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Research article

Efficiency measurement and inefficiency analysis of low-carbon logistics in the Beijing–Tianjin–Hebei region, China

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ABSTRACT

Under the dual-carbon goals, enhancing the green development level of logistics industry and realizing its low-carbon transformation are important issues that need to be solved urgently. Amidst the continuous escalation in the total energy consumption of the national logistics industry, the Beijing-Tianjin-Hebei (BTH) region has exhibited a favorable descending trajectory in this respect. It is necessary to investigate the underlying reasons. Based on the panel data from 2012 to 2021, the DEA and Malmquist index are employed to analyze the low-carbon logistics efficiency of the BTH region from both static and dynamic perspectives. Furthermore, the inefficiency analysis is conducted to identify the deficiencies of low-carbon logistics industry in this region. Results show that (1) from the static perspective, the development of low-carbon logistics industry in the BTH region is relatively unbalanced. Compared to Tianjin and Hebei, Beijing's low-carbon logistics efficiency is significantly lower, becoming the focal area for attention; (2) from the dynamic perspective, technological progress is the main reason for the fluctuation of total factor productivity in the BTH region and a constraining factor for further improvements; (3) from the results of inefficiency analysis, the forthcoming emphasis on low-carbon logistics in Beijing should be on optimizing the number of logistics practitioners, transportation efficiency, and energy efficiency. Economic output and energy efficiency are relatively vulnerable aspects in Tianjin and Hebei, respectively, warranting due consideration. The research results of this paper have important practical implications for better developing low-carbon logistics in the BTH region and leveraging its leading role nationwide.

1. Introduction

The rapid development of industrial economy has brought new challenges to the global environment. Countries have been trying to deal with the environmental degradation caused by economic development [1]. At the 75th session of the United Nations General Assembly, China pledged to strive for a peak in carbon dioxide emissions before 2030 and achieve carbon neutrality by 2060 (i.e., the dual-carbon goals). Low-carbon economy has emerged as an integral facet of China's sustainable development strategy. The logistics industry stands as a foundational pillar for national economic development and is also a key field for reducing energy consumption and carbon emissions [2]. Since 2020, the total value growth rate of social logistics goods in China has consistently exceeded GDP growth, evolving into a new engine driving the country's economic prosperity. Fig. 1 presents the development of China's logistics industry from 2011 to 2021. During the ten years, the total value of social logistics goods continued to grow. It reached 335.2 trillion yuan in

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2021, reaching a new pinnacle in logistics demand. Meanwhile, the total energy consumption of the national logistics industry increased from 296.94 million tons of standard coal to 439.35 million tons of standard coal, with an average annual growth rate of 5.24 %. The only decline occurred during the COVID-19 pandemic. Furthermore, in terms of logistics costs, China's total social logistics costs in 2021 were 16.7 trillion yuan, accounting for 14.6 % of GDP [3], far higher than regions such as the United States, Japan, and the European Union. It is palpable that China's logistics industry is expansive but not sustainable, facing various issues such as high costs, high emissions, and low efficiency [4]. With the continuous increase in national logistics demand, the task of energy conservation and emission reduction in the logistics industry will continue to intensify. Developing low-carbon and efficient logistics has become an inevitable choice for the sustainable development of China's logistics industry.

The BTH region, consisting of Beijing, Tianjin, and Hebei Province, forms the "Capital Economic Circle" and serves as the core zone for economic development in northern China. As of the end of 2022, the GDP of the BTH region exceeded 10 trillion yuan, accounting for 8.26 % of the national total, making it a crucial growth pole in the Chinese economy [5]. Regional logistics act as an accelerator for regional economic growth, playing a significant role in promoting regional industrial restructuring, optimizing resource allocation, and enhancing regional economic competitiveness [6,7]. According to the statistical yearbooks of the three regions, from 2012 to 2021, the GDP of logistics industry in the BTH region increased from 352.7 billion yuan to 491.8 billion yuan, with an average annual growth rate of 3.76 %. Meanwhile, against the backdrop of a continuous increase in the total energy consumption of the national logistics industry, the BTH region has shown a preliminary positive development trend. The total energy consumption of logistics industry decreased from 24.71 million tons of standard coal to 23.33 million tons of standard coal. Hereto, has the low-carbon logistics development level in the BTH region improved? Are there significant differences among different regions? How can further optimization and improvement be achieved? Under the dual-carbon goals, answers to these questions hold practical significance for better developing low-carbon logistics in the BTH region and leveraging its leading role nationwide.

Low-carbon logistics efficiency is an effective way to assess the development level of low-carbon logistics in a country or region and provide feedback for improvement. The research on low-carbon logistics efficiency has continuously attracted the attention of scholars from different perspectives, including concept [8], framework [9,10], approach [11,12], and mechanism [13]. Energy performance and carbon efficiency are two aspects of low-carbon logistics efficiency [14]. Scholars have utilized the stochastic frontier analysis (SFA) or data envelopment analysis (DEA) to calculate the efficiency scores of low-carbon logistics at national, provincial, municipal, and enterprise levels [15,16]. For example, Liang et al. used the three-stage Super-SBM model to measure the efficiency of low-carbon logistics of 13 cities in Jiangsu Province. They found that the efficiency of low-carbon logistics of the 13 cities increased steadily, but technological progress has not reached the optimal level yet [17]. In the study of Deng et al. the SBM-DEA was employed to evaluate the logistics performance with and without carbon emissions constraints of 30 provinces/municipalities in China [4]. Wang and Xin analyzed the impact of China's trade with the Belt and Road Initiative (BRI-participating economies) on China's logistics industry's ecological total factor energy efficiency (ETFEE) [18].

The previous research has laid a solid theoretical foundation for this paper. However, some limitations still exist. For example, Many studies have assessed low-carbon logistics efficiency at various levels, including national, provincial, city, and enterprise levels. However, the low-carbon development of regional logistics plays a pioneering role in leading national logistics toward low-carbon transformation. There has been less focus on the low-carbon efficiency of regional logistics within urban agglomerations. Additionally, some existing research has paid much attention to the comprehensiveness of evaluation indicators, the complexity of models, and the diversity of data, but has overlooked a critical aspect that comes after evaluation, i.e., inefficiency analysis. Inefficiency analysis is a

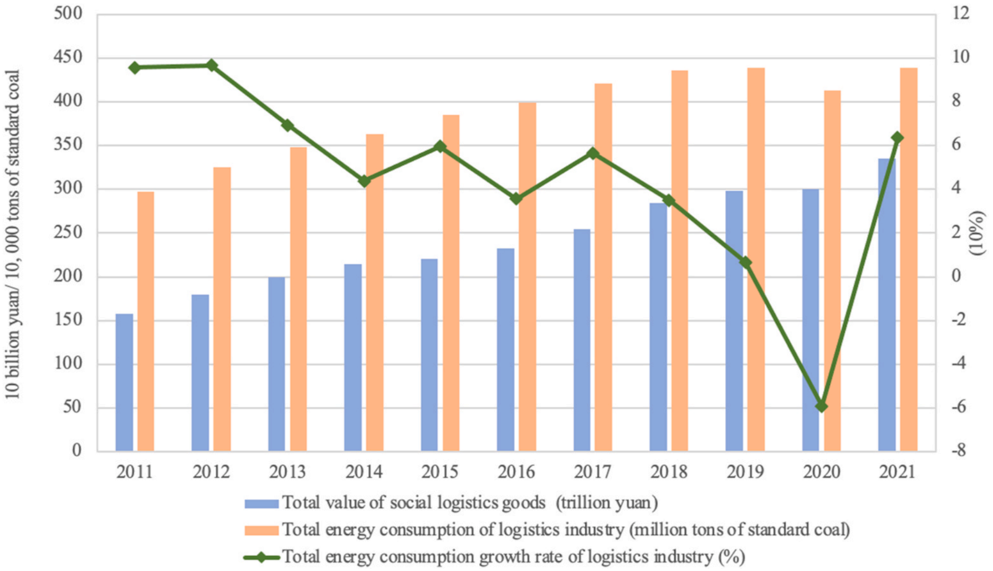

Fig. 1. The development of China's logistics industry.

valuable method for further exploring the reasons for low-carbon logistics inefficiency and proposing targeted countermeasures.

This study attempts to improve these limitations in previous research and makes contributions by (1) constructing an evaluation index system for low-carbon logistics efficiency that simultaneously considers economic benefits, energy efficiency, and carbon efficiency; (2) in the static perspective, applying CCR and BCC models to explore the efficiency structure of the BTH region; in the dynamic perspective, applying the DEA-Malmquist index to analyze the reasons for the fluctuation of low-carbon logistics efficiency in the BTH region; and (3) conducting projection analysis on inefficient DMUs, calculating the input redundancy and output deficiency ratios of low-carbon logistics industry, and proposing feasible measures to improve the efficiency. This study fills the gaps in existing research on low-carbon logistics at the regional level and provides decision support for enhancing the efficiency of low-carbon logistics in the BTH region.

The remainder of this paper is organized as follows. Section 2 reviews the existing literature related to the low-carbon efficiency of regional logistics. Section 3 introduces the paper's research methodology. Section 4 establishes the index system for measuring low-carbon logistics efficiency. Section 5 presents the analysis results and discusses the main findings. Section 6 concludes and puts forward policy implications.

2. Literature review

This section reviews the relevant studies from the following three aspects that have laid a theoretical foundation for this study: (1) low-carbon logistics, (2) efficiency evaluation of low-carbon logistics, and (3) urban agglomeration and regional logistics.

2.1. Low-carbon logistics

When the economy reaches a certain level, growing environmental problems arise [19]. Moreover, the instability of economic development increases the uncertainty of environmental protection [20]. It is essential to establish a symbiotic relationship between economic development and environmental protection [21]. The logistics industry is a crucial pillar industry in any economic entity [22]. On the one hand, the development level of logistics industry directly determines the flow of various products in economic activities [23]. On the other hand, this industry is closely related to the ecological environment [24,25]. Therefore, with a deepening understanding of the low-carbon economy, scholars integrated the principles of sustainable development and carbon reduction into the logistics and proposed the concept of low-carbon logistics. According to the "National Standard of the People's Republic of China: Logistics Terms", low-carbon logistics is considered a logistics model with low energy consumption and low pollution that achieves the highest efficiency and the least greenhouse gas emissions [26].

The research on low-carbon logistics is becoming increasingly abundant, yielding fruitful results. The calculation of carbon emissions in the logistics industry is the foundation and prerequisite for such research. Currently, two primary methods have been established: the IPCC method and the model method [27–29]. Typically, the IPCC method is used to calculate carbon dioxide emissions by industry sector [16]. On this basis, the study of influencing factors of carbon emissions in the logistics industry has gradually become an important direction [30–32]. Based on the panel data of China's 30 provinces from 2005 to 2019, Xu and Xu adopted quantile regression to investigate the influence mechanism of incentive and mandatory environmental regulations on the energy efficiency and carbon dioxide emissions of logistics industry [2]. Quan et al. used the LMDI decomposition model to decompose the influencing factors of carbon emissions from the logistics industry, including carbon emission coefficient, energy intensity, energy structure, economic level, and population size [33]. Finally, regarding the fundamental issue of how to develop low-carbon logistics, He et al. developed a general PMS with 42 indicators from 12 dimensions. On this basis, they identified the barriers and strategies for developing low-carbon logistics [10]. Pan et al. found that the implementation of the Smart Logistics Policy (SLP) can restrain carbon emissions significantly, with a continuous impact in the second year [34]. Zhang et al. developed two sets of carbon efficiency evaluation methods to identify the provincial patterns of reducing carbon emissions and proposed targeted pathways considering the variability of regional development [14].

2.2. Efficiency evaluation of low-carbon logistics

Reducing energy consumption and minimizing carbon emissions are key goals in the development of low-carbon logistics. Scholars have extensively explored the assessment of energy performance and carbon efficiency of the logistics industry [35,36]. Carbon efficiency refers to the extent to which economic production activities, at a given input level, can maximize the reduction of carbon dioxide emissions while maximizing the desired output [37]. Similarly, energy performance reflects the extent to which economic production activities, at given input and expected output levels, can maximize the reduction of energy input. Both aim to strike a balance between economic development and the ecological environment.

The evaluation methods for energy performance and carbon efficiency can be categorized into single-indicator and multiple-indicators. For energy performance, the single-indicator refers to the ratio of a single output to energy consumption, such as economic energy efficiency which is often measured by energy intensity per unit of economic output [38,39]. For carbon efficiency, the single-indicator refers to the ratio of carbon emissions to a single input, such as carbon productivity and carbon intensity [40,41]. However, the single-indicator approach only considers the proportional relationship between a certain factor and energy consumption or carbon emissions. It neglects other inputs and outputs that make significant contributions, such as labor, capital, resources, economic benefits, and social benefits. Therefore, it has certain limitations [14]. In this regard, scholars proposed the multiple-indicators evaluation methods which encompass various factors.

There are two commonly used multiple-indicators evaluation methods: the parameter method [42–44], and the non-parameter method [15,18]. Yu et al. applied the DEA model to study the energy eco-efficiency (EEE) of logistics industry in China and its provinces from 2010 to 2019 [16]. Du and Li adopted the SBM-DEA model, which includes indicators of input, desirable output, and undesirable output, to measure the green logistics efficiency of 285 Chinese cities [12]. The DEA model can only measure the efficiency of low-carbon logistics from a static perspective. To further analyze the dynamics of efficiency, the combination method of DEA and Malmquist index was proposed and applied by scholars [45,46]. The Malmquist index is determined by the distance of DMUs from the efficiency scores and can measure changes in efficiency over time [47,48]. Yang et al.analyzed the carbon emissions performance of logistics industry in 16 cities in Yunnan Province from both the static and dynamic perspective by using the DEA model and Malmquist index [6].

2.3. *Urban agglomeration and regional logistics*

Studies have shown that trade openness promotes economic growth but curbs the increase in carbon emissions [49]. With the rapid development of economic globalization, competition between cities is no longer carried out at the city level, but in urban agglomeration [23]. Urban agglomeration refers to a compact spatial organization formed by one or more major cities closely economically connected within a specific geographical region [50]. It aims to achieve a high degree of integration based on well-developed transportation and infrastructure networks. This pattern can enhance factor allocation, optimize industrial layout, and improve resource utilization. A robust and cohesive economic community is formed [51]. Efficient allocation of production factors and industrial consolidation contribute to increased industrial efficiency within urban agglomerations. Therefore, the advantages of urban agglomerations lay a solid foundation for the establishment, expansion, and efficiency improvement of low-carbon logistics systems in related urban [52]. The regional logistics industry can further effectively promote the overall development of urban agglomerations by linking various industries [6].

According to existing studies, scholars often conducted research on low-carbon logistics at the national [53–55], provincial [4,56], urban [13,31,57], and enterprise levels [58], lacking attention to the regional low-carbon logistics within urban agglomeration. More importantly, the inefficiency analysis after efficiency evaluation is often insufficient. In order to address these gaps, this paper quantitatively evaluates the efficiency of low-carbon logistics in the BTH region and conducts an inefficiency analysis. The contributions of this research to the previous literature can be explained as follows. First, we focus on the low-carbon logistics development at the regional level from both static and dynamic perspectives. Second, we deeply analyze the reasons for the inefficient DMUs through the projection analysis. They are crucial for further improving the development level of low-carbon logistics in the BTH region and becoming a pioneer and demonstration area for China's logistics transformation and upgrading.

3. Methodology

3.1. *Indicator selection*

The efficiency scores exhibit a strong correlation with the evaluation indicators. Referring to Yao et al. and Zheng et al. we conclude and adhere to the following four principles for constructing the evaluation index system: (a) comprehensively the representativeness, importance, and data accessibility of the indicators [15,59]; (b) ensure that the quantity of input-output indicators complies with the requirement of "the number of DMUs is more than twice the number of indicators"; (c) input indicators are cost-type, and output indicators are benefit-type; (d) there is a certain correlation between input and output indicators.

3.1.1. *Input indicators*

In the present study, we comprehensively considered the economic benefits, energy efficiency, and carbon efficiency of logistics industry in the operational process. As in Zhang et al. and Yu et al. we chose input indicators from the perspectives of people, materials, finance, and energy, respectively [16,32]. First, the logistics industry is labor-intensive. Thus, we select the indicator "number of employees in the logistics industry" to represent the human input [23]. Second, the total mileage of transportation lines such as highways and railways reflects the scale of infrastructure construction in the logistics industry. Therefore, the indicator "length of transportation lines" is chosen to represent the material input of logistics industry [4,12]. Third, the amount of fixed-asset investment can reflect the region's financial input and level of emphasis on the industry. Hence, the indicator "fixed-asset investment in the logistics industry" is chosen to represent the financial input [23]. Finally, according to the research objectives of this paper, energy performance is an undeniable key point. Therefore, we select the indicator "annual energy consumption of the logistics industry" to represent the energy input [14].

3.1.2. *Output indicators*

Based on the objective of evaluating low-carbon logistics efficiency, we categorize the output indicators into two types: desirable output and undesirable output [18]. Desirable output can be further divided into two dimensions: economic output and scale output. For economic output, we choose the indicator "gross domestic product of the logistics industry" to reflect the impact of logistics industry on the economic development in the BTH region [23]. For scale output, we choose the indicators "the volume of freight transport" and "turnover volume of freight transport" to reflect the logistics industry's contribution to the growth of economic scale in the BTH region [4,12]. The above three indicators show a positive correlation with logistics efficiency. In a low-carbon economy, the lower the carbon dioxide emissions, the higher the carbon efficiency of industry. The carbon efficiency is inversely correlated with carbon dioxide emissions. Therefore, we use the indicator “Carbon dioxide emissions from the logistics industry” as an undesirable output indicator to characterize the environmental pollution caused by the logistics industry [14].

Based on the input and output indicators selected above, an index system for measuring the low-carbon logistics efficiency is established, as shown in Fig. 2.

3.2. Evaluation model

In existing research on low-carbon logistics efficiency, the DEA is feasible and widely used due to its advantages of avoiding the assumptions of measurement functional forms and prior conditions, capturing the relationships between multiple inputs and outputs, and clearly identifying benchmark technologies [12,23,60,61]. However, the efficiency scores of the DEA model cannot reflect the dynamic changes in DMUs’ efficiency over time [6]. Thus, we further adopt the DEA-Malmquist method to dynamically analyze the efficiency trend of low-carbon logistics, aiming to obtain a more comprehensive analysis result [62,63].

3.2.1. Static evaluation: DEA model with undesirable outputs

Considering that carbon emissions are undesirable outputs, we first employ the DEA model with undesirable outputs to evaluate the efficiency of low-carbon logistics in the BTH region. According to whether returns to scale are variable, the DEA model is divided into the CCR model and the BCC model [64]. The CCR model assumes constant returns to scale (CRS), and its efficiency score is an overall technical efficiency that includes both pure technical efficiency (PTE) and scale efficiency (SE). The BCC model assumes variable returns to scale (VRS), and its value is the PTE. Thus, the SE can be obtained by dividing the value of the CCR model by the value of the BCC model.

Assume that there are N decision-making units (DMUs) and the jth DMU ($j = 1, 2, \dots, \mathrm{N}$) uses input quantities X_j to produce desirable output quantities Y_j^E and undesirable output quantities Y_j^U. We also assume that $X=(x_{ij}) \in R^{M\times N}$, $Y^E=(y_{rj}^E) \in R^{S\times N}$ and $Y^U=(y_{lj}^U) \in R^{Q\times N}$ are non-negative. Then, the CCR model with undesirable outputs can be described as:

$$\min \theta$$
$$s.t.\begin{cases} \sum_{j=1}^{n} x_j\lambda_j \le \theta x_{j0} \\ \sum_{j=1}^{n} y_j^E\lambda_j \ge y_{j0}^E \\ \sum_{j=1}^{n} y_j^U\lambda_j \le y_{j0}^U \\ \lambda_j \ge 0, j = 1, 2, \cdots, n \end{cases} \tag{1}$$

in Eq. (1), λ_j denotes the weights of the input-output indicators, θ is the j_0th DMU’s overall technical efficiency, and $\theta \in (0, 1]$. The larger the θ is, the higher the overall technical efficiency is. If $\theta = 1$, it indicates the DMU is overall technically efficient, otherwise, it is

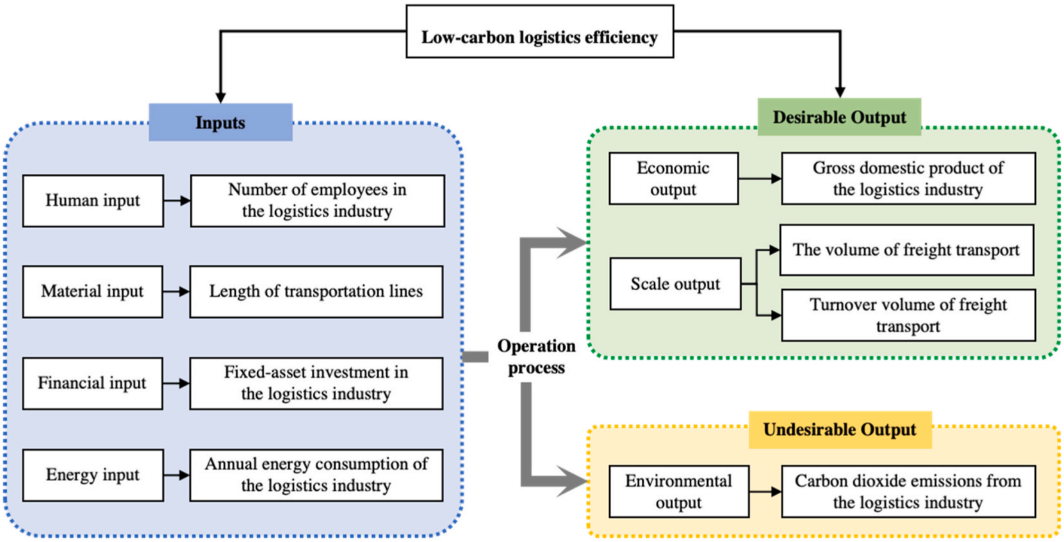

Fig. 2. Evaluation index system for low-carbon logistics efficiency.

overall technically inefficient.

Similarly, the BCC model with undesirable outputs is expressed as follows.

$$\min \rho$$

$$s.t.\begin{cases} \sum_{j=1}^{n} x_j\omega_j \le \rho x_{j0} \\ \sum_{j=1}^{n} y_j^E\omega_j \ge y_{j0}^E \\ \sum_{j=1}^{n} y_j^U\omega_j \le y_{j0}^U \\ \sum_{j=1}^{n} \omega_j = 1 \\ \lambda_j \ge 0, j = 1, 2, \cdots, n \end{cases} \tag{2}$$

in Eq. (2), ω_j denotes the weights of the input-output indicators, ρ is the j_0th DMU's pure technical efficiency, and $\rho \in (0, 1]$. The larger the ρ is, the higher the pure technical efficiency is. If $\rho = 1$, it indicates the DMU is pure technically efficient, otherwise, it is pure technically inefficient.

Finally, the scale efficiency σ can be calculated in Eq. (3). The larger the σ is, the higher the scale efficiency is. If $\sigma = 1$, it indicates the DMU is scale efficient, otherwise, it is scale inefficient.

$$\sigma = \theta / \rho \tag{3}$$

3.2.2. Dynamic evaluation: DEA-Malmquist index

The Malmquist Index was originally proposed by Malmquist and developed by Caves et al. [47,65]. It analyzes potential changes in technology and efficiency over the two periods to evaluate the overall efficiency progress of an economic system. The expression is as follows.

$$TFP = \left[\frac{D^t(x^{t+1}, y^{t+1})}{D^t(x^t, y^t)} \times \frac{D^{t+1}(x^{t+1}, y^{t+1})}{D^{t+1}(x^t, y^t)}\right]^{\frac{1}{2}} \tag{4}$$

In Eq. (4), D represents the distance function, (x^t, y^t) and (x^{t+1}, y^{t+1}) represent the input and output vectors for periods t and t+1, respectively, and TFP represents the total factor productivity. The TFP value greater than 1 signifies efficiency improvement, less than 1 indicates a decline, and equal to 1 implies no change.

Färe et al. extended the Malmquist index by decomposing the TFP into the technical efficiency change index (EC) and the technological change index (TC) [66]. Furthermore, the EC also can be broken down into the pure technical efficiency change (PTEC) and the scale efficiency change (SEC) when the variability of scale payout is taken into account Huang et al. [67]. The specific decomposition formula of TFP is shown in Eq. (5).

$$TFP = EC \times TC = PTEC \times SEC \times TC \tag{5}$$

The EC value measures how the technical efficiency evolves at the same input and output levels. If EC > 1, it indicates an improvement in technical efficiency; if EC < 1, it signifies a decline. The TC value reflects the impact of technological progress or regression on technical efficiency. If TC > 1, it indicates technological progress; if TC < 1, it signifies technological regression. The PTEC value measures the change in technical efficiency with scale efficiency held constant. The SEC value measures the efficiency change due to scale expansion or contraction with technical efficiency held constant. These indices offer in-depth insights into the changes in efficiency between two time periods for the low-carbon logistics industry, as well as the fundamental reasons behind these changes.

3.3. Data source

China's industry classification system does not explicitly define the scope of logistics industry. Given that the GDP of transportation, warehousing, and postal services accounts for more than 85 % of China's logistics industry GDP, we use these three industries to collectively represent the logistics industry [17,40]. In the three regions, i.e., Beijing, Tianjin, and Hebei, panel data from 2012 to 2021 are selected as the DMUs for evaluating low-carbon logistics efficiency. The data mainly come from the China Statistical Yearbook, China Energy Statistical Yearbook, as well as the statistical yearbooks of Beijing, Tianjin, and Hebei, as shown in Table 1.

$$TCE = \sum_{i=1}^{n} (E_i \times \varepsilon_i \times \theta_i) \tag{6}$$

In Eq. (6), the subscript j represents the type of energy; TCE is the total carbon emissions; E_i is the energy consumption; ε_i is the standard coal coefficient, and θ_i is the CO_2 emission factors. Table 2 displays the standard coal coefficient and CO_2 emission factors for each energy source.

Note that the data for annual energy consumption and carbon dioxide emissions in the logistics industry cannot be directly obtained and needs to be calculated based on relevant data and methods. First, we add up the energy consumption of eight types of energy in the transportation, warehousing, and postal services as the total energy consumption of logistics industry. The eight types of energy include coal, gasoline, kerosene, diesel, fuel oil, liquefied petroleum gas (LPG), natural gas, and electricity. Each energy consumption here needs to be converted into standard coal. Then, the widely used methodology for measuring carbon dioxide emissions, proposed by the United Nations Intergovernmental Panel on Climate Change (IPCC), is used to measure the carbon dioxide emissions from the logistics industry [68]. The formula is as follows.

4. Results and discussions

In this section, we conduct an efficiency measurement and inefficiency analysis of low-carbon logistics in the BTH Region based on the aforementioned methodologies.

4.1. Static evaluation results

4.1.1. Overall technical efficiency analysis

The overall technical efficiency of low-carbon logistics in the BTH region from 2012 to 2021 is obtained using the CCR model, as shown in Table 3. Overall, the average overall technical efficiency of low-carbon logistics industry in the BTH region over the decade is 0.882, indicating a relatively high level. Among the three regions, Tianjin has the best performance, followed by Hebei Province, while Beijing shows a significant gap compared to the other two regions.

It can be seen that the overall technical efficiency of low-carbon logistics in Tianjin fluctuated between 0.924 and 1.000 over the past decade, with a mean of 0.983. The fluctuation range is relatively small and continues to maintain a high level, indicating that the input and output structure of Tianjin's low-carbon logistics is reasonable and the resource allocation is relatively optimal. In contrast, the average overall technical efficiency of low-carbon logistics in Beijing is 0.709. It is lower than that of both Tianjin and Hebei Province. Furthermore, the overall technical efficiency score in each year is consistently below the average level of the BTH region. This suggests that Beijing's low-carbon logistics development may have problems such as insufficient utilization of input resources and mismatched input-output resources, which require further in-depth analysis and optimization. Finally, the average overall technical efficiency of low-carbon logistics in Hebei Province is 0.955, positioning it between Tianjin and Beijing. From 2012 to 2016, only one DMU was technically efficient in Hebei. Then, four DMUs were technically efficient after 2017. Thus, Hebei's low-carbon logistics industry has been gradually developing and maturing in recent years. To summarize, the BTH region shows significant regional differences in low-carbon logistics efficiency. Tianjin performs excellently and becomes a pioneer in the BTH region; Hebei, while starting from a less favorable position, exhibits steady growth and positive outcomes; despite recent improvements in low-carbon logistics efficiency, Beijing still has considerable room for enhancement and is an area of key concern in the BTH region.

4.1.2. Pure technical efficiency and scale efficiency analysis

In this paper, PTE refers to the utilization of production inputs in the low-carbon logistics industry after removing the influence of scale efficiency. A PTE value equal to 1 implies that the production inputs have maximized their value under the current technological conditions and do not require improvement. SE represents the gap between the actual production scale and the optimal production

Table 1
The data source of the indicator.

Category	Indicator	Unit	Source
Inputs	Number of employees in logistics industry	10, 000 people	China Statistical Yearbook (2013–2022)
	Length of transportation lines	10, 000 km	China Statistical Yearbook (2013–2022)
	Fixed-asset investment in logistics industry	100 million CNY	Beijing Statistical Yearbook (2013–2022), Tianjin Statistical Yearbook (2013–2022), Hebei Statistical Yearbook (2013–2022)
	Annual energy consumption of logistics industry	10, 000 tons of standard coal	China Energy Statistical Yearbook (2013–2022)
Outputs	Gross domestic product of logistics industry	100 million CNY	Beijing Statistical Yearbook (2013–2022), Tianjin Statistical Yearbook (2013–2022), Hebei Statistical Yearbook (2013–2022)
	The volume of freight transport	10, 000 tons	China Statistical Yearbook (2013–2022)
	Turnover volume of freight transport	100 million ton-km	China Statistical Yearbook (2013–2022)
	Carbon dioxide emissions from logistics industry	10, 000 tons	China Energy Statistical Yearbook (2013–2022)

Table 2
CO_2 emission coefficients of various energy.

Energy	Standard coal coefficient	CO_2 emission factors
Coal	0.7143 kgce/kg	1.9003 kg-CO_2/kg
Gasoline	1.4714 kgce/kg	2.9251 kg-CO_2/kg
Kerosene	1.4714 kgce/kg	3.0179 kg-CO_2/kg
Diesel	1.4571 kgce/kg	3.0959 kg-CO_2/kg
Fuel oil	1.4286 kgce/kg	3.1705 kg-CO_2/kg
Liquefied petroleum gas (LPG)	1.7143 kgce/kg	3.1013 kg-CO_2/kg
Natural gas	1.3300 kgce/m^3	0.4226 kg-CO_2/m^3
Electricity	0.1229 kgce/kW-h	0.7140 kg-CO_2/kW-h

Data source: China Energy Statistical Yearbook

Table 3
The overall technical efficiency of low-carbon logistics in the BTH region.

Region	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	均值	Rank
Beijing	0.586	0.623	0.658	0.657	0.680	0.731	0.824	0.831	0.708	0.793	0.709	3
Tianjin	1.000	1.000	0.998	0.924	0.973	0.989	1.000	0.957	0.993	1.000	0.983	1
Hebei	1.000	0.859	0.911	0.880	0.874	1.000	1.000	0.980	1.000	1.000	0.955	2
Mean	0.862	0.827	0.856	0.820	0.842	0.907	0.941	0.923	0.900	0.931	0.882	–

scale of low-carbon logistics industry. A value of 1 indicates that the production scale of the industry is reasonable and has reached an optimal state. The PTE and SE results of low-carbon logistics in the BTH region are shown in Table 4.

Regarding pure technical efficiency, the overall average for the BTH region is 0.918, and its ranking from highest to lowest is as follows: Tianjin, Hebei, and Beijing. It aligns consistently with the ranking of overall technical efficiency. The average pure technical efficiency for Tianjin is 0.995. From 2012 to 2021, seven out of the ten years had a pure technical efficiency value of 1.000, indicating that Tianjin's input factors are used reasonably, and resources are almost fully utilized. The average pure technical efficiency for Hebei is 0.954, second only to Tianjin and maintaining a relatively high level. This suggests that Hebei's input resources have also been well-utilized. Beijing, with an average pure technical efficiency of 0.806, shows a significant difference compared to Hebei and Tianjin. This further means that, relative to Tianjin and Hebei, the resource utilization in Beijing's low-carbon logistics industry is suboptimal.

Regarding scale efficiency, the overall average for the BTH region is 0.956, which is higher than the average overall technical efficiency and the average pure technical efficiency. This indicates that the scale of low-carbon logistics industry in the BTH region is more efficient. Within the region, the ranking of scale efficiency from highest to lowest is Hebei, Tianjin, and Beijing. Between 2012 and 2021, the scale efficiency values of Hebei were primarily distributed between 0.981 and 1.000, and the average scale efficiency was 0.996. This suggests that the scale efficiency in Hebei is approaching an optimal state. The average scale efficiency for Tianjin is 0.988, indicating a relatively high level of scale efficiency. Beijing, with an average scale efficiency of 0.884, still remains at the lowest level, highlighting a significant gap between the actual production scale and the optimal scale in the low-carbon logistics industry.

4.1.3. Efficiency structure analysis

Based on the PTE and SE scores in the three regions, we use 0.9 as the cut-off point and further divide the efficiency types of low-carbon logistics into four categories: (1) the "dual-high type" with both pure technically efficient and scale efficient, (2) the "high-low type" with pure technically efficient but scale inefficient, (3) the "low-high type" with pure technically inefficient but scale efficient, and (4) the "dual-low type" with both pure technically inefficient and scale inefficient (Table 5). To visually illustrate the structure characteristics of low-carbon logistics efficiency in the BTH region, a scatter graph of the efficiency is plotted with PTE as the horizontal axis and SE as the vertical axis, as seen in Fig. 3.

The above figure further confirms the uneven structure of low-carbon logistics efficiency among the three regions, with Tianjin performing the best, followed by Hebei, and Beijing relatively poorer. This result is consistent with the study of Guo et al. and Zhao et al. [7,69]. Specifically, the low-carbon logistics industry efficiencies over the past decade in Tianjin all fall into the "dual-high type", and the pure technical efficiency is slightly higher than the scale efficiency. This indicates that the utilization of input resources and

Table 4
The PTE and SE of low-carbon logistics in the BTH region.

Region		2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Mean
Beijing	PTE	0.744	0.755	0.731	0.718	0.715	0.767	1.000	1.000	0.712	0.919	0.806
	SE	0.788	0.825	0.900	0.915	0.951	0.953	0.824	0.831	0.994	0.863	0.884
Tianjin	PTE	1.000	1.000	1.000	0.968	1.000	0.998	1.000	0.983	1.000	1.000	0.995
	SE	1.000	1.000	0.998	0.954	0.973	0.991	1.000	0.974	0.993	1.000	0.988
Hebei	PTE	1.000	0.860	0.929	0.882	0.877	1.000	1.000	0.992	1.000	1.000	0.954
	SE	1.000	0.999	0.981	0.998	0.996	1.000	1.000	0.989	1.000	1.000	0.996

Note: PTE represents pure technical efficiency, SE represents scale efficiency.

production scale in Tianjin's low-carbon logistics industry has reached a relatively optimal state. In Hebei Province, the efficiency of low-carbon logistics in 2013, 2015, and 2016 belongs to the "low-high type", while the rest falls into the "dual-high type". It suggests that Hebei has maintained good scale efficiency, with a relatively insufficient pure technical efficiency before 2017, but an improvement after 2017. Therefore, in the future, while Hebei continues to expand the industry scale of low-carbon logistics, it should still focus on optimizing the utilization of input resources. Then the overall efficiency of low-carbon logistics can be maintained at a high level. Finally, the development of low-carbon logistics efficiency in Beijing is more complicated. The efficiency belonged to the "double-low type" during 2012–2013, developed into the "low-high type" during 2014–2017, and then fell into the "high-low type" during 2018–2021. The erratic efficiency structure implies that Beijing's low-carbon logistics industry has multiple problems such as unreasonable industry scale, insufficient utilization of input resources, and the lack of coordination in the development. In response, Beijing should gradually increase logistics resource input, steadily expand industry scale, and simultaneously focus on addressing technological deficiencies. Ultimately, these measures can enhance the technological level in the low-carbon logistics industry, and achieve a comprehensive improvement in overall technical efficiency.

4.2. Dynamic evaluation results

4.2.1. Temporal heterogeneity analysis

Applying the Malmquist index method, we calculated the TFP, EC, TC, PTEC, and SEC for the low-carbon logistics industry in the BTH region from 2012 to 2021 (Table 6). Over the decade, the average TFP and TC are both less than 1, indicating that the total factor productivity and technological change index of low-carbon logistics in the region have declined. It is slightly different from the study of Wang and Tian [70]. This is due to the fact that we assess the overall low-carbon logistics efficiency of Beijing, Tianjin, and Hebei at the regional level. It is more conducive for the government to understand the differences in low-carbon logistics development among the three regions at a macro level. The average EC, PTEC, and SEC are all greater than 1, indicating that the overall technical efficiency, pure technical efficiency, and scale efficiency of low-carbon logistics in the region have improved. Thus, technological progress may have become the main factor restricting the further improvement of total factor productivity in the BTH region.

To delve into the relationship between TFP, EC, and TC, Fig. 4 illustrates the fluctuation curves of these three indices. It can be observed that the TFP values in the region experienced a decline during 2012–2013, 2014–2015, and 2018–2020, with an upward trend during 2013–2014, 2015–2018, and 2020–2021. The TC values exhibited nearly identical development trends during the same periods. Correspondingly, the EC values demonstrated a pattern of "uniform and small-scale fluctuations", differing from the fluctuation patterns of TFP and TC. The above results further indicate that the progress or regression of technology in the BTH region is a key factor contributing to fluctuations in total factor productivity. Thus, technological progress is essential to improve the total factor productivity of the region. Continuous introduction of advanced technologies and encouragement of innovation in low-carbon technologies are effective ways.

Fig. 5 depicts the development trends of EC and its decomposition indices in the BTH region during 2012–2021. From 2014 to 2019, the PTEC values of low-carbon logistics in the region were all equal to 1, indicating that its pure technical efficiency remained basically unchanged. At this time, the change curve of EC was completely consistent with the change curve of SEC. It suggests that the changes in the overall technical efficiency of low-carbon logistics were mainly affected by the changes in scale efficiency. Then after 2019, the changes in SEC weakened, and PTEC showed significant fluctuations, which were basically consistent with the EC. This implies that the overall technical efficiency began to be influenced by the pure technical efficiency in these three years. Therefore, integrating advanced technologies and applying them across the entire supply chain is the key to achieving more efficient low-carbon logistics in the future. Advanced technologies include the Internet of Things (IoT), blockchain, smart warehousing, automation technologies, and so on.

4.2.2. Spatial heterogeneity analysis

The efficiency changes in the BTH region are further analyzed from the spatial perspective, aiming to clarify the differences among Beijing, Tianjin, and Hebei. The calculation results are presented in Table 7.

According to the TFP values, the three regions, i.e., Beijing, Tianjin, and Hebei, can be divided into two intervals with TFP = 1 as the dividing threshold, as seen in Fig. 6.

First interval: TFP $\in [1, +\infty]$

Hebei and Beijing fall within this interval, indicating an increasing trend in both cities' total factor productivity. Specifically,

Table 5

Four types of low-carbon logistics efficiency and their characteristics.

Type	Dual-high type	High-low type	Low-high type	Dual-low type
PTE	>0.9	>0.9	<0.9	<0.9
SE	>0.9	<0.9	>0.9	<0.9
Characteristic	The overall level of low-carbon logistics industry is relatively high, requiring only slight adjustments.	Adjustments are needed in the industry scale to increase scale efficiency.	an emphasis on technological investments is required to enhance resource utilization efficiency.	Simultaneous efforts are needed to enhance low-carbon logistics level by focusing on both industry scale and resource utilization efficiency.

Note: PTE represents pure technical efficiency, SE represents scale efficiency.

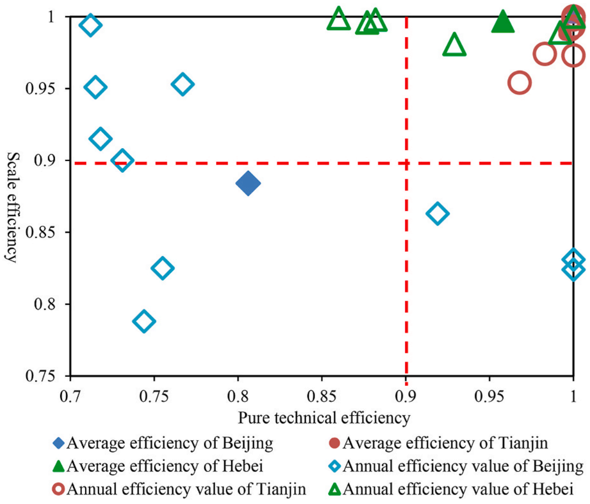

Fig. 3. Efficiency structure in the BTH region.

Table 6
The TFP and its decomposition indices of low-carbon logistics in the BTH region from 2012 to 2021.

Year	EC	TC	PTEC	SEC	TFP
2012–2013	1.090	0.778	1.063	1.026	0.848
2013–2014	1.003	1.029	1.000	1.003	1.032
2014–2015	0.999	0.899	1.000	0.999	0.898
2015–2016	0.945	1.072	1.000	0.945	1.012
2016–2017	1.014	1.106	1.000	1.014	1.122
2017–2018	1.020	1.028	1.000	1.020	1.048
2018–2019	1.005	0.966	1.000	1.005	0.971
2019–2020	0.963	1.013	0.951	1.012	0.975
2020–2021	1.036	1.070	1.038	0.998	1.108
Mean	1.008	0.991	1.005	1.002	0.998

Note: EC represents efficiency change, TC represents technical change, PTEC represents pure technical efficiency change, SEC represents scale efficiency change, TFP represents total factor Productivity.

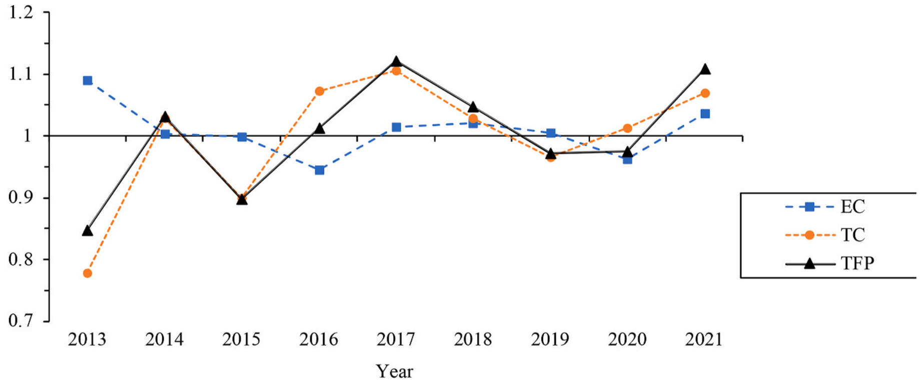

Fig. 4. Changes of TFP and its decomposition indices in the BTH region during 2012–2021.

Beijing's TFP is 1.028, ranking first among the three regions. This means that the efficiency of low-carbon logistics in Beijing has grown at an average rate of 2.8 %. Compared with the static evaluation results in Section 4.1, it is evident that while the efficiency of Beijing's low-carbon logistics industry may not have reached a high level, it shows a favorable development trend and has the prospect of continuous improvement. In general, both Beijing and Hebei have great development potential in the low-carbon logistics industry. Future efforts should focus on integrating social resources and promoting overall efficiency improvement in the low-carbon logistics industry through strengthening technological innovation and other means.

Second interval: TFP ∈ [0, 1]

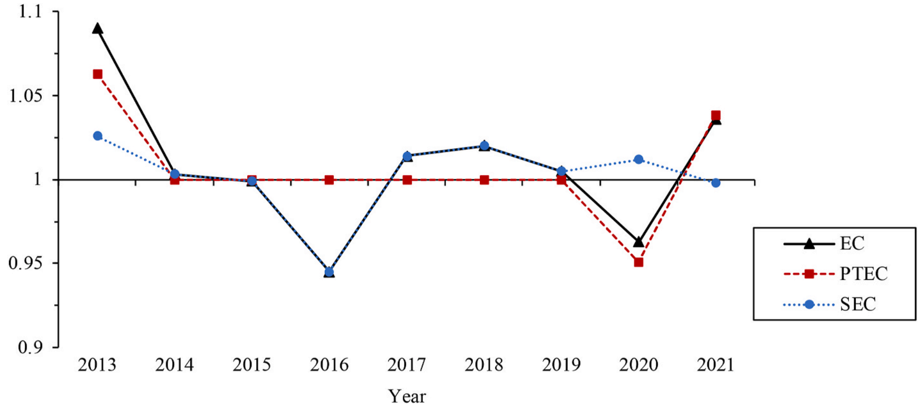

Fig. 5. Changes of EC and its decomposition indices in the BTH region during 2012–2021.

This interval includes one region, i.e., Tianjin, indicating a declining trend in Tianjin's total factor productivity. Further decomposition of Tianjin's TFP, it is found that the TC is less than 1, implying the decline in Tianjin's TFP is caused by a decrease in technological progress. In other words, the level of technological progress in Tianjin's low-carbon logistics industry is relatively low, which to some extent restricts the development of low-carbon logistics. Thus, to maintain a consistently high level of efficiency in Tianjin's low-carbon logistics industry, the government should further increase its investment in scientific research.

4.3. Inefficiency analysis

Another research objective of this paper is to identify the shortcomings of low-carbon logistics industry in the BTH region, thereby proposing feasible measures to improve the low-carbon logistics efficiency. Specifically, each inefficient DMU is projected onto the efficiency frontier by reducing the current inputs while maintaining the outputs or increasing the outputs while keeping the inputs constant, then achieving the transformation of DMUs from inefficient to efficient. We initially conduct a projection analysis for the inefficient DMUs in Beijing's low-carbon logistics industry, and calculate the input redundancy ratios and output deficiency ratios, as shown in Table 8.

It can be observed that the low-carbon logistics industry in Beijing faces significant issues of either excessive input or insufficient output. From the perspective of economic development between 2012 and 2021, the input redundancy in the region primarily manifests in excessive practitioners in the logistics industry, with 35.70 % of labor being overinvested. The underlying reason for this lies in the sustained rise in the number of migrant workers in Beijing over the past few years. As the logistics industry has a low entry barrier and is labor-intensive, an increasing number of migrant workers choose to engage in the logistics sector. While the expansion of logistics industry workforce propels the sector's development, an excessive workforce can lead to the wastage of human resources, consequently affecting the efficiency of low-carbon logistics. The insufficient output is mainly reflected in the inadequacy of freight volume and freight turnover volume. With input held constant, the freight volume and freight turnover volume in the logistics industry in Beijing could increase by 92.96 % and 234.99 %, respectively. This indicates a lower transportation efficiency in Beijing. Therefore, slowing down the growth rate of logistics practitioners and improving transportation efficiency are effective measures for enhancing the efficiency of low-carbon logistics in Beijing.

From the perspective of the energy and environment between 2012 and 2021, the logistics industry in Beijing has the potential to save energy by 19.12 % and reduce carbon dioxide emissions by 20.49 %. This indicates significant room for improvement in both energy consumption and carbon dioxide emissions in this region. In the future, Beijing should pay particular attention to the energy efficiency of logistics industry. Optimizing the structure of energy inputs, implementing relevant standards or management regulations, and strengthening the supervision and control of carbon emissions from logistics enterprises are effective measures for promoting the energy efficiency of low-carbon logistics.

The input redundancy ratios and output deficiency ratios for Tianjin's low-carbon logistics industry are presented in Table 9. From 2012 to 2021, only the indicator of freight turnover volume shows a 5.14 % shortfall in output, while the remaining indicators do not

Table 7
The TFP and its decomposition indices of low-carbon logistics in Beijing, Tianjin, and Hebei.

Region	EC	TC	PTEC	SEC	TFP	Rank
Beijing	1.023	1.005	1.016	1.006	1.028	1
Tianjin	1.000	0.951	1.000	1.000	0.951	3
Hebei	1.000	1.016	1.000	1.000	1.016	2
Mean	1.008	0.991	1.005	1.002	0.998	–

Note: EC represents efficiency change, TC represents technical change, PTEC represents pure technical efficiency change, SEC represents scale efficiency change, TFP represents total factor Productivity.

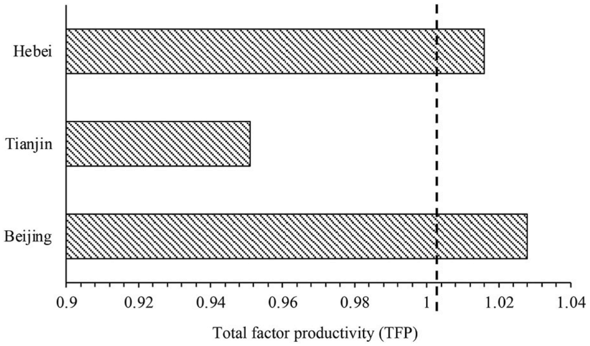

Fig. 6. The TFP for the three regions of Beijing, Tianjin and Hebei.

Table 8
The input redundancy ratios and output deficiency ratios in Beijing from 2012 to 2021.

Year	Input indicators				Output indicators			
	Number of employees in logistics industry	Fixed-asset investment in logistics industry	Length of transportation lines	Annual energy consumption of logistics industry	Gross domestic product of logistics industry	The volume of freight transport	Turnover volume of freight transport	Carbon dioxide emissions from logistics industry
2012	50.84 %	0	0	28.11 %	19.04 %	88.91 %	376.07 %	−27.49 %
2013	52.90 %	0	0	30.33 %	18.14 %	98.45 %	209.72 %	−32.43 %
2014	50.44 %	0	0	30.03 %	3.35 %	84.84 %	389.96 %	−30.76 %
2015	48.58 %	0	0	29.31 %	0	143.15 %	539.34 %	−30.41 %
2016	47.02 %	0	0	30.80 %	0	149.55 %	445.55 %	−33.40 %
2017	34.67 %	2.79 %	0	23.49 %	0	144.12 %	143.97 %	−27.63 %
2018	0	0	0	0	0	0	0	0
2019	0	0	0	0	0	0	0	0
2020	45.70 %	0	0	19.14 %	0	145.76 %	168.29 %	−22.50 %
2021	26.86 %	0	0	0	0	74.86 %	76.95 %	−0.33 %
均值	35.70 %	0.28 %	0	19.12 %	4.05 %	92.96 %	234.99 %	−20.49 %

exhibit significant input redundancy or output deficiency. The development of Tianjin's low-carbon logistics industry is relatively favorable, aligning with the earlier conclusion of the high efficiency scores for Tianjin's low-carbon logistics industry. In light of this, increasing the freight turnover volume stands out as a crucial measure for Tianjin to maintain the low-carbon logistics efficiency at a high level.

Table 10 shows the input redundancy ratios and output deficiency ratios in Hebei. From 2012 to 2021, there were improvement ratios of 4.10 % for energy consumption and 4.03 % for carbon emissions in the region. The remaining indicators did not show significant input redundancy or output deficiency. Therefore, Hebei should focus on the energy consumption and carbon emissions of logistics industry in the future. Optimizing the structure of energy inputs, implementing relevant standards or management regulations, and strengthening the supervision and control of carbon emissions from logistics enterprises are also effective measures that Hebei needs to take.

5. Conclusion and implication

The logistics industry plays a foundational and strategic role in the process of national socio-economic development. In the current context of a low-carbon economy, the Chinese logistics industry is facing challenges in transitioning and upgrading. While the GDP of logistics industry in the BTH region has maintained steady growth, its total energy consumption has decreased. Therefore, studying the efficiency of low-carbon logistics in the BTH region at the regional level is of great theoretical and practical significance for enriching the literature on logistics industry performance evaluation and better developing regional low-carbon logistics. To this end, this paper constructs a comprehensive low-carbon logistics efficiency evaluation system that considers economic benefits, energy performance, and carbon efficiency. We apply the DEA-Malmquist index to measure and analyze the low-carbon logistics efficiency in the BTH region from 2012 to 2021 in both static and dynamic perspectives. Finally, the following conclusions are drawn.

First, from the static perspective, there are significant differences in the efficiency of low-carbon logistics among the three regions of Beijing-Tianjin-Hebei, reflecting an imbalance in the development of low-carbon logistics industries in the region. Specifically, the low-carbon logistics efficiency of Beijing is significantly lower than that of Tianjin and Hebei. An analysis of the efficiency structure reveals several issues in Beijing's low-carbon logistics industry, including the unreasonable industry scale, insufficient utilization of input resources, and the lack of coordination in the development of the two aspects.

Table 9

The input redundancy ratios and output deficiency ratios in Tianjin from 2012 to 2021.

Year	Input indicators				Output indicators			
	Number of employees in logistics industry	Fixed-asset investment in logistics industry	Length of transportation lines	Annual energy consumption of logistics industry	Gross domestic product of logistics industry	The volume of freight transport	Turnover volume of freight transport	Carbon dioxide emissions from logistics industry
2012	0	0	0	0	0	0	0	0
2013	0	0	0	0	0	0	0	0
2014	0	0	0	0	0	0	0	0
2015	1.10 %	6.94 %	0	0	0.98 %	0	31.03 %	0
2016	0	0	0	0	0	0	0	0
2017	6.63 %	0	0	0	2.48 %	0	6.70 %	0
2018	0	0	0	0	0	0	0	0
2019	6.05 %	0	0	5.11 %	0	0.62 %	13.70 %	0
2020	0	0	0	0	0	0	0	0
2021	0	0	0	0	0	0	0	0
均值	1.38 %	0.69 %	0	0.51 %	0.35 %	0.06 %	5.14 %	0

Table 10

The input redundancy ratios and output deficiency ratios in Hebei from 2012 to 2021.

Year	Input indicators				Output indicators			
	Number of employees in logistics industry	Fixed-asset investment in logistics industry	Length of transportation lines	Annual energy consumption of logistics industry	Gross domestic product of logistics industry	The volume of freight transport	Turnover volume of freight transport	Carbon dioxide emissions from logistics industry
2012	0	0	0	0	0	0	0	0
2013	0	0	0	5.64 %	0	0	0	−6.81 %
2014	6.09 %	0	3.03 %	5.42 %	5.50 %	0	0	−6.48 %
2015	3.59 %	0	3.65 %	0	0	3.68 %	0	−0.29 %
2016	0.69 %	0	2.64 %	10.55 %	0.12 %	0	0	−11.38 %
2017	0	0	0	0	0	0	0	0
2018	0	0	0	0	0	0	0	0
2019	0	10.42 %	0	19.44 %	0	2.76 %	3.24 %	−15.35 %
2020	0	0	0	0	0	0	0	0
2021	0	0	0	0	0	0	0	0
均值	1.04 %	1.04 %	0.93 %	4.10 %	0.56 %	0.64 %	0.32 %	−4.03 %

Second, from the dynamic perspective, technological progress is identified as the primary cause of fluctuations in the total factor productivity across the entire BTH region. Moreover, it has emerged as a key factor constraining further enhancement of the region's total factor productivity. Although the efficiency of low-carbon logistics in Beijing and Hebei provinces lags behind that of Tianjin, both regions exhibit positive developmental trends, indicating promising prospects for sustainable improvement.

Third, from the results of the inefficiency analysis, the low-carbon logistics industry in Beijing exhibits serious input redundancy and output deficiency issues. The optimization of logistics practitioners, transportation efficiency, and energy efficiency should be the focal points for future low-carbon logistics development in the city. In comparison, the development of low-carbon logistics in Tianjin and Hebei is favorable, but transportation efficiency and energy efficiency are relatively weak points that require appropriate attention in both regions.

The above results provide recommendations for low-carbon logistics development at the industrial level in the BTH region, but there is a lack of more macro-level development strategies from the government. In light of this, and in conjunction with the research findings, this paper proposes the following two insights. First, to address the unbalanced development of low-carbon logistics in the BTH region, governments should collaboratively formulate a low-carbon logistics development strategy, undertake unified planning for the logistics industry in the region, coordinate resources such as transportation infrastructure and technological equipment to create complementary advantages, and ultimately promote the coordinated development of low-carbon logistics in the BTH region [70,71]. Second, in response to the issue of technological progress constraining the further improvement of the overall factor productivity, the BTH region should promote the in-depth integration of high-tech with the low-carbon logistics industry, such as the Internet, big data, cloud computing, artificial intelligence, and the Internet of Things [72,73]. This involves establishing a regional intelligent logistics platform to facilitate the sharing and utilization of logistics information and data, thereby enhancing the informatization and intelligence of logistics industry.

This paper has some limitations. First, this study only includes conventional input and output indicators within the logistics industry. External environmental variables such as regional economics, innovation, and urbanization, which may affect low-carbon logistics efficiency, are neglected due to the availability of high-quality data. Second, this paper solely analyzes the low-carbon logistics efficiency in the BTH region, and it is limited to extending the research results to a wider range of regions because of the single case. Additionally, a horizontal comparison with more regions, such as the Yangtze River Delta, Pearl River Delta, etc., might provide further insights. Therefore, future research should consider more evaluation indicators and regions to achieve a more comprehensive assessment and further investigate influencing factors of low-carbon logistics efficiency at the regional level.

Data availability statement

Publicly available datasets were analyzed in this study. Data will be made available on request.

CRediT authorship contribution statement

Di Yao: Writing – original draft, Methodology, Funding acquisition, Formal analysis. **Jinmei Wang:** Validation, Software, Investigation, Conceptualization. **Yuqing Guo:** Investigation, Data curation. **Ying Qiu:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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