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RESEARCH ARTICLE

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Exploring the coupling relationship of industrial agglomeration and low-carbon economy considering spatiotemporal differentiation: An empirical study in China's construction machinery industry

Abstract Although China's construction machinery thrives to meet the needs of construction, a number of challenges still remain to be overcome, such as lack of thorough knowledge of regional disparities and several limitations in terms of carbon emissions and economic development. Meanwhile, a low-carbon economy was proposed and implemented in China. This research aims to investigate the differences in industrial agglomeration of construction machineries and further explore the relationship between industrial agglomeration and low-carbon economy. On this basis, spatiotemporal analysis was performed to evaluate the levels of industrial agglomeration in different regions based on the situations of China's construction machinery industry. Furthermore, this study explored the interaction between industrial agglomeration and low-carbon economy utilizing the coupling coordination analysis method. Results showed that the coupling coordination of the two subsystems was extremely unbalanced in 2006, and it maintained an increasing trend, reaching a relatively high level in 2018. Finally, suggestions, such as establishing a policy guarantee system and implementing variable policies in different regions, were proposed to provide guidelines for the government decision-making and promote the sustainable development of China's construction machinery industry.

Keywords spatiotemporal differentiation, industrial agglomeration, low-carbon economy, construction machinery industry, empirical study

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1 Introduction

China's construction machinery industry has experienced rapid growth since reform and opening-up, and demands for the industry to exert efforts to produce intelligent, digital, and environmental-friendly products have intensified. The development cycle of construction machinery industry is influenced by macro-economic factors, such as domestic demands, exports, and supporting policies (Sun et al., 2019). The urbanization rate in China increased to 63.89% by the end of 2020, and is estimated to increase to 74.39% in 2035, with the growth in construction activities and public–private partnerships (Guan et al., 2018; Xu et al., 2022). This advancement will promote the development of the real estate and infrastructure construction and further drive the demand for construction machines. In this context, China's industrial capital elements have been converging in the spatial distribution, with the extension of industrial chain to create economies of scale and scope, the market-oriented reform of the economic system, and the inclination of preferential policies promulgated by the government (He et al., 2020). Currently, considerable industrial clusters have emerged in China, and an obvious central–peripheral model was established, thoroughly directed by local governments, stimulating a variety of economic zones, including industrial parks, technical innovation parks, and free-trade areas (Hong et al., 2020). Local governments have also implemented industrial development policies and local protection strategies for industrial development in recent years.

Industrial agglomeration, as a dynamic spatial form, acts on economic development through various mechanisms. Theoretically, industrial agglomeration has an impact on regional economic development by means of the scale effect (Zhu et al., 2017). Economic development is a critical component in improving industrial agglomeration (Liu et al., 2020). Currently, more attention has been paid to the impacts of industrial agglomeration on economic growth (Chen et al., 2019; Gao et al., 2021), and the externalities caused by industrial agglomeration can promote economic efficiency, with the differentiation of spatial agglomeration generally ignored by the existing studies. In practice, the agglomeration of China's construction machinery industry effectively optimizes the industrial structure, stimulates construction machinery competition, and increases innovation efficiency, thus improving regional competitiveness. However, disparities can be observed in the changes in the concentration scale in different regions in China, and the construction machinery industry lags behind the economic development in some regions in the process of industrial agglomeration, causing an adverse impact on the whole construction machinery industry. Hence, the spatiotemporal differentiation of construction machinery industrial agglomeration must be explored to facilitate targeted planning of industrial development areas and propose policies to maximize the positive impacts of the agglomeration effect on the economic development in China.

Another problem is that the construction machinery industry suffers from severe energy consumption and environmental pollution challenges in the process of industrial agglomeration (Li et al., 2021). Accordingly, a low-carbon economy has been proposed and widely advocated to reduce carbon emissions by means of improved energy efficiency, upgraded industrial structure, and converted driving force of economic growth from key input factors and investment to innovation (Meng et al., 2018). The low-carbon economy, which functions as a typical economic program, minimizes the output of greenhouse gasses. Tian et al. (2019) pointed out that the relationship between construction machinery industrial agglomeration and low-carbon economic development is becoming increasingly close. Consequently, industrial agglomeration must be combined with low-carbon economy to study the interaction between the two subsystems and seek a sustainable path for the coordinated development between construction machinery industrial agglomeration and low-carbon economy in China. This initiative can offer theoretical support for the sustainable economic development of the construction machinery industry and the transformation of low-carbon economy model in China.

In this regard, this work has two main objectives. The first objective is to explore the spatiotemporal differentiation of construction machinery industrial agglomeration. The second objective is to further examine the coordination between industrial agglomeration and low-carbon economy in China and propose relevant guidelines for the construction machinery industry. An indicator system was firstly established in China in 2006–2018 for this purpose. A comprehensive subsystem level was obtained, and a coupling coordination degree (CCD) model was then developed to investigate the coupling coordination between construction machinery industrial agglomeration subsystem and low-carbon economic subsystem under the context of the Five-Year Plan for Economic and Social Development of China (the Five-Year Plan for short). The findings could help in the formulation of more sustainable and effective policies for China's construction machinery industry with an optimized spatial layout and a developed low-carbon economic environment.

2 Literature review

2.1 Industrial spatial distribution

Considerable research has been conducted on economic distribution, industrial structure, land use efficiency, and regional policies, utilizing assessments of industrial spatial distribution. Numerous scholars have attempted to investigate the differences in economic distribution (Li and Wang, 2019) and industrial spatial structures (Wang et al., 2020). Tang et al. (2020) analyzed the regional disparities of China's industrial circular economy from the perspectives of time and space. They found that the spatial agglomeration pattern of China's industrial circular economy is similar to that of China's economic development. The fast-food industry was closely associated with the economic growth in China through the cross-sectional and longitudinal spatial analysis (Xue et al., 2017). Meanwhile, demands for land use in the context of urbanization have intensified, and effective land-use is intimately linked with certain factors, such as sustainable economic growth and industrial policies. Hence, the land use efficiency and polices received considerable attention.

Overall, few empirical studies of industrial spatial distribution from a comprehensive perspective have included a range of enterprises in different regions. Some research suffered some problems, such as incomplete data of industrial enterprises and bases, and insufficient geographical information in different regions, causing data quality problems. Therefore, this study collected comprehensive panel data from construction machinery industry sector and conducted a spatiotemporal analysis based on the situations of the construction machinery industry to overcome the shortcomings of existing studies and improve the objectivity and accuracy in decision-making.

2.2 Industrial agglomeration

Industrial agglomeration is defined as a concentration of industry in a certain geographic area where the elements of industrial capital continue to converge within the space and is regarded as the most dynamic spatial form (Liu and Zhang, 2021). This concept, which was popularized by Marshall (1920), derives from economic geography. Some studies have directly investigated the degree and role of industrial agglomeration in the context of manufacturing industries. Other scholars have indicated that the externalities caused by industrial agglomeration can promote economic development and energy efficiency (Kim et al., 2021). Accordingly, several studies attempted to analyze the combination of industrial agglomeration and economic development, especially the spatial interaction between industrial agglomeration and economic development among different regions. The economic consequences of industrial agglomeration could be gauged in different ways. Most studies focused on the positive impacts, while some concentrated on linking industrial agglomeration with energy efficiency.

A considerable number of studies focused on the impact of industrial agglomeration on environmental pollution to address the increasingly severe issues caused by environmental pollution. Zheng and Lin (2018) pointed out that industrial agglomeration may generate positive and negative effects on environmental pollution according to the external economic theory. Feng et al. (2019) investigated the effects of urban sprawl and industrial agglomeration on environmental efficiency utilizing the Slacks-based Measure model. They found that the negative impacts have been tested and then partially decreased with the continued improvement of industrial agglomeration. Li et al. (2021) analyzed the spatial spillover effect of industrial agglomeration on haze pollution. The result showed that haze pollution has a significant positive relationship with the industrial agglomeration levels in the local and neighboring regions. Dong et al. (2020) measured the impacts of industrial agglomeration on pollution agglomeration utilizing the Geographically and Temporally Weighted Regression model. They found that industrial agglomeration promotes pollution agglomeration.

In conclusion, existing studies have made great progress in terms of the measurement of industrial agglomeration in manufacturing industries. Industrial agglomeration has been analyzed to maintain the pairwise relationship with economic development, energy efficiency, and environmental pollution. However, there is scarcity of research on the relationship of construction machinery industrial agglomeration and economic development, as well as spatiotemporal distribution characteristics and quantitative investigations on the pairwise relationship.

2.3 Coupling coordination analysis

This study aims to explore the coordination relationship between the industrial agglomeration and low-carbon economy. Considerable empirical studies have been conducted to explore the interaction between economic development and the environment. The comprehensive index system and CCD model were commonly utilized in various studies. Li et al. (2016) studied the relationship between social economy and water environment. Li et al. (2012) took Lianyungang, China, as an example to analyze the coupling coordination between urbanization and the environment using panel data. Fan et al. (2019) investigated the coupling coordination between social economy and ecological environment based on the panel data of China’s 31 provincial regions.

The aforementioned literature has yielded significant results in the study of the interaction between the economy and the environment. Energy and industrial structural adjustments have been implemented to achieve a low-carbon economy (Xiang et al., 2013). The relationship between industrial agglomeration and low-carbon economy has been a concern in recent years and only theoretically discussed in some studies. Considering this situation, and based on the existing studies and the panel data of China’s construction machinery from 2006 to 2018, this study empirically analyzed the internal relationship between construction machinery industrial agglomeration and the low-carbon economy and proposed targeted countermeasures and suggestions.

3 Research methodology

Based on the comprehensive literature review, the evaluation of industrial agglomeration in China’s construction machinery industry was less explored as a special issue. The objective of this work is to investigate the differences in industrial agglomeration and to further analyze its coupling relationship with the low-carbon economy to improve understanding of the situations of China’s construction machinery industry and promote the coordinated development of China’s construction machinery industry and the low-carbon economy.

To achieve this goal, this work created a workflow (Fig. 1) that illustrates the prototypical framework in calculating the spatiotemporal differentiation and CCD. The Kernel Density Analysis method, which can be used in an inductive way to provide knowledge and new insights, was suitable for analyzing spatiotemporal differentiation of the construction machinery industrial agglomeration and examining the similarity and disparities between regions, which are valuable references for further study (Nakaya and Yano, 2010). Then, this work has also examined the interactive relationships between industrial agglomeration and low-carbon economy subsystems to provide an informative study. Considering the systematic and complicated coupling relationship of the two subsystems, the CCD model has been performed to explore the synergistic interaction and feedback among various determinants (Liu et al., 2018b). A coupling coordination framework must be established to measure the interaction between the two subsystems. The three main steps of coupling coordination analysis are the establishment of an indicator system, the determination of the trends of the comprehensive levels of the two subsystems, and the calculation of the coupling coordination between the two subsystems (Zhang and Li, 2020). During this process, the entropy weighting method was utilized to determine the indicators' weights of two subsystems to avoid subjectivity or computational complexity. The overall research methodology is shown in Fig. 1.

3.1 Subsystem indexes design

Considering the complicated relationship between industrial agglomeration and low-carbon economy, this study aims to objectively and comprehensively measure the level of industrial agglomeration in China's construction machinery industry in the process of low-carbon economy development. The industrial agglomeration index subsystem and low-carbon economy index subsystem must be separately established for this purpose. Based on the relevant documents and related literature, the indicators were firstly identified according to the following selection criteria of indices: (1) The indicators were most cited; and (2) The indicators were selected to facilitate data collection, understanding, and dissemination (Liu et al., 2018b). Then, the selected indicators were optimized and determined with the assistance of an expert. Finally, 6 evaluation indexes of the industrial agglomeration subsystem and 12 evaluation indexes of the low-carbon economy subsystem were determined (Table 1).

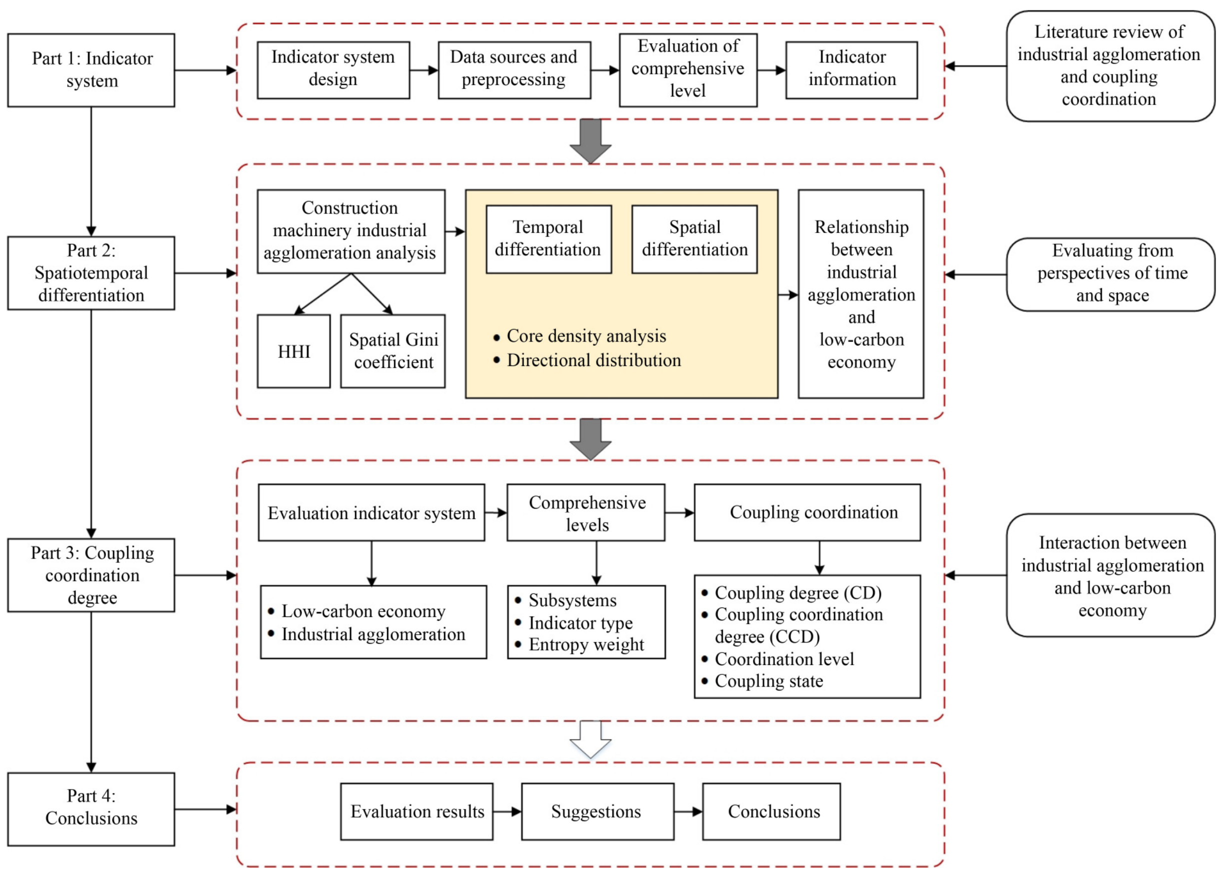

Fig. 1 Overall research methodology proposed in this study.

Table 1 Indexes of low-carbon economy and industrial agglomeration subsystems

Subsystem	First-level indexes	Second-level indexes	References
Low-carbon economy	Economic development	Gross domestic product (GDP) per capita (yuan)	Jiang et al. (2010); Zeqiraj et al. (2020)
		Per capita disposable income of urban residents (yuan)	Zhang et al. (2018)
	Industrial structure	Proportion of the second industry in GDP (%)	Dong et al. (2020)
		Proportion of the third industry in GDP (%)	Dong et al. (2020)
	Carbon output	Carbon productivity (t)	Li et al. (2020)
		Carbon consumption per unit of GDP (t)	Xiang et al. (2013)
	Carbon consumption	Carbon emission per capita (t)	Kokkinos et al. (2020)
		Carbon intensity per unit of energy (t)	Zeqiraj et al. (2020)
	Environment	Forest coverage (%)	Mohanty (2011)
		Green area per capita (m^2)	Mohanty (2011)
	Resources	Proportion of coal in energy consumption (%)	Kokkinos et al. (2020)
		Proportion of green energy in energy consumption (%)	Newbery (2016); Uddin and Rahman (2012)
Industrial agglomeration	Agglomeration scale	Industry turnover (yuan)	Li et al. (2021)
		Number of enterprises	Zhang et al. (2016)
		Number of employees	Su and Yu (2020)
	Agglomeration benefits	Market concentration rate (%)	Zhang et al. (2020)
		Herfindahl-Hirschman Index (HHI)	Dong et al. (2020)
		Spatial Gini coefficient	Liu et al. (2018a; 2019)

3.2 Data sources and preprocessing

The data in this work were collected from *China Machinery Industry Year Book*, *China Statistical Yearbook*, *Statistical Communiqué of the People's Republic of China on the National Economic and Social Development* to ensure the reliability and validity of the data. Furthermore, partial missing data were processed via spline interpolation.

After the data have been collected and processed, the data were then standardized according to Eqs. (1)–(2) to eliminate the influence of dimension, magnitude, and orientations due to the differences among the indicators' dimension and type (Liu et al., 2018b).

$$\text{Positive indicator}: \frac{x_{ij} - x_{\min j}}{x_{\max j} - x_{\min j}}, \quad (1)$$

$$\text{Negative indicator}: \frac{x_{\max j} - x_{ij}}{x_{\max j} - x_{\min j}}, \quad (2)$$

where x_{ij} represents the value of indicator j in year i, and $x_{\max j}$ and $x_{\min j}$ represent the maximum and minimum values of indicator j, respectively, from 2006 to 2018.

3.3 Evaluation of the comprehensive level

The entropy method was adopted in this research to assess the degree of dispersion of an indicator or the degree of order in a system to measure the comprehensive levels of industrial agglomeration and low-carbon economy. The entropy value is a measure of uncertainty that represents the amount of information that can be used to calculate weight. The weight of each indicator of the two subsystems was calculated according to the information entropy and variations in the indicators to analyze the relationship between industrial agglomeration and low-carbon economy as follows.

$$\text{The proportion of indicator } j \text{ in year } i: \; P_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}, \quad (3)$$

Information entropy of indicator j:

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^{m} (P_{ij} \times \ln P_{ij}), \; (0 \leqslant e_j \leqslant 1), \quad (4)$$

$$\text{Entropy redundancy of indicator } j: \; r_j = 1 - e_j, \quad (5)$$

$$\text{Weight of indicator } j: \; W_j = \frac{r_j}{\sum_{j=1}^{n} r_j}, \quad (6)$$

$$\text{Evaluation of single indicator } j: \; C_{ij} = W_j \times x_{ij}, \quad (7)$$

$$\text{Comprehensive level in year } i: \; C_i = \sum_{j=1}^{n} C_{ij}. \quad (8)$$

3.4 CCD model

Coupling degree (CD) describes the level of coupling relation and reflects the degree to which systems or system elements interact with each other (Fan et al., 2019). CCD can reflect the coordinated relationship between the internal elements of the system and determine the sequence and trend of the system, which is from disorder to order. Therefore, the CCD could provide important guidance for the sustainable development of the low-carbon economy and industrial agglomeration. A CCD model was established to accurately describe the comprehensive coordination level between the industrial agglomeration and the low-carbon economy.

Comprehensive evaluation indicator:

$$T = aI(x) + bL(y), \tag{9}$$

$$\mathrm{CD}: CD = \frac{I(x)^K \times L(y)^K}{T^{2K}}, \tag{10}$$

$$\mathrm{CCD}: CCD = \sqrt{C \times T}. \tag{11}$$

In Eq. (9), T represents the comprehensive evaluation index of the two subsystems; $I(x)$ and $L(y)$ are the comprehensive level of the industrial agglomeration subsystem and the low-carbon economy subsystem, respectively, and in this study, $I(x)$ and $L(y)$ can be calculated by C_i described in Eq. (8); and a and b represent the contribution of the industrial agglomeration and the low-carbon economy subsystem, respectively, and in this work, $a = b = 0.5$ (Ai et al., 2016). K is the regulation factor ($K = 2$) (Liu et al., 2018b). C represents the degree of coupling; when the sum of $I(x)$ and $L(y)$ is constant, C represents the CD between industrial agglomeration and low-carbon economy subsystems. CCD can be categorized into three classes, ten levels, and thirty modes (Table 2).

Table 2 Discriminating standard of CCD between low-carbon economy (L) and industrial agglomeration (I)

Classes	Levels of CCD		Development modes between subsystems	
Balanced development	$0.9 < CCD < 1.0$	Extremely balanced development	$L(y) < I(x)$	Extremely balanced development with L lagged
			$L(y) = I(x)$	Extremely balanced development between L and I
			$L(y) > I(x)$	Extremely balanced development with I lagged
	$0.8 < CCD \leqslant 0.9$	Superiorly balanced development	$L(y) < I(x)$	Superiorly balanced development with L lagged
			$L(y) = I(x)$	Superiorly balanced development between L and I
			$L(y) > I(x)$	Superiorly balanced development with I lagged
	$0.7 < CCD \leqslant 0.8$	Favorably balanced development	$L(y) < I(x)$	Favorably balanced development with L lagged
			$L(y) = I(x)$	Favorably balanced development between L and I
			$L(y) > I(x)$	Favorably balanced development with I lagged
	$0.6 < CCD \leqslant 0.7$	Moderately balanced development	$L(y) < I(x)$	Moderately balanced development with L lagged
			$L(y) = I(x)$	Moderately balanced development between L and I
			$L(y) > I(x)$	Moderately balanced development with I lagged
Transitional development	$0.5 < CCD \leqslant 0.6$	Barely balanced development	$L(y) < I(x)$	Barely balanced development with L lagged
			$L(y) = I(x)$	Barely balanced development between L and I
			$L(y) > I(x)$	Barely balanced development with I lagged
	$0.4 < CCD \leqslant 0.5$	Slightly balanced development	$L(y) < I(x)$	Slightly balanced development with L lagged
			$L(y) = I(x)$	Slightly balanced development between L and I
			$L(y) > I(x)$	Slightly balanced development with I lagged
	$0.3 < CCD \leqslant 0.4$	Slightly unbalanced development	$L(y) < I(x)$	Slightly unbalanced development with L lagged
			$L(y) = I(x)$	Slightly unbalanced development between L and I
			$L(y) > I(x)$	Slightly unbalanced development with I lagged
Unbalanced development	$0.2 < CCD \leqslant 0.3$	Moderately unbalanced development	$L(y) < I(x)$	Moderately unbalanced development with L lagged
			$L(y) = I(x)$	Moderately unbalanced development between L and I
			$L(y) > I(x)$	Moderately unbalanced development with I lagged
	$0.1 < CCD \leqslant 0.2$	Seriously unbalanced development	$L(y) < I(x)$	Seriously unbalanced development with L lagged
			$L(y) = I(x)$	Seriously unbalanced development between L and I
			$L(y) > I(x)$	Seriously unbalanced development with I lagged
	$0 < CCD \leqslant 0.1$	Extremely unbalanced development	$L(y) < I(x)$	Extremely unbalanced development with L lagged
			$L(y) = I(x)$	Extremely unbalanced development between L and I
			$L(y) > I(x)$	Extremely unbalanced development with I lagged

4 Spatiotemporal differentiation of construction machinery industrial agglomeration

4.1 Situations of China's construction machinery industrial agglomeration

Before analyzing the coupling coordination between construction machinery industrial agglomeration and low-carbon economy, this work first explored the situations of China's construction machinery industry.

According to *China Construction Machinery Industry Yearbook*, key enterprises represent the industrial advantages of a region in terms of production resources, technology, and other aspects. In this study, the top 100 enterprises in terms of industry revenue and corporate revenue of the construction machinery industry from 2006 to 2018 are selected as the key enterprises. Then, the industry concentration ratio CR_4, CR_8, and CR_{100} values can be calculated, representing the shares of the top 4, 8, and 100 enterprises, respectively, as shown in Table 3.

Table 3 CR_n of China's construction machinery industry

Year	CR_4	CR_8	CR_{100}	Industry turnover (100 million yuan)
2006	0.141785	0.233508	0.569599	1620.8
2007	0.192780	0.295613	0.620384	2223.2
2008	0.247293	0.326780	0.632831	2773.0
2009	0.402049	0.506154	0.733377	3157.0
2010	0.432175	0.592315	0.883579	4367.0
2011	0.507073	0.643506	0.925669	5465.0
2012	0.515777	0.602049	0.793241	5626.0
2013	0.455846	0.543895	0.769705	5663.0
2014	0.455840	0.548296	0.699567	5175.0
2015	0.459059	0.524390	0.655479	4570.0
2016	0.430443	0.500625	0.650395	4795.0
2017	0.419538	0.515458	0.713856	5403.0
2018	0.422395	0.516417	0.710916	5964.0

Bain's classification method is commonly used to classify and measure the level of industrial agglomeration with high credibility after practical applications (González et al., 2019). The results showed that China's construction machinery industry maintained a competitive state before 2009, with a low market concentration rate. In 2009, CR_4 and CR_8 has increased to exceed 35% and 45%, respectively, showing that the construction machinery industry has skipped the low-concentration oligopoly, directly turning into a state of middle-low concentration. CR_4 and CR_8 reached their peaks in 2012 and 2011, respectively, and then remained between 40% and 46% and 50% and 55%, respectively. Furthermore, a slightly increasing trend was observed from 2017 to 2018. Overall, the construction machinery industry maintains concentrated, although it has kept a downward trend in recent years.

As shown in Table 4, the Herfindahl-Hirschman Index (HHI) value maintained between 0.05 and 0.10 after 2009, which belongs to competition type I from the perspective of market structure classification. Before 2009, the HHI was at a low level, and it swiftly climbed in 2008–2009, which is consistent with the trend of industrial agglomeration. The results showed that the market concentration of the construction machinery industry maintains a relatively low level in the past 10 years.

The construction machinery industry has a certain degree of concentration. This sector manifested as the cliff-type monopoly of the top three companies with a lower degree of monopoly. Higher-level enterprises have a monopoly on lower-level enterprises, with top 15 large-scale monopolistic enterprises and small- and medium-sized enterprises. The market size and overall market concentration have witnessed an increase with the recovery of the entire construction machinery industry.

The spatial Gini coefficient is one of the indices to measure the industrial agglomeration degree. Table 5 demonstrates the spatial Gini coefficient value of the industry from 2006 to 2018. The value of the spatial Gini coefficient is between 0 and 1. According to Table 5, the spatial Gini coefficient increased to approximately 0.1,

Table 4 HHI of China's construction machinery industry

Year	2006	2007	2008	2009	2010	2011	2012
HHI	0.0101965	0.0153636	0.0214454	0.0521382	0.0606027	0.0808599	0.0835952
Year	2013	2014	2015	2016	2017	2018	
HHI	0.0656793	0.0644205	0.0656108	0.0576364	0.0563445	0.056262	

Table 5 Spatial Gini coefficient of China's construction machinery industry

Year	2006	2007	2008	2009	2010	2011	2012
Spatial Gini coefficient	0.03536	0.03995	0.05019	0.07406	0.08183	0.11841	0.12576
Year	2013	2014	2015	2016	2017	2018	
Spatial Gini coefficient	0.10017	0.10497	0.10563	0.08986	0.10177	0.08239	

indicating a low level of spatial agglomeration of industrial capital in the construction machinery industry.

4.2 Temporal differentiation of industrial agglomeration

After analyzing the situations of China’s construction machinery industrial agglomeration, this work further explored the differentiation of industrial agglomeration from the perspectives of time and space.

The study sampled above 50000 enterprises in the construction machinery industry as the spatial point elements with their registered addresses, and input them into Google Earth software to transform their address information into spatial data. Finally, the spatial data were imported into ArcGIS software for core density analysis by region in 2006, 2010, 2014 and 2018. The number of enterprises in each year can be seen in Table 6.

With the rapid development of the construction machinery industry, the density of clusters continued to rise from 2006 to 2010. The gathering area in Liaoning Province expanded, and the density increased. Tianjin, Zibo and Dongying in Shandong Province, Xuzhou in Jiangsu Province, and Zhengzhou in Henan Province are the agglomeration centers in the middle section of the central coastal agglomeration belt, with an increase in the agglomeration density, forming a small-scale core area within the Tianjin−Hebei−Shandong−Henan−Jiangsu−Anhui agglomeration area, the largest agglomeration area in the country, and high-density areas have expanded to the north. Low-density clusters can be found in Changsha (Hunan) and Quanzhou and Xiamen (Fujian) in the south of China. The intensity and scope of clusters in Wuhan (Hubei), Sichuan–Chongqing area, and Wenzhou (Zhejiang) increased and maintained an increasing trend in the central coastal areas centered on the junction of four provinces, namely, Shandong, Henan, Jiangsu, and Anhui. Meanwhile, the standard deviation ellipse remained constant.

In 2011, the construction machinery industry witnessed an unprecedented low ebb. The growth rate of the industry was once at a low level due to the global financial crisis. During this period, the construction machinery industry went through a survival of the fittest stage. Among the multi-nucleus accumulation centers in the central coastal agglomeration zone, the three main accumulation centers of Liaoning Province, Zhengzhou City in Henan Province, and the Yangtze River Delta region have decreased their accumulation density and distribution range. The accumulation of Xingtai, Hengshui and Shijiazhuang in Hebei Province, Dezhou in Shandong Province, and Xuzhou in Jiangsu Province was slight. The peak of the aggregation intensity at the junction of the four provinces has shifted from Zhengzhou (Henan) to Xuzhou (Jiangsu), and the core aggregation area extended from the southwest to Hebei Province. Moreover, the density and scale of the agglomeration areas in Quanzhou and Xiamen in Fujian Province, Changsha in Hunan Province, and Foshan and Guangzhou in Guangdong Province increased, while the intensity of agglomeration in Sichuan–Chongqing area declined. Meanwhile, the intensity of the scattered aggregation centers in the south increased, while the aggregation intensity of the north and south ends of the central coastal aggregation zone decreased. The intensity of the middle section increased, resulting in the standard deviation ellipse slightly moving to the southeast.

Table 6 The number of enterprises by region in 2006, 2010, 2014 and 2018, respectively

Province/City	2006	2010	2014	2018
Anhui	481	789	1043	1180
Beijing	251	273	271	258
Fujian	332	501	845	1068
Gansu	97	128	145	128
Guangdong	277	324	440	668
Guangxi	155	213	293	300
Guizhou	59	97	184	213
Hebei	786	1203	2057	3168
Henan	1168	1818	1974	2229
Heilongjiang	545	771	779	863
Hubei	766	791	962	966
Hunan	252	382	505	644
Jilin	288	365	413	442
Jiangsu	3188	4327	5687	6240
Jiangxi	189	215	296	334
Liaoning	1562	1907	2006	2125
Inner Mongolia	80	110	124	199
Ningxia	49	57	83	82
Qinghai	9	11	8	11
Shandong	1658	2411	3129	3919
Shanxi	282	361	474	624
Shaanxi	202	302	398	493
Shanghai	345	439	493	499
Sichuan	501	707	822	849
Tianjin	346	499	658	689
Tibet	4	9	10	12
Xinjiang	84	122	183	235
Yunnan	55	82	99	142
Zhejiang	834	1100	1419	1526
Chongqing	225	254	305	297
Hainan	24	25	42	38
Sum	15094	20593	26147	30441

The period from 2014 to 2018 is the economic recovery stage of the construction machinery industry. The Yangtze River Delta region in southern Jiangsu continued to maintain an absolute agglomeration advantage, and the concentration center moved slightly northward during this period. At the junction of the four provinces, the range and intensity of Xuzhou (Jiangsu)'s agglomeration have increased, meanwhile, the agglomeration intensities of Tai'an and Yantai (Shandong) and Zhengzhou (Henan) significantly increased. Xingtai and Handan in Hebei Province rapidly developed, with the range and intensity increasing faster than those of the other places, and quickly became a new gathering center within 5 years. In addition, the gathering center in Tianjin moved south to Cangzhou and Hengshui in Hebei Province. The gathering situation in Liaoning Province remained unchanged, while Daqing and Suihua in Heilongjiang Province had low-level gatherings. The southern regions, Changsha in Hunan Province, Foshan and Guangzhou in Guangdong Province, and Xiamen in Fujian Province, have expanded and strengthened to varying degrees, while Wuhan in Hubei Province and Sichuan–Chongqing area remained constant.

4.3 Spatial differentiation of industrial agglomeration

China's construction manufacturing industry is mainly distributed in the central and eastern regions, showing obvious linear aggregation patterns. The centralization trend of construction machinery industry in the Bohai Rim and the Yangtze River Delta regions becomes more distinct. Yangtze River Delta region has replaced Liaoning Province as the largest gathering area of construction machinery after 2010. Meanwhile, the concentration of Liaoning Province has gradually declined. The relative agglomeration of Liaoning Province has continued to decrease with the rapid development of the provincial border area. A large-area multi-nucleus agglomeration area was formed, with the Yangtze River Delta region as the peak concentration density and multiple small peaks in the central coastal gathering zone. Considerable scattered agglomeration areas can be observed in the southern regions (i.e., Sichuan–Chongqing agglomeration area, Changsha (Hunan) agglomeration area, Wuhan (Hubei) agglomeration area, Liuzhou (Guangxi) agglomeration area, Wenzhou (Zhejiang) agglomeration area, Quanzhou (Fujian) agglomeration area, and Guangzhou (Guangdong) agglomeration area). The central coastal agglomeration zone is connected to the Liaoning agglomeration area in the north, and to the Hubei, Hunan, and Zhejiang (mainly Wenzhou) agglomeration areas in the south. A concentrated-decentralized type of agglomeration was formed in 2018, characterized by continuous belt-type agglomeration areas around the Bohai Sea and the Yangtze River Delta, with point-shaped agglomeration areas scattered in the central and southern regions.

According to Paul Krugman's theory, the industrial advantages of a region promote the agglomeration of enterprises, which strengthens the external economic benefits and forms a cycle of positive stimulation. Hence, this work further explored the differentiation of key enterprises among different regions in China. As shown in Fig. 2, the values of Jiangsu–Zhejiang–Shanghai, Shandong–Henan, and Beijing–Tianjin–Hebei regions are significantly different from those of other regions. The number of key enterprises had an obvious second-order positive relationship with the total number of enterprises in the region.

Shandong and Zhejiang are part of the Bohai Rim region and Yangtze River Delta region, respectively. The Shandong cluster is located at the junction of Hebei, Shandong, Henan, Jiangsu, and Anhui Provinces, while the Zhejiang cluster is located at the borders of northern Zhejiang and southern Jiangsu. The figure for enterprises that gather is partly in Henan, Hebei, and northern Jiangsu, and the number of enterprises will continue to increase. This work examined the relationship between

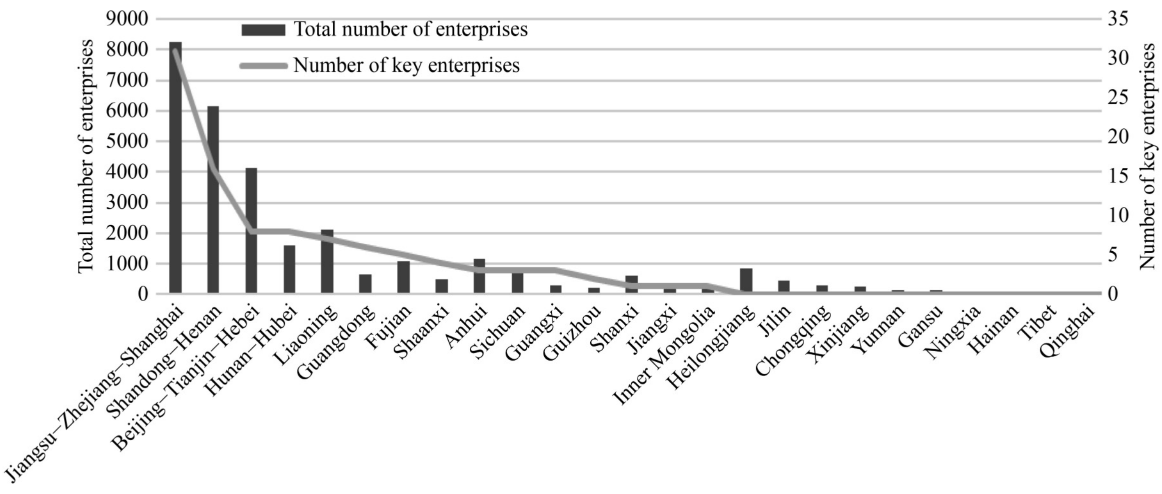

Fig. 2 Number of all enterprises and key enterprises in different regions.

the number of key enterprises and all enterprises in different regions to further explore the differentiation of distribution of key enterprises in different regions. Figure 3 reveals an obvious second-order positive relationship between the number of key enterprises and all enterprises in different regions. These regions can be categorized into four main clusters, including Jiangsu−Zhejiang−Shanghai, Shandong−Henan, Beijing−Tianjin−Hebei, and other regions. The key enterprises have a dominant advantage in the Jiangsu–Zhejiang–Shanghai area (number of key enterprises (NK) = 30), followed by the Shandong−Henan area (NK = 15). The Beijing−Tianjin−Hebei area has the third largest number of key enterprises (NK = 8). Meanwhile, the industrial agglomeration in the other regions maintained a relatively low level, with less than 8 key enterprises.

5 Coupling coordination between the industrial agglomeration and the low-carbon economy

This work explored the temporal and spatial differentiation of construction machinery industrial agglomeration and analyzed the main gathering centers, including central areas and Yangtze River Delta region, based on the results above. Theoretically, industrial agglomeration acts on carbon productivity by means of various mechanisms (Wang and Cao, 2021). Specifically, industrial agglomeration has an effect on carbon productivity through scale, technology spillover, and competition effects (Liu and Zhang, 2021). In this case, the negative externality of scale resulted in more carbon emissions with the evolution of construction machinery industrial agglomeration. Therefore, the relationship between construction machinery industrial agglomeration and low-carbon economy must be explored to better achieve the development goals of construction featuring low carbon emission and high efficiency.

5.1 Indicator system

An evaluation indicator system must be established, and the weight of the indicators must be determined to measure the two subsystems comprehensively and accurately. The coupling indicator system has two categories of indicators, namely, positive indicators denoted as "+" and negative indicators denoted as "−" in Table 7. The positive indicators promote the development of the two subsystems, while the negative indicators generate negative impacts on the two subsystems (Liu et al., 2018b). Carbon consumption had the maximum weight and was therefore an indicator with the most significant influence on the comprehensive level of the low-carbon economy at the subsystem level, followed by economic development and industrial structure. The most significant influencing indicator in the industrial agglomeration subsystem was market concentration rate.

5.2 Trends of comprehensive levels

Figure 4 shows the changing trend of comprehensive levels of the construction machinery industrial agglomeration subsystem and low-carbon economy subsystem. The industrial agglomeration subsystem showed a significant fluctuation each year. From 2006 to 2011, the comprehensive level rapidly increased, reaching the top in 2011, greatly exceeding that of the low-carbon economy

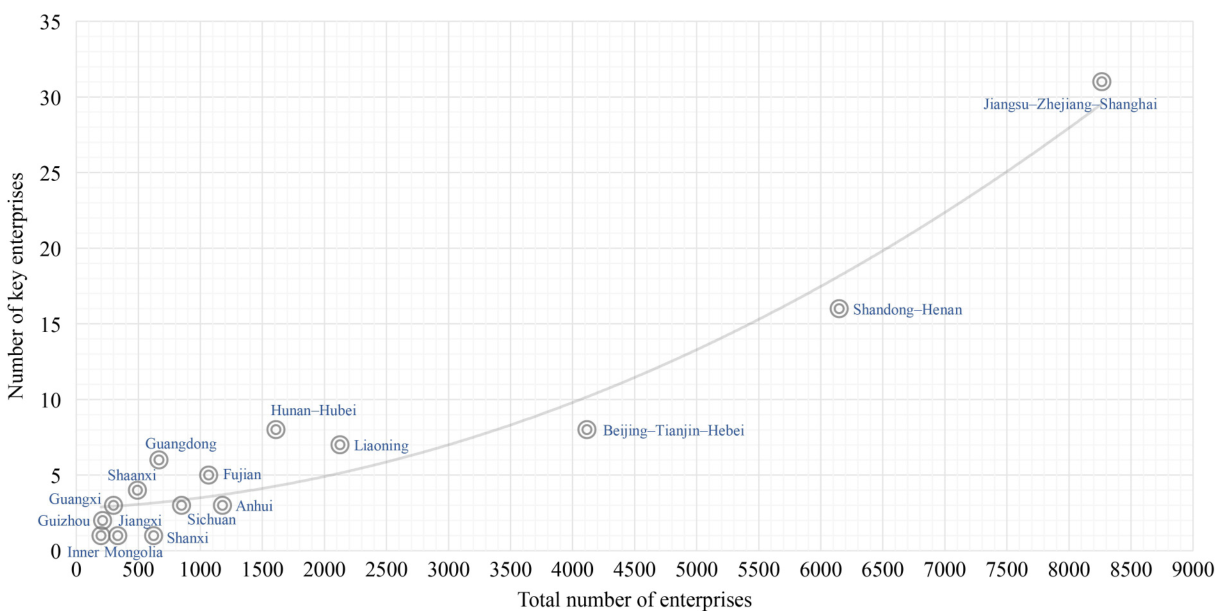

Fig. 3 Scatter diagram of all enterprises and key enterprises in different regions.

Table 7 Entropy weight of the two subsystems

Subsystem	First-level indexes	Second-level indexes	Indicator type	Entropy weight
Low-carbon economy	Economic development	GDP per capita (yuan)	+	9.09%
		Per capita disposable income of urban residents (yuan)	+	10.69%
	Industrial structure	Proportion of the second industry in GDP (%)	−	11.19%
		Proportion of the third industry in GDP (%)	+	6.93%
	Carbon output	Carbon productivity (t)	+	4.22%
		Carbon consumption per unit of GDP (t)	−	6.84%
	Carbon consumption	Carbon emission per capita (t)	−	9.03%
		Carbon intensity per unit of energy (t)	−	12.05%
	Environment	Forest coverage (%)	+	6.25%
		Green area per capita (m^2)	+	8.92%
	Resources	Proportion of coal in energy consumption (%)	−	4.34%
		Proportion of green energy in energy consumption (%)	+	10.46%
Industrial agglomeration	Agglomeration scale	Industry turnover (yuan)	+	15.28%
		Number of enterprises	+	13.94%
		Number of employees	+	19.48%
	Agglomeration benefits	Market concentration rate (%)	+	22.53%
		HHI	+	16.52%
		Spatial Gini coefficient	+	12.26%

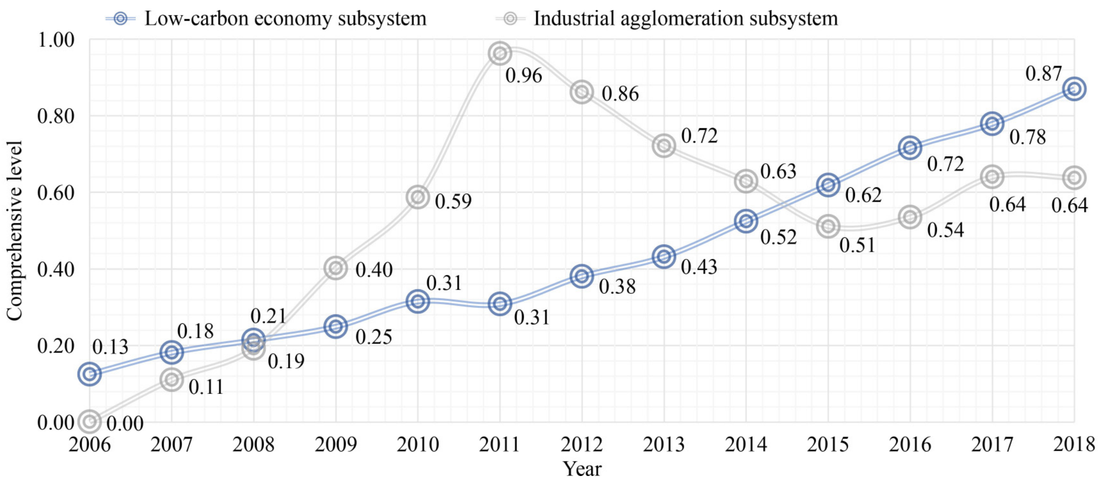

Fig. 4 Trends of the comprehensive level of the two subsystems.

subsystem. But, a remarkable decrease was observed from 2012 to 2015, and the comprehensive level in 2015 was only 0.51, nearly half of 2011. Thereafter, the comprehensive level of the industrial agglomeration subsystem slowly increased from 2016 to 2018. The overall level of the low-carbon economy subsystem steadily increased from 2006 to 2018. Totally, the comprehensive level of the low-carbon economy subsystem was lower than that of industrial agglomeration subsystem from 2009 to 2014; however, it showed significant superiority to that of industrial agglomeration subsystem from 2015 to 2018.

5.3 Coupling coordination

Table 8 illustrates the coupling coordination results of two subsystems. The coupling coordination between two subsystems witnessed a significant increase from 2006 to 2018, indicating that the coordination development pattern between two subsystems was greatly enhanced and evolved from seriously unbalanced development (CCD = 0.106) to superiorly balanced development (CCD = 0.863). In combination with the data shown in Table 8, the coupling development in the following three stages was analyzed.

Table 8 Coupling coordination results of the two subsystems

Year	*CD*	*CCD*	Coordination level	Coupling state
2006	0.177	0.106	2	Seriously unbalanced development
2007	0.970	0.376	4	Slightly unbalanced development
2008	0.999	0.451	5	Slightly balanced development
2009	0.972	0.563	6	Barely balanced development
2010	0.953	0.656	7	Moderately balanced development
2011	0.857	0.738	8	Favorably balanced development
2012	0.922	0.757	8	Favorably balanced development
2013	0.968	0.747	8	Favorably balanced development
2014	0.996	0.758	8	Favorably balanced development
2015	0.995	0.750	8	Favorably balanced development
2016	0.989	0.787	8	Favorably balanced development
2017	0.995	0.840	9	Superiorly balanced development
2018	0.988	0.863	9	Superiorly balanced development

(1) 2006–2010: In 2006, the first year of the 11th Five-Year Plan period, the CCD of the two subsystems was 0.106, showing a serious unbalanced development. A remarkable increase in the coordination level was observed during this period. The development of the low-carbon economy in China was superior to that of industrial agglomeration from 2006 to 2008. However, industrial agglomeration rapidly developed in 2009 and 2010 with the progress of coordination, and it was relatively forward, while the low-carbon economy in China was relatively backward at the end of the 11th Five-Year Plan period.

(2) 2011–2015: The coordination level has greatly improved during the 12th Five-Year Plan period compared with the general poor coordination level in the 11th Five-Year Plan period. Although a slight fluctuation of the CCD can be observed, the industrial agglomeration subsystem maintained a favorably balanced development with the low-carbon economy subsystem. Specifically, from 2011 to 2014, the two subsystems maintained a favorably balanced development level, and the low-carbon economy subsystem was lagged. In 2015, the CCD of the two subsystems was 0.750 with industrial agglomeration subsystem hindered.

(3) 2016–2018: The coordination level has showed a steadily upward trend from 2016 to 2018, and the figure arrived at 0.863, indicating that the development of the two subsystems reached a superiorly balanced level. During this period, the development of the low-carbon economy subsystem was totally forward with the development of the industrial agglomeration subsystem lagged.

6 Discussion

This study first analyzed the spatiotemporal differentiation of the construction machinery industry. The overall agglomeration type of China's construction machinery industry is a monopoly with moderately lower degree. According to the results of the temporal and spatial analysis, the Bohai Rim and the Yangtze River Delta are the dominant agglomeration areas, with scattered point agglomeration areas in the central and southern part of China. The enterprises reveal a northeast–southwest directional distribution. However, the long axis of the distribution standard deviation ellipse has been continuously shortened, with a trend of indentation to the center. Jiangsu Province, Shanghai City, and Shandong Province have a high density of industrial agglomeration. The technical innovation capacity could be improved with the development of advanced technology to accelerate the upgrading of industrial structure in these regions. Meanwhile, appropriate preferential policies should be implemented in these regions. Shandong Province has fewer research institutes, and the relevant investment could be raised to attract research-oriented professionals. Guangxi Province failed to have a large industrial agglomeration advantage due to transaction and transportation cost problems. The local government should encourage investment in the upstream of the industry chain to reduce product costs. The degree of spatial agglomeration in Hunan Province has gradually increased in recent years. The local government should adopt preferential policies to encourage investment in weak links of industrial chain and policies to promote knowledge circulation in the region. Furthermore, in the provinces located in Bohai Rim and Pearl River Delta regions, the coastal distribution facilitates the import and export trade, allowing local resources to be appropriately invested in the construction machinery industry sector. Meanwhile, Sichuan, Hubei, Heilongjiang, and other inland provinces could maintain the development of the construction machinery industry.

This study further examined the coupling coordination between the construction machinery industrial agglomeration and the low-carbon economy, and the relationship experienced three main stages according to the context of the Five-Year Plan.

Coupling relationship in the 11th Five-Year Plan period: Industrial agglomeration was relatively manifested as a forward trend, while the low-carbon economy in China was relatively backward. The global financial crisis initiated in 2008 generated a negative impact on China's economic growth, and "four trillion yuan" investment measures were accordingly adopted to further boost the domestic demand for the railway, public infrastructure, and real estate investment (Yuan et al., 2010). This situation prompts the construction machinery industry to hoard capacity, which rapidly developed at this period, with more agglomeration in terms of enterprises, industry bases, and research institutes. The low-carbon economy is defined by efficient energy use and clean energy exploration, with technological innovation of energy, reduction of carbon emissions, transformation of the industrial structure, and citizens' conceptions as the primary problems (Jiang et al., 2010). The low-carbon economy in China is consistent with Chinese characteristics, paving the way for China's sustainable and scientific development (Jiang et al., 2010; Xu and Lin, 2021). However, China's low-carbon economy progressed slowly because it was still in its infancy. A seriously unbalanced development of the two subsystems was observed. This condition is probably due to the few policies for the low-carbon economy regarding the construction machinery industry before this period. A carbon emission plan was first proposed in the 11th Five-Year Plan period. Hence, the construction machinery industry gradually responded to policy requirements, resulting in a rising trend in the coupling coordination status. Moreover, the CCD between the two subsystems was unbalanced, preventing the low-carbon economic development.

Coupling relationship in the 12th Five-Year Plan period: In 2011, the global financial crisis continued to have negative impacts on China's construction machinery industry, which reached an unprecedented low ebb with a low growth rate (López et al., 2014). During this period, China's construction machinery industry faced severe challenges, such as high inventories, price wars, and financing difficulties, showing clear survival of the fittest. Specifically, fierce price competition among construction machinery enterprises intensified, and measures, such as zero down payment and price reductions in disguise, were frequently utilized in the process of industrial agglomeration. Although this strategy may increase sales in the short term, vicious competition could damage and overdraft the long-term development of the enterprise, bring challenging risks to the enterprise, lower the threshold for competitors to enter, and disrupt the construction market order (Sun et al., 2014). The aforementioned factors resulted in the significant decline in the comprehensive level of the Chinese construction machinery industry. However, the low-carbon economy steadily progressed due to more importance attached to the sustainable development of the economy. During this period, the coordination level of the two subsystems has showed a favorably balanced trend with industrial agglomeration lagged from 2014 to 2015.

Coupling relationship in the 13th Five-Year Plan period: During this period, the demand in the construction machinery market is oriented by investments in fixed assets, such as the real estate and infrastructure (Cannas et al., 2019), which, combined with relevant national policies, has promoted the construction machinery industry. The demand for construction machinery will increase with the increase in investment. The steady economic environment and ever-improving infrastructure construction resulted in a stable uptrend of the comprehensive level of the two subsystems. During this period, the industrial agglomeration was relatively backward, while the low-carbon economy in China was relatively forward. The two subsystems were superiorly balanced and showed an upward trend as more policies and regulations regarding low-carbon economy were implemented. The superior interactions between the two subsystems gradually formed since 2016 and maintained from 2017 to 2018. The main findings in this period are that low-carbon economy development promoted the improvement of industrial agglomeration, and the superior interaction provided guarantees for the sustainable development of China's construction machinery industry. To achieve a higher-level balanced development of the two subsystems, the comprehensive level should be improved, and the interaction between the two subsystems could be further optimized.

In conclusion, the level of the low-carbon economy in industrial agglomeration areas and construction machinery industry policies are conducive to the development of the low-carbon economy. The industrial agglomeration and the low-carbon economy reveal a more coordinated trend with further advancement of the low-carbon economy in China.

7 Conclusions and suggestions

This study took China's construction machinery industry as an example to analyze the spatiotemporal differentiation of industrial agglomeration and further established an indicator system regarding low-carbon economy and industrial agglomeration from 2006 to 2018. Then, a coupling coordination model based on the panel data was adopted to analyze the coupling coordination state of the two subsystems from the dimension of time. The main conclusions are drawn as follows: First, Yangtze River Delta region replaced Liaoning Province and became the largest gathering area of the construction machinery industry. Tianjin, Hebei, Shandong, Henan, Jiangsu, and Anhui have formed a large area of industrial agglomeration, with the Yangtze River Delta region as the peak of the concentration density and multiple small peaks in the central and eastern areas of China from 2006 to 2018. Overall, a moderate degree of industrial agglomeration in the construction machinery industry was observed in 2006, which has increased since then, with a downward trend from 2012 to 2018. Second, the proportion of carbon consumption played a crucial role in the low-carbon economy subsystem, followed by economic development. In terms of industrial agglomeration, agglomeration scale and agglomeration benefits are the two main key factors in the subsystem. The relationship between the two subsystems in China is complex, and the degree of coupling and coordination has maintained an increasing trend from 2006 to 2018, arriving at superior coordination level in 2018. These findings could aid in the understanding of the relationship of industrial agglomeration and low-carbon economic development and promotion of the development of the construction machinery industry in China.

To ensure the sustainable development of China’s construction machinery industry, this study suggests that a policy guarantee system should be established for the coordinated development of industrial agglomeration and the low-carbon economy. Moreover, the government can implement different policies in various regions that consider specific situations and take advantage of resources. Considering the advanced development of Jiangsu, Shanghai, and Shandong and the relatively high density of industrial and spatial agglomeration, resource tilt and policy support could be provided to increase the agglomeration intensity and enhance regional competitiveness. Preferential policies must be implemented in regions with low intensity of spatial agglomeration to encourage investment on the industrial chain. In addition, the government can form a coordinated organization with cross-provincial or cross-city clusters to achieve a coordinated pattern of sustainable development of China’s construction machinery industry and low-carbon economy.

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