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Abstract

As the most developed city circle in northern China, allocating CO_2 emission quotas at the Bohai Rim Economic Circle (BREC) city level is essential for developing specific abatement policies. Thus, with reflecting multi-principles (fairness, efficiency, sustainability, and feasibility), this paper formulates the CO_2 emission quotas allocation among cities in BREC in 2030 based on the multi-objective decision approach. We first propose three allocation schemes based on the principles of fairness, efficiency, and sustainability, which are conducted by entropy method, zero-sum gains data envelopment (ZSG-DEA) model, and CO_2 sequestration share method, respectively.

Then, the CO_2 allocation satisfaction is defined and used to measure the feasibility principle which is integrated as the objective function of the multi-objective decision model together with three allocation schemes to obtain the optimal allocation results. The results show that cities with large energy consumption and less CO_2 sequestration capacity, such as Tianjin, Handan, and Tangshan, experience a decrease in the emission quota shares from 2017 to 2030, indicating that these cities would undertake large emissions reduction obligations. Conversely, there is an increase in the shares of CO_2 emission quotas when it comes to Beijing, Chengde, and Dalian, whose GDP, population, and CO_2 sequestration capacity are relatively large. Sensitivity analysis shows that Beijing, Zibo, and Jinan are more sensitive to minimum satisfaction changes, and the total satisfaction experiences an increase first and declines thereafter. Based on the results above, cities with large pressure to reduce CO_2 emissions should not only promote the economic development, but also improve the capacity of CO_2 sequestration by enhancing environmental protection to realize emission reduction targets.
Keywords: CO_2 emission quota allocation; Multi-principles; Cities in Bohai Rim Economic Circle; Multi-objective decision model; Allocation satisfaction.

1. Introduction

In order to combat climate change, the Chinese government has undertaken to reduce the national carbon emission intensity by 60%-65% in 2030 compared with 2005 and reach the CO_2 emissions peak before 2030. Besides, in October 2020, China made further commitments to achieve carbon-neutral before 2060. To reduce carbon emissions intensity, China has committed to implementing the emissions trading scheme (ETS), which is an effective way to reduce CO_2 emissions through the market mechanism (Han et al., 201 7; Kong et al., 2019; Hu et al.,2020). After implementing seven carbon-trading pilot programs in 2011, China's national ETS was officially launched in December 2017 and started by covering the power sector in this system, while the remaining sectors will be incorporated gradually.

As one of the most essential prerequisites for national ETS, allocating CO_2 emission quotas scientifically and reasonably has attracted increasing attention. Studies have focused on CO_2 emission quotas allocation at different levels, for example, country level (Benestad, 1994; Pan et al., 2014; Momeni et al., 2018), China's provincial level (Yi et al., 2011; Kong et al., 2019; He and Zhang 2020; Zhou et al., 2021) and several provinces within specific regions (Han et al., 2016; Chang et al., 2020). With respect to determining the CO_2 emission quotas by cities, Li et al. (2018) constructed a comprehensive index using the maximum deviation method to allocate CO_2 emission quotas among nine cities in the Pearl River Delta region by 2020. Zhou et al. (2018) evaluated emission performance and allocated CO_2 emission quotas to Chinese 71 cities based on the data envelopment analysis (DEA) model. Besides, Liu et al. (2018) determined the CO_2 emission quotas among 25 cities in the Yangtze River Delta region by constructing a comprehensive index. The same case study was conducted by Zhang et al. (2020), who simulated the CO_2 emission quotas allocation by the ZSG-DEA model. In summary, few studies and methods are focusing on the CO_2 emission quotas allocation at the city level.

As the main subject of CO_2 emissions, cities play an essential role in achieving carbon emission reduction targets, providing more accurate information than the provincial level to formulate targeted policies for emissions reduction. Besides, as the most developed area in northern China, BREC consumed a lot of energy, accounting for 25.4% of the national total in 2017 (Chang et al., 2020). The realization of its regional coordinated carbon reduction has strategic importance for realizing China's national emission reduction target. Chang et al. (2020) proposed a two-stage allocation model to simulate the CO_2 emission quotas allocation for five provinces in BREC in 2030. Han et al. (2016) issued CO_2 emission quotas to three provinces in the Beijing-Tianjin-Hebei region using the composite index approach. However, few studies have been conducted to allocate the CO_2 emission quotas among the cities in BREC. Therefore, it is of great importance to investigate provincial emission quotas allocation among cities. This paper aims to formulate the CO_2 emission quotas allocation for cities in BREC in 2030.

Furthermore, the principles and methods used can be induced from the existing literature. Generally, fairness and efficiency are two main principles followed by the most current studies. For example, Pan et al. (2014) formulated the fair CO_2 emissions quotas allocation at national levels following equal cumulative emission per capita. As for the efficiency principle, three allocation strategies (spatial, temporal, and spatial-temporal) were adopted by Zhou et al. (2014), who formulated the optimal allocation of CO_2 emission quotas using centralized DEA models. Also, Dong et al. (2018) applied an improved fixed cost allocation model by taking fairness and efficiency principles both into consideration. The same principles were considered by Kong et al. (2019) and He and Zhang (2020), who combined the entropy method with the DEA model to establish a comprehensive index for the allocation of provincial CO_2 emission quotas. Although the principle of fairness and efficiency are most commonly used, the indicators measuring the fairness and efficiency principles failed to reach a unified conclusion. Besides, considering production consistency, feasibility principle was also proposed in the various studies since they believe the CO_2 emission quotas should be allocated with strong operational and more readily accepted in practice (Zetterberg et al., 2012; Zhou and Wang, 2016; Li et al.,2018; Zhu et al.,2018; Fang et al., 2018; Fang et al., 2019). In addition, increasing attention has been paid to the principle of sustainability, which caters to the CO_2 emission demand of future development (Fang et al., 2018; Fang et al., 2019; Cui et al., 2020; Li et al., 2020; Zhou et al., 2021). For instance, the environmental factors, including the absorptive capacity to sequestrate CO_2 and ecosystem service value, are used to reflect the sustainability principle (Fang et al., 2019; Zhou et al., 2021).

To improve the adaptability, multi-criteria scheme has been proposed. For example, Fang et al. (2019) considered the indicators quantifying the principles of fairness, efficiency, feasibility, and sustainability into an improved ZSG-DEA model to determine the CO_2 emission quotas at the provincial level. Zhou et al. (2021) carried out a study of China's CO_2 emission quotas allocation program design and efficiency evaluation by 2020, which integrated the principles of fairness, efficiency, and sustainability together to construct a comprehensive index based on entropy method.

Generally, considering multiple principles to explore a compromise scheme is increasingly recognized. Thus, this paper aims to explore the CO_2 emission quotas allocation of cities to achieve the multi-criteria objective.

The commonly used allocation methods to build multi-criteria allocation schemes can be concluded as indicator approach, DEA, nonlinear programming models, game theory, and hybrid or other approaches. The indicator approach, especially the composite index, has been widely used to respond to different principles. For example, Yi et al. (2011) simulated the allocation of national emission target by 2020, integrating carbon reduction responsibility, potential and capacity. Similar studies were conducted by Chang et al. (2016), Han et al. (2016), Tang et al. (2019), and Zhou et al. (2021). Besides, many studies also constructed the comprehensive index combining the DEA model (Qin et al., 2017; Zhou et al., 2017; Liu et al., 2018; Kong et al., 2019; Zhou et al., 2019). However, its subjectivity and arbitrariness have been criticized (Fang et al., 2019). For one thing, most of the indicators selected by previous studies are inconsistent, and the differences in natural resources and the environment have been ignored to a certain extent, except for the studies of Fang et al. (2018) and Zhou et al. (2021). The environmental factor, especially carbon absorption, has a significant impact on the ecosystem's carbon cycle, which affects the realization of carbon neutrality. Besides, how to determine the weights for different indicators is still controversial.

DEA and ZSG-DEA models have emerged to solve the problem by focusing on the whole system's efficiency. As a typical optimization method, researchers have proposed various improved DEA models, which provide more innovative ideas and solutions for

CO_2 emission quotas allocation. Similar models can be found in the studies of Zhou et al. (2014), Feng et al. (2015), Wu et al. (2016), An et al. (2017), Momeni et al. (2018), Xie et al. (2019) and Yu et al. (2019). On the basis of the DEA model, THE ZSG-DEA model was developed by reallocating the remaining resources based on the cooperation or competition among DMUs (decision-making units). Wang et al. (2013), Miao et al. (2016), Cucchiella et al. (2018), Cai et al. (2019), Yu et al. (2019), and Fang et al. (2019) used the ZSG-DEA model, selecting different indicators as input and output variables to allocate the CO_2 emission quotas. Besides, Yang et al. (2020) proposed a ZSG-DEA model by improving the iterative approach, which introduces the fairness principle into the efficiency-oriented model to optimize the CO_2 emission reduction scheme for Chinese provinces by 2030. The mechanism of DEA gives priority to the efficiency principle, which may underestimate the effects of other principles. Besides, some studies regarded collaborative carbon abatement as the basis of allocation by game theory (Filar and Gaertner, 1997; Li and Piao, 2013; Zhang et al., 2014). However, the game theory is too complicated to be suitable for the allocation of Chinese cities level. By contrast, the nonlinear optimization model has emerged as another common method, which explores using the multi-objective decision approach for resource allocation. Table 1 describes the use of nonlinear optimization models with their constraint condition, specifically, considering optimization based on fairness principle (Fang et al., 2018), efficiency principle (Li et al., 2018; Ye et al., 2019), and both fairness and efficiency principles (Yang et al., 2019; Ma et al.,2020). Besides, Zhu et al. (2018) proposed a multi-objective decision model incorporating the principles of fairness, efficiency, and feasibility to allocate CO_2 emission quotas to six industries in Guangdong. The environmental Gini coefficient is mainly used to realize fairness optimization, while the optimization of efficiency mostly focuses on maximizing economic benefits and minimizing carbon reduction costs. However, the environmental Gini coefficient minimization model cannot consider historical emissions. This study intends to build CO_2 emission quotas allocation solutions with more consensus on fairness and efficiency. In addition, as increasing guidelines are applied to multi-criteria, most nonlinear optimization models for CO_2 emission quotas allocation need to be improved in defining and reflecting allocation principles other than the principles of fairness and efficiency. Thus, it is of great significance to integrate the feasibility and sustainability principles into the multi-objective decision with carbon intensity reduction targets towards 2030.

Considering the prevalence of the multi-objective decisions approach, which can transform the allocation principles into specific mathematical models with constrained boundary condition, this paper proposes a multi-objective decision model, integrating the principles of fairness, efficiency, sustainability, and feasibility, to formulate the allocation of CO_2 emission quotas among cities in BREC by 2030. Specifically, we put forward three allocation schemes based on fairness, efficiency, and sustainability, respectively. The first allocation scheme is based on the principle of fairness. We construct a composite index integrating different fair indicators, including population, GDP, historical CO_2 emissions, and historically accumulated net CO_2 emission, where the historically cumulative net CO_2 emissions are calculated by deducting the CO_2

sequestration of vegetation. Based on this composite index, we use the entropy method to allocate the emission quotas to each city in BREC. As for the second allocation scheme, we simply take the efficiency principle into consideration and use the ZSG-DEA model to obtain each city's CO_2 emission quotas. The third allocation scheme is based on the sustainability principle and conducted using the proportion of regional carbon sequestration. After receiving three schemes, we further define the CO_2 allocation satisfaction to reflect the feasibility principle. Ultimately, three allocation schemes, as well as the allocation satisfaction (feasibility principle), are integrated into the multi-objective decision model as objective functions. Thus, this multi-objective decision model is proposed to explore the optimal allocation results.

Overall, the contributions of this paper can be described as (1) selecting the cities in BREC as the research object to analyze its CO_2 emission quotas allocation in 2030; (2) integrating the principles of fairness, efficiency, sustainability, and feasibility into a multi-objective decision model; (3) proposing and optimizing the allocation schemes based on the principles of fairness, efficiency, and sustainability to improve the adaptability of schemes; (4) integrating the CO_2 allocation satisfaction for each city to ensure the feasibility of allocation scheme.

Table 1. The summary of multi-objective optimization models.

Research purposes	Optimization objectives	Constraint condition
CO_2 emission quotas allocation for Chinese provinces (Fang et al., 2018)	Minimize the sum of Gini coefficients (accumulated percentage of population, ecological productive land, GDP and fossil energy resources）	Gini coefficient constraint CO_2 emission intensity reduction constraint The restraint of CO_2 emission intensity reduction ratio in different regions:

Allocating CO_2 emission quotas to the Pearl River Delta cities (Li et al., 2018)	The minimization of regional abatement costs The maximization of individual interests	Total emissions constraint The low and up emission limits
CO_2 emission quotas allocation for six industries in Guangdong (Zhu et al 2018)	Efficiency principle: economic benefits maximization Fairness principle: the basic emission right and development performance emission right Feasibility principle: grandfathering	Constraints of physical capital stock Constraints of human capital Constraints of CO_2 emission
Carbon quotas allocation at the provincial level in China (Yang et al., 2019)	Minimize the carbon Gini coefficient Minimize total CO_2 emission reduction cost	
Allocation of SO_2 emission permits among eight key industries in Jilin (Duan et al., 2019)	Maximize regional industrial output Minimize pollutant emissions	Industrial output Pollutant emissions development scale of each industry Industrial restructuring labor resource environmental protection expenditure
CO_2 emission quotas allocation for eight key industries in Guangdong (Ye et al., 2019)	Energy goal: improving emission efficiency Economic goal: reducing abatement cost	Controlling total emissions
Regional coal de-capacity allocation in China (Ma et al., 2020)	Maximize the weighted average efficiency based on DEA model Minimize the Gini coefficients	Total coal capacity constraints Provincial coal capacity constraints Labor restraint

The remainder of this paper is conducted as follows. Section 2 interprets the methods and data sources. Section 3 introduces the CO_2 emission quotas allocation results under single and multi-principles. The sensitivity analysis is provided in Section 4. Section 5 concludes this paper and provides some policy implications.

2. Methodology and data sources

Fig 1. illustrates the schematic of the CO_2 emission quotas allocation adopted by this paper. First, three allocation schemes based on fairness, efficiency, and sustainability are conducted, respectively. Second, we define the CO_2 allocation satisfaction to measure the feasibility principle of the allocation scheme. Finally, a multi-objective model is established to explore the optimal CO_2 emission quotas allocation solution considering the principles of fairness, efficiency, sustainability, and feasibility together. In this section, we begin with the method of allocation scheme based on the fairness principle. Then, we introduce the method of allocation schemes based on the principles of efficiency and sustainability, respectively, following which we explain the measurement of feasibility principle. Section 2.5 presents the multi-objective decision model integrating the principles of fairness, efficiency, sustainability, and feasibility. Finally, this section introduces the data sources.

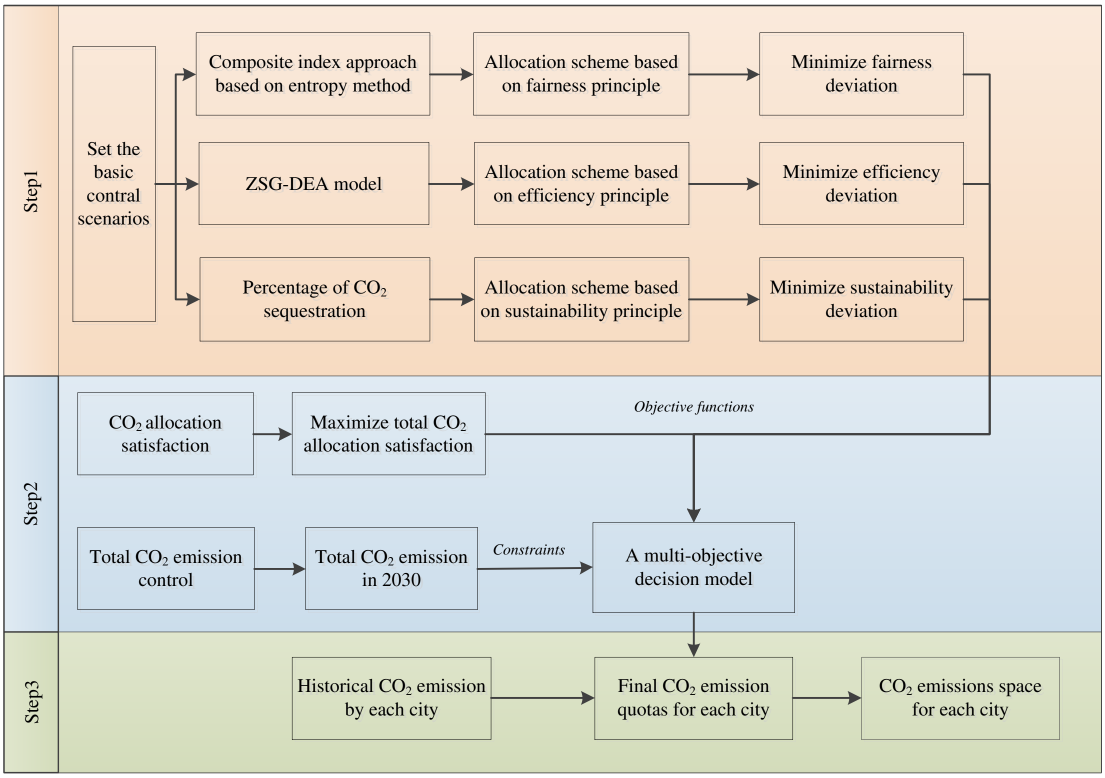

Fig. 1. Schematic of CO_2 emission quotas allocation.

2.1 Allocation scheme based on the fairness principle

This paper intends to build the compromise allocation scheme considering the fairness principle by constructing a composite index. The indicators selected in this paper follow different perspectives of the fairness principle, as shown in Table 2. It should be noted that the accumulated historical net CO_2 emissions express as the accumulated historical CO_2 emission after deducting CO_2 sequestration from 2005 to 2017, which reflects the attention on environmental factors.

Table 2. Four indicators with their criteria and interpretations.

Indicators	Criterion	Interpretation
Population (p_1)	Egalitarianism	All people have equal right to pollute and to be protected from pollution (+).
Accumulated historical net CO_2 emission (p_2)	Polluter pays/Historical responsibility	Reflect that cities with more historical emissions need to take more abatement burdens, calculated from 2005 to 2017 (-).
GDP (p_3)	Economic activity/ Horizontal fairness	Reflect the allocation should be allowed to maintain their standard of living (+).
Historical CO_2 emissions (p_4)	Sovereignty / Grandfathering	All cities have equal right to pollute and to be protected from pollution (+).

To quantify the comprehensive index, we employ the entropy method to determine the weight of each indicator, which has been widely used to build the comprehensive index of CO_2 emission quotas allocation (Feng et al., 2018; Liu et al., 2018; Kong et al.,2019; He and Zhang 2020). The methods are shown as follows:

The following equation can normalize the positive indicator and negative indicator:

$$x_{ij} = \frac{p_{ij} - \min_i p_{ij}}{\max_i p_{ij} - \min_i p_{ij}} \quad (i = 1, \ldots, 30; j = 1, 2, 3, 4) \tag{1}$$

$$x_{ij} = \frac{\max_i p_{ij} - p_{ij}}{\max_i p_{ij} - \min_i p_{ij}} \quad (i = 1, \ldots, 30; j = 1, 2, 3, 4) \tag{2}$$

where p_{ij} is the value of indicator j of the city; $\max_i p_{ij}$ and $\min_i p_{ij}$ are the maximum and minimum values of cities, respectively; x_{ij} is the normalized value of p_{ij}.

Then, we calculate the entropy value of indicator j using equations (3) and (4).

$$y_{ij} = \frac{x_{ij}}{\sum_{i=1}^{44} x_{ij}} \quad (i = 1, \ldots, 44; j = 1, 2, 3, 4) \tag{3}$$

$$m_j = -(\ln 44)^{-1} \sum_{i=1}^{44} [(y_{ij} \times \ln (y_{ij})] \quad (i = 1, \ldots, 44; j = 1, 2, 3, 4) \tag{4}$$

where y_{ij} is the share of indicator j of city i in the sum of indicator j of all cities; m_j is the entropy of indicator j. And if $y_{ij} = 0$, then $\ln (y_{ij}) = 0$.

Next, we calculate the weight of each indicator and construct a comprehensive index. The weight of indicator j (r_j) can be calculated using equation (5).

$$r_j = \frac{1 - m_j}{\sum_j (1 - m_j)} \quad (j = 1, 2, 3, 4) \tag{5}$$

The comprehensive index (h_i) can be built by equation (6).

$$h_i = r_1 y_{i1} + r_2 y_{i2} + r_3 y_{i3} + r_4 y_{i4} \quad (i = 1, \ldots, 44) \tag{6}$$

Finally, we calculate the weight for city i by equation (7).

$$w_i = \frac{h_i}{\sum_{i=1}^{44} h_i} \quad (i = 1, \ldots, 44) \tag{7}$$

After the comprehensive index of each city was obtained, we calculate the CO_2 emission quotas that each city should be allocated, represented as the equation (8).

$$C_{fi} = w_i \times C_{2030} \quad (i = 1, \ldots, 44) \tag{8}$$

where C_{fi} is the CO_2 emission quotas of the city i allocated based on the fairness principle, C_{2030} is the total CO_2 emissions in BREC in 2030.

The optimization of fairness requires the allocation results to be as close as possible to C_{fi} with the constraints. We develop the fairness degree function of CO_2 emission allocation as $F_1 = \sum_{i=1}^{n} (C_i - C_{fi})^2$. If $F_1 = 0$, the allocation results are consistent with the fairness scheme. The objective function of fairness is expressed as:

$$min\ F_1 = \sum_{i=1}^{n} (C_i - C_{fi})^2 \tag{9}$$

2.2 The allocation scheme based on the efficiency principle

This paper applies the ZSG-DEA model to search for optimal CO_2 emissions with all cities on the DEA efficiency frontier. As the total CO_2 emissions in 2030 remain constant, the ZSG-DEA model can obtain the optimal allocation results by reallocating the redundant CO_2 emission among all cities. And it has been widely used to allocate CO_2 emission quotas, for example, taking CO_2 emissions as undesirable output, Wang et al.(2013) and Miao et al. (2016) adopted output-oriented ZSG-DEA model to formulate the allocation of CO_2 emission quotas. Conversely, the input-oriented ZSG-DEA models are also developed considering CO_2 emission as an input variable to formulate the allocation of CO_2 emission quotas (Cai et al.,2019; Fang et al.,2019; Yu et al.,2019). We adopt an input-oriented ZSG-DEA model to obtain optimal CO_2 emissions for each city. We consider energy consumption, labor, and GDP as three output variables and CO_2 emissions as an input variable, as shown in Table 3. The initial CO_2 emissions for each city in 2030 are obtained by the proportion of CO_2 emissions in 2017, where is called grandfathering.

Table 3. Input and output variables of the ZSG-DEA model.

	Variable	Explanation
Inputs	Labor	The number of staffs in each city
	Energy	The energy consumption in each city, with being computed into coal equivalent
	GDP	GDP of each city, with all the values being converted into 2005 constant price
Output	CO_2 emissions	CO_2 emissions in each city in 2030, calculated by grandfathering

The input-oriented ZSG-DEA model is expressed as:

$$\begin{cases} \min \varphi_0 \\ \sum_{i=1}^{44} \lambda_i C_{gi} \left[1 + \frac{C_0(1-\varphi_0)}{\sum_{i \neq 0} C_{gi}}\right] \leq \varphi_0 C_0 \\ \sum_{i=1}^{44} \lambda_i E_i \geq E_0 \\ \sum_{i=1}^{44} \lambda_i L_i \geq L_0 \\ \sum_{i=1}^{44} \lambda_i Y_i \geq Y_0 \\ \sum_{i=1}^{44} \lambda_i = 1 \\ \lambda_i \geq 0 \ (i = 1, \ldots, 44) \end{cases} \tag{10}$$

where φ_0 is the efficiency value of the DMU being evaluated; C_0, Y_0, L_0, E_0, A_0 are the values of the corresponding variables of the DMU being evaluated; E_i, L_i, Y_i are the energy consumption, labor and GDP of the i*th* DMU in 2030, respectively. λ_i is the share of the i*th* DMU; C_{gi} is the actual CO_2 emission of the *ith* DMU in 2030.

For DMU_k $(k = 1, \ldots, 44)$ with an inefficient DEA efficiency of φ_k and an initial emission quota of C_k must reduce its CO_2 emissions by $C_k (1 - \varphi_k)$. The remaining DMUs must increase their CO_2 emissions by $C_i \times \frac{C_k (1-\varphi_k)}{\sum_{i \neq k} C_I}$ (Fang et al., 2019).

Finally, we can obtain the optimal CO_2 emission of each city, expressed by C_{ei}.

After obtaining each city's optimal CO_2 emissions (C_{ei}), the efficiency objective of CO_2 emission allocation is built as $F_2 = \sum_{i=1}^{n}(C_i - C_{ei})^2$. If $F_2 = 0$, the allocation results follow the optimal efficiency scheme. The optimal solution is built to minimize $\sum_{i=1}^{n}(C_i - C_{ei})^2$, which can be described by the following equation:

$$min\ F_2 = \sum_{i=1}^{n}(C_i - C_{ei})^2 \tag{11}$$

2.3 The allocation scheme based on sustainability principle

When allocating CO_2 emission quotas, increasing attention has been paid to the principle of sustainability. Fang et al. (2018) used urbanization rate, the proportion of the tertiary industry, and forest coverage rate to represent the sustainability principle of social, economic, and environmental dimensions, respectively. A similar approach was used by Li et al. (2020), who applied forest coverage rate, population growth rate, and GDP growth rate as sustainability indicators. Zhou et al. (2021) adopted ecosystem service value as the indicator to reflect the sustainability principle.

This paper uses carbon sequestration capacity as the sustainability principle of CO_2 emission quotas allocation. We can calculate the CO_2 emission quotas based on the CO_2 sequestration capacity of each city, as shown in the following equation.

$$C_{si} = \frac{S_i}{\sum_{i=1}^{44} S_i} \times C_{2030} \tag{12}$$

where C_{si} is CO_2 emission quotas of city i, allocated based on the sustainability principle. S_i is CO_2 sequestration of city i in 2017.

Similarly, the sustainability objective of CO_2 emission allocation can be built as $F_2 = \sum_{i=1}^{n}(C_i - C_{si})^2$. If $F_2 = 0$, the allocation results are equal to C_{si} for each city. The objective function is shown as:

$$min\ F_3 = \sum_{i=1}^{n}(C_i - C_{si})^2 \tag{13}$$

2.4 The feasibility of CO_2 emission quotas allocation

The feasibility principle means that the allocation of CO_2 emission quotas should maintain production consistency, which is easy to be accepted and implemented (Zhu et al., 2018). This paper uses the "CO_2 allocation satisfaction" to estimate the feasibility of CO_2 emission quotas allocation. For each city, if the allocated CO_2 emission quotas are larger than the CO_2 emission expectation, the degree of satisfaction is 1; by contraries, if the minimum CO_2 emission expectation is not met, the satisfaction degree is 0. The CO_2 allocation satisfaction function degree is described as follows:

$$U_i = \begin{cases} \frac{C_i - C_i^{min}}{C_i^{max} - C_i^{min}} & C_i^{max} < C_i < C_i^{min} \\ 1 & C_i \geq C_i^{max} \\ 0 & C_i \leq C_i^{min} \end{cases} \tag{14}$$

where C_i^{max} and C_i^{min} are the upper and lower limits of CO_2 emission feasibility interval for city *i*, respectively. Although grandfathering has less impact on production and fewer political barriers (Zetterberg et al., 2012; Zhu et al., 2018), it has been criticized for its limitations on punishing efficient carbon firms while rewarding carbon-intensive firms (Zhou and Wang, 2016). Feng et al. (2018) proposed a weighted voting model to quantify the voting rights of each city to select the CO_2 allocation schemes based on population, GDP, and historical emissions, which are intuitive and clear. Besides, Dong et al. (2018) analyzed the allocation schemes based on historical emissions, population, and per capita GDP (pays ability egalitarian), then optimized the CO_2 emission quotas based on a modified fixed cost allocation model. Inspired by the work of Dong et al. (2018) and Feng et al. (2018), this paper analyzes the three scenarios (population, GDP, and historical emissions) to determine the feasibility of CO_2 emissions quotas allocation as well as allocation satisfaction interval, presented as:

$$C_i^{max} = max\ (C_{popi}, C_{gdpi}, C_{gi}) \tag{15}$$

$$C_i^{min} = min\ (C_{popi}, C_{gdpi}, C_{gi}) \tag{16}$$

where C_{popi}, C_{gdpi} and C_{gi} are allocation results based on population, GDP, and historical emissions. The year 2017 is considered as a reference.

As for the feasibility of CO_2 emission quotas allocation, there is no doubt that the higher CO_2 allocation satisfaction, the easier it to accept and implement. And the most acceptable scheme requires maximizing the satisfaction of each city. However, it is impossible for all of the cities to reach their maximum CO_2 allocation satisfaction. We aim at maximizing the sum of minimum CO_2 allocation satisfaction for all cities, described as:

$$max\, F_4 = \sum_{i=1}^{n} U_i \tag{17}$$

2.5 The multi-objective CO_2 emission quotas allocation

As stated in Section 2.1-2.4, the multi-objective CO_2 emission quotas allocation model can be described as follows:

$$\begin{cases} \min F_1 = \sum_{i=1}^{n}(C_i - C_{fi})^2 \\ \min F_2 = \sum_{i=1}^{n}(C_i - C_{ei})^2 \\ min\, F_3 = \sum_{i=1}^{n}(C_i - C_{si})^2 \\ max\, F_4 = \sum_{i=1}^{n} U_i \\ \sum_{i=1}^{n} C_i = C_{2030} \end{cases} \tag{18}$$

The proposed model (18) is a multi-objective model. We can convert multiple goals into a single-objective model to seek the optimal value. Although equation (17) maximizes the total minimum CO_2 allocation satisfaction, it may be based on sacrificing the satisfaction of some cities. Considering the feasibility of allocation for each city, equation (17) is converted by the following constraint:

$$1 \geq U_i \geq a \tag{19}$$

where α is the minimum satisfaction acceptable to each city.

The original model (18) can be converted into the following form.

$$\begin{cases} \min F = b_1 * F_1 + b_2 * F_2 + b_3 * F_3 \\ \sum_{i=1}^{n} C_i = C_{2030} \\ 1 \geq U_i \geq a \\ b_1 + b_2 + b_3 = 1 \\ b_1 > 0, b_2 > 0, b_3 > 0 \end{cases} \tag{20}$$

where b_1, b_2 and b_3 are the weights of fairness, efficiency, and sustainability principles.

2.6 Data sources

This paper allocates the CO_2 emission quotas for 44 cities in BREC. GDP is collected from China Statistical Yearbook (China National Bureau of Statistics, 2006-2018a), Hebei Statistical Yearbook (Hebei Provincial Bureau of Statistics, 2006-2018), Shandong Statistical Yearbook (Shandong Provincial Bureau of Statistics, 2006-2018), and Liaoning Statistical Yearbook (Liaoning Provincial Bureau of Statistics, 2006-2018). The population and labor are from the China City Statistical Yearbook (China National Bureau of Statistics, 2006-2018b).

Original data of provincial energy consumption in this paper is collected from the China Energy Statistical Yearbook (China National Bureau of Statistics, 2006-2018c). The historical CO_2 emissions and CO_2 sequestration capacity are collected from the work of Chen et al. (2020). More information about the calculation of CO_2 emissions at the city level can be found in the study of Chen et al. (2020). To ensure that the sum of CO_2 emissions in all cities are in line with the provincial total CO_2 emissions, this paper makes correction about the CO_2 emissions in each city by dividing a correction factor, which is calculated as the ratio of total CO_2 emissions in all cities to the provincial CO_2 emissions. The provincial CO_2 emissions are calculated from fossil energy consumption. Based on the city's CO_2 emissions, we calculate the standard coal consumption of each city by dividing the CO_2 emissions by the emission coefficient.

Since we do the emissions allocation in 2030, the total CO_2 emissions in BREC in 2030 are required. The China's emission reduction target is to reduce the carbon intensity by 60%-65% in 2030, compared with 2005. We set the same reduction target for BERC and assume that the emission target of 60% in 2030 will be realized. The total CO_2 emissions in BREC in 2030 (C_{2030}) can be calculated as $C_{2030} = (1 - 60\%) \times CI_{2005}GDP_{2030}$, where CI_{2005} is the CO_2 intensity in 2005 and GDP_{2030} is the GDP in 2030.

As illustrated in the methods, the population, labor, GDP, and energy consumption in this paper should be predicted to 2030. We first calculate the total population of each city in 2030 based on the annual average growth rate of population for each city from 2005 to 2017. According to the provincial development planning, the populations in Beijing, Tianjin, Hebei, Shandong, and Liaoning in 2030 are 2300, 2150, 7910, 4500, and 10667 ten thousand, respectively. To ensure that the sum of the population of cities in each province is consistent with the provincial predictions from provincial development planning, we correct the estimated population of each city in 2030 using the reference data of the total provincial population. The initial estimate data is divided by a correction factor, defined as the ratio of the sum of population in all cities to the provincial predictions. Based on the population forecast, we multiply the population by the share of the labor force in the population of each city to calculate the labor, which is calculated by the proportion of employees to the population in 2017.

To estimate the GDP of each city, we first forecast provincial GDP using the annual average growth rate of GDP for each province from 2005 to 2017. According to Energy Outlook 2050 (2019), China's GDP growth rate will be approximately 6.7% before

2020 and approximately 5% between 2021 and 2035. Based on the related growth rate of China's GDP, we predict China's GDP until 2030. Then using China's GDP, we correct the provincial GDP by a correction factor, which is calculated by the ratio of the sum of GDP in all provinces to the national predictions. All the values are converted into 2005 constant price. After the provincial GDP is obtained, we use the same prediction method with population to estimate the GDP of each city in 2030. Following the same method, we estimate the energy consumption of each city in 2030. We assume that China's total energy consumption is 6 billion tons of standard coal for reference. The reference data is from the energy production and consumption revolution strategy (2016-2030).

2.7 Scenario setting

We attempt to analyze the CO_2 emission quotas allocation results under various decision preferences of decision-makers. Four scenarios include equal weights, preferring fairness, preferring efficiency, preferring sustainability. b_1, b_2 and b_3 in Table 4 are the weights of the allocation principles of fairness, efficiency, and sustainability, respectively.

Table 4. The weights in four cases.

Weight	b_1	b_2	b_3
Case 1: equal weights	1/3	1/3	1/3
Case 2: preferring fairness	0.6	0.2	0.2
Case 3: preferring efficiency	0.2	0.6	0.2
Case 4: preferring sustainability	0.2	0.2	0.6

3. Results

3.1 Allocation results based on fairness principle

According to the interpretation of fair CO_2 emission quotas allocation in previous literature, this paper uses four indicators selected from different perspectives of fairness principle to obtain the allocation scheme based on fairness, including population, GDP, historical cumulative net CO_2 emissions, and historical carbon emission. We calculated the weights of these four indicators using the entropy method. As shown in Table 5, the weight of GDP is the largest, followed by population and historical CO_2 emission, while historical cumulative net CO_2 emissions appears the minimal importance. The environmental Gini coefficient based on population is 0.115 less than 0.2, which means that the allocation results are absolutely fair.

Table 5. The weights of indicators and fairness test of the CO_2 emission allocation scheme

Principle	Fairness				Fairness test
Indicator	Population	GDP	Historical cumulative net carbon emissions	Historical carbon emissions	G_{pop}
Weight	30.19%	44.92%	5.08%	19.81 %	0.115

G_{pop} is the environmental Gini coefficient based on population, which is calculated by trapezoidal area method referring to the formula of Kong et al (2019).

Fig. 2 displays the results of CO_2 emission quotas allocation based on fairness in 2030. The regions with higher GDP, population, and historical CO_2 emission, tend to obtain more CO_2 emission quotas, even though their historical responsibility may be larger, as the weight of historical cumulative net carbon emissions is the smallest. For example, Beijing, Tianjin, Qingdao, and Shijiazhuang, are the four cities having the highest emission quotas allocation, accounting for more than 25.10% of the total. The share of CO_2 emission quotas in fourteen cities are less than 1.0 % in 2030. Among them, Laiwu and Fuxin enjoy the lowest CO_2 emission quotas allocation proportions of 0.31% and

0.38%, respectively.

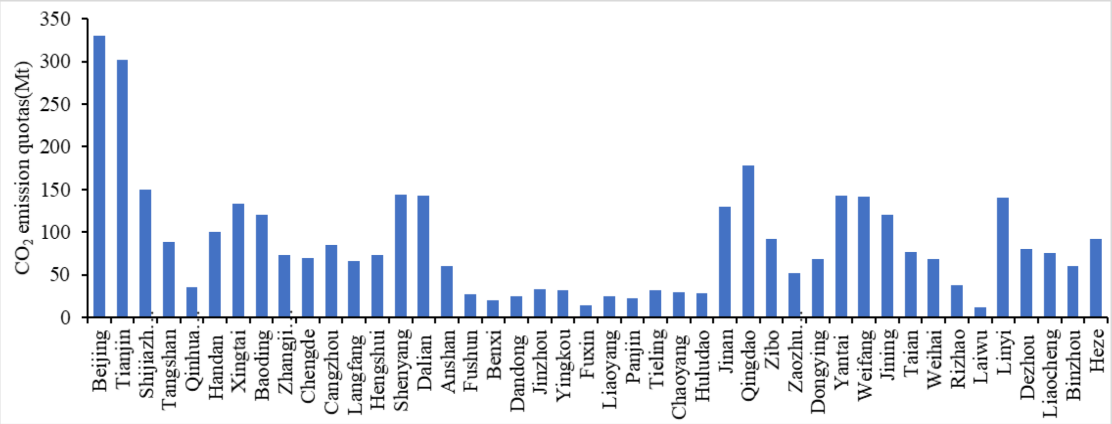

Fig. 2. The CO_2 emissions quotas allocation based on fairness in 2030.

3.2 Allocation results based on efficiency principle

This paper uses the ZSG-DEA model to attain each city's CO_2 emission quotas based on the efficiency principle. Fig. 3 depicts the DEA efficiency changes for each allocation. The allocation efficiency using the ZSG-DEA model in twenty-one cities is less than the average initial allocation efficiency of 0.89. Only five out of 44 cities have reached the DEA frontier. Tangshan experiences the lowest initial allocation efficiency of 0.8. After the first reallocation, tremendous changes are found, in which the DEA efficiency of all cities is above 0.97 and the average efficiency increases to 0.99, even though no additional cities achieve optimal DEA efficiency. With the completion of the second reallocation, twelve cities have the efficiency of 1, while the remaining cities are close to DEA frontier. Ultimately, all the cities obtain the optimal efficiency of 1.

Fig. 4 describes the initial CO_2 emission and reallocation results for each city. The initial CO_2 emission is completely dependent on each city's historical emissions. We can find that CO_2 emission quotas increase in fifteen cities (e.g., Tianjin, Beijing, Dalian). Conversely, a decrease in the CO_2 emission quotas is witnessed in nineteen cities, including Tangshan, Shijiazhuang, Cangzhou, and Langfang. Besides, the CO_2 emission quotas in Jining, Taian, Rizhao, Linyi, Liaocheng, Zaozhaung, Shenyang, and Xingtai remain stable. The reallocation results indicate that Tianjin reports the largest CO_2 emission quotas with the value of 302 million tons (Mt), followed by Beijing (183 Mt), Tangshan (155 Mt), Shijiazhuang (144 Mt), and Weifang (138 Mt). While Laiwu, Dandong, Benxi, Fuxin, and Rizhao experience the smallest, with the value of 13 Mt, 34 Mt, 36 Mt, 37 Mt, and 38 Mt, respectively.

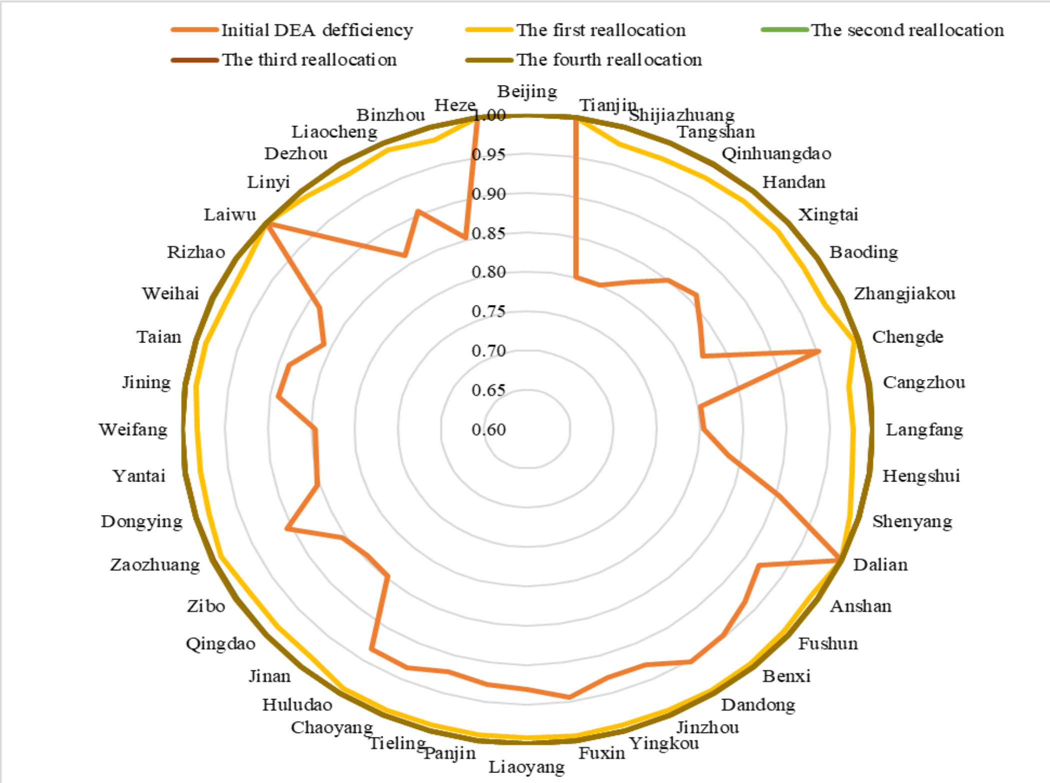

Fig. 3. The DEA efficiency of initial allocation and reallocation.

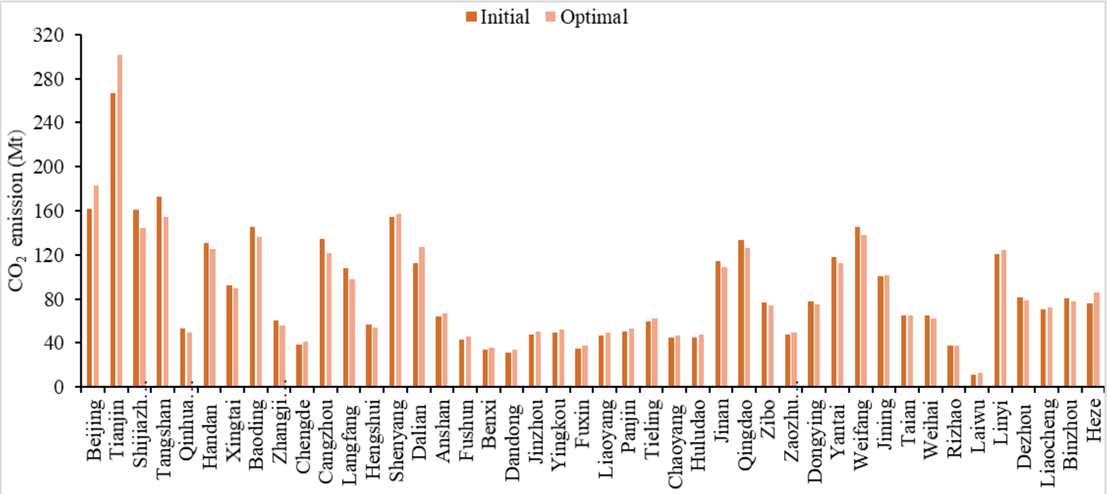

Fig. 4. The initial CO_2 emission and its reallocation results.

3.3 Allocation results based on sustainability principle

Fig. 5 compares each city's CO_2 emission with their CO_2 sequestration and measures the environment pressure defined as CO_2 emission minus CO_2 sequestration in 2017. It can be found that the majority of cities have produced excessive CO_2 emissions, and the CO_2 sequestration of BREC is 776.45 Mt in 2017, which is far lower than the CO_2 emissions (1485 Mt) in the same period. Thus, it is difficult to achieve carbon neutralization only through the absorption effect of the environment on CO_2. Meanwhile, negative environment pressure can be found in Chengde, Zhangjiakou, Dandong, Chaoyang, Fushun, Benxi, and Dalian, whose CO_2 sequestration has already exceeded their CO_2 emission by 41Mt, 31 Mt, 21 Mt, 10 Mt, 7 Mt, 6 Mt, 5 Mt, respectively. Fuxin, Tieling, and Huludao have a slight surplus of CO_2 sequestration, which are approaching to the breakeven point (less than 0.30 Mt). By contrast, Laiwu, Rizhao, Jinzhou, Yingkou, Qinhuangdao, Weihai, and Liaoyang are under relatively low environmental pressure (less than 10.0 Mt). The remaining cities, including Beijing, Tianjin, and Shijiazhuang, are facing higher environmental pressure with a massive shortage of CO_2 sequestration (more than 10.0 Mt).

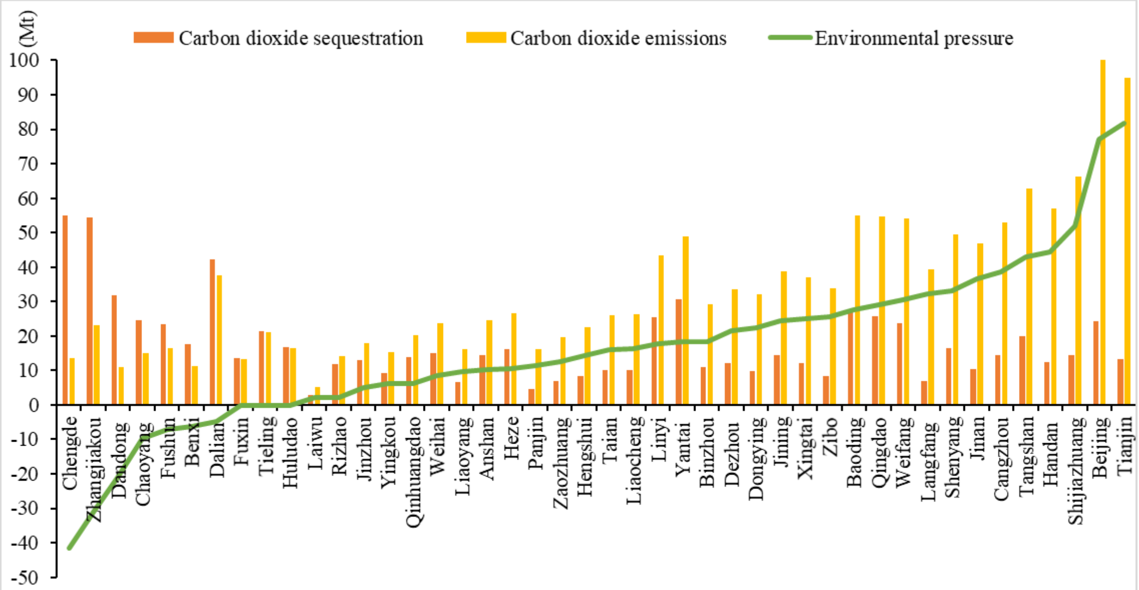

Fig. 5. The comparison of CO_2 emission of each city with CO_2 sequestration and their environment pressure.

The CO_2 emissions quotas allocation based on sustainability in 2030 are shown in Fig. 6. The cities with higher carbon sequestration capacity will be allocated with larger shares of emission quotas. Chengde, Zhajiakou and Dalian, account for the largest proportion with 7.1 %, 7.0%, and 5.4%, respectively. The emissions quotas in five cities, including Laiwu, Panjin, Liaoyang, Langfang, and Zaozhuang, stay at the lowest level and account for less than 1% of the total in 2030.

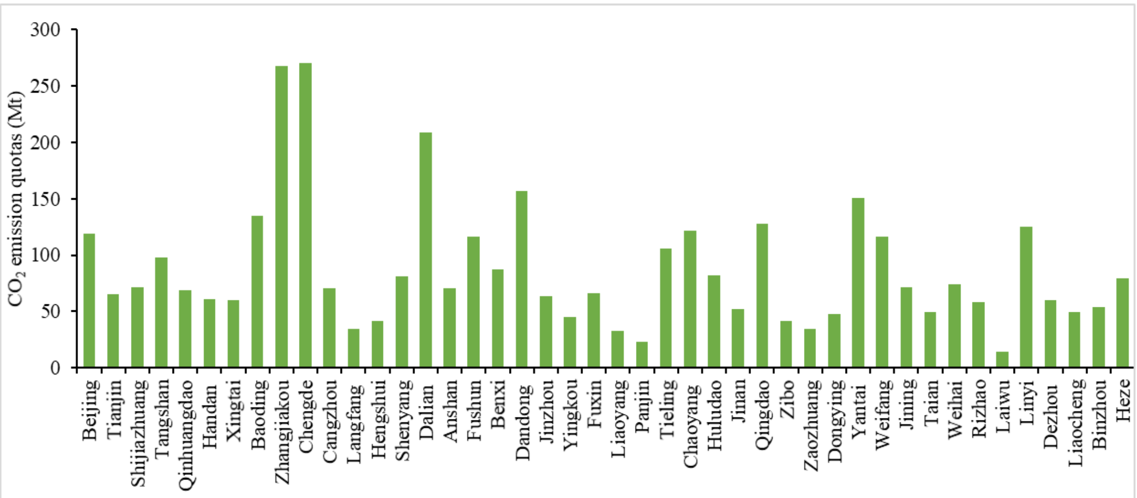

Fig. 6. The CO_2 emissions quotas allocation based on sustainability in 2030.

3.4 The feasibility interval of CO_2 emission quotas

Different from the principles of fairness, efficiency, and sustainability, this paper defines the CO_2 allocation satisfaction to measure the feasibility principle. Specifically, inspired by Feng et al. (2018), who provided three allocation schemes, including population-based, GDP-based and historical emissions-based, for each region to select its incline one, we analyze the above three scenarios to determine the allocation interval. Although there is no allocation scheme that can satisfy the favor of all cities, it is deemed as better to obtain more emission quotas (Feng et al., 2018; Xie et al.,2019). Therefore, each city tends to choose the option that is most beneficial to them. Table 6 presents the allocation selected by each city, and the CO_2 allocation satisfaction interval is also given. The allocation based on GDP is dominant in fifteen cities, such as Beijing, Tianjin, and Xingtai. There are sixteen cities, who choose the allocation scheme based on historical CO_2 emission, classified into the second echelon, while the population-based allocation scheme contributes the most to the remaining thirteen cities. As for the satisfaction interval span, the gap between the maximum and minimum CO_2 emissions of Beijing is the largest (287 Mt), followed by Tianjin (220 Mt), Tangshan (144 Mt), Baoding (142 Mt), and Handan (133 Mt). The differences between upper and lower bounds of CO_2 allocation satisfaction interval in Laiwu, Rizhao, Benxi, Anshan, Dongying, Fushun, Yingkou, Zhangjiakou, and Zaozhuang are less than 20 Mt. Among them, those of Laiwu and Rizhao are 9 and 10 Mt, respectively.

Table 6. The allocation schemes selected by each city (Unit: Mt).

Cities	Selected schemes	Maximum	Minimum	Interval span

		emissions	emissions	
Beijing	GDP	449	162	287
Tianjin	GDP	385	165	220
Shijiazhuang	Historical emission	161	132	29
Tangshan	Historical emission	173	28	144
Qinhuangdao	Historical emission	53	28	25
Handan	Population	166	33	133
Xingtai	GDP	148	93	55
Baoding	Population	190	48	142
Zhangjiakou	GDP	78	60	17
Chengde	GDP	89	38	51
Cangzhou	Historical emission	135	33	102
Langfang	Historical emission	108	46	62
Hengshui	GDP	85	57	28
Shenyang	Historical emission	154	116	38
Dalian	GDP	180	94	86
Anshan	GDP	67	54	13
Fushun	Historical emission	43	26	17
Benxi	Historical emission	34	23	10
Dandong	Population	37	23	15
Jinzhou	Historical emission	48	26	22
Yingkou	Historical emission	49	32	17
Fuxin	Historical emission	35	8	27
Liaoyang	Historical emission	47	24	23
Panjin	Historical emission	51	21	30
Tieling	Historical emission	60	17	42
Chaoyang	Population	53	15	38
Huludao	Historical emission	45	19	26
Jinan	GDP	151	101	50
Qingdao	GDP	221	127	94
Zibo	GDP	117	68	48
Zaozhuang	Population	66	48	18
Dongying	GDP	100	31	69
Yantai	GDP	173	103	70
Weifang	Population	148	123	25
Jining	Population	139	101	38
Taian	Population	90	65	25
Weihai	GDP	96	40	56
Rizhao	Population	48	38	10
Laiwu	GDP	21	11	9
Linyi	Population	182	104	77
Dezhou	Population	94	70	23
Liaocheng	Population	100	60	40
Binzhou	Historical emission	81	55	26

Heze	Population	160	44	116
Total	-	5108	2614	-

3.5 The comparison of allocation results based on single principle

Fig. 6 delineates the contributions of the principles of fairness, efficiency, and sustainability to each city. Generally, there are both conflicts and agreements between the principles of fairness, efficiency, and sustainability. The fairness principle is gained prominence in eleven cities, including Beijing, Xingtai, Tianjin, Jinan, Zibo, Qingdao, and Shijiazhuang, whose proportion of allocation results based on the fairness principle is the largest compared with the other two principles. In the case of Beijing, for example, results indicate that the proportion of fairness has reached 52.2%. Eleven cities (e.g., Langfang, Tangshan, Tianjin, Shenyang) have the advantage of reflecting the efficiency principle, many of which are located in Hebei and Liaoning. The sustainability principle is dominated in thirteen cities (e.g., Dandong, Chengde, Zhangjiakou, Fushun, Benxi), especially in Chengde, the allocation proportion based on sustainability is 71.0%. Additionally, the agreements exist in the remaining ten cities, in which the principles contribute similarly. For example, the proportion of fairness, efficiency, and sustainability principles in Linyi is 35.9%, 32.0%, 32.1%.

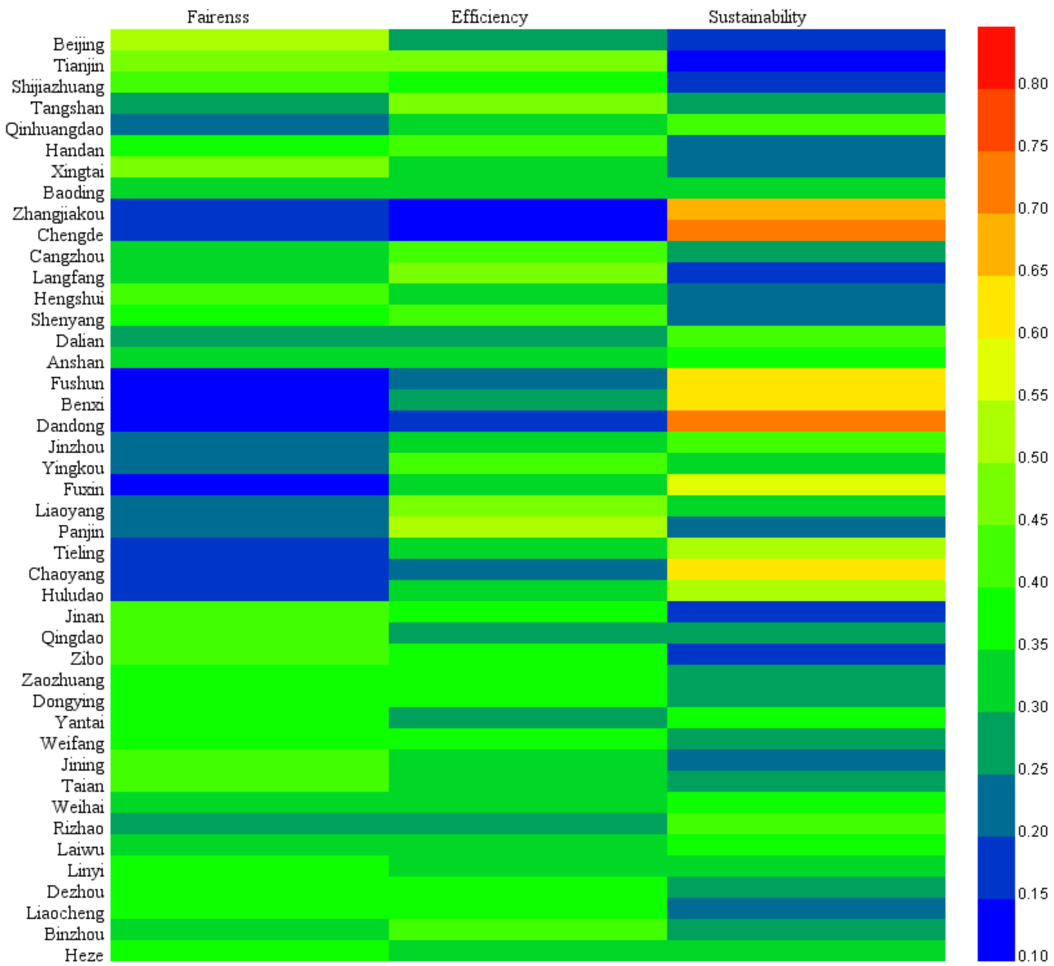

Fig. 6. The contribution of fairness, efficiency and sustainability principles to each city.

We further calculate the satisfaction of single principle-based allocation scheme using Eq (14)-(16). As shown in Fig. 7, the average of CO_2 allocation satisfaction based on the efficiency principle is the largest (0.53), followed by the principles of sustainability (0.44) and fairness (0.40). Thus, the allocation scheme based on the efficiency principle is the most feasible one. However, there are thirteen cities with low satisfaction (less than 0.2), among which the CO_2 allocation satisfaction in six cities is equal to 0. Only eight cities' satisfaction is lower than 0.2 in the fairness allocation scheme. Furthermore, this situation in the allocation scheme based on sustainability appears even worse than the principles of fairness and efficiency, which emerges as eighteen cities have low CO_2 allocation satisfaction, with which less than 0.1. The standard variance of CO_2

allocation satisfaction is the smallest in the fairness allocation scheme (0.12) among the three allocation schemes.

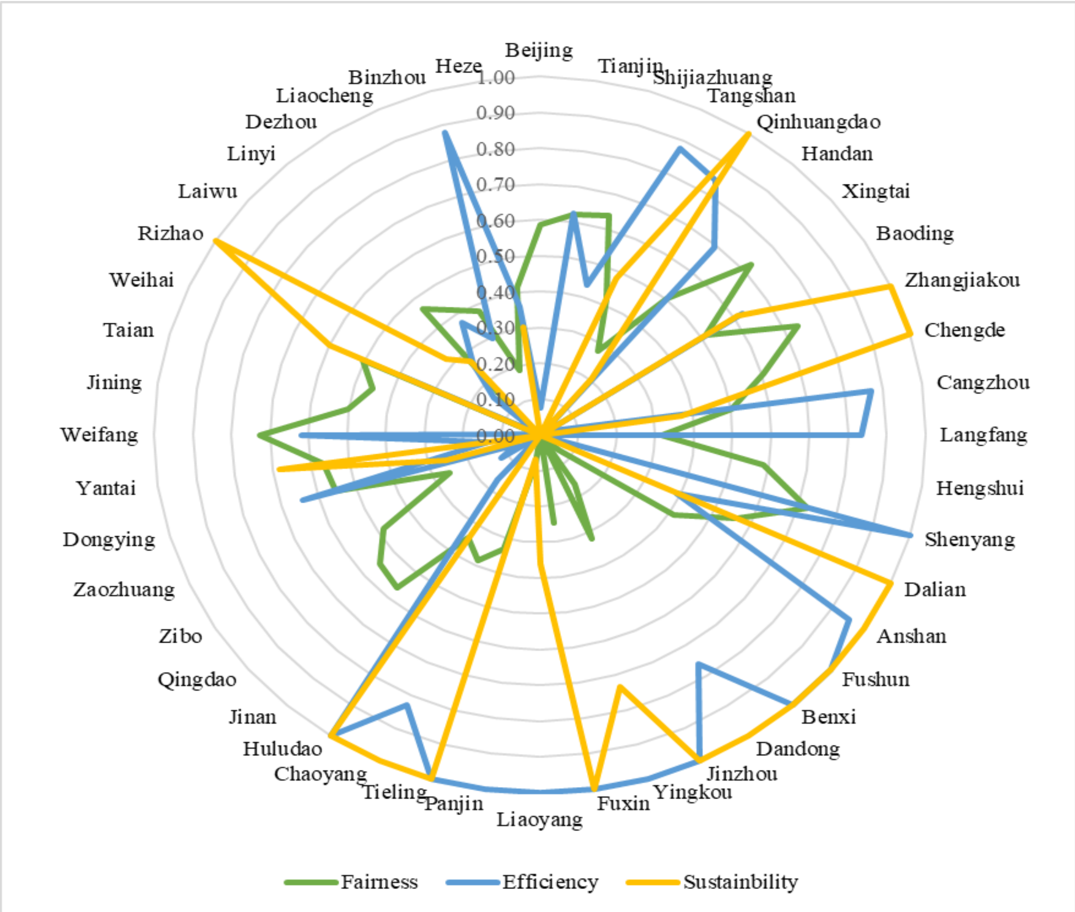

Fig. 7. The satisfaction of CO_2 allocation of cities by based on each principle.

3.6 Multi-objective CO_2 quotas allocation results

In order to improve the allocation results based on single principle, this paper proposes a multi-objective CO_2 emission quotas allocation model. The results of different cases are reported in Table 7. The minimum CO_2 allocation satisfaction a=0.3 is set as the baseline scenario. The CO_2 emission quotas in seventeen cities, such as Shijiazhuang, Chaoyang, Huludao, Jinan, and Liaocheng, are approximately equal in different cases. We also find that the satisfaction of those cities is close to the upper and lower limits of constraints, which means the CO_2 allocation satisfaction constraint decides their allocation results. Different characteristics are shown in the remaining cities. For example, Dalian obtains the largest CO_2 emission quotas under Case 4 (preferring sustainability) with 180 Mt. In comparison, the lowest one is case 3 (preferring efficiency) with 143 Mt. Beijing is allocated with the highest CO_2 emission quotas in Case 2 (preferring fairness) with 260 Mt. Emission quotas obtained by Beijing are the same in remaining cases. For Tianjin, the allocation results in Cases 1 and 4 are equal to 231 Mt, AND the largest quota is from Case 2 (255 Mt), followed by Case 3 (251Mt). In Case 1 (equal weights), Beijing, Tianjin, Dalian, Shijiazhuang, Yantai, Weifang, and Linyi enjoy the largest CO_2 emission quotas, 1180 Mt in total, and accounting for 31%. Compared with the initial CO_2 emissions obtained by grandfathering, the final results under the case of equal weights indicate that fifteen out of the 44 cities are found to cut down their CO_2 emission quotas, including Langfang, Tangshan, and Cangzhou, while ten cities (Qinhuangdao, Anshan, Fushun, and Benxi) remain stable and the remaining nineteen cities such as Beijing, Qingdao, and Yantai, experience the increase of emission quotas.

Table 7. The CO_2 emission quotas allocation results in 2030 under various decision preferences (Unit: Mt).

Cities	Initial CO_2 emissions (grandfathering)	Case 1: equal weights	Case 2: preferring fairness	Case 3: preferring efficiency	Case 4: preferring sustainability
Beijing	162	248	260	248	248
Tianjin	267	231	255	251	231
Shijiazhuang	161	140	140	140	140
Tangshan	173	115	105	126	109
Qinhuangdao	53	52	46	47	53
Handan	131	96	98	103	84
Xingtai	93	109	111	109	109

Baoding	145	132	128	129	134
Zhangjiakou	60	78	78	78	78
Chengde	38	89	89	89	89
Cangzhou	135	93	90	100	86
Langfang	108	67	67	75	65
Hengshui	57	65	65	65	65
Shenyang	154	128	135	136	128
Dalian	113	160	154	143	180
Anshan	64	67	64	62	67
Fushun	43	43	43	43	43
Benxi	34	34	34	34	34
Dandong	31	37	37	37	37
Jinzhou	48	48	44	46	48
Yingkou	49	44	40	43	46
Fuxin	35	35	30	35	35
Liaoyang	47	36	32	37	36
Panjin	51	34	30	37	31
Tieling	60	60	53	60	60
Chaoyang	45	53	53	53	53
Huludao	45	45	44	45	45
Jinan	114	116	116	116	116
Qingdao	133	155	159	155	155
Zibo	77	83	83	83	83
Zaozhuang	48	53	53	53	53
Dongying	78	65	67	65	60
Yantai	118	136	139	124	144
Weifang	145	133	136	131	130
Jining	101	112	112	112	112
Taian	65	72	72	72	72
Weihai	65	69	69	62	73
Rizhao	38	45	43	41	48
Laiwu	11	14	14	14	16
Linyi	121	131	135	127	130
Dezhou	81	77	77	77	77
Liaocheng	71	72	72	72	72
Binzhou	81	65	63	66	63
Heze	76	87	90	82	85

Table 7 shows that Case 2 is beneficial to Beijing, Tianjin, Dongying, Weifang, Linyi, and Heze, in which they obtain the largest emission quotas among the four cases. Conversely, it is not beneficial to Tangshan, Qinhuangdao, Jinzhou, Yingkou. Some cities such as Tangshan, Handan, Cangzhou, Shenyang, Liaoyang, and Panjin prefer

Case 3, while Qinhuangdao, Baoding, Dalian, and Yantai incline to choose Case 4.

Fig. 8 displays the sum of CO_2 allocation satisfaction of 44 cities with different decision cases. The greatest CO_2 allocation satisfaction is Case 4 with 25.58. The following are Cases 1 and 3, which are 25.12 and 24.07, respectively, while the lowest one is Case 2 with 23.72. Therefore, the allocation preferring sustainability is the most feasible among the four cases.

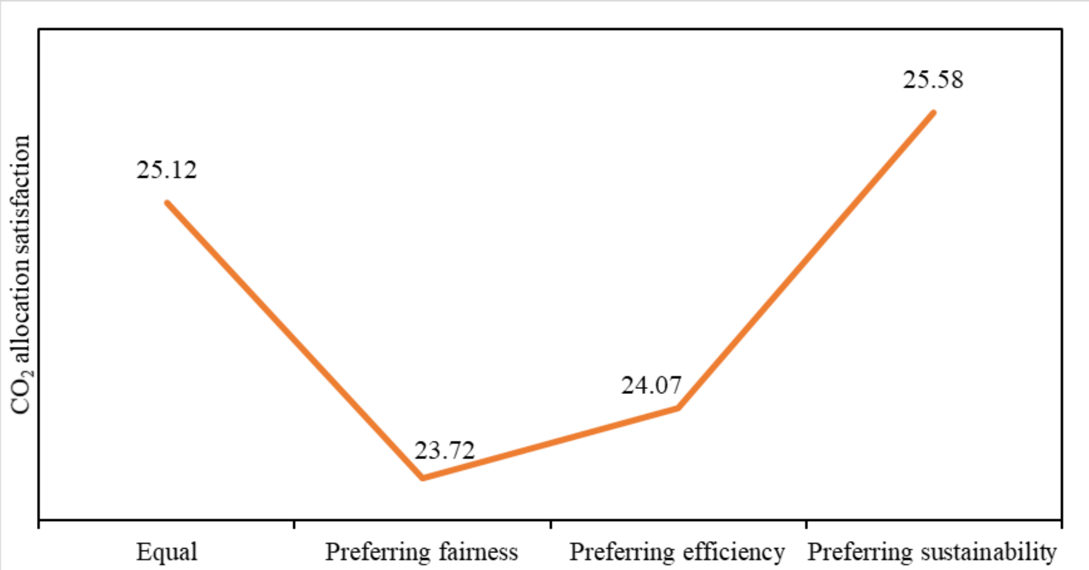

Fig. 8 The sum of CO_2 allocation satisfaction with various decision preferences.

Compared with the single principle-based allocation scheme, fewer differences exist in the results of multi-object models with various cases, which means that allocation results of multi-objective models under different cases present a smaller variance. For example, the CO_2 emission quotas of Heze are equal to 37 Mt in multi-objective models under four cases. In contrast, the largest CO_2 emission quotas in the single principle-based allocation scheme are 6.26 times the size of the smallest. Allocation schemes based on fairness and sustainability principles have low CO_2 allocation satisfaction, conflicting with the feasibility principle. The scheme based on efficiency cannot achieve a fair allocation. Serious conflicts exist in the principles of fairness, efficiency and, sustainability in some cities (e.g., Beijing, Langfang, Tieling). Therefore, the scheme based on a single principle inevitably distorts the allocation results. However, the multi-objective model can effectively integrate the principles of fairness, efficiency, sustainability, and feasibility, the results can eliminate the conflicts between multiple principles and become more reasonable with less discrepant across various cases.

4. Sensitivity analysis

The minimum CO_2 allocation satisfaction (a) measures the feasibility of the allocation scheme, which is exogenously set by estimation and the authority. The value of a decides the CO_2 emissions constraint for each city and play an essential role in the allocation. Therefore, it is necessary to consider the robustness tests.

We set $a=0.3$ as the baseline scenario and only change the value of a to test the sensitivity of carbon emission quotas allocation. Expressly, we set a at low and high levels: 0 and 0.48, and search the optimal solutions, respectively. When the minimum CO_2 allocation satisfaction (a) is higher than 0.48, the model has no feasible solution. The sum of minimum CO_2 emissions of all cities would exceed the targeted total CO_2 emission. We take the case of equal weight as an example. The allocation results of choosing different values of a are shown in Table 8.

Table 8. The CO_2 emission quotas allocation results with the change of value a (Unit: Mt).

Cities	a=0	a=0.1	a=0.2	a=0.3	a=0.4	a=0.45	a=0.48
Beijing	217	216	219	248	277	291	300
Tianjin	229	228	227	231	253	264	271
Shijiazhuang	132	135	138	140	143	145	146
Tangshan	120	119	118	115	105	94	98
Qinhuangdao	53	53	53	52	42	40	40
Handan	101	101	100	96	86	93	97
Xingtai	100	100	104	109	115	118	119

Baoding	137	136	135	132	122	112	116
Zhangjiakou	78	78	78	78	78	78	76
Chengde	89	89	89	89	89	89	71
Cangzhou	98	98	97	93	83	79	82
Langfang	72	72	71	67	71	74	76
Hengshui	62	62	63	65	68	70	71
Shenyang	133	133	132	128	131	133	134
Dalian	165	165	164	160	150	140	135
Anshan	67	67	67	67	60	60	61
Fushun	43	43	43	43	43	43	34
Benxi	34	34	34	34	34	28	28
Dandong	37	37	37	37	37	37	30
Jinzhou	48	48	48	48	40	36	37
Yingkou	49	49	48	44	39	40	41
Fuxin	35	35	35	35	30	20	21
Liaoyang	41	41	40	36	33	34	35
Panjin	39	38	37	34	33	34	35
Tieling	60	60	60	60	57	47	38
Chaoyang	53	53	53	53	53	46	34
Huludao	45	45	45	45	44	33	32
Jinan	102	106	111	116	121	123	125
Qingdao	150	150	149	155	164	169	172
Zibo	75	75	78	83	88	90	91
Zaozhuang	51	51	51	53	55	56	56
Dongying	70	70	68	65	58	62	64
Yantai	141	141	140	136	131	135	137
Weifang	138	137	136	133	133	134	135
Jining	103	105	109	112	116	118	119
Taian	69	69	70	72	75	76	77
Weihai	74	74	73	69	63	65	67
Rizhao	48	48	48	45	42	42	43
Laiwu	19	19	18	14	15	16	16
Linyi	136	136	135	131	135	139	141
Dezhou	79	78	77	77	80	81	81
Liaocheng	72	71	70	72	76	78	80
Binzhou	70	70	68	65	65	67	67
Heze	92	92	90	87	90	96	100

When a is up from 0 to 0.48, cities with low CO_2 allocation satisfaction increase their CO_2 emission quotas, typical examples including Beijing, Tianjin, Shijiazhuang, Jinan, Zibo, Zaozhuang, Jining, and Taian. Conversely, eighteen cities (e.g., Tangshan, Qinhuangdao, Chaoyang) first keep their CO_2 emission quotas constant with the increase of value *a*. Then their emission quotas decrease when *a* exceeds a specific value. Besides, the CO_2 emission quotas in some cities such as Handan, Baoding, Linyi, Heze, decrease first and increase thereafter. The emission quotas in Beijing increase by 38.2%, followed by Zibo and Jinan, with 22.2% and 21.8%, respectively. Fuxin, Chaoyang, and Tieling show the largest reduction proportion of their emission quotas (more than 30%). Some cities are less sensitive to the change of value *a.* for instance, Shenyang only increases by 0.9%, and Weifang decreases by 2.0%.

Fig. 9 reflects the tendency of the sum of CO_2 allocation satisfaction in all cities under various values of *a.* The sum of CO_2 allocation satisfaction experiences an increase first and then declines continuously, and it peaked when *a* is close to 0.1 at 26.211. The total CO_2 allocation satisfaction is 26.206 when *a* is equal to 0, which is only a little lower than the peak. When *a* at high levels (more than 0.2), the sum of CO_2 allocation satisfaction is sensitive to increasing value *a*, presenting a faster decrease trend, therefore, it is more likely to obtain a higher level of satisfaction by controlling the value of *a* at lower levels (less than 0.2). However, it may cause low CO_2 allocation satisfaction in some cities. For example, the CO_2 allocation satisfaction in Shijiazhuang is 0 in the case of a=0. Thus, the policy makers must adopt reasonable minimum CO_2 allocation satisfaction to ensure the feasibility of all cities.

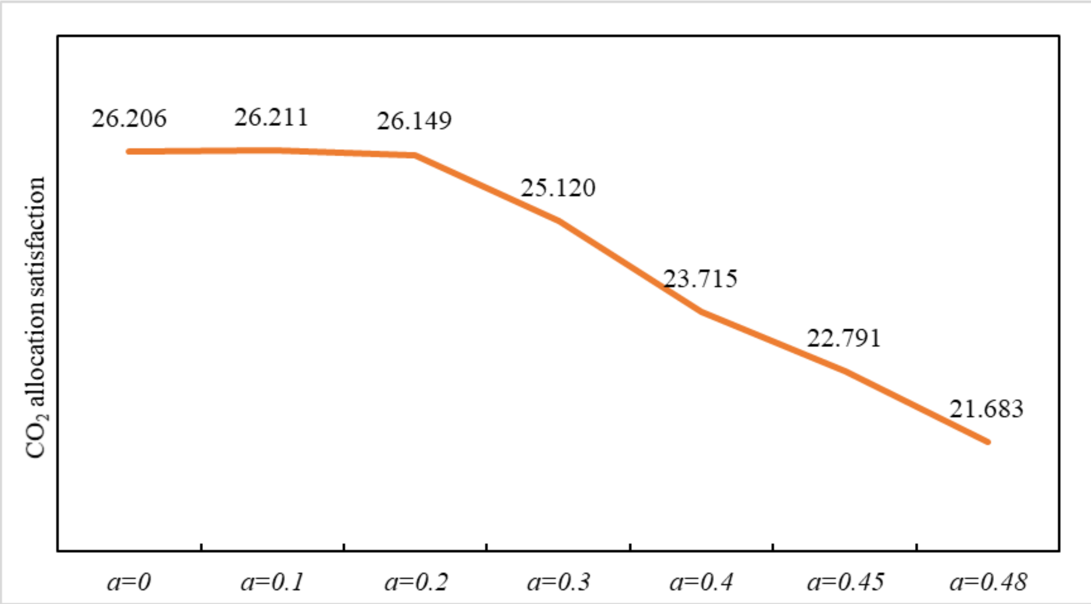

Fig. 9. The sum of CO_2 allocation satisfaction in all cities with the change of value *a*.

5. Conclusions and policy implications

This paper develops a multi-objective decision model integrating the principles of fairness, efficiency, sustainability, and feasibility to allocate the CO_2 emission quotas at the city level. Taking BREC as an example, we formulate the CO_2 emission quotas allocation for 44 cities in 2030. The main findings are as follows:

Results in the case of equal weights show that Beijing, Tianjin, Dalian, Shijiazhuang, Yantai, Weifang, and Linyi enjoy the largest CO_2 emission quotas 1179.94 Mt in total and accounting for 31%. Compared with the initial CO_2 emissions obtained by grandfathering, fifteen out of the 44 cities are found to cut down their CO_2 emission quotas including Langfang, Tangshan, and Cangzhou, while nineteen cities such as Beijing, Qingdao and Yantai have increased their emission quotas in 2030 that can be sellers in the carbon trading market. The emission quotas in the remaining ten cities (Qinhuangdao, Anshan, Fushun, and Benxi) remain stable, compared to initial CO_2 emissions.

The single principle-based allocation results display that the principles of fairness, efficiency, sustainability, and feasibility significantly conflict with each other in most cities. Generally, allocation scheme that considers only single principle tends to be less satisfactory. Fairness and sustainability principles, with low satisfaction of CO_2 emission quotas allocation, apparently partially go against the feasibility. Similarly, the efficiency principle departs from fairness and sustainability, even though it is more feasible. The sustainability principle, which only considers the environmental factors, cannot achieve fair and efficient allocation results.

Compared with the single principles allocation scheme, the multi-objective allocation model performs much better integrating the principles of fairness, efficiency, sustainability and feasibility and effectively avoiding distorting the allocation results. Results in the multi-objective allocation model under various cases show fewer differences from each other. The satisfaction degree function in CO_2 emission quotas allocation ensures the results more reasonable and acceptable. Also, it avoids sacrificing the satisfaction of any city effectively. Furthermore, the multi-objective allocation model provides various available options for policymakers by simply adjusting the weights of each principle. Sensitivity analysis indicates that the total CO_2 allocation satisfaction experiences an increase first and then declines constantly, and it reaches the peak when a is close to 0.1 at 26.211.

Based on the empirical results, we further put forward several policy implications. First, policymakers need to select reasonable indicators to allocate emission quotas so that it adapts to the development stages of different cities. In addition to focusing on economic development level, population, and emission efficiency, attention also should be paid to the environmental factors. To achieve the emissions reduction target, for one thing, the local governments should develop and use clean and renewable energy sources. For another, the investment in afforestation should be promoted to improve the CO_2 sequestration capacity.

Second, local governments should formulate targeted policies for emission reduction based on quotas allocation and their situation. The policy orientation must be suitable for the local development. For the cities with heavy emission reduction burden, namely, Langfang, Tangshan, Cangzhou, Handan, Panjin, Liaoyang, and Binzhou, besides developing the economy, the governments should also practice the concept of green development and promote green consumption at both enterprise and individual levels. For the cities with relatively small emission reduction burden, such as Beijing, Dalian, Zhangjiakou, Chaoyang, and Xingtai, technology innovation for energy saving and emissions reduction should be encouraged. For example, promoting carbon capture and storage technologies and optimizing the production process.

Third, the results show that the principles of fairness, efficiency, sustainability, and feasibility are irreconcilable. Thus, policymakers should explore a compromise solution to eliminate the limitations of allocation schemes based on a single principle. The multi-objective allocation model provides options for decision-makers and can be advocated when allocating CO_2 emission quotas at the city level.

Finally, policymakers must pay attention to the relationship between the total CO_2 allocation satisfaction and the individual city's CO_2 allocation satisfaction. Although *a* at low levels can achieve the higher total satisfaction, it is based on sacrificing the satisfaction of some cities. Therefore, it is of critical importance to set the value of *a* to make the CO_2 emission quotas allocation for cities more reasonable.

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Declarations

- **Ethics approval and consent to participate**

Not applicable

- **Consent for publication**

Not applicable

- **Availability of data and materials**

The datasets generated and analyzed during the current study are available in the National Bureau of Statistics of China, China Energy Statistics Yearbook, and China City Statistical Yearbook. http://www.stats.gov.cn/tjsj/ndsj/

- **Competing interests**

The authors declare that they have no competing interests

- **Funding**

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Authors' contributions

Zhiyuan Li: conceptualization, methodology, software, resources, data curation, writing-original draft, writing-review and editing; Huadun Chen: validation, investigation, resources, data curation, writing-review and editing; Juan Wang: conceptualization, investigation, writing-original draft writing-review and editing; Tao Zhao: methodology, formal analysis, writing-review and editing.

Figures

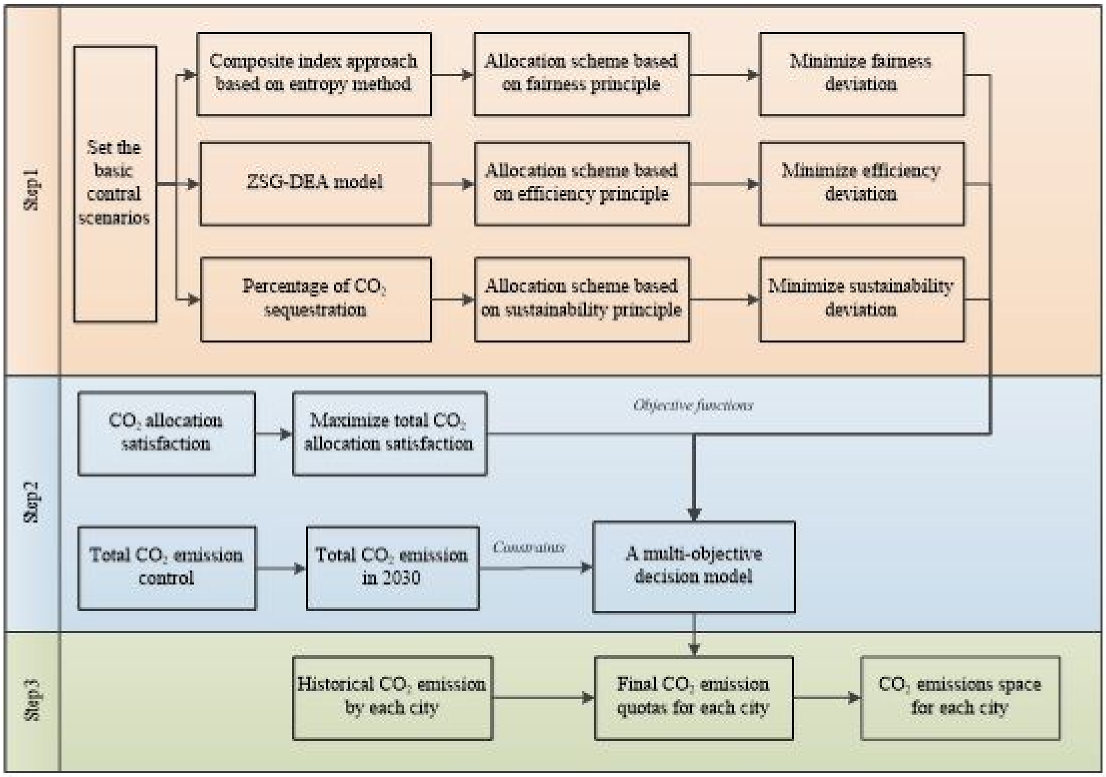

Figure 1

Schematic of CO2 emission quotas allocation.

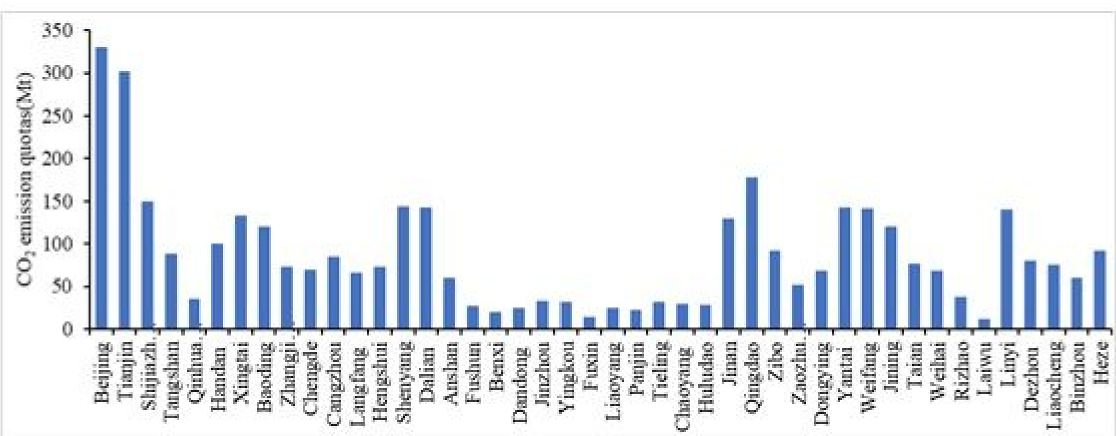

Figure 2

The CO2 emissions quotas allocation based on fairness in 2030.

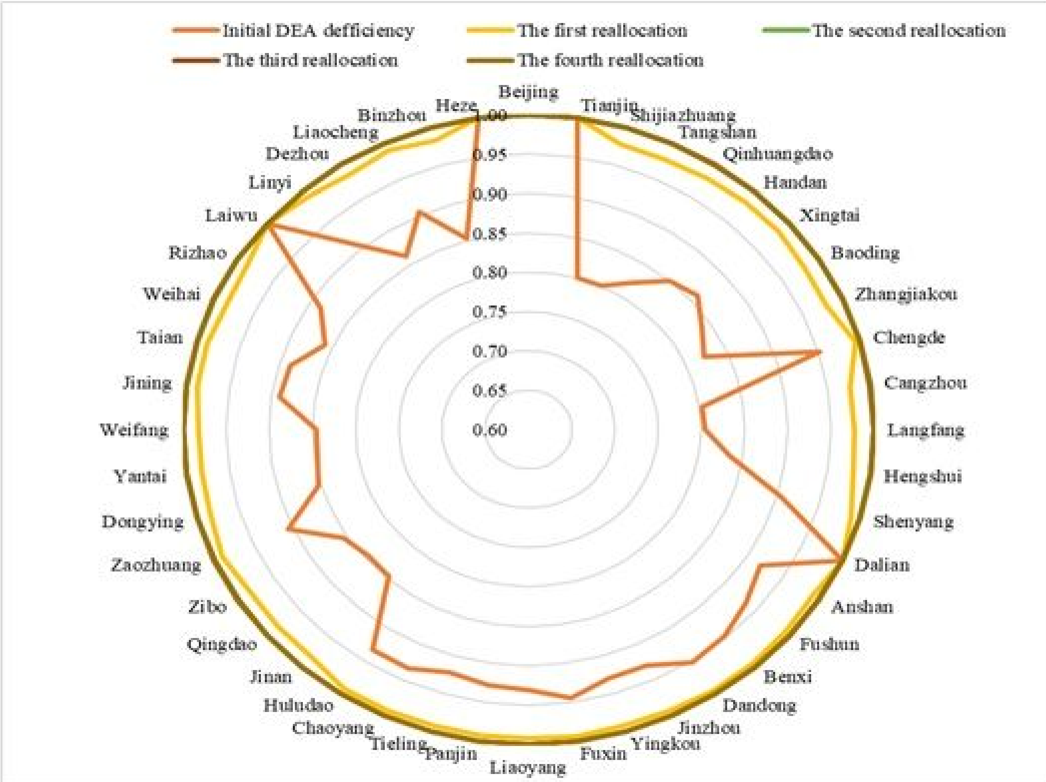

Figure 3

The DEA efficiency of initial allocation and reallocation.

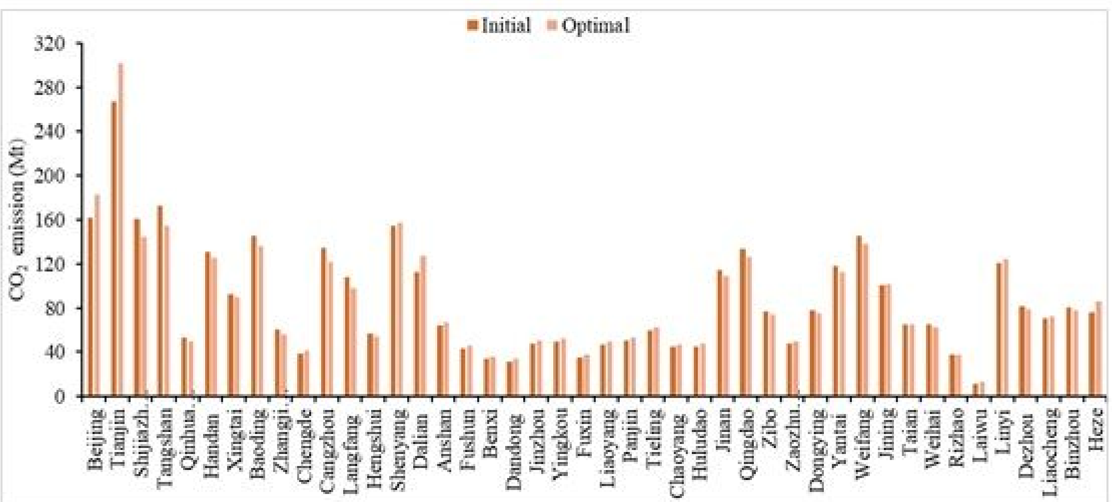

Figure 4

The initial CO2 emission and its reallocation results.

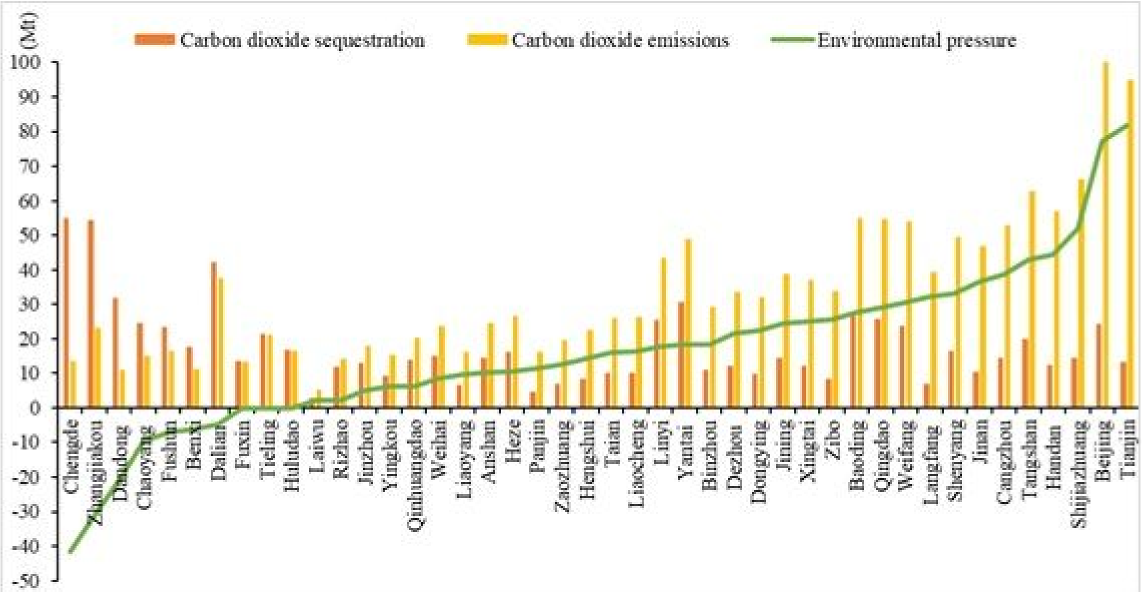

Figure 5

The comparison of CO2 emission of each city with CO2 sequestration and their environment pressure.

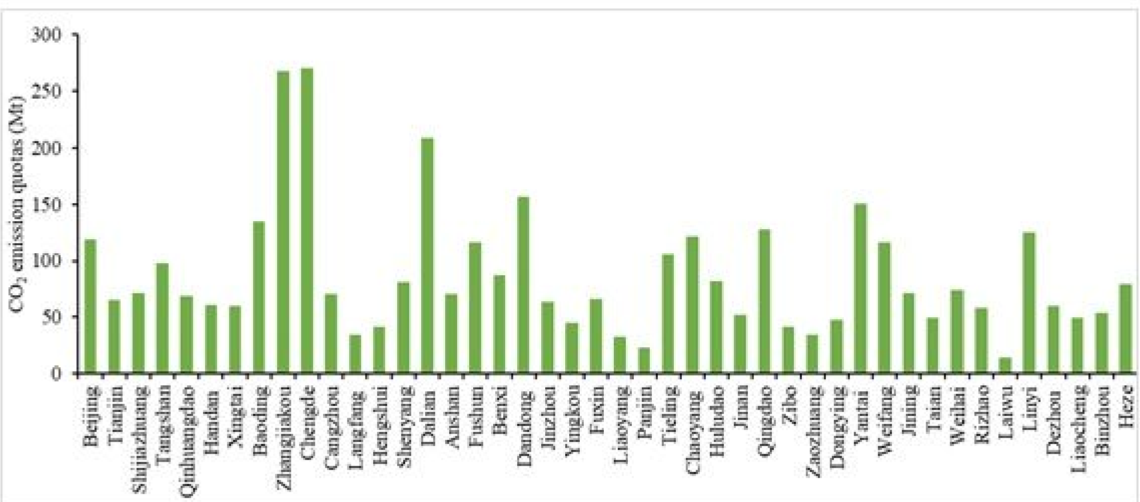

Figure 6

The CO2 emissions quotas allocation based on sustainability in 2030.

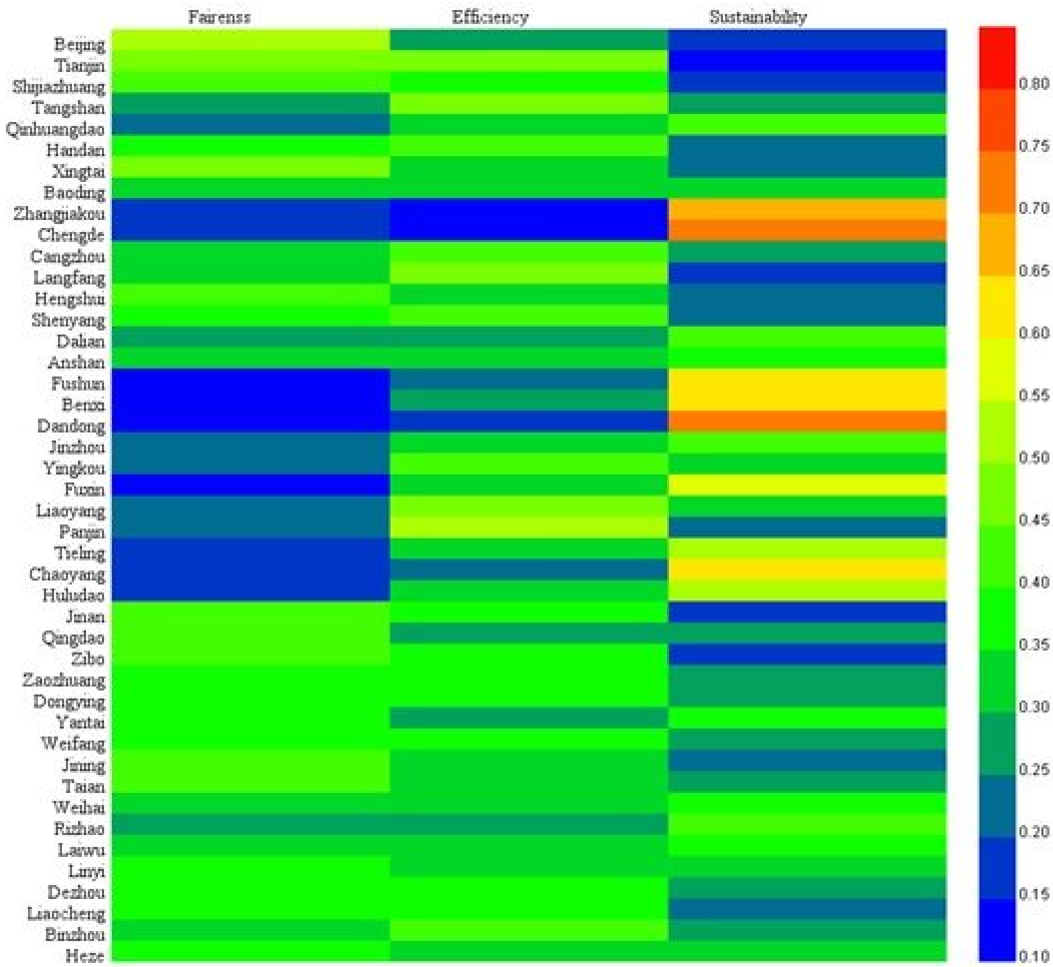

Figure 7

The contribution of fairness, efficiency and sustainability principles to each city.

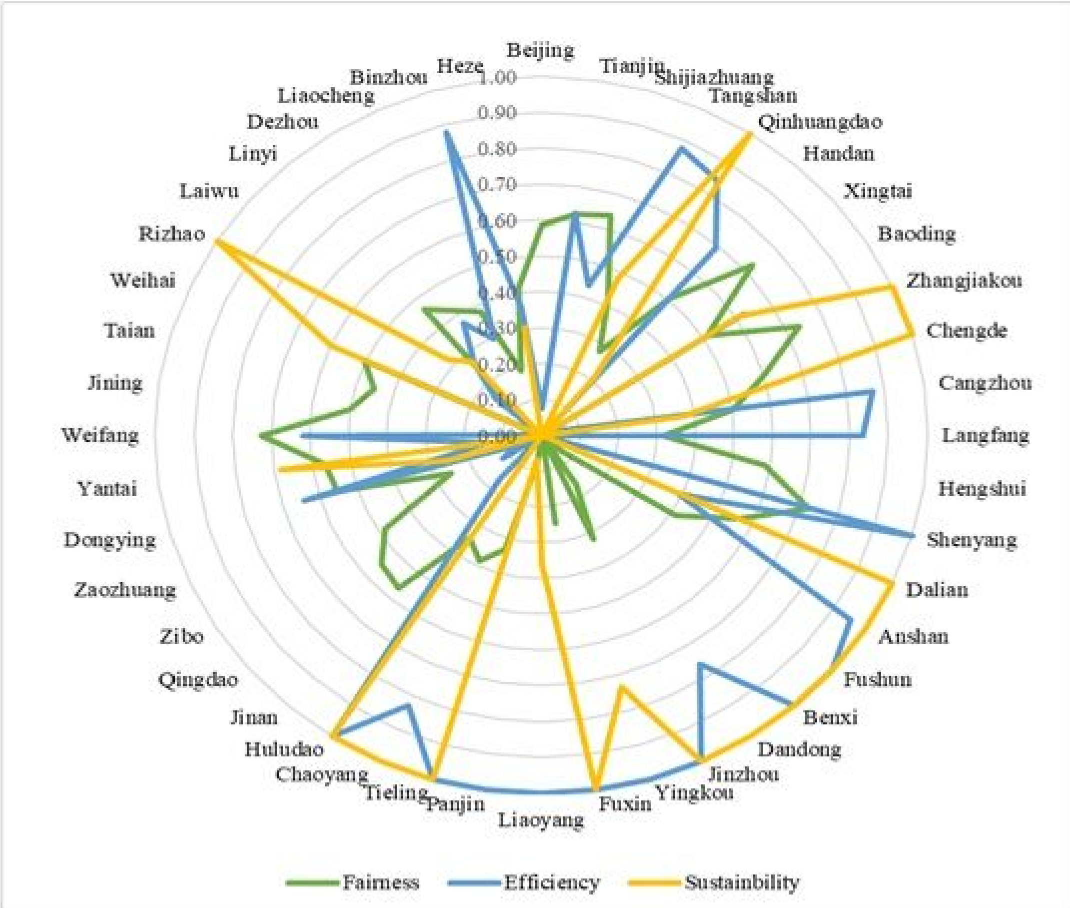

Figure 8

The satisfaction of CO2 allocation of cities by based on each principle.

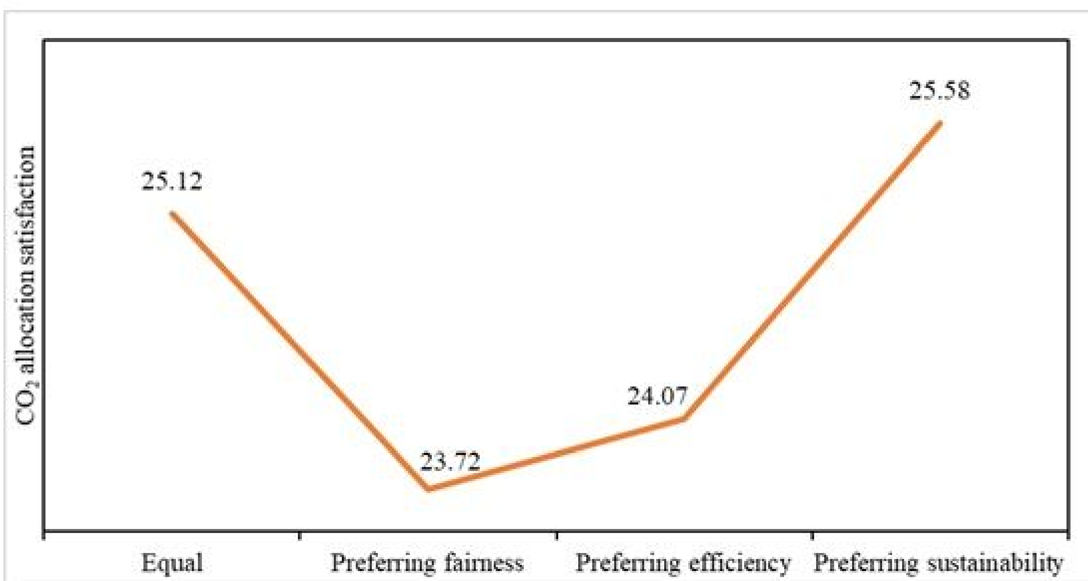

Figure 9

The sum of CO2 allocation satisfaction with various decision preferences.

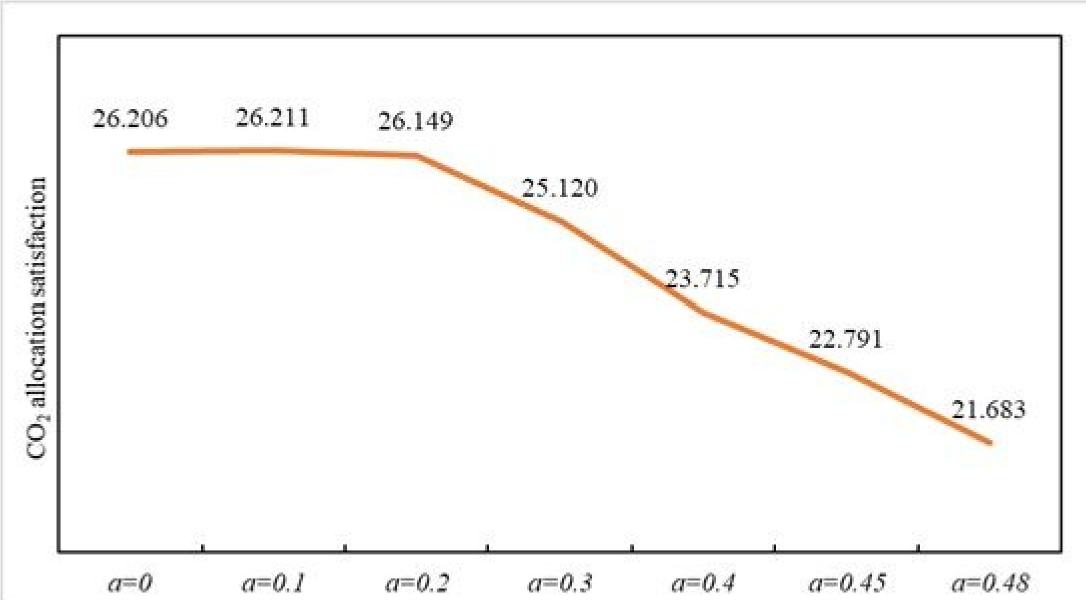

Figure 10

The sum of CO2 allocation satisfaction in all cities with the change of value a.