scientific reports

OPEN

Research on the coupling coordination of high-quality development and carbon emission in China's construction industry

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Accelerating the coordinated development of the high-quality development and carbon emission (HQD-CE) system in China's construction industry is of great significance in achieving carbon peak and carbon neutrality. The coupling coordination degree model (CCDM) was constructed, and spatial and temporal distribution characteristics and dynamic evolution laws of the coupled and coordinated development of HQD-CE of the construction industry in 30 provinces in China from 2012 to 2021 were explored by using spatial autocorrelation and spatial Markov chain. Results show the following: (1) The CCD showed an increasing trend, and the spatial pattern was higher in the southeast and lower in the northwest. (2) The spatial autocorrelation of CCD was significant, and the club effect was obvious, which made it difficult to realize the hierarchical leap in a short period. (3) The spatial spillover effect of CCD was significant, provinces with basic coupling dissonance faced the risk of horizontal solidification, and there were too few provinces with high-quality coupling coordination to drive the others, which could result in provinces with basic coupling coordination being influenced by provinces with basic coupling dissonance and falling back in development. The conclusions of this study can provide a reference basis for the policy formulation of low-carbon development in the construction industry.

Keywords Construction industry, High-quality development, Carbon emission, Coupling coordination degree, Spatial Markov chain

The report of the 20th National Congress of the Communist Party of China (CPC) pointed out that it is necessary to accelerate the green transformation of the development mode, and actively and steadily promote carbon peaking and carbon neutrality. The Fourteenth Five-Year Plan proposes that priority should be given to energy conservation, especially in several areas such as construction, the development of intelligent construction, the promotion of green building materials, prefabricated assembled buildings and steel-framed dwellings, and the focus on the development of green buildings and the construction of low-carbon cities. In the context of new urbanization, the continuous increase in the area of building construction, operating hours and energy consumption demand has directly increased the scale of carbon emissions from the construction industry and its proportion in the total carbon emissions, leading to a doubling of the pressure on carbon emission (CE) reduction in the construction industry. The energy consumption of the construction industry exceeds one-fifth of the energy consumption of the whole society, and the growth trend is significant, energy saving and emission reduction potential is large, which is an important entry point to realize CE reduction.

Therefore, high-quality development (HQD) of the construction industry is the core driving force to reduce carbon emissions from the construction industry and realize the goal of "double carbon", and the in-depth integration of HQD of the construction industry and CE reduction is the key to realizing a win-win situation for ecological environmental protection and the transformation and development of the construction industry. Since there are obvious differences in HQD and CE of the construction industry in China's provinces and regions, whether CE can be harmonized with HQD of the construction industry is a real problem that needs to be explored and solved. Based on the principle of coupling coordination, this study measured the coupling coordination degree (CCD) between HQD-CE of the construction industry in China's provincial areas, and on this basis, revealed the temporal and spatial evolution characteristics of the CCD, to promote the interaction and integration of them and reach synergistic optimization among provinces and regions, and then realize the

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comprehensive green transformation of the mode of economic development to provide a reference for decision-making.

Existing studies on CE mainly focus on measurement methods[1], spatial and temporal evolution[2–4] and influencing factors[5,6]. The CE factor method[7,8], the life cycle method[9] and the input-output method[10,11] are mostly used. In the study of CE influencing factors, the STIRPAT model[12], exponential decomposition method[13] and structural decomposition method[14] are mostly used; some scholars found that factors such as population[15], technology[16], industrial structure[17] and government intervention[18] correlate with the intensity of CE; some scholars start from the industrial level[19–21] or focus on the administrative region[22–26] to explore the spatial and temporal changes of CE. The research on HQD of the construction industry mainly focused on the connotation, the construction of the evaluation index system and the analysis of influencing factors, etc. Gao and Wang[27] constructed the evaluation index system for HQD of the construction industry from five dimensions based on the concept of HQD of the economy, combined with the characteristics of the development of the construction industry in China. Wang and Wu[28] included CE as a non-desired output in the evaluation system and investigated the characteristics of spatial and temporal differentiation, the evolution of dynamic trends, and their drivers of HQD in China's construction industry. Song et al.[29] and Wang et al.[30] studied the influencing factors of green building development at the national and municipal levels, respectively.

By reviewing existing literature, it can be found that scholars currently have in-depth research on the subfields of HQD and CE of the construction industry, but there are not yet many studies on the relationship between the two, and there are fewer studies on the relationship between the two coupled and coordinated development. Related studies are more common to analyze the countermeasures and paths for HQD of the construction industry under the low-carbon goal[31,32]. In this paper, based on clarifying the coupling and coordination mechanism between HQD and CE of the construction industry, 30 provinces in China are taken as the research objects, the CCDM is constructed, and the dynamic evolution trend of the coupling and coordinating of the two systems is investigated with the help of the spatial autocorrelation and the Markov chain. Compared to previous literature, this paper has made the following innovations and contributions. First of all, this paper establishes the HQD system for the construction industry from six aspects: economy, innovation, green, coordination, sharing and openness, which enriches the existing evaluation index system for HQD of the construction industry. Secondly, realizing the goals of carbon peaking and carbon neutrality requires not only controlling carbon emissions but also improving the efficiency of carbon emissions. Therefore, unlike the construction of CE systems in the previous literature, this study evaluates CE in terms of both the efficiency of carbon emissions and the current status of CE. Finally, the temporal and spatial evolution characteristics of CCD of the HQD-CE system in the construction industry are analyzed from both static and dynamic perspectives, which provides a reference for the scientific formulation of CE reduction programs in the construction industry.

The remaining parts of this research are as follows: Sect. 2 explains the mechanisms of coupled coordination relationships; Sect. 3 introduces the research methodology; Sect. 4 and Sect. 5 demonstrate the empirical results and discussion; Sect. 6 draws conclusions, provides policy implications and points out limitations.

The mechanism of coupling coordination

The HQD-CE of the construction industry is an open system with rich content and wide coverage, and the elements constituting the system interact and influence each other. It is of great significance to analyze the interaction mechanism between the two for the sustainable and high-quality development of the construction industry and the achievement of the "dual-carbon" goal.

On the one hand, China is gradually promoting the transformation of the green and HQD of the construction industry. China has increased policy and financial support, guided all sectors to allocate funds and other elements to green industries, accelerated the research and development of energy-saving and carbon-reducing advanced technologies, and contributed to the improvement of CE efficiency in terms of funding and technology; vigorously promoting green and low-carbon buildings, optimizing energy-saving and carbon-reducing design of newly built buildings, advancing energy-saving renovation of existing buildings, and establishing a regulatory system for energy-saving in public buildings to reduce carbon emissions are important drivers for the realization of the "dual carbon" goal. On the other hand, under the crisis of the unsustainable traditional development mode, taking CE as the general grip, breaking the traditional path dependence of high energy consumption and high emission, forcing the transformation and upgrading of the economic structure, energy structure and industrial structure, and continuously empowering HQD of the construction industry. The mechanism of the coupling and coordination relationship of HQD-CE in the construction industry is shown in Fig. 1.

Materials and methods

Comprehensively analyzing HQD and CE of China's construction industry, this paper argues that the two systems have a complex coupling relationship and are constantly changing in time and space dimensions. Therefore, this paper constructs a coupling coordination framework and evaluation index system to measure the development level of the two systems, and adopts a spatial autocorrelation model and Markov chain to portray its spatial evolution characteristics.

The evaluation indicator system

High-quality development of construction industry indicator system

Regarding the connotation and characteristics of HQD in the construction industry has not yet formed a unified standard, and the existing studies have generally taken the five development concepts of "innovation, coordination, green, openness and sharing" as the evaluation criteria for HQD. According to the overall requirements and main tasks of The Fourteenth Five-Year Plan, combined with the connotation and characteristics of HQD of the

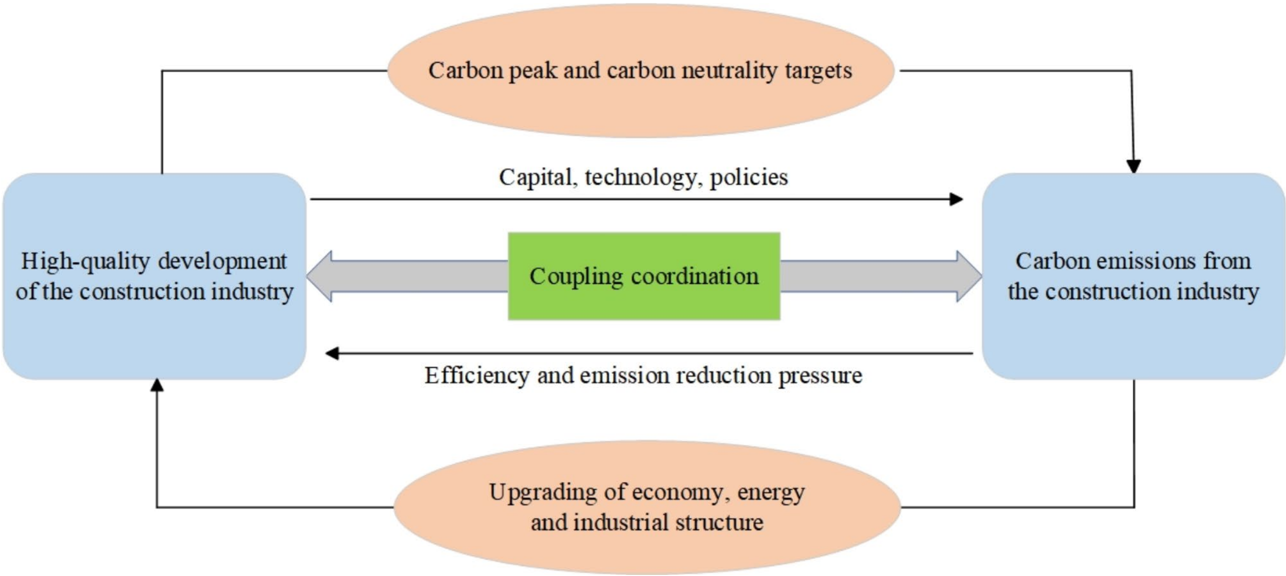

Fig. 1. The mechanism of coupling coordination.

Standard layer	Indicator layer	Units	Indicator attributes
Economic benefits	Proportion of total construction output to GDP	%	+
	Amount of construction contracts awarded	10,000yuan	+
	Amount of profit and tax per capita	yuan/person	+
	The gearing ratio of construction firms	%	–
Innovative development	Rate of technological equipment	yuan/person	+
	Power equipment rate	kilowatt/person	+
	Labor productivity	yuan/person	+
	Percentage of senior titles in survey and design organizations	%	+
Green development	Greening coverage in built-up areas	%	+
	Steel and cement consumption per 10,000 yuan of output value	tons/10,000yuan	–
	Energy consumption per 100 million yuan of output value	10,000 Tons of standard coal/100 million yuan	–
Coordinated development	Percentage of output value of state-owned enterprises	%	+
	The gross output value of special-level and first-level general contracting enterprises and first-level specialized contracting enterprises	10,000yuan	+
Shared development	The average wage of persons employed in urban units	yuan/year	+
	Housing floor space per urban resident	m^2	+
	Green space per capita in parks	m^2	+
	Percentage of completed areas for research, education, medical care, culture, sports and recreation housing	%	+
Open development	The gross output value of the enterprise completed in other provinces	10,000yuan	+
	Percentage of private enterprises' gross output value	%	+

Table 1. High-quality development (HQD) of the construction industry evaluation index system.

construction industry, and based on the principles of scientific, systematic and accessible, and with reference to the studies of Cao et al.[33], Gao & Wang[27], Zhang & Zhang[34] and Zhang et al.[35], the index system of HQD of the construction industry constructed in this paper includes a total of 19 indexes in six aspects, including economic efficiency, innovative development, green development, coordinated development, shared development, and open development. As shown in Table 1.

Carbon emission of construction industry indicator system

To realize the goal of carbon peak and carbon neutrality, it is not only necessary to control carbon emissions but also to improve carbon emissions efficiency. Applying the 'Energy Indicators for Sustainable Development: Guidelines and Methodologies', jointly published by the International Atomic Energy Agency and the United Nations Department of Economic and Social Affairs as a reference, combined with the studies of Chen et al.[36], Fu et al.[37] and Jiang et al.[38], the carbon emission index system of the construction industry was established, including 2 aspects of carbon emission efficiency and carbon emission status. Efficiency indicators are used to reflect the internal performance of the CE system, while status indicators are used to reflect the external performance. The specific indicators are shown in Table 2.

Data sources

The relevant data from 30 provinces in China from 2012 to 2021 are collected for the study (Tibet, Hong Kong, Macao and Taiwan were not included in the study due to a large amount of data missing). The indicators data are mainly from China Statistical Yearbook (2013–2022), China Construction Industry Statistical Yearbook (2013–2022), China Energy Statistical Yearbook (2013–2022) of the National Bureau of Statistics of China, as well as the local statistical yearbook and China Carbon Accounting Database. For very few missing data, the linear interpolation method is used to complete. According to the standards of the National Bureau of Statistics, the country's 30 provinces are divided into four regions: eastern, central, western and northeastern regions, as shown in Fig. 2.

Research methodology

The entropy method

The Entropy method is an objective empowerment method, which determines the indicator weights according to the observed values of each indicator, which can avoid the interference brought by human factors to the greatest extent, and make the measurement of HQD and the level of CE of the construction industry more reasonable. The specific steps are as follows:

Standardization of data:

Positive indicator

$$Z_{ij} = \frac{X_{ij} - \min X_{ij}}{\max X_{ij} - \min X_{ij}} \tag{1}$$

Negative indicator

$$Z_{ij} = \frac{\max X_{ij} - X_{ij}}{\max X_{ij} - \min X_{ij}} \tag{2}$$

where Z_{ij} is the standard value, if Z_{ij} is 0, it is replaced by 0.00001. X_{ij} represents the value of the indicator *j* of the system *i*, max X_{ij} and min X_{ij} represent the maximum and minimum values of the indicator X_{ij}, respectively.

Calculation of the weights of the indicators:

$$p_{kj} = \frac{Z_{ij}}{\sum_{i=1}^{n} Z_{ij}} \tag{3}$$

$$e_j = -\frac{1}{\ln(n)} \cdot \sum_{i=1}^{n} p_{kj} \ln(p_{kj}) \tag{4}$$

$$w_j = \frac{1 - e_j}{n - \sum_{j=1}^{n} e_j} \tag{5}$$

where p_{kj} is the weight of the indicator *j* in the province *k*, *n* is the number of provinces, e_j is the entropy value of the indicator *j* and w_j is the weight of the indicator *j*.

Calculation of a comprehensive system development index:

$$U_i = \sum_{i=1}^{n} w_j Z_{ij} \tag{6}$$

Standard layer	Indicator layer	Units	Indicator attributes
Carbon emission efficiency	Technical efficiency	%	+
	Pure technical efficiency	%	+
	Scale efficiency	%	+
Carbon emission status	Carbon emissions per capita	ton/person	–
	Energy consumption	10,000 Tons of standard coal	–
	Carbon intensity	tons/10,000 yuan	–
	Carbon productivity	yuan/ton	+
	Carbon emissions	million tons	–
	Carbon emission density	10,000t/km^2	–

Table 2. Carbon emission (CE) of construction industry evaluation index system.

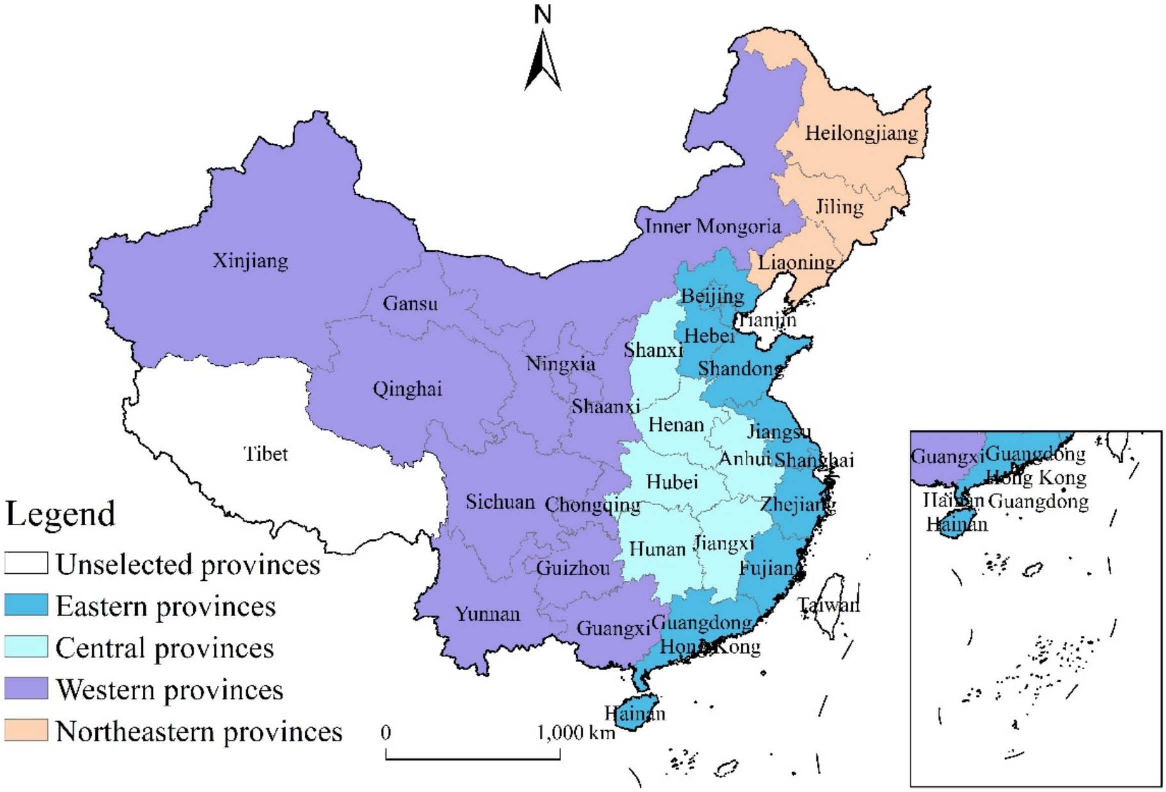

Fig. 2. China's four major regions and provincial administrative divisions.

Coupling coordination degree model

In this paper, the degree of interconnection between the HQD-CE systems of the construction industry is defined as the degree of coupling, and the degree of coordinated development of the two systems is defined as the coupling coordination degree (CCD). Referring to the existing studies, the coupling model is introduced to analyze the CCD of HQD-CE systems of the construction industry. In order to avoid the problem of underestimation of the coupling degree, the calculation formula is as follows:

$$C = \frac{2\sqrt{U_1 \times U_2}}{U_1 + U_2} \tag{7}$$

$$D = \sqrt{C \times T} \tag{8}$$

$$T = \alpha U_1 + \beta U_2 \tag{9}$$

Where C represents the coupling degree; D represents CCD, ranging from 0 to 1; T is the degree of integration of the two systems; α and β represent the weights of the two systems; U_1 and U_2 represent HQD and the level of CE in the construction industry, respectively. Considering that the HQD system is as equally important as the CE system, both α and β are assigned a value of 0.5, and the coupling degree and the CCD are graded. In order to make the coupling coordination value informative, based on the research of Li et al.[39] and combined with the actual measurement results, this paper divides the CCD into four grades, as shown in Table 3.

Spatial autocorrelation analysis

In view of the fact that the CCD of HQD-CE of the construction industry may have a clustering state at the provincial spatial level, this paper introduces the global Moran's I to test the spatial correlation, and the formulas are as follows:

Coupling coordination degree	Type of coupling coordination	Type
0.00 ~ 0.25	Serious coupling dissonance	I
0.25 ~ 0.50	Basic coupling dissonance	II
0.50 ~ 0.75	Basic coupling coordination	III
0.75 ~ 1.00	High-quality coupling coordination	IV

Table 3. Classification of coupling coordination degree (CCD).

$$I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}\left(X_i - \overline{x}\right)\left(X_j - \overline{x}\right)}{S^2 \sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}} \tag{10}$$

$$S^2 = \sum_{i=1}^{n}\left(X_j - \overline{x}\right) \tag{11}$$

where X_i and X_j represent the coupling coordination degree of HQD of the construction industry and carbon emission in each province, $\bar{x}$ is the mean value, n is the number of provinces, and W_{ij} is the spatial weight matrix. Moran's I is used to measure the global spatial pattern characteristics of the CCD, ranging from − 1 to 1, and positive values indicate positive spatial correlation, negative values indicate negative spatial correlation, and equal to 0 indicates that its spatial distribution is in a random state, with no obvious correlation.

The global Moran's I is mainly used to explore the spatial correlation of the region as a whole, but it is easy to ignore the differentiated characteristics within the region, which in turn leads to the homogenization of the research results[40]. For this reason, it is necessary to introduce the local Moran's I to examine the local spatial autocorrelation of the CCD of HQD-CE in the construction industry, with the formula:

$$I_i = \frac{\left(X_i - \overline{x}\right)}{S^2} \sum\nolimits_{j=1}^{n} W_{ij}\left(X_j - \overline{x}\right) \tag{12}$$

where X_i, X_j, $\bar{x}$, n, S^2, W_{ij} are consistent with the settings in the global Moran's I. A positive value of I_i indicates that a province's coupling coordination is positively correlated with neighboring provinces, while a negative value of I_i indicates a negative correlation.

Spatial Markov chain

Due to the differences in geographic location, resource endowment and economic development level, the CCD of HQD-CE of the provincial construction industry may have regional correlation and dependence in a geographical sense, and this paper tries to explore this issue by introducing Markov chains. The CCD is regarded as a discrete time series and discretized into three types.

Let $M_t = \left[M_{1,t}, M_{2,t}, M_{3,t}, \ldots, M_{k,t}\right]$ be the probability distribution vector of each state at the moment t, then the transfer between different moments can be regarded as a Markov state transfer probability matrix of order $k * k$, as shown in Eq. (13).

$$P = \begin{bmatrix} p_{11} & \cdots & p_{1k} \\ \vdots & \ddots & \vdots \\ p_{k1} & \cdots & p_{kk} \end{bmatrix} \tag{13}$$

where P_{ij} represents the probability that the coupled coordination of HQD-CE in the construction industry shifts from type i at moment t to type j at moment t+1; $P_{ij} = a_{ij}/a_i$, a_{ij} represents the sum of the number of provinces that shifted from type i at moment i to the state of j at moment t+1 in the study period, and a_i represents the sum of the number of provinces that belong to type i in the study period.

The change of the coupled coordination state of HQD-CE in China's provincial construction industry is not an isolated spatial evolution process but is in a domain environment with state characteristics, which is influenced by the coupled coordination state of the neighboring domains and has spatial spillover effects. Therefore, the concept of "spatial lag" is introduced into the traditional Markov chain to obtain a spatial Markov chain, and the influence of the CCD of neighboring provinces on the dynamic evolution of the coupling coordination state of the province is examined. The spatial Markov matrix, conditional on the spatial lag type of the base period year (assuming that there are k spatial lag types), decomposes the ordinary Markov matrix of order k * k into k k * k conditional transfer probability matrices, and P_{ij} represents the probability of transferring from the type i in the year t to the type j in the year t+1 conditional on the spatial lag type k of a certain province at the moment of t. This will reveal the dynamic role of spatial factors in the coupled coordinated state transfer process.

Results

Analysis of the HQD system of the construction industry

Figure 3 shows the temporal trend of the comprehensive index of the HQD system of China's construction industry. The HQD system composite index increased from 0.2629 in 2012 to 0.4102 in 2021, with an average annual growth rate of 5.6%, indicating an overall positive trend in HQD of the construction industry.

The spatial pattern of the HQD system of the construction industry in 2012, 2015, 2018 and 2021 is presented in Fig. 4, separating the composite index of the HQD system into four levels, from low to high. In 2012, HQD of the construction industry was concentrated at a higher level in central and eastern coastal areas, while it was at a lower level in western and northeastern regions. The provinces with a high level of HQD of the construction industry were mainly concentrated in central and eastern coastal areas, while it was at a low level in western and northeastern regions. Zhejiang, Jiangsu, Beijing, Tianjin, Guangdong, Shanghai, Hebei, Hunan, Jiangxi, Shaanxi, Shandong and Liaoning were at the second level. It is worth noting that the composite index of HQD of the construction industry in Liaoning and southeast coastal provinces was at the same level. However, the composite index of HQD of the construction industry in Liaoning is 0.2533, while the southeast coastal provinces are about 0.4. there is still a gap between the two. In 2021, the southeast coastal areas remained higher than the inland provinces. Jiangsu was at the fourth level with a composite index of 0.8204. Jiangsu was at the fourth level with a composite index of 0.8204, Beijing, Hubei, Guangdong and Zhejiang were at the third level, Heilongjiang was at the first level, and the remaining provinces were at the second level. Beijing, Hubei, Guangdong and Zhejiang are at the third level, Heilongjiang is at the first level, and the other provinces are at the second level. In general, the level of HQD of the construction industry in 30 provinces has progressed significantly, but there is an imbalance in regional development.

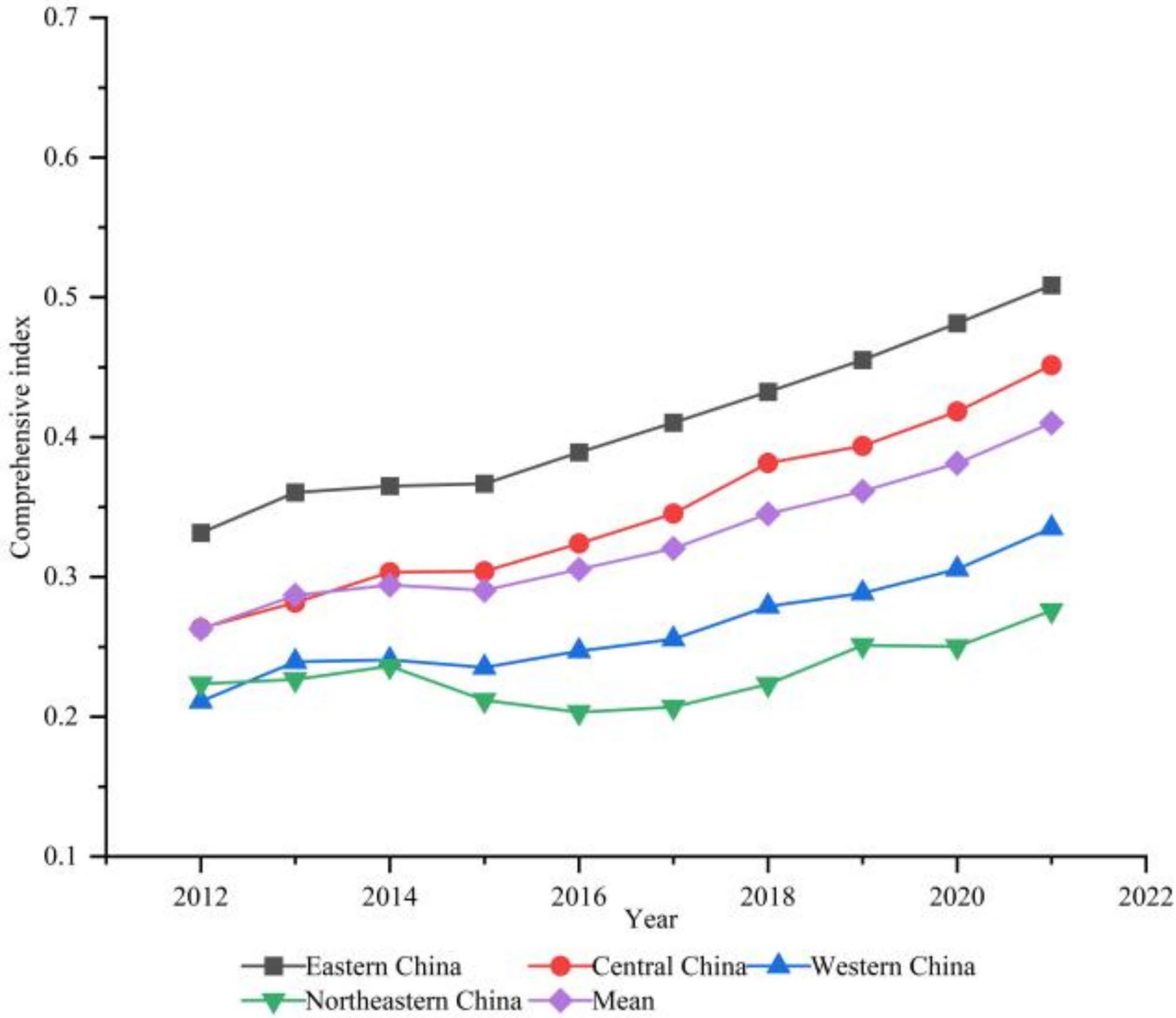

Fig. 3. Temporal evolution trend of HQD of China's construction industry from 2012 to 2021.

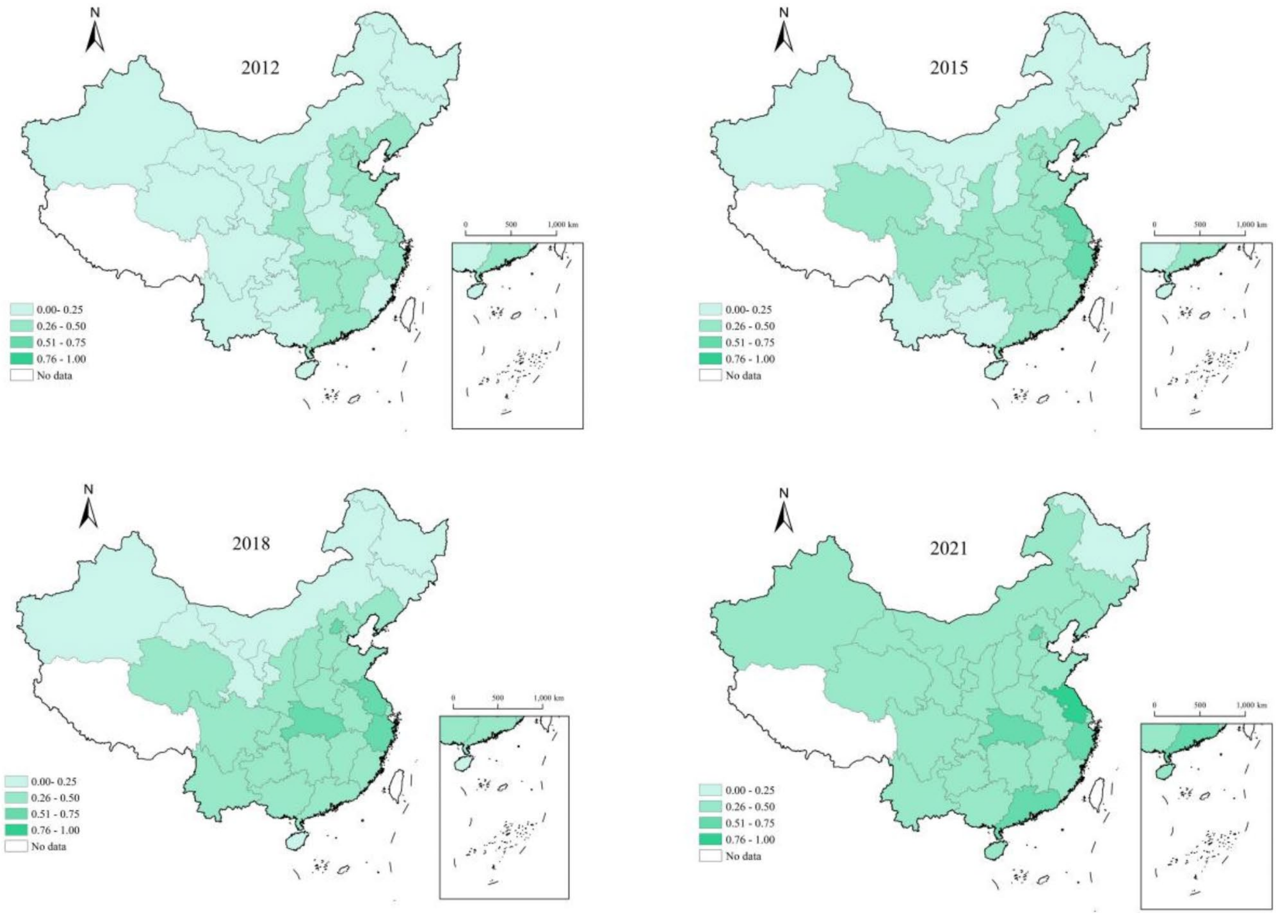

Fig. 4. Spatial pattern of HQD of China's construction industry in 2012, 2015, 2018 and 2021.

Analysis of the CE system of the construction industry

Figure 5 presents the temporal trend of the composite index of the CE system of China's construction industry. The CE system composite index was less volatile, with the maximum and minimum values of 0.2464 in 2021 and 0.2064 in 2012, respectively. The eastern, central and western regions showed similar trends. However, the comprehensive index of the CE system in the northeast region fluctuated greatly from 2013 to 2019, exhibiting a development trend of "down-up-down", with no significant change in the front and back levels.

The spatial pattern of the CE system of the construction industry in 2012, 2015, 2018 and 2021 is presented in Fig. 6, separating the comprehensive index of the CE system into four levels, from low to high. In 2012, the higher-level provinces were mainly concentrated in the eastern region, and the lower-level provinces were primarily distributed in the central and western regions. Hainan, Guangxi, Jiangsu, Heilongjiang, Beijing, Jiangxi and Zhejiang were at the second level, while other provinces were at the first level. In 2021, Jiangsu was at the fourth level, most provinces in the eastern region were at the second level, while most provinces in the central and western regions were still at the first level. In addition, the comprehensive index of the CE system of Tianjin, Inner Mongolia, Jilin, Heilongjiang, Zhejiang and Anhui showed a decreasing trend. Overall, differences in the CE system of the construction industry are evident among provinces, and the eastern provinces were generally higher than the provinces in the central and western regions.

Analysis of coupling coordination degree

Then, the CCD between HQD-CE systems of the construction industry in 30 provinces in China from 2012 to 2021 is calculated based on the CCDM. As shown in Fig. 7, the average value of the CCD of HQD-CE of the construction industry increased from 0.4744 in 2012 to 0.5416 in 2021. The CCD in all of China's 30 provinces showed a fluctuating upward trend, indicating that the coordination relationship of the HQD-CE systems of the construction industry in these regions was continuously improved, and the green, low-carbon and high-quality development of the construction industry was gradually promoted. Four years (2012, 2015, 2018 and 2021) were selected to analyze the evolution trend of the CCD of HQD-CE of the construction industry, as shown in Fig. 8.

In 2012, none of the provinces reached the high-quality coupling coordination stage, Beijing, Tianjin, Heilongjiang, Jiangsu, Zhejiang, Jiangxi, Guangxi and Hainan were in the basic coupling coordination stage, and the values of CCD of the remaining provinces were in the basic coupling dissonance stage, and no province was in a stage of serious coupling dissonance. In 2015, Beijing, Jiangsu, Zhejiang, Jiangxi, Guangxi and Hainan were still in the basic coupling coordination stage, Hubei transitioned from basic coupling dissonance to basic

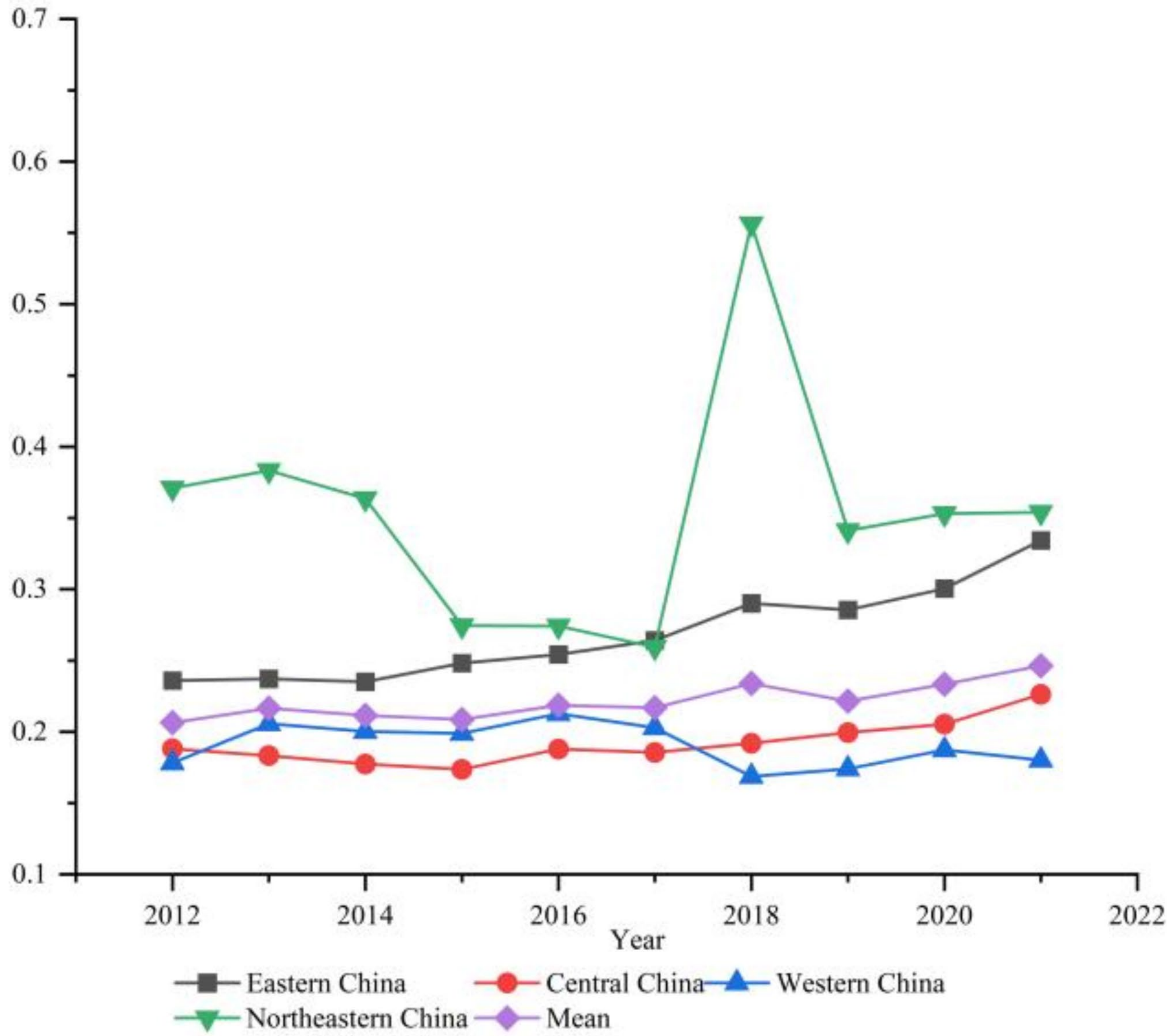

Fig. 5. Temporal evolution trend of CE of China's construction industry from 2012 to 2021.

coupling coordination, and the values of CCD of the remaining provinces were in a basic coupling dissonance state, which changed little compared with 2012. In 2018, Jiangsu took the lead in achieving a breakthrough, becoming the first province in the country to reach a high-quality coupling coordination state, and Liaoning, Shandong, Shanghai, Fujian, Guangdong, and Chongqing transformed from basic coupling dissonance to basic coupling coordination. In 2021, the values of CCD improved, and Beijing became the second province to reach the high-quality coupling coordination stage, Hebei, Anhui, Hunan, Shaanxi and Sichuan transformed from basic coupling dissonance to basic coupling coordination, and the rest of the provinces are still in the basic coupling dissonance stage.

Overall, the CCD of HQD-CE of the construction industry in China's 30 provinces has improved on the whole, showing a spatial distribution and evolution pattern of high in the southeast, low in the northwest, and decreasing from the coastland to the inland.

Spatial correlation analysis of coupling coordination degree

From 2012 to 2021, the global Moran's I measurement results of the CCD of HQD-CE in the construction industry are shown in Table 4. The Moran's I of all years are positive, and except for 2013, the global Moran's I of the rest of the years are significant at the 10% level, showing obvious spatial positive correlation.

Furthermore, in this research, the local spatial features of CCD are categorized into four kinds of spatial associations: high-high (H-H), low-high (L-H), low-low (L-L), and high-low (H-L), as shown in Fig. 9.

A H-H cluster indicates high CCD in an area and adjacent areas. In 2012, Beijing, Tianjin, Jiangsu, Zhejiang, Jiangxi and Hunan were all in this category. In 2021, the number of provinces with H-H clusters increased to eight, including Shanghai, Fujian, Hubei, Hunan, Guangdong and so on. A L-H cluster indicates low CCD in

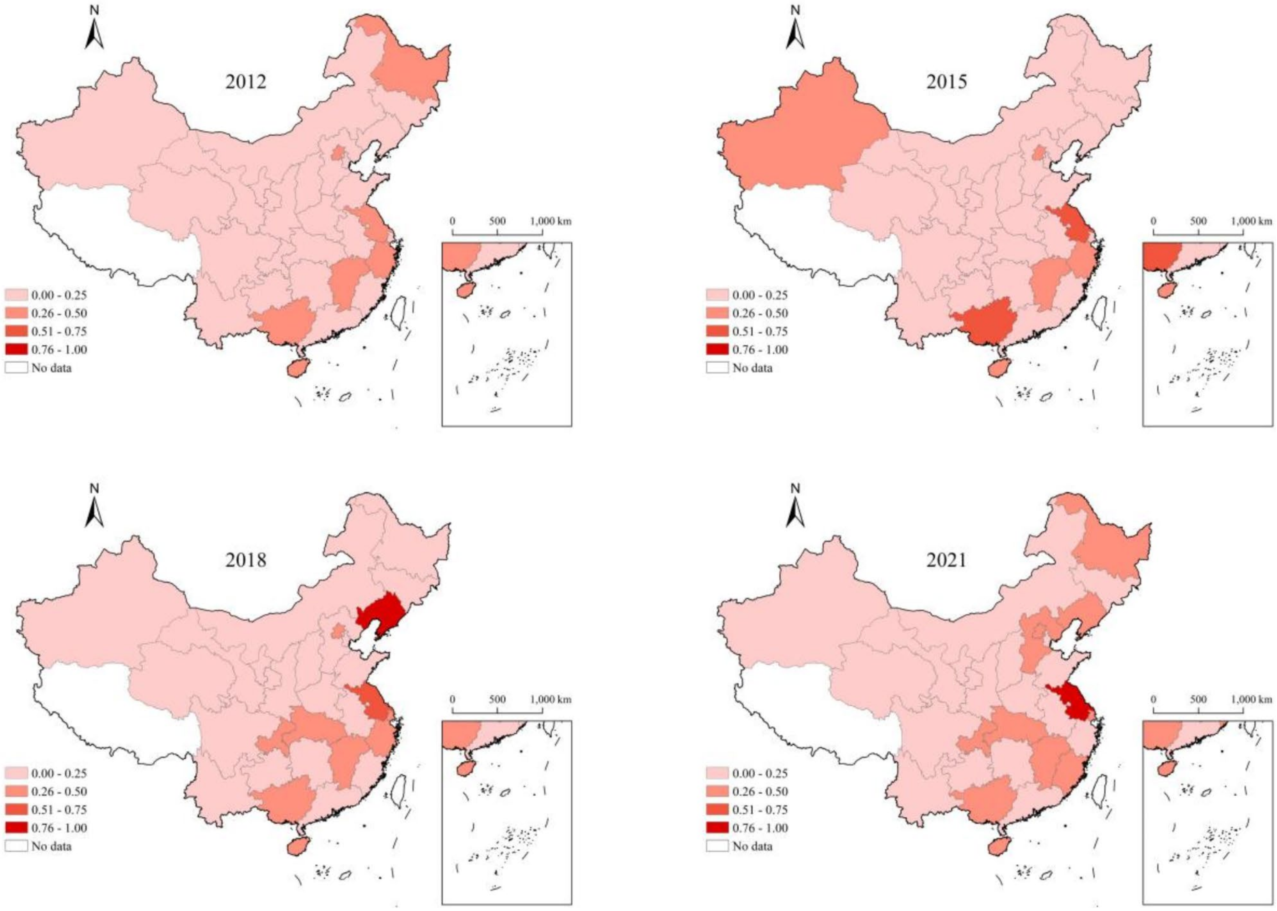

Fig. 6. Spatial pattern of CE of China's construction industry in 2012,2015,2018 and 2021.

an area, with high CCD in adjacent areas. In 2012, Shanghai, Anhui, Fujian, Shandong, Hubei and Guangdong were in this category. In 2021, Tianjin, Anhui, Shandong, Henan and Hainan were in this category, showing signs of shifting from the southeast to the central region. A L-L cluster is low CCD in an area and adjacent areas. In 2012, L-L clusters included Hebei, Shanxi, Inner Mongolia, Henan, Chongqing, Sichuan and so on. In 2021, L-L clusters mainly included Jilin, Heilongjiang, Guizhou, Yunnan, Shaanxi, Gansu, etc., appearing phenomena transferring from the central region to the northeast. A H-L outlier is high CCD in this area, with low CCD in adjacent areas. Liaoning, Heilongjiang, Guangxi and Hainan were in this category in 2012, and Beijing, Hebei, Liaoning, Guangxi and Chongqing were in this category in 2021. On the whole, it can be seen that most of the provinces in 2012 and 2021 showed the characteristics of H-H agglomeration or L-L agglomeration. The H-H cluster areas are concentrated in the economically developed areas in the east, while the L-L cluster areas are mostly concentrated in the western areas. Thus it can be seen that the homogeneous agglomeration effect is always dominant, and the spatial evolution pattern is relatively stable.

Markov chain transfer probability analysis for CCD

Referring to the study of Chen et al.[41], the traditional Markov probability transfer matrix is introduced to explore the evolutionary characteristics of CCD. The results are shown in Table 5, the probability values on the diagonal are much larger than other probability values in the same row, which indicates that each type of CCD is biased to maintain the original state unchanged when the state transition occurs, and has obvious "club convergence" characteristics. The convergence characteristics of high-quality coupling coordination are more obvious, and there is a "high-level monopoly" phenomenon.

The calculation results of the spatial Markov chain probability transfer matrix are given in Table 6. By comparing with the conventional Markov transfer probability matrix, these results can be obtained. When the neighborhood context of each region is considered, the transition probability of CCD shows a significant change. The probability on the diagonal is still the maximum in the same row, which indicates that the probability of inter-type transition of CCD is low. There is a spatial spillover effect of CCD, and the probability of upward transfer increases significantly when a province is adjacent to a region with a high CCD level; conversely, the probability of upward transfer is suppressed when it is adjacent to a region with a low CCD level. For example, when the adjacent region of a type II province changes from type II to type III, the probability of its CCD shifting upward increases from 8.3 to 19.6%.

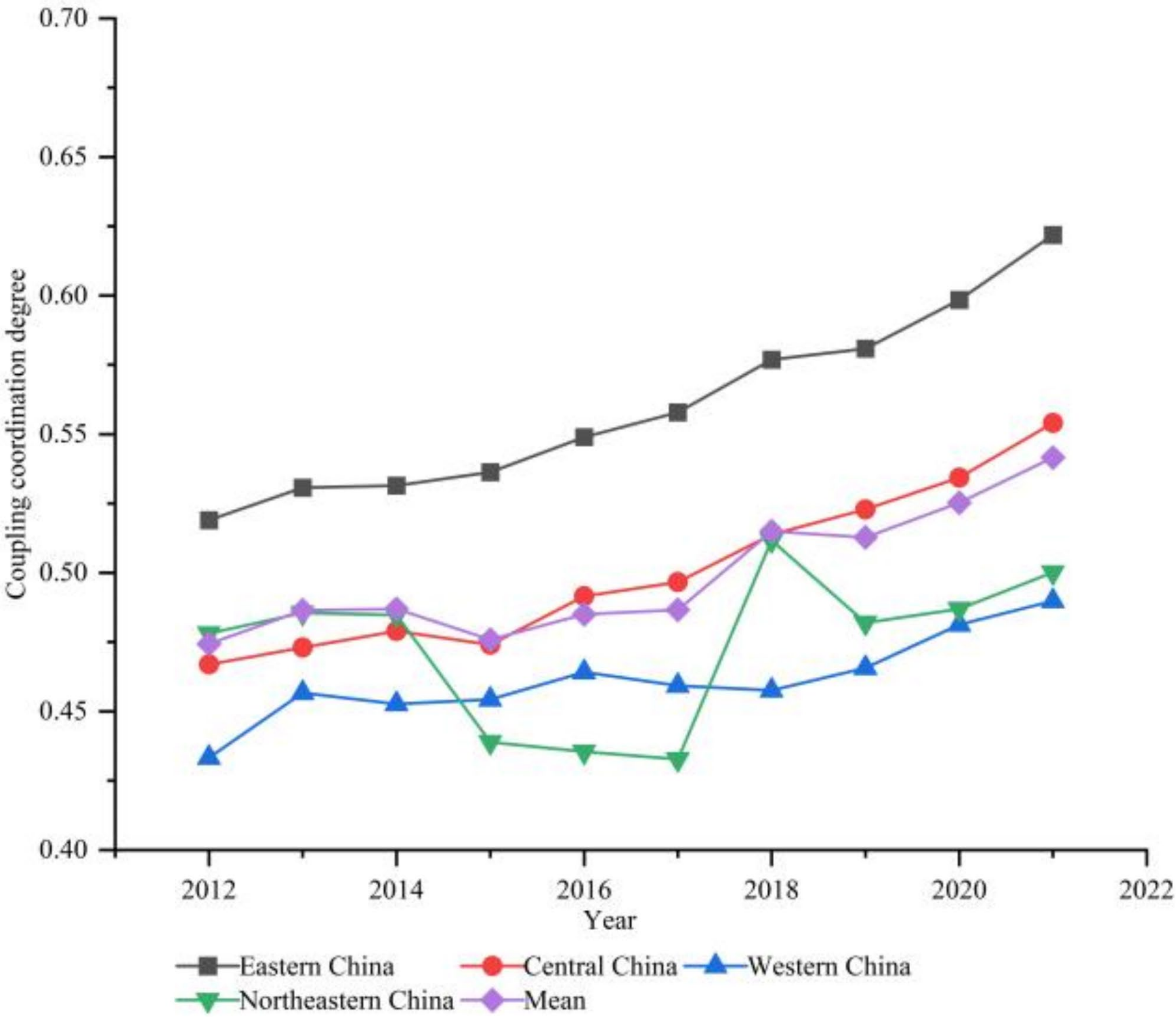

Fig. 7. Temporal evolution trend of CCD from 2012 to 2021.

Discussion

Spatial and temporal dynamic changes of HQD-CE systems in the construction industry

The level of HQD of China's construction industry rose during the study period. Due to different development conditions (i.e. economy, innovation and openness)[42], there are obvious regional differences in the HQD level of the construction industry. The eastern and central regions have been leading in comparison to the northeastern and western provinces, because of developed economies, sound infrastructure and strong policy support for science and technology innovation; however, the western and northeastern regions are economically backward, with lagging infrastructure construction and insufficient policy support.

From a general perspective, The values of the CE system in China's construction industry had increased slightly, and the values were higher in the eastern than in the western region. The eastern region has introduced a series of carbon reduction policies and advocated the development of green and low-carbon buildings, while the western region is still in the development stage of urbanization, and the construction industry plays an important role in the process of urbanization[43]. From a provincial perspective, the values of the CE system of the construction industry in Hebei and Jiangsu have increased evidently. However, Tianjin has insufficient investment in scientific research and innovation, and Henan's construction industry has a low level of technology and management, resulting in a significant reduction in the values of the two provinces. The values of the CE system of the construction industry in western provinces such as Inner Mongolia, Xinjiang and Gansu showed a decreasing trend, which is related to the accelerated promotion of infrastructure construction in western regions.

Spatial and temporal dynamic changes of CCD

From a temporal perspective, the average CCD between HQD-CE systems of China's construction industry witnessed a steady growth, from 0.4744 in 2012 to 0.5416 in 2021, from the basic coupling dissonance stage to the

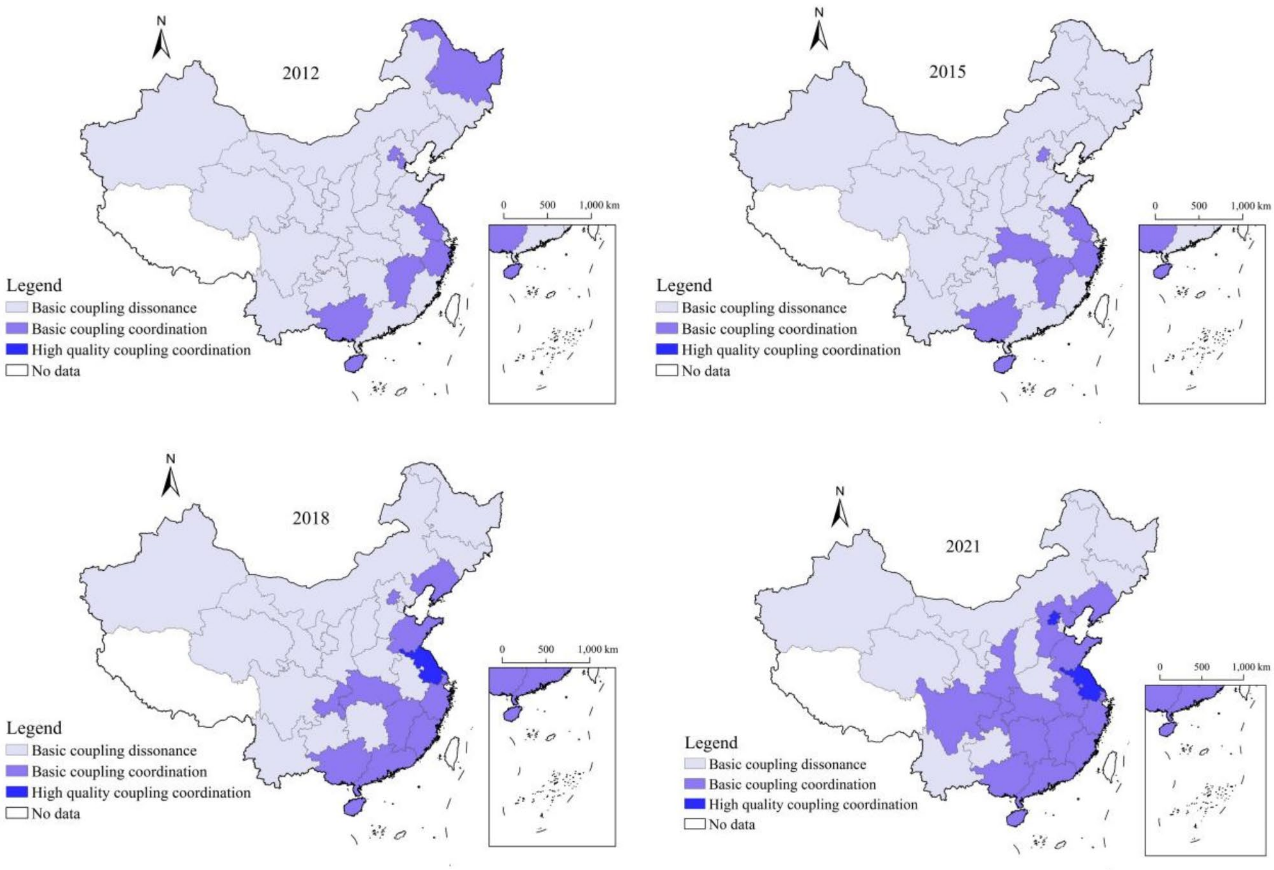

Fig. 8. Spatial distribution of CCD in 2012,2015,2018 and 2021.

Year	Z	Moran's I	*P*
2012	1.771	0.183	0.038
2013	1.133	0.104	0.129
2014	1.333	0.129	0.091
2015	1.506	0.15	0.066
2017	2.297	0.247	0.011
2018	2.24	0.24	0.013
2019	1.463	0.145	0.072
2020	1.819	0.188	0.034

Table 4. Global spatial autocorrelation of CCD.

basic coupling coordination stage. This result indicates that the green, low-carbon and high-quality development of China's construction industry has achieved remarkable results. Various measures for HQD of the construction industry have improved the CE status, and the improvement of the CE status of the construction industry has promoted HQD, so the coupling and coordination level between the two have been optimized as a whole.

From a spatial perspective, the CCD of HQD-CE of the construction industry generally presents a spatial distribution of high in the southeast and low in the northwest and an evolution pattern of decreasing from coastland to inland, which is positively correlated with the economic development level of different regions in China. As an important region of China's economic development, the eastern region has sufficient reserves of capital and talent and has a high level of technology and innovation ability. With the promotion of HQD, construction enterprises in the eastern region have responded to the national call for active transformation, low carbon and high-quality development routes. As an economically developed province in the east, Jiangsu plays a leading role in promoting the coordinated development of HQD-CE in the construction industry[44]. At present, the CCD of HQD-CE of the construction industry has been basic coupling coordination in most provinces, but the provinces located in the western region have been in the stage of basic coupling dissonance for a long time. The overall development of the construction industry in the western region started late, the infrastructure is

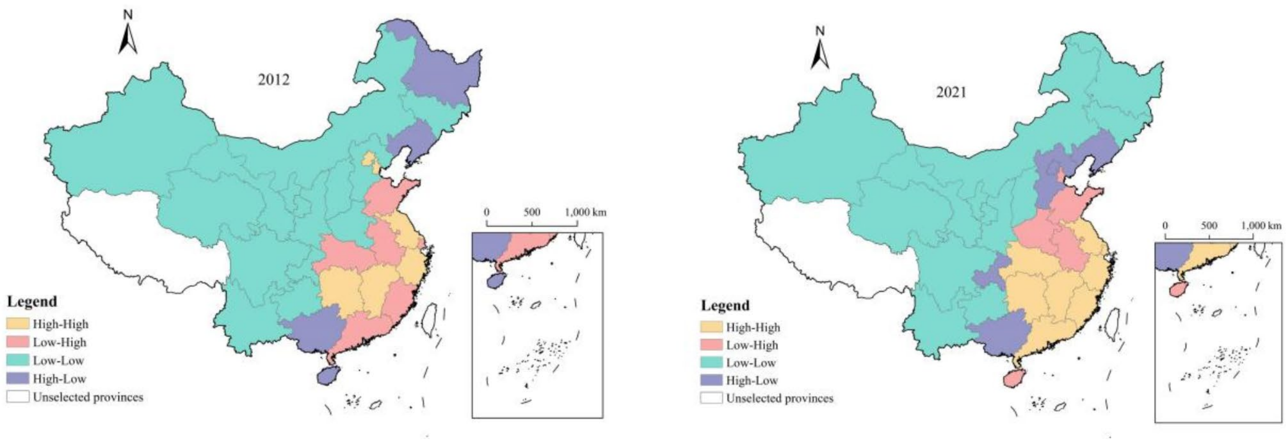

Fig. 9. Local spatial autocorrelation of CCD.

t/t+1	*n*	II	III	IV
II	171	0.883	0.117	0.000
III	95	0.105	0.874	0.021
IV	4	0.000	0.000	1.000

Table 5. Markov transition probability matrix from 2012 to 2021.

		2012–2021			
Neighbor type	t/t+1	n	II	III	IV
II	II	120	0.917	0.083	0.000
	III	42	0.167	0.810	0.024
	IV	0	0.000	0.000	0.000
III	II	51	0.804	0.196	0.000
	III	53	0.057	0.925	0.019
	IV	4	0.000	0.000	1.000
IV	II	0	0.000	0.000	0.000
	III	0	0.000	0.000	0.000
	IV	0	0.000	0.000	0.000

Table 6. Spatial Markov transition probability matrix of CCD from 2012 to 2021.

backward, and the industrial structure is unreasonable, which leads to its poor economic level. At the same time, highly educated talents are more inclined to go to developed regions such as eastern China, resulting in a serious brain drain, and the western region lacks the impetus for scientific and technological innovation[45]. It is necessary to guard against these provinces becoming obstacles to HQD of the construction industry and the realization of the "double carbon" goal.

Conclusion and policy implications

Conclusion

Since the reform and opening up, China's construction industry has continued to develop rapidly, accompanied by the rapid growth of carbon emissions. Therefore, an in-depth understanding of the HQD-CE development status of the construction industry in China is of great significance to guide the low-carbon and HQD of the construction industry and drive the achievement of the "dual carbon" goal.

Taking 30 provinces in China as the research object, this research analyzes the spatio-temporal evolution of the CCD of HQD-CE of the construction industry from 2012 to 2021 by using the CCDM, spatial autocorrelation model and Markov chain. The main conclusions are as follows: (1) The comprehensive level of the HQD system of the construction industry continued to improve, presenting high spatial characteristics in the central and eastern regions and low in the western regions, and it still needs to be further improved. (2) The comprehensive index of the CE system of the construction industry showed a slow upward trend and showed the spatial characteristics that the eastern coastal region were higher than the central and western regions. The CE system levels are the lowest in major coal-producing areas, such as Inner Mongolia. (3) The CCD of HQD-

CE of the construction industry continues to rise, gradually transforming from "basic coupling dissonance" to "basic coupling coordination", with obvious regional differences, showing the spatial distribution characteristics of eastern region > central region > northeastern region > western region. (4) The CCD has a significant spatial correlation, and the H-H clustering is mainly concentrated in the eastern region and has a trend of transferring to the central region; L-L clustering is mainly concentrated in the western region. (5) The CCD basically obeys the steady-state distribution, and the "club convergence" feature is obvious. The development evolution of CCD of each province is affected by the neighboring regions, with type II provinces facing the problem of low-level solidification, and type IV provinces being fewer in number and with insufficient driving effects.

Policy implications

In conclusion, it can provide guidance and suggestions for promoting the coordinated development of HQD-CE in the construction industry from the perspectives of government intervention, scientific and technological innovation and industrial structure. Strengthen top-level design, and establish a sound policy system for the coordinated development of HQD-CE in the construction industry. At present, there are significant differences in the coordination level between the HQD-CE systems of the construction industry in China's 30 provinces, the resource allocation mechanism needs to be improved to promote the efficiency of inter-regional resource allocation. Policymakers should give appropriate preference to regions with low CCD levels, and avoid a "one-size-fits-all" approach to policy formulation. Local governments can establish cross-regional coordination organizations, build information technology resource platforms and encourage inter-regional resource co-construction and sharing to alleviate regional development imbalances. Especially, the western provinces with low CCD could pair with the eastern provinces to help each other and promote the coordination level of the western region.

In addition, adhere to innovative development, actively introduce and train high-quality technical personnel, increase research and development investment, increase the application of information technology in the construction industry, to improve the innovation driving force of the construction industry. Accelerate the transition of the construction industry structure, promote the application of new digital construction technologies, integrate Internet technology with the traditional construction industry, and optimize the management and operation of construction projects through information and intelligent means. In-depth implementation of the concept of green development is an important path for the construction industry to achieve low-carbon, high-quality coordinated development.

Study limitations

The empirical findings of this study can provide a reference for the policy formulation of the green, low-carbon and high-quality development of the construction industry. Nevertheless, this study has some limitations which we will share for future research. If more detailed data is available (such as prefecture-level cities), we will delve into more granular levels such as cities or regions in future studies. Second, the key indicators of the HQD-CE systems in the construction industry were identified but were not examined in depth in this study, and future research could further investigate the specific impact of key indicators on the CCD in each province, for example, through a geographically weighted regression model. Thirdly, there may be some simplifications in the weight setting of the CCDM, which will be improved in future research.

Data availability

The basic data used in the research can be found on the website of National Bureau of Statistics (https://www.stats.gov.cn/) and CEADs (https://www.ceads.net.cn/).

Received: 26 October 2024; Accepted: 21 March 2025
Published online: 01 October 2025

References

1. Li, Y. W. et al. A review on carbon emission accounting approaches for the electricity power industry. *Appl. Energy*. **359**, 17. https://doi.org/10.1016/j.apenergy.2024.122681 (2024).
2. Zhou, K. L., Yang, J. N., Yang, T. & Ding, T. Spatial and Temporal evolution characteristics and spillover effects of China's regional carbon emissions. *J. Environ. Manag.* **325**, 11. https://doi.org/10.1016/j.jenvman.2022.116423 (2023).
3. Zhu, E. Y., Qi, Q. Y., Chen, L. S. & Wu, X. H. The spatial-temporal patterns and multiple driving mechanisms of carbon emissions in the process of urbanization: A case study in Zhejiang, China. *J. Clean. Prod.* **358**, 10. https://doi.org/10.1016/j.jclepro.2022.131954 (2022).
4. Jin, Y. Z., Zhang, K. R., Li, D. Y., Wang, S. Y. & Liu, W. Y. Analysis of the spatial-temporal evolution and driving factors of carbon emission efficiency in the Yangtze river economic belt. *Ecol. Indic.* **165**, 13. https://doi.org/10.1016/j.ecolind.2024.112092 (2024).
5. Xiao, Y. P. et al. Spatiotemporal differentiation of carbon emission efficiency and influencing factors: from the perspective of 136 countries. *Sci. Total Environ.* **879**, 16. https://doi.org/10.1016/j.scitotenv.2023.163032 (2023).
6. Wei, M., Cai, Z., Song, Y., Xu, J. G. & Lu, M. Q. Spatiotemporal evolutionary characteristics and driving forces of carbon emissions in three Chinese urban agglomerations. *Sust Cities Soc.* **104**, 17. https://doi.org/10.1016/j.scs.2024.105320 (2024).
7. Sun, Y. H., Hao, S. Y. & Long, X. F. A study on the measurement and influencing factors of carbon emissions in China's construction sector. *Build. Environ.* **229**, 10. https://doi.org/10.1016/j.buildenv.2022.109912 (2023).
8. Tian, Y. H., Zhu, Q. H. & Geng, Y. An analysis of energy-related greenhouse gas emissions in the Chinese iron and steel industry. *Energy Policy*. **56**, 352–361. https://doi.org/10.1016/j.enpol.2012.12.068 (2013).
9. Xiao, L. S., Li, W. Y., Dong, L. J., Wu, X. & Ye, H. Characterizing Spatiotemporal dynamics of carbon emissions in peri-urban residential communities: A life cycle perspective. *J. Clean. Prod.* **448**, 141613. https://doi.org/10.1016/J.JCLEPRO.2024.141613 (2024).
10. Su, B., Ang, B. W. & Li, Y. Z. Input-output and structural decomposition analysis of Singapore's carbon emissions. *Energy Policy*. **105**, 484–492. https://doi.org/10.1016/j.enpol.2017.03.027 (2017).

11. Nässén, J., Holmberg, J., Wadeskog, A. & Nyman, M. Direct and indirect energy use and carbon emissions in the production phase of buildings:: an input-output analysis. *Energy* **32**, 1593–1602. https://doi.org/10.1016/j.energy.2007.01.002 (2007).
12. Wang, C. J. et al. Examining the driving factors of energy related carbon emissions using the extended STIRPAT model based on IPAT identity in Xinjiang. *Renew. Sustainable Energy Rev.* **67**, 51–61. https://doi.org/10.1016/j.rser.2016.09.006 (2017).
13. Ang, B. W. & Choi, K. H. Decomposition of aggregate energy and gas emission intensities for industry: A refined divisia index method. *Energy J.* **18**, 59–73 (1997).
14. Radwan, A., Hongyun, H., Achraf, A. & Mustafa, A. M. Energy use and energy-related carbon dioxide emissions drivers in Egypt's economy: focus on the agricultural sector with a structural decomposition analysis. *Energy* **258**, 15. https://doi.org/10.1016/j.energy.2022.124821 (2022).
15. Yan, Y. & Huang, J. B. The role of population agglomeration played in China's carbon intensity: A city-level analysis. *Energy Econ.* **114**. https://doi.org/10.1016/j.eneco.2022.106276 (2022).
16. Zeng, J. T. & Yang, M. R. Digital technology and carbon emissions: evidence from China. *J. Clean. Prod.* **430**, 14. https://doi.org/10.1016/j.jclepro.2023.139765 (2023).
17. Zhang, H., Guo, S. D., Qian, Y. B., Liu, Y. & Lu, C. P. Dynamic analysis of agricultural carbon emissions efficiency in Chinese provinces along the belt and road. *PloS One.* **15**, 22. https://doi.org/10.1371/journal.pone.0228223 (2020).
18. Zhang, W., Li, J., Li, G. X. & Guo, S. C. Emission reduction effect and carbon market efficiency of carbon emissions trading policy in China. *Energy* **196**, 9. https://doi.org/10.1016/j.energy.2020.117117 (2020).
19. Zhou, Y., Jin, H. M., Li, C. S. & Ding, L. Y. Spatio-temporal patterns and impact mechanisms of CO 2 emissions from China's construction industry under urbanization. *Sust Cities Soc.* **106**, 11. https://doi.org/10.1016/j.scs.2024.105353 (2024).
20. Zhao, S. J., Song, Q. B., Zhao, D. F. & Wang, Y. Q. Identifying the Spatiotemporal carbon footprint of the petroleum refining industry and its mitigation potential in China. *Energy* **284**, 12. https://doi.org/10.1016/j.energy.2023.129240 (2023).
21. Huang, Y., Zhu, H. M. & Zhang, Z. Q. Y. The heterogeneous effect of driving factors on carbon emission intensity in the Chinese transport sector: evidence from dynamic panel quantile regression. *Sci. Total Environ.* **727**, 14. https://doi.org/10.1016/j.scitotenv.2020.138578 (2020).
22. Zhang, X. C., Sun, J. Y., Zhang, X. Q. & Wang, F. L. Assessment and regression of carbon emissions from the Building and construction sector in China: A provincial study using machine learning. *J. Clean. Prod.* **450**, 17. https://doi.org/10.1016/j.jclepro.2024.141903 (2024).
23. Wang, Z. Y., Zhang, J. X., Luo, P. J., Sun, D. Q. & Li, J. M. Revealing the spatio-temporal characteristics and impact mechanism of carbon emission in China's urban agglomerations. *Urban CLim.* **52**, 16. https://doi.org/10.1016/j.uclim.2023.101733 (2023).
24. Yang, X. L. et al. Spatial-temporal differentiation and influencing factors of carbon emission trajectory in Chinese cities - A case study of 247 prefecture-level cities. *Sci. Total Environ.* **928**, 13. https://doi.org/10.1016/j.scitotenv.2024.172325 (2024).
25. Liu, C., Hu, S. G., Wu, S., Song, J. R. & Li, H. Y. County-level land use carbon emissions in China: Spatiotemporal patterns and impact factors. *Sust Cities Soc.* **105**, 16. https://doi.org/10.1016/j.scs.2024.105304 (2024).
26. Zhao, Y. B. et al. Spatiotemporal patterns of global carbon intensities and their driving forces. *Sci. Total Environ.* **818**, 13. https://doi.org/10.1016/j.scitotenv.2021.151690 (2022).
27. Gao, X. Z. & Wang, H. M. Evaluation index system of construction industry development under the high-quality development. *E3S Web Conf.* **248**, 03060. https://doi.org/10.1051/E3SCONF/202124803060 (2021).
28. Wang, Y. & Wu, X. Research on high-quality development evaluation, space-time characteristics and driving factors of China's construction industry under carbon emission constraints. *Sustainability* **14**, 19. https://doi.org/10.3390/su141710729 (2022).
29. Song, Y. et al. Factors affecting green Building development at the municipal level: A cross-sectional study in China. *Energy Build.* **231**, 8. https://doi.org/10.1016/j.enbuild.2020.110560 (2021).
30. Wang, W., Tian, Z., Xi, W. J., Tan, Y. R. & Deng, Y. The influencing factors of China's green Building development: an analysis using RBF-WINGS method. *Build. Environ.* **188**, 10. https://doi.org/10.1016/j.buildenv.2020.107425 (2021).
31. Li, Y. & Ma, G. Z. A study on the high-quality development path and implementation countermeasures of China's construction industry toward the carbon peaking and carbon neutralization goals. *Sustainability* **16**, 14. https://doi.org/10.3390/su16020772 (2024).
32. Wang, D. & Cheng, X. D. Study on the path of high-quality development of the construction industry and its applicability. *Sci. Rep.* **14**, 14727. https://doi.org/10.1038/s41598-024-64786-y (2024).
33. Cao, S. S., He, Z. L., Niu, J. L., Wang, S. M. & Zhao, L. Spatial differentiation and convergence trend of high-quality development level of China's tourism economy. *Chin. Geogr. Sci.* **34**, 230–249. https://doi.org/10.1007/s11769-024-1413-1 (2024).
34. Zhang, L. X. & Zhang, J. R. Evaluation and promotion path of high-quality development in the Chinese construction industry under the context of carbon neutrality. *Environ. Dev. Sustain.* **32**. https://doi.org/10.1007/s10668-024-04837-6 (2024).
35. Zhang, Q. F., Li, J. F., Li, Y. & Huang, H. Coupling analysis and driving factors between carbon emission intensity and high-quality economic development: evidence from the yellow river basin, China. *J. Clean. Prod.* **423**, 16. https://doi.org/10.1016/j.jclepro.2023.138831 (2023).
36. Chen, L. et al. Coupling and coordinated evolution characteristics of regional economy-energy-carbon emission multiple systems: A case study of main China's basin. *J. Environ. Sci.* **140**, 204–218. https://doi.org/10.1016/j.jes.2023.07.007 (2024).
37. Fu, C., Gui, X. Y. & Akter, F. Discrete Fourier transform (DFT)-based computational intelligence model for urban carbon emission and economic growth. *Math. Probl. Eng.* **10**. https://doi.org/10.1155/2022/4225080 (2022).
38. Jiang, J. K., Zhu, S. L., Wang, W. H., Li, Y. & Li, N. Coupling coordination between new urbanisation and carbon emissions in China. *Sci. Total Environ.* **850**, 13. https://doi.org/10.1016/j.scitotenv.2022.158076 (2022).
39. Li, D. L. et al. Coupling coordination degree and driving factors of new-type urbanization and low-carbon development in the Yangtze river delta: based on nighttime light data. *Environ. Sci. Pollut Res.* **29**, 81636–81657. https://doi.org/10.1007/s11356-022-21400-w (2022).
40. Anselin, L. Local indicators of Spatial association - LISA. *Geogr. Anal.* **27**, 93–115. https://doi.org/10.1111/j.1538-4632.1995.tb00338.x (1995).
41. Chen, X. L., Meng, Q. G., Wang, K. K., Liu, Y. F. & Shen, W. F. Spatial patterns and evolution trend of coupling coordination of pollution reduction and carbon reduction along the yellow river basin, China. *Ecol. Indic.* **154**, 13. https://doi.org/10.1016/j.ecolind.2023.110797 (2023).
42. Wan, J. et al. Assessing the development and multidimensional constraints of the high-quality construction industry in the Chengdu-Chongqing twin-city economic circle. *Eng. Constr. Archit. Manage.* **32**, 507–535. https://doi.org/10.1108/ecam-11-2022-1093 (2025).
43. Ouyang, T., Liu, F. & Huang, B. Dynamic econometric analysis on influencing factors of production efficiency in construction industry of Guangxi Province in China. *Sci. Rep.* **12**, 1–14. https://doi.org/10.1038/s41598-022-22374-y (2022).
44. Luo, C., Gao, Y., Jiang, Y., Zhao, C. & Ge, H. Predictive modeling of carbon emissions in Jiangsu Province's construction industry: An MEA-BP approach. *J. Build. Eng.* **86**. https://doi.org/10.1016/j.jobe.2024.108903 (2024).
45. Mao, J., Wang, Z. & Ma, T. Dynamic evolution of high-quality economic development levels: regional differences and distribution in West China. *Land* **12**. https://doi.org/10.3390/land12111975 (2023).

Author contributions

WQ.S. collected data, used software and wrote original manuscript. YY.Z. prepared formal analysis, methodology and edited. LJ.C. supervised and revised the manuscript. All authors reviewed the manuscript.

Declarations

Competing interests
The authors declare no competing interests.

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