))

(*continued on next page*)

(*continued*)

	C_1	C_2	C_3	C_4	C_5
R_7	((0.44,0.59,0.64,0.76; 1,1), (0.53,0.59,0.64,0.69; 0.9,0.9))	((0.62,0.78,0.83,0.94; 1,1), (0.72,0.78,0.83,0.88; 0.9,0.9))	((0.66,0.82,0.86,0.96; 1,1), (0.75,0.82,0.86,0.90; 0.9,0.9))	((0.26,0.46,0.51,0.66; 1,1), (0.36,0.46,0.51,0.56; 0.9,0.9))	((0.50,0.67,0.72,0.84; 1,1), (0.60,0.67,0.72,0.77; 0.9,0.9))
R_8	((0.50,0.69,0.74,0.88; 1,1), (0.60,0.69,0.74,0.79; 0.9,0.9))	((0.54,0.71,0.76,0.88; 1,1), (0.64,0.71,0.76,0.81; 0.9,0.9))	((0.62,0.78,0.83,0.94; 1,1), (0.72,0.78,0.83,0.88; 0.9,0.9))	((0.34,0.54,0.59,0.74; 1,1), (0.44,0.54,0.59,0.64; 0.9,0.9))	((0.50,0.67,0.72,0.84; 1,1), (0.60,0.67,0.72,0.77; 0.9,0.9))
R_9	((0.22,0.42,0.47,0.62; 1,1), (0.32,0.42,0.47,0.52; 0.9,0.9))	((0.58,0.75,0.80,0.92; 1,1), (0.68,0.75,0.80,0.85; 0.9,0.9))	((0.42,0.61,0.66,0.80; 1,1), (0.52,0.61,0.66,0.71; 0.9,0.9))	((0.38,0.58,0.63,0.78; 1,1), (0.480.58,0.63,0.68; 0.9,0.9))	((0.58,0.74,0.77,0.86; 1,1), (0.66,0.74,0.77,0.80; 0.9,0.9))
R_{10}	((0.30,0.50,0.55,0.70; 1,1), (0.40,0.50,0.55,0.60; 0.9,0.9))	((0.38,0.57,0.62,0.76; 1,1), (0.48,0.57,0.62,0.67; 0.9,0.9))	((0.66,0.81,0.85,0.94; 1,1), (0.75,0.81,0.85,0.89; 0.9,0.9))	((0.26,0.46,0.51,0.66; 1,1), (0.36,0.46,0.51,0.56; 0.9,0.9))	((0.54,0.71,0.76,0.88; 1,1), (0.64,0.71,0.76,0.81; 0.9,0.9))
R_{11}	((0.50,0.70,0.75,0.90; 1,1), (0.60,0.70,0.75,0.80; 0.9,0.9))	((0.38,0.56,0.61,0.74; 1,1), (0.48,0.56,0.61,0.66; 0.9,0.9))	((0.66,0.81,0.85,0.94; 1,1), (0.75,0.81,0.85,0.89; 0.9,0.9))	((0.22,0.42,0.47,0.62; 1,1), (0.32,0.42,0.47,0.52; 0.9,0.9))	((0.50,0.69,0.74,0.88; 1,1), (0.60,0.69,0.74,0.79; 0.9,0.9))
R_{12}	((0.26,0.42,0.47,0.62; 1,1), (0.34,0.42,0.47,0.52; 0.9,0.9))	((0.46,0.63,0.68,0.80; 1,1), (0.56,0.63,0.68,0.73; 0.9,0.9))	((0.66,0.81,0.85,0.94; 1,1), (0.75,0.81,0.85,0.89; 0.9,0.9))	((0.50,0.69,0.74,0.88; 1,1), (0.60,0.69,0.74,0.79; 0.9,0.9))	((0.40,0.64,0.68,0.80; 1,1), (0.55,0.64,0.68,0.72; 0.9,0.9))
R_{13}	((0.46,0.64,0.69,0.82; 1,1), (0.56,0.64,0.69,0.74; 0.9,0.9))	((0.38,0.56,0.61,0.74; 1,1) ,(0.48,0.56,0.61,0.66; 0.9,0.9))	((0.58,0.75,0.80,0.92; 1,1), (0.68,0.75,0.80,0.85; 0.9,0.9))	((0.38,0.58,0.63,0.78; 1,1), (0.48,0.58,0.63,0.68; 0.9,0.9))	((0.54,0.71,0.76,0.88; 1,1), (0.64,0.71,0.76,0.81; 0.9,0.9))
R_{14}	((0.18,0.38,0.43,0.58; 1,1), (0.28,0.38,0.43,0.48; 0.9,0.9))	((0.34,0.53,0.58,0.72; 1,1), (0.44,0.53,0.58,0.63; 0.9,0.9))	((0.70,0.85,0.89,0.98; 1,1), (0.79,0.85,0.89,0.93; 0.9,0.9))	((0.26,0.45,0.50,0.64; 1,1), (0.36,0.45,0.50,0.55; 0.9,0.9))	((0.34,0.54,0.59, 0.74; 1,1), (0.44, 0.54,0.59,0.64; 0.9,0.9))
R_{15}	((0.22,0.42,0.47,0.62; 1,1), (0.32,0.42,0.47,0.52; 0.9,0.9))	((0.46,0.64,0.69,0.82; 1,1), (0.56,0.64,0.69,0.74; 0.9,0.9))	((0.50,0.68,0.73,0.86; 1,1), (0.60,0.68,0.73,0.78; 0.9,0.9))	((0.38,0.58,0.63,0.78; 1,1), (0.480.58,0.63,0.68; 0.9,0.9))	((0.62,0.78,0.83,0.94; 1,1), (0.72,0.78,0.83,0.88; 0.9,0.9))

References

Abdulrahman, M.D., Gunasekaran, A., Subramanian, N., 2014. Critical barriers in implementing reverse logistics in the Chinese manufacturing sectors. Int. J. Prod. Econ. 147 (1), 460–471.

Afshari, H., Sharafi, M., Elmekkawy, T.Y., Peng, Q., 2016. Multi-objective optimisation of facility location decisions within integrated forward/reverse logistics under uncertainty. Int. J. Bus. Perform. Supply Chain Model. 8 (3), 250–276.

Aguezzoul, A., 2014. Third-party logistics selection problem: a literature review on criteria and methods. Omega Int. J. Manag. S. 49 (1), 69–78.

Alshamsi, A., Diabat, A., 2015. A reverse logistics network design. J. Manuf. Syst. 37, 589–598.

Altekin, F.T., Suyabatmaz, C.A., Şahin, G., 2014. Hybrid simulation-analytical modeling approaches for the reverse logistics network design of a third-party logistics provider. Comput. Ind. Eng. 70 (2), 74–89.

Alvarez-Valdes, R., Belenguer, J.M., Benavent, E., Bermudez, J.D., Muñoz, F., Vercher, E., Francisco Verdejo, F., 2016. Optimizing the level of service quality of a bike-sharing system. Omega Int. J. Manag. S. 62, 163–175.

Amin, S.H., Zhang, G., 2012. An integrated model for closed-loop supply chain configuration and supplier selection: multi-objective approach. Expert Syst. Appl. 39 (8), 6782–6791.

Ayhan, M.B., Kilic, H.S., 2015. A two stage approach for supplier selection problem in multi-item/multi-supplier environment with quantity discounts. Comput. Ind. Eng. 85 (C), 1–12.

Bing, X., Bloemhof-Ruwaard, J.M., Jack, G.A., van der Vorst, J., 2014. Sustainable reverse logistics network design for household plastic waste. Flex. Serv. Manuf. J. 26 (1–2), 119–142.

Chemla, D., Meuniera, F., Calvo, R.W., 2013. Bike sharing systems: solving the static rebalancing problem. Discrete Optim. 10 (2), 120–146.

Chen, S.M., Kuo, L.W., 2017. Autocratic decision making using group recommendations based on interval type-2 fuzzy sets, enhanced Karnik-Mendel algorithms, and the ordered weighted aggregation operator. Inf. Sci. 412–413, 174–193.

Chen, T.Y., Chien, H.C., Lu, J.F.R., 2013. The extended QUALIFLEX method for multiple criteria decision analysis based on interval type-2 fuzzy sets and applications to medical decision making. Eur. J. Oper. Res. 226 (3), 615–625.

Chen, W., Yang, Z.L., Zhou, W., Chen, H., 2016. Dynamic intuitionistic fuzzy compromise decision making method based on time degrees. Oper. Res. Manag. Sci. 25 (2), 83–89.

Chen, Q., Liu, M., Liu, X., 2018. Bike fleet allocation models for repositioning in bike-sharing systems. IEEE Intel. Transp. Sy. 10 (1), 19–29.

China Institute of Information and Communications, 2018. See. http://www.caict.ac.cn/.

Cohen, B., Muñoz, P., 2016. Sharing cities and sustainable consumption and production: towards an integrated framework. J. Clean. Prod. 134 (3), 87–97.

Cruz, F., Subramanian, A., Bruck, B.P., Iori, M., 2016. A heuristic algorithm for a single vehicle static bike sharing rebalancing problem. Comput. Oper. Res. 79, 19–33.

Dai, L.F., Wang, X.F., 2014. Research on mixed intelligent arithmetic of reuse reverse logistics centers' location model. Adv. Mater. Res. 945–949, 3246–3251.

Dell'Amico, M., Hadjicostantinou, E., Iori, M., Novellani, S., 2014. The bike sharing rebalancing problem: mathematical formulations and benchmark instances. Omega Int. J. Manag. S. 45 (2), 7–19.

Diabat, A., Kannan, D., Kaliyan, M., Svetinovic, D., 2013. An optimization model for product returns using genetic algorithms and artificial immune system. Resour. Conserv. Recycl. 74, 156–169.

Diego, F., Federico, F., Schiraldi, M.M., 2012. A logistics provider evaluation and selection methodology based on AHP, DEA and linear programming integration. Int. J. Prod. Res. 50 (17), 4822–4829.

Dobos, I., Vörösmarty, G., 2014. Green supplier selection and evaluation using DEA-type composite indicators. Int. J. Prod. Econ. 157 (1), 273–278.

Erdogan, G., Battarra, M., Calvo, R.W., 2015. An exact algorithm for the static rebalancing problem arising in bicycle sharing systems. Eur. J. Oper. Res. 245 (3), 667–679.

Faghih-Imani, A., Hampshire, R., Marla, L., Eluru, N., 2017. An empirical analysis of bike sharing usage and rebalancing: evidence from Barcelona and Seville. Transport. Res. A-Pol. 97, 177–191.

Fishman, E., Washington, S., Haworth, N., Watson, A., 2015. Factors influencing bike share membership: an analysis of Melbourne and Brisbane. Transport. Res. A-Pol. 71, 17–30.

Forma, I.A., Raviv, T., Tzur, M., 2015. A 3-step math heuristic for the static repositioning problem in bike-sharing systems. Transport. Res. B-Meth. 71, 230–247.

Frade, I., Ribeiro, A., 2015. Bike-sharing stations: a maximal covering location approach. Transport. Res. A-Pol. 82, 216–227.

Fukuta, M., Anzai, F., Motozawa, M., Terawaki, H., Yanagisawa, T., 2014. Performance of radial piston type reciprocating expander for CO2, refrigeration cycle. Int. J. Refrig. 42 (3), 48–56.

García-Palomares, J.C., Gutiérrez, J., Latorre, M., 2012. Optimizing the location of stations in bike-sharing programs: a GIS approach. Appl. Georg. 35 (1–2), 235–246.

Ghosh, S., Varakantham, P., Adulyasak, Y., Jaillet, P., 2017. Dynamic repositioning to reduce lost demand in bike sharing systems. J. Artif. Intell. Res. 58, 387–430.

Govindan, K., Soleimani, H., Kannan, D., 2015. Reverse logistics and closed-loop supply chain: a comprehensive review to explore the future. Eur. J. Oper. Res. 240 (3), 603–626.

Govindan, K., Paam, P., Abtahi, A.R., 2016. A fuzzy multi-objective optimization model for sustainable reverse logistics network design. Ecol. Indicat. 67, 753–768.

Guarnieri, P., Sobreiro, V.A., Nagano, M.S., Serrano, A.L.M., 2015. The challenge of selecting and evaluating third-party reverse logistics providers in a multi criteria perspective: a Brazilian case. J. Clean. Prod. 96, 209–219.

Guo, J.Q., Liu, X.X., Jo, J.B., 2017a. Dynamic joint construction and optimal operation strategy of multi-period reverse logistics network: a case study of Shanghai apparel E-commerce enterprises. J. Intell. Manuf. 28, 819–831.

Guo, Y., Zhou, J., Wu, Y., Li, Z., 2017b. Identifying the factors affecting bike-sharing usage and degree of satisfaction in Ningbo, China. PloS One 12 (9), 1–22.

Gupta, D.K., Dasgupta, M.S., 2014. Simulation and performance optimization of finned tube gas cooler for trans-critical CO2, refrigeration system in Indian context. Int. J. Refrig. 38, 153–167.

Hatefi, S.M., Jolai, F., 2014. Robust and reliable forward–reverse logistics network design under demand uncertainty and facility disruptions. Appl. Math. Model. 38 (9–10), 2630–2647.

Hbspca, 2017. See. http://www.hbspcar.com/.

Hiselius, L.W., Åse, S., 2017. E-bike use in Sweden-CO2 effects due to modal change and municipal promotion strategies. J. Clean. Prod. 141, 818–824.

Ho, S.C., Szeto, W.Y., 2014. Solving a static repositioning problem in bike-sharing systems using iterated tabu search. Transport. Res. E-Log. 69 (3), 180–198.

Jayant, A., Gupta, P., Garg, S.K., Khan, M., 2014. TOPSIS-AHP based approach for selection of reverse logistics service provider: a case study of mobile phone industry. Procedia Eng. 97, 2147–2156.

Ji, S., Cherry, C.R., Han, L.D., Jordan, D.A., 2014. Electric bike sharing: simulation of user demand and system availability. J. Clean. Prod. 85, 250–257.

Jin, H.P., Cho, H.J., Kwun, Y.C., 2013. Extension of the VIKOR method to dynamic intuitionistic fuzzy multiple attribute decision making. Comput. Math. Appl. 65 (4), 731–744.

Kafa, N., Hani, Y., Mhamedi, A.E., 2015. An integrated sustainable partner selection approach with closed-loop supply chain network configuration. IFAC-PaperSOnLine 48 (3), 1840–1845.

Kilic, H.S., Cebeci, U., Ayhan, M.B., 2015. Reverse logistics system design for the

waste of electrical and electronic equipment (WEEE) in Turkey. Resour. Conserv. Recycl. 95, 120–132.
Lin, J.R., Yang, T.H., Chang, Y.C., 2013. A hub location inventory model for bicycle sharing system design: formulation and solution. Comput. Ind. Eng. 65 (1), 77–86.
Liu, C.L., Lyons, A.,C., 2011. An analysis of third-party logistics performance and service provision. Transportat. Res. E-Log. 47 (4), 547–570.
Liu, Q., Zhang, C.Y., Zhu, K., Rao, Y.Q., 2014. Novel multi-objective resource allocation and activity scheduling for fourth party logistics. Comput. Oper. Res. 44 (2), 42–51.
Lourenzutti, R., Krohling, R.A., 2016. A generalized TOPSIS method for group decision making with heterogeneous information in a dynamic environment. Inf. Sci. 330, 1–18.
Mafakheria, F., Nasirib, F., 2013. Revenue sharing coordination in reverse logistics. J. Clean. Prod. 59 (18), 185–196.
Ministry of commerce of the People's Republic of China Department of Circulation Industry Development, 2017. See. http://ltfzs.mofcom.gov.cn/article/date/201705/20170502568040.shtml.
Ministry of Industry and Information Technology of the People's Republic of China, 2011. See. http://www.miit.gov.cn.
Nair, R., Miller-Hooks, E., 2014. Equilibrium network design of shared-vehicle systems. Eur. J. Oper. Res. 235 (1), 47–61.
Opricovic, S., Tzeng, G.H., 2004. Compromise solution by MCDM methods: a comparative analysis of VIKOR and TOPSIS. Eur. J. Oper. Res. 156 (2), 445–455.
Opricovic, S., Tzeng, G.H., 2007. Extended VIKOR method in comparison with outranking methods. Eur. J. Oper. Res. 178 (2), 514–529.
Pelechrinis, K., Zacharias, C., Kokkodis, M., Lappas, T., 2017. Economic impact and policy implications from urban shared transportation: the case of Pittsburgh's shared bike system. PloS One 12 (8), 1–21.
Pishvaee, M.S., Torabi, S.A., Razmi, J., 2012. Credibility-based fuzzy mathematical programming model for green logistics design under uncertainty. Comput. Ind. Eng. 62 (2), 624–632, 2012.
Prakash, C., Barua, M.K., 2017. Flexible modeling approach for evaluating reverse logistics adoption barriers using fuzzy AHP and IRP framework. Int. J. Oper. Res. 30 (2), 151–171.
Qin, J., Liu, X., Pedrycz, W., 2017. An extended TODIM multi-criteria group decision making method for green supplier selection in interval type-2 fuzzy environment. Eur. J. Oper. Res. 258 (2), 626–638.
Raviv, T., Tzur, M., Forma, I.A., 2013. Static repositioning in a bike-sharing system: models and solution approaches. J. Transport. Log. 2 (3), 187–229.
Ren, Z., Xu, Z., Wang, H., 2017. Dual hesitant fuzzy VIKOR method for multi-criteria group decision making based on fuzzy measure and new comparison method. Inf. Sci. 388–389, 1–16.
Rezaie, K., Ramiyani, S.S., Nazari-Shirkouhi, S., Badizadeh, A., 2014. Evaluating performance of Iranian cement firms using an integrated fuzzy AHP–VIKOR method. Appl. Math. Model. 38 (21–22), 5033–5046.
Sadiq, R., Tesfamariam, S., 2007. Probability density functions based weights for ordered weighted averaging (OWA) operators: an example of water quality indices. Eur. J. Oper. Res. 182 (3), 1350–1368.
Sanayei, A., Mousavi, S.F., Yazdankhah, A., 2010. Group decision making process for supplier selection with VIKOR under fuzzy environment. Expert Syst. Appl. 37 (1), 24–30.
Sasikumar, P., Noorul, H.A., 2001. Integration of closed loop distribution supply chain network and 3PRLP selection for the case of battery recycling. Int. J. Prod. Res. 49 (11), 3363–3385.
Schuijbroek, J., Hampshire, R.C., Hoeve, W.J.V., 2016. Inventory rebalancing and vehicle routing in bike sharing systems. Eur. J. Oper. Res. 257 (3), 992–1004.
Senthil, S., Srirangacharyulu, B., Ramesh, A., 2014. A robust hybrid multi-criteria decision making methodology for contractor evaluation and selection in third-party reverse logistics. Expert Syst. Appl. 41 (1), 50–58.
Shemshadi, A., Shirazi, H., Toreihi, M., 2011. A fuzzy VIKOR method for supplier selection based on entropy measure for objective weighting. Expert Syst. Appl. 38 (10), 12160–12167.
Singh, S., Dasgupta, M.S., 2016. Evaluation of research on CO2, trans-critical work recovery expander using multi attribute decision making methods. Renew. Sustain. Energy Rev. 59, 19–129.
Snežana, T., Slobodan, Z., Mladen, K., 2014. A novel hybrid MCDM model based on fuzzy DEMATEL, fuzzy ANP and fuzzy VIKOR for city logistics concept selection. Expert Syst. Appl. 41 (18), 8112–8128.
Tian, H., Ma, Y.T., Li, M.X., Guan, H.Q., Liu, Z.Y., 2011. Influence of a non-condensable gas on the performance of a piston expander for use in carbon dioxide trans-critical heat pumps. Appl. Therm. Eng. 31 (11–12), 1943–1949.
Tsai, W.H., Hung, S.H., 2009. Treatment and recycling system optimization with activity-based costing in WEEE reverse logistics management: an environmental supply chain perspective. Int. J. Prod. Res. 47 (19), 5391–5420.
Tuğba, E., Semih, Ö., Elif, K., 2008. A holistic approach for selecting a third-party reverse logistics provider in the presence of vagueness. Comput. Ind. Eng. 54 (2), 269–287.
Wan, S.P., Wang, F., Dong, J.Y., 2016. A preference degree for intuitionistic fuzzy values and application to multi-attribute group decision making. Inf. Sci. 370–371, 127–146.
Wu, D., Mendel, J.M., 2007. Uncertainty measures for interval type-2 fuzzy sets. Inf. Sci. 177 (23), 5378–5393.
Wu, Z., Ahmad, J., Xu, J., 2016. A group decision making framework based on fuzzy VIKOR approach for machine tool selection with linguistic information. Appl. Soft Comput. 42, 314–324.
Xinhuanet, 2017. See. http://www.xinhuanet.com/city/2017-06/20/c_129636485.htm.
Xu, Z., 2005. An overview of methods for determining OWA weights: research Articles. Int. J. Intell. Syst. 20, 843–865.
Xu, Z., Yager, R.R., 2008. Dynamic intuitionistic fuzzy multi-attribute decision making. Int. J. Approx. Reason. 48, 246–262.
Xu, F.Q., Liu, J.C., Lin, S.S., Yuan, J.H., 2017. A VIKOR-based approach for assessing the service performance of electric vehicle sharing programs: a case study in Beijing. J. Clean. Prod. 148, 254–267.
Yager, R.R., 2004. OWA aggregation over a continuous interval argument with applications to decision making. IEEE Trans. Syst. Man Cybern. Part B (Cybernetics) 34 (5), 1952–1963.
Yang, Y.P.O., Shieh, H.M., Tzeng, G.H., 2013. A VIKOR technique based on DEMATEL and ANP for information security risk control assessment. Inf. Sci. 232 (5), 482–500.
Yeh, W.C., Chuang, M.C., 2011. Using multi-objective genetic algorithm for partner selection in green supply chain problems. Expert Syst. Appl. 38 (4), 4244–4253.
You, X.Y., You, J.X., Liu, H.C., Zhen, L., 2015. Group multi-criteria supplier selection using an extended VIKOR method with interval 2-tuple linguistic information. Expert Syst. Appl. 42 (4), 1906–1916.
Zarbakhshnia, N., Soleimani, H., Ghaderi, H., 2018. Sustainable third-party reverse logistics provider evaluation and selection using fuzzy SWARA and developed fuzzy COPRAS in the presence of risk criteria. Appl. Soft Comput. 65, 307–319.
Zhang, F.S., Liu, S.Y., Qin, C.,D., 2012. VIKOR extension method for dynamic triangular fuzzy multi-attribute decision making. Comput. Integr. Manuf. Syst. 18 (1), 186–191.
Zhang, Z., Ma, Y., Li, M., Zhao, L., 2013. Recent advances of energy recovery expanders in the transcritical CO2 refrigeration cycle. HVAC R Res. 19 (4), 376–384.
Zhang, L., Zhang, J., Duan, Z.Y., Bryde, D., 2015. Sustainable bike-sharing systems: characteristics and commonalities across cases in urban China. J. Clean. Prod. 97, 124–133.
Zhou, Y., Chan, C.K., Wong, K.H., Lee, Y.C.E., 2015. Intelligent optimization algorithms: a stochastic closed-loop supply chain network problem involving oligopolistic competition for multiproducts and their product flow routings. Math. Probl Eng. (2–3), 1–22.