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# Explaining the changes in the green technology innovation efficiency of construction enterprises

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Based on the objective of global carbon emission reduction, the green technology innovation efficiencies of construction enterprises (GTIE-CE) have attracted attention in various countries and regions worldwide. However, researchers have not yet assessed GTIE-CE from the perspectives of asymmetric innovation theory, resource orchestration theory and eco-innovation theory. To reveal the changes in GTIE-CE, an index system is constructed to measure this efficiency based on resource orchestration theory and eco-innovation theory. In addition, based on the asymmetric innovation theory, this study uses the spatial variance function and PVAR model to reveal the evolution mechanism of GTIE-CE with respect to market, government and technology dimensions. The main conclusions are as follows. (1) Regional heterogeneity is present in GTIE-CE in China, and the appearance of high efficiency spreads from the Yangtze River Delta and Pearl River Delta to the surrounding areas. (2) The market dimension positively affects the green technology innovation efficiency of construction enterprises, but this effect is delayed. (3) The government dimension significantly promotes the improvement in GTIE-CE, but this effect is delayed. This study provides an integrated theoretical perspective that reveals the mechanism of GTIE-CE, helps to broaden the research in the field of GTIE-CE, in addition to insights from China to further promote the green transformation of these enterprises.

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Introduction

As the industry with the most carbon emissions and greatest energy consumption in the world, construction has received global attention to promote carbon emission reduction and green transformation. Currently, the United States, Canada, and the United Kingdom have introduced relevant policies and plans to promote green innovation in the construction industry to address carbon emissions by changing resources and guiding policies (United Nations Environment Programme, 2022a; United Nations Environment Programme, 2022b; New buildings institute, 2022). The construction industry is an important pillar industry for the healthy development of China's economy, as the production process of the construction industry is related to the production activities of many sectors such as building materials, machinery and chemicals. The green transformation and development of construction enterprises and the improvement of green technology innovation efficiency (GTIE) play an important role in promoting the transformation and upgrading of the social and economic structure, and enhancing the efficiency of economic development and the level of green and low-carbon. However, as the trade in China with the greatest energy consumption and most carbon emissions, the construction industry accounted for 45.5% of the national total energy consumption and 50.9% of the national total carbon emissions in 2020 (Energy Consumption and Carbon Emission Specialised Committee of China Building Energy Conservation Association, 2022). It can be seen that Chinese construction companies urgently need to improve GTIE in order to break through the carbon emission and transformation dilemma. Improving the GTIE of construction enterprises (GTIE-CE) and enhancing the utilization rate of resources are the main approaches for solving the problems of high energy consumption and carbon emissions in the construction industry. GTIE reflects the resource utilization level of enterprises throughout green technology innovation (GTI), and it is determined by the ratio of various resource inputs to benefit outputs during this process (Li and Zeng, 2020). Improving GTIE has become a clear key to realizing the green transformation of construction enterprises (Chen et al., 2020). At present, what is the evolutionary mechanism of GTIE-CE in the Chinese region? How to reveal the mechanism and evolution of GTIE-CE and its influencing factors through an integrated theoretical perspective? These questions remain to be solved.

In previous studies, scholars extensively examined GTIE (Liu et al., 2022). Some studies were focused on the innovation output of GTIE in construction enterprises without evaluating the environmental benefits of this innovation (Shin et al., 2021). To further the research related to the measurement of GTIE-CE, both solid waste and carbon emissions in the construction industry are considered herein when measuring the

environmental output of GTI. In addition, most of the existing studies involved discussions of the underlying mechanisms of the factors influencing GTIE while ignoring the changes in GTIE-CE. Although GTIE has attracted the attention of scholars in the manufacturing industry (Zhang et al., 2023), high-tech industry (Wang Hao, 2022) and high-pollution industry (Li Zeng, 2020), these researchers could not find the evolution mechanisms of GTIE-CE. Therefore, the scientific questions addressed in this study are as follows: how can the GTIE-CE be measured, and how can its evolution mechanism be revealed through an integrated theoretical model? The aim of this study is to measure the value of GTIE-CE through the super-slack-based measurement (super-SBM) model for efficiency from the perspectives of asymmetric innovation theory, resource orchestration theory and eco-innovation theory. Moreover, the spatial variance function and the panel vector autoregression (PVAR) model are utilized to reveal the evolution mechanisms of GTIE-CE in China from 2010 to 2020 in relation to the dimensions of market, government and technology.

The main contributions of this study are as follows. (1) For the first time, an integrated theoretical model based on resource orchestration theory, eco-innovation theory, and asymmetric innovation theory is constructed. This model not only uniquely measures GTIE-CE but also reveals the evolution mechanism of this efficiency in China. (2) Solid waste is innovatively introduced into the GTIE-CE output index, thus providing new construction enterprise data for input-output-related research. (3) The literature on GTIE is enriched. Moreover, this study can serve as a reference for governments to adopt reasonable policies during decision-making to promote GTIE-CE.

Theoretical foundation and literature review

**Theoretical foundation.** In this paper, an integrated theoretical model based on resource orchestration theory, asymmetric innovation theory, and eco-innovation theory is constructed. First, asymmetric innovation theory offers a rationale for exploring the mechanisms by which the government, technology and market dimensions interact with GTIE-CE. Second, resource orchestration theory and eco-innovation theory provide theoretical support for investigating the influences of these dimensions on GTIE-CE. In addition, eco-innovation theory and resource orchestration theory provide a rationale for the selection of input and output indicators for measuring GTIE-CE. Studies related to asymmetric innovation theory, resource orchestration theory, and eco-innovation theory are shown in Table 1. Asymmetric innovation theory, resource orchestration theory, and eco-innovation theory are successively reviewed in this section.

Table 1 Literature related to theoretical foundations.		
Researchers	Theoretical foundation	Theoretical application
(Zhu et al., 2022)	Asymmetric innovation theory	Based on the asymmetric innovation theory, the realization path of GTIE in Chinese regions was discussed from the three-dimensional framework of market-institution-technology.
(Wei et al., 2023)	Asymmetric innovation theory	Based on the asymmetric innovation theory, the path for improving China's industrial data governance capacity in the context of digital intelligence drive was explored.
(Zhang et al., 2023)	Resource orchestration theory	The impacts of intellectual capital and its components and digital transformation on the performance of construction firms were studied based on resource orchestration theory
(Zhou et al., 2024)	Resource orchestration theory	The impact of digital transformation on the green innovation efficiency of enterprises from the perspective of resource orchestration theory was explored
(Natasha and Zhang, 2019)	Eco-innovation theory	The evolution of eco-innovation theory and future research directions were analysed.
(Salim et al., 2019)	Eco-innovation theory	Based on the perspective of eco-innovation theory, the internal factors for enhancing the eco-innovation ability of manufacturing enterprises were analysed.

The theory of asymmetric innovation proposes an asymmetric scenario for Chinese enterprises in the process of innovation catch-up. “Asymmetry” refers to the scarcity of special resources that Chinese enterprises have compared with international leading enterprises, and these resources are the competitive advantages that international leading enterprises do not have, which mainly include the strong government system, the large market pattern and the weak technological system (Wei et al. 2016). Therefore, under the asymmetric government, market and technology scenarios, the GTI behaviour of enterprises is affected by the government, market and technology dimensions to different degrees. In the government dimension, the government controls some critical properties, including resources, power and land, and the behaviour of enterprises is widely constrained by government regulations (Borghesi et al., 2015). In the market dimension, the large value provides enterprises with abundant market demand, and GTI can give enterprises relatively strong market competitiveness (Li et al., 2019). In the technology dimension, GTI requires the integration and development of different information, and the completeness of available technological systems significantly affects the GTIE (Rennings et al., 2006). Asymmetric innovation theory provides a basis for exploring the roles of the market, technology and government dimensions in the GTIE–CE (Wei et al., 2023). However, no study has revealed the changes in different dimensions and the GTIE–CE from the perspective of asymmetric innovation theory or explored the interaction relationships among various factors. Therefore, based on the perspective of asymmetric innovation theory, this study constructs an integrated theoretical framework by combining asymmetric innovation theory, resource orchestration theory and eco-innovation theory. Based on this theoretical framework, this study will reveal the evolutionary mechanism of GTIE–CE.

Resource orchestration theory suggests that the dynamic management of resources by enterprises to form a combination of resources and capabilities that match the external environment is the basis for value creation in enterprises (Sirmon et al., 2011). Existing studies have shown that resource input is the basis for enterprises to perform GTI, and the effective combination of enterprise capabilities and resources can promote the transformation of resource value and the utilization efficiency (Makadok, 2001). Furthermore, the integration of enterprise resources and knowledge absorption capacity can help enterprises improve the development efficiency of innovative products (Su et al., 2013). Therefore, GTI requires not only the input of enterprise resources but also the effective combination of these strategic resources and managerial capabilities. Resource orchestration theory is often employed to analyse the impact of the integration of various types of resources on GTIE. Resource orchestration theory provides the perspective of material resources and technical resources for exploring the role mechanism of GTIE. However, limiting to the perspective of enterprise resource endowment only and ignoring the influence of government system on enterprise behaviour, it cannot comprehensively explore the mechanism of GTIE–CE. Therefore, it is necessary to construct an integrated theoretical framework by combining asymmetric innovation theory. Resource orchestration theory provides a basis for resource management and resource input in the process of GTI of construction enterprises, and it also provides theoretical support for the influence factors of market dimension and technology dimension in asymmetric innovation theory. Based on resource orchestration theory, it is helpful to measure the value of GTIE–CE from the perspective of enterprise resource management. However, no scholar has measured the GTIE–CE with resource orchestration theory. Therefore, the input indicators of GTIE–CE are determined herein based on resource orchestration theory.

Eco-innovation theory suggests that by creating new production processes, services, management techniques or business methods, firms can increase economic performance and reduce negative environmental impacts (Kemp Pearson, 2007). Existing research suggests that GTI is a means of maintaining technological leadership and targeting improvements in the environmental performance of enterprises (Ahlvik et al., 2014); furthermore, GTI can reduce production costs and bring economic benefits to enterprises (Heffels et al., 2014). Therefore, construction enterprises have gained both economic and environmental benefits through GTI. Eco-innovation theory has often been employed in analysing the environmental benefits generated by GTI in enterprises. This theory provides a basis for innovation and ecological output during GTI in construction enterprises. The eco-innovation theory helps to comprehensively measure the output indicators in GTIE–CE. However, no scholar has analysed the environmental output of the GTI of construction enterprises from the perspective of eco-innovation theory. Therefore, the output indicators of GTIE–CE are identified herein from the perspective of eco-innovation theory. In summary, this study identifies the output indicators of GTIE–CE from the perspective of eco-innovation theory and builds an integrated theoretical framework by combining asymmetric innovation theory and resource orchestration theory. Based on this theoretical framework, this study will reveal the evolution mechanism of GTIE–CE.

## Literature review

*Green technology innovation efficiency.* Research on GTIE has been widely considered by scholars from various fields. GTI is defined as technological innovation behaviour that promotes the recycling of resources and reduces environmental pollution (Zhu et al., 2021). From this perspective, GTIE reflects the resource utilization level of enterprises during GTI; this efficiency is calculated by the ratio of various resource inputs to the benefit outputs in the GTI process (Li and Zeng 2020). The main technique for measuring GTIE is to construct a corresponding index system. On the one hand, a measurement index of GTIE in terms of resource input and benefit output has previously been constructed (Xia et al., 2022; Gao et al., 2021). On the other hand, the GTI process has been decomposed into two stages—the transformation of innovative resources into innovative results and the transformation of innovative results into economic benefits—and multistage GTIE measurement indicators have been constructed (Zhang et al., 2021). Although the existing research provides a reference for the GTIE index system, GTIE measurement indices for construction enterprises have not yet been constructed from the perspectives of asymmetric innovation theory, eco-innovation theory, and resource orchestration theory. As shown in Table 2, the GTIE has received extensive attention from scholars.

*Market dimension and GTIE.* The GTI behaviour of enterprises is often constrained by the market environment, and a good market environment can motivate enterprises to carry out this innovation (Zhao et al., 2015). Specifically, current research concerning the factors influencing the market dimension of GTIE has focused primarily on openness to the world, industrial structure and enterprise size. First, openness to the world reflects the exchange of capital and technology between enterprises and the international market, which can help to improve GTIE–CE by integrating the information and capital of the international market (Zhu, 2016). Second, a good industrial structure promotes the coordinated innovation of enterprises in different industrial chains and reduces the GTI costs of construction enterprises. Moreover, a good industrial structure shares GTI benefits among

Table 2 Relevant studies regarding the GTIEs of enterprises.					
Researchers	Environmental regulation	Government support	Economic resources	Industrial structure	Technical resources
(Guo et al., 2022)	×	×	✓	✓	✓
Guo et al. (2022) failed to consider the impact of government environmental regulations on the GTIE of enterprises.					
(Zhou et al., 2024)	×	×	✓	×	✓
Zhou et al. (2024) analysed the mechanism of the GTIE of enterprises from the perspective of enterprise resource allocation.					
(Xu et al., 2024)	✓	✓	×	×	×
Xu et al. (2024) failed to consider the impact of the market environment and technological resources of a firm on the GTIE.					
(Cai et al., 2024)	×	✓	✓	✓	✓
Cai et al. (2024) neglected the influence of the government on the green innovation efficiency of enterprises.					
(Wu and Fan, 2023)	×	×	×	✓	×
Wu and Fan (2023) discussed the changes in green innovation efficiency in cities in Northeast China, while ignoring the mechanism of the role of GTIE.					
(Ijaz et al., 2024)	×	×	✓	×	×
Ijaz et al. (2024) ignored the impact of technological resources on the green innovation efficiency of enterprises.					

enterprises, which helps to upgrade industry and optimize the allocation of resources, thus promoting GTIE–CE (Yin et al., 2022). Finally, the scale of the same enterprise in the market reflects the intensity of market competition, and fierce market competition weakens the return on GTI investment; this weakening is not conducive to the transformation of GTI and weakens the GTIE of enterprises (Li et al., 2019). Although existing studies have revealed the mechanism of market dimension influences on GTIE–CE from different perspectives. however, no study has yet explored the evolution mechanism of GTIE–CE and market dimension influences based on an integrated theoretical framework. Therefore, three aspects of the market environment affecting GTIE–CE openness to the world, industrial structure and enterprise size—are measured in this study.

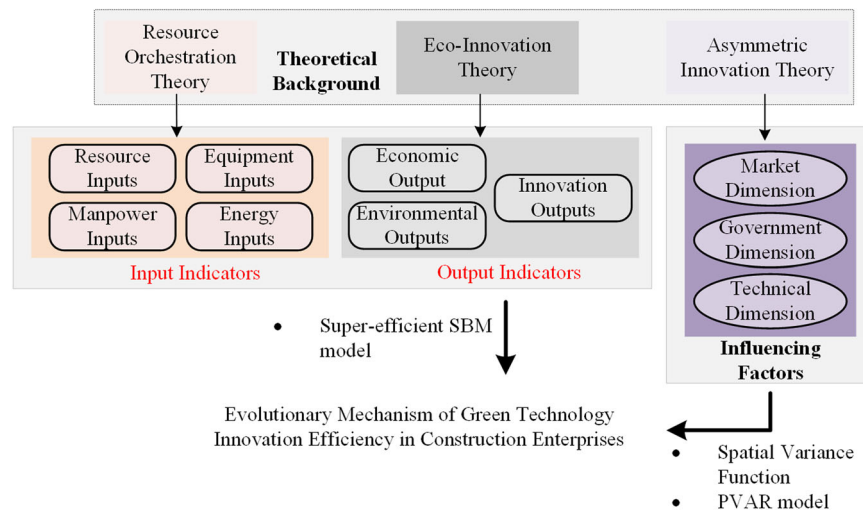
**Government dimension and GTIE.** The behaviour of enterprises is mandated by government regulations, and the introduction of different environmental policies obliges enterprises to meet their environmental performance requirements through technological innovation or pollution control (Wang et al., 2019). Furthermore, to encourage enterprises to actively solve environmental problems in enterprise development through GTI, the government has introduced many innovation incentive policies. Existing research on the government influence on GTIE has focused mainly on environmental and innovation incentive policies. On the one hand, Environmental policies can have a forcing effect on enterprise GTI, forcing enterprises to increase their investment in GTI. In the face of the government’s environmental policy, enterprises will eliminate the burden of environmental policy for enterprises by continuously improving the GTIE, so as to promote the GTIE (Miao et al., 2017). On the other hand, innovation incentives share the cost of GTI and simultaneously stimulate the efficiency of enterprises in integrating and transforming external technologies, thus promoting the enhancement of the GTIE (Liu Feng, 2019). Based on resource orchestration theory, innovation incentives can be seen as a valuable resource for GTI. Government innovation incentives not only reduce the risks and costs of GTI, but also government support for green innovation helps to create a green image for the enterprise, signalling to the market that the enterprise has been certified by the government, and bringing more market revenue and financial support to the enterprise. Therefore, a combination of environmental and innovation encouragement policies can cause enterprises to actively carry out GTI. Asymmetric innovation theory suggests that Chinese enterprises face a special scenario of a strong government system, which has a significant impact on the development and transformation of enterprises. Although the mechanism of the role of the government dimension on enterprises’ GTIE is

fully discussed in existing studies, however, the evolution mechanism of GTIE–CE and the government dimension based on an integrated theoretical framework has not yet been explored by studies. Hence, the government dimension that affects GTIE–CE is evaluated from the perspectives of environmental and innovation encouragement policies.

**Technology dimension and GTIE.** The integration and development of information is the key to realizing GTI, and a good technological system can help promote GTIE. Existing research on the factors influencing the technology dimension of GTIE has focused on three main aspects: social innovation capacity, human resources for research and development (R&D), and the education level of employees. First, social innovation capacity reflects the level of technology in different regions and is the basis for enterprises to collect and integrate knowledge. Good innovation capacity can improve the GTIE of enterprises. Second, GTI requires not only the input of technological resources but also related human resources, which are the basis for the development of green technology. A scientific combination of technical resources and R&D human resources is an effective approach for improving GTIE (Chen et al., 2016). Finally, existing research shows that enterprises with employees with high education levels are more inclined to choose GTI to solve their environmental problems than those with employees with low education levels. A relatively high employee education level can provide enterprises with efficient knowledge transformation ability, which indirectly helps promote the GTIE of enterprises (Heffels et al., 2014). Although existing studies have analysed the role of technological dimensions on GTIE–CE from the perspectives of technological resources and knowledge absorption, no study has yet explored the evolution of GTIE–CE and technological dimensions based on an integrated theoretical framework. Therefore, the technology dimension that influences GTIE–CE is evaluated from the aspects of social innovation capacity, human resources for R&D, and the education level of employees.

**Methods and data sources**  
This study reveals a mechanism for the changes in GTIE–CE according to asymmetric innovation theory, resource orchestration theory, and eco-innovation theory. Figure 1 provides a theoretical framework of the evolution mechanisms of the GTIE–CE. Figure 1 displays the 2-part composition of the theoretical framework built in this paper. (1) The super-SBM was adopted to measure the GTIE–CE according to resource orchestration theory and eco-innovation theory. (2) The spatial variance function and PVAR model were used to reveal the evolution mechanism of GTIE–CE according to asymmetric innovation theory.





**Fig. 1 Theoretical framework for the evolution mechanisms of GTIE-CE.** (1) The super-SBM was adopted to measure the GTIE-CE according to resource orchestration theory and eco-innovation theory. (2) The spatial variance function and PVAR model were used to reveal the evolution mechanism of GTIE-CE according to asymmetric innovation theory.

**Super-SBM model.** Relative to conventional data envelopment analysis (DEA) models, the super-SBM model can produce more accurate efficiency results. The super-SBM model can not only reflect the slack improvement value of each input and output but also distinguish the size of the decision unit when the efficiency values are all 1 (Wang et al., 2022). Thus, the GTIE-CE is measured through the super-SBM model. Equation (1) can be used to create the super-SBM model (Guo and Yuan, 2020).

$$\min \rho = \frac{1 - \frac{1}{m} \sum_{i=1}^m \frac{s_i^-}{x_{ik}}}{1 + \frac{1}{p_1 + p_2} \left( \sum_{r=1}^{p_1} \frac{s_r^+}{y_{rk}} + \sum_{n=1}^{p_2} \frac{s_n^-}{b_{nk}} \right)} \quad (1)$$

$$s.t. \begin{cases} x_k = X\gamma + s^- \\ y_k = Y\gamma + s^+ \\ b_k = B\gamma + s^- \\ \gamma \geq 0, s^- \geq 0, s^+ \geq 0, s^{b-} \geq 0 \end{cases}$$

where  $\rho$  is the value of GTIE-CE in each region;  $m$  is the number of resource inputs in each decision unit, i.e., capital inputs, human inputs, equipment inputs, and energy inputs;  $p_1$  is the number of desired outputs, i.e., economic outputs and innovation outputs;  $p_2$  is the number of undesired outputs, i.e., environmental outputs;  $s^-$ ,  $s^+$ ,  $s^+$  are the relaxation variables of the resource inputs, desired outputs, and undesired outputs, respectively; and  $X$ ,  $Y$ ,  $B$  are the resource input matrix, desired output matrix, and undesired output matrix, respectively.

**Spatial variance function.** Based on the super-efficiency SBM model, this study will further apply the spatial variance function to reveal the evolution process of GTIE-CE and its influencing factors. In terms of spatial analysis, existing studies have constructed a new combined approach to modelling and identifying regional transport trajectories and potential sources of study objects based on detailed study data. However, as an effective tool for analysing the spatial distribution pattern and variability of regional variables, the spatial variance function can reveal the structural variability characteristics of regional variables and the correlations between different regions (Emery and Ortiz, 2007). To reveal the evolutionary characteristics of GTIE-CE, this study analyses the spatial variation characteristics of the GTIE-CE, the government dimension, the market dimension, and the influencing factors of the technology dimension through the spatial

variation function. Equation (2) provides the expression of the spatial variance function (Arbia, 2001).

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \quad (2)$$

where  $\gamma(h)$  is the spatial variance function;  $h$  is the distance between different samples;  $Z(x_i)$  and  $Z(x_i + h)$  are the values of the variables at  $x_i$  and  $x_i + h$  [ $i = 1, 2, \dots, N(h)$ ], respectively;  $N(h)$  is the number of samples at distance  $h$ ;  $C_0$  is the nugget value, which indicates the smooth value presented with increasing spacing;  $C_0 + C$  is the abutment value, indicating that a smooth value is presented with increasing spacing;  $\frac{C_0}{C_0 + C}$  is the nugget coefficient, indicating the degree of spatial variability of the regional coefficients  $a$  is the variance range, indicating the maximum distance of the variance function to reach the abutment value; and  $D$  is the subdimension that indicates the curvature of the variance function, and the magnitude of the  $D$  value reflects the degree of spatial variability of the variables. Equation (3) gives the relationship between the subdimension  $D$  and the spatial variance function  $\gamma(h)$ .

$$2\gamma(h) = h^{(4-2D)} \quad (3)$$

**Panel vector autoregression models.** The PVAR model can avoid the endogenous influence between variables and reveal the internal mechanisms of different variables (Holtz-Eakin et al., 1988). To integrate the GTIE-CE and the market, government and technology dimensions into a systematic framework to examine the dynamic correlations among them and the impacts among variables, a PVAR model is constructed by taking the government, market and technology dimensions as the main variables of the GTIE-CE. Equation (4) gives the PVAR model (Abrigo and Love, 2016).

$$Y_{it} = \alpha_0 + \sum_{j=1}^n \alpha_j Y_{it-j} + \beta_i + \mu_t + \varepsilon_{it} \quad (4)$$

where  $Y_{it}$  is the column vector of the GTIE-CE, government dimension, market dimension, and technology dimension;  $i$  is the region;  $t$  is the time;  $n$  is the number of lag orders;  $\alpha_0$  is the intercept term;  $\alpha_j$  is the parameter matrix of lag order  $j$ ;  $\beta_i$  and  $\mu_t$

Table 3 Input–output efficiency indicators of GTI in construction enterprises.			
	Factor	Data Name	Data source
Input–Output indicators of GTIE–CE	Capital investment	Government funding of R&D costs	(National Bureau of Statistics, 2022)
		Internal expenditure on R&D in the construction industry	(National Bureau of Statistics, 2022)
	Manpower inputs	Full-time equivalents of R&D personnel in the construction industry	(National Bureau of Statistics, 2022)
		Enterprise labour productivity	(National Bureau of Statistics, 2022)
	Equipment inputs	Technical equipment rate of construction enterprises	(National Bureau of Statistics, 2022)
	Energy inputs	Energy consumption in construction	(National Bureau of Statistics, 2022)
	Economic output	Revenue from property development enterprises	(National Bureau of Statistics, 2022)
		Completed housing area of property development enterprises	(National Bureau of Statistics, 2022)
	Innovation outputs	Green patents in construction	(National Bureau of Statistics, 2022)
	Environmental outputs	Total carbon emissions of construction enterprises	(Feng Wang, 2015)
		Solid waste emissions	(Xu et al. 2019)

are the individual fixed effect term and time effect term, respectively; and  $\varepsilon_{it}$  is the random perturbation term.

**Indicator selection and data sources.** Since the data on R&D expenditure, solid waste emission and part of energy consumption in the construction industry stop updating after 2020, this study selects the panel data of construction enterprises in 30 provinces and cities in China from 2010 to 2020, which are obtained from the Chinese Statistics Yearbook of Science and Technology, the Chinese Statistics Yearbook of the Construction Industry the Chinese Statistics Yearbook of Energy, the National Bureau of Statistics of China (National Bureau of Statistics, 2022), and the China National Knowledge Network Database (China National Knowledge Infrastructure, 2022). The specific indicators and data sources used are as follows.

Based on the resource orchestration theory, in this study, the GTI inputs of construction enterprises are measured in terms of capital, labour, equipment and energy. Green innovation entails significant capital investment to sustain new technology development, and the capital investment in the GTI of construction enterprises is reflected in the internal spending on R&D in the construction industry (Xiang et al., 2019) and the funding of R&D costs from the government (Gao et al., 2021). Moreover, a combination of resource input and resource application is a key to improving GTIE, and the full-time equivalent of R&D personnel in the construction industry (Gao et al., 2021) and the labour productivity of enterprises both reflect the human input of GTI in construction enterprises. In addition, equipment and energy consumption provide R&D platforms and motivation for enterprises to carry out GTI. Herein, the technological equipment rate of construction enterprises (Wen et al., 2020) and the energy consumption of the construction industry are used to measure the equipment and energy inputs in the GTI of construction enterprises (Mohmand et al., 2017). Based on eco-innovation theory, in this study, the output indicators of GTI in construction enterprises are measured in terms of economic, innovation, and environmental outputs. In terms of economic output, GTI can provide enterprises with good economic benefits, and this study adopts the revenue and the completed housing area values of real estate development enterprises to measure the economic output of GTI in construction enterprises (Chancellor Lu, 2016). In terms of innovation output, GTI leads to the development of new products and the generation of new technologies. In this study, the number of green patents in the construction industry is used to reflect the innovation output of GTI in construction enterprises (Thomas et al., 2011). In terms of

environmental output, the production process inevitably leads to emissions and waste generation. In this study, the environmental outputs of GTI are measured using total construction enterprise carbon emissions (Gao et al., 2021) and the solid waste generated in the construction industry (Xu et al., 2019) as unexpected outputs. Table 3 lists the input and output indicators and data sources of the GTIE–CE.

Table 4 gives the definitions and data sources of the influencing factors of the market, government and technology dimensions of the green technology innovation efficiency of construction enterprises, detailed as follows: In the market dimension, the market environment for GTI by construction enterprises is evaluated from the perspectives of openness to the world of the market, the industrial structure in the construction industry, and the number of construction enterprises. Openness to the world determines the exchange of capital and technology between construction enterprises and the international market, and foreign direct investment is used herein to measure this parameter. Moreover, the industrial structure reflects the transfer of resources and information in the market, and this the ratio of the output value of the construction industry to the total output value is adopted to evaluate the industrial structure of construction enterprises (Yin et al., 2022). The scale of construction enterprises reflects the intensity of competition in the global market, and the number of construction enterprises is utilized to measure the scale of construction enterprises (Li et al., 2019). In the government dimension, in this study, the government environment for GTI in construction enterprises is measured through environmental policies and innovation incentives. The impacts of environmental policies and innovation incentives introduced by the government on GTIE–CE are determined. In this study, the number of environmental policies and local financial expenditures on science and technology are used to measure the environmental policies and innovation incentives in each region (Li et al., 2017). The technology dimension for GTI in construction enterprises is measured by using social innovation capacity, R&D human resources, and people’s education levels. The numbers of patent applications and researchers are firm representations of regional innovation achievements and technological innovation human resources. The numbers of patent applications and the researchers are considered to evaluate social innovation capacity and R&D human resources (Gao et al., 2021). Moreover, the education level of employees significantly impacts the knowledge absorptive capacity of enterprises; the number of university students is utilized to measure this parameter (Heffels et al., 2014). To eliminate the influence of the scale, the data are

**Table 4 Influences of the market, government and technology dimensions of the GTIE-CE.**

Dimension	Factor	Definition	Data source
Market dimension	Market openness to the world	Foreign direct investment	(China's National Bureau of Statistics, 2021)
	Industrial structure of the construction industry	Construction output/total output	(China's National Bureau of Statistics, 2021)
	Size of construction enterprises	Number of construction enterprises	(China's National Bureau of Statistics, 2021)
Government dimension	Environmental policy	Number of environmental policies	(China National Knowledge Infrastructure, 2022)
	Innovation incentive policy	Local financial expenditure on science and technology	(China's National Bureau of Statistics, 2021)
Technology dimension	Social innovation capability	Number of patent applications	(China's National Bureau of Statistics, 2021)
	R&D human resources	Number of researchers	(China's National Bureau of Statistics, 2021)
	People's education level	Number of college students	(China's National Bureau of Statistics, 2021)

**Table 5 Results of the spatial variance function of the GTIE-CE, market, government, and technology dimensions.**

	Year	Variance range (km)	Nugget value	Abutment value	Nugget coefficient	Fit model	Coefficient of determination
GTIE	2010	933	0.2460	0.7580	0.675	Exponential	0.791
	2015	508	0.0002	0.2084	0.999	Spherical	0.470
	2020	669	0.2415	0.5150	0.531	Spherical	0.686
Market dimension	2010	6157	0.0157	0.2414	0.935	Gaussian	0.794
	2015	2960	0.0264	0.1110	0.762	Gaussian	0.836
	2020	1825	0.0141	0.0329	0.571	Gaussian	0.814
Government dimension	2010	3907	0.5580	3.1260	0.821	Gaussian	0.924
	2015	4110	0.3300	1.6140	0.796	Spherical	0.844
	2020	1735	0.0099	0.0440	0.775	Spherical	0.800
Technology dimension	2010	2199	0.0189	0.0762	0.752	Exponential	0.909
	2015	2069	0.0286	0.0792	0.639	Gaussian	0.912
	2020	1170	0.0041	0.0519	0.921	Exponential	0.824

normalized according to previous studies (Li et al., 2024). Table 4 shows the influences and data sources of the market, government and technology dimensions of the GTIE-CE.

## Results

**Spatial evolution mechanism of the GTIE-CE considering the government, technology and market dimensions.** The spatial variance function can effectively reveal the evolutionary characteristics of the variables within a region and the links with different regions. To explore the spatial evolution characteristics from 2010 to 2020, the spatial variance functions of GTIE-CE with respect to the market, government and technology dimensions are calculated; different computational models are adopted to fit the results; the numbers of subdimensions of different variables in different directions are calculated; and further kriging interpolation is conducted. The results of the spatial variance function are given in Table 5. The nugget coefficient of GTIE-CE first increases and then decreases, which indicates that the spatial variance in GTIE-CE first increases and then decreases. The variance parameter of GTIE-CE first decreases and then increases, indicating that the range of spatial correlation caused by spatial differences is increasing (Li et al., 2023). The nugget coefficient of the market dimension continues to decrease, indicating that the spatial difference of regions from this dimension and its variable range parameter also continue to decrease (Tang et al., 2022). Furthermore, the spatial correlation range of the

market dimension continues to decrease. In terms of the government dimension, the fluctuation of its nugget coefficient is not significant, indicating that the spatial variance in the government dimension does not change significantly over the study period (Filiou et al., 2023). However, the variable range parameter of the government dimension continues to decrease, suggesting that the range of its spatial correlation gradually decreases. For the technology dimension, its nugget coefficient first decreases and then increases, and its spatial variance first increases and then decreases (Li et al., 2021). The variance trend indicates that the spatial correlation range of the technology dimension decreases.

Table 6 gives the subdimension numbers of GTIE-CE and the social, government and technology dimensions. The all-directional subdimension number of GTIE-CE first decreases and then increases, gradually approaching the ideal homogeneous distribution. This finding indicates that GTIE-CE is relatively balanced in omnidirectional distribution. The subdimension number of the southeast-northwest direction decreases, and spatial differences are mainly reflected in the southeast-northwest direction (Wang et al., 2019). For the market dimension, the omnidirectional subdimension number of the market dimension increases, indicating that its overall spatial difference is gradually decreasing. However, the number of subdimensions in the southeast-northwest direction of the market dimension is relatively small, and the southeast-northwest direction is the main source of spatial differences in the market dimension (Zhu et al., 2022). In terms of the government dimension, the overall subdimension number of the government

Table 6 Subdimensions of GTIE-CE, social, governmental, and technology dimensions of GTIE.											
	Year	Omnidirectional		East-west		Northeast-southwest		South-north		Southeast-northwest	
		D	R	D	R	D	R	D	R	D	R
GTIE	2010	1.915	0.629	1.997	0.014	1.917	0.234	1.962	0.008	1.719	0.901
	2015	1.872	0.376	1.841	0.304	1.523	0.293	1.896	0.021	1.636	0.106
	2020	1.927	0.613	1.833	0.449	1.918	0.029	1.831	0.204	1.617	0.088
Market dimension	2010	1.786	0.581	1.981	0.004	1.785	0.283	1.907	0.026	1.741	0.249
	2015	1.764	0.732	1.969	0.006	1.766	0.209	1.712	0.130	1.579	0.657
	2020	1.805	0.854	1.855	0.335	1.671	0.766	1.743	0.044	1.605	0.801
Government dimension	2010	1.777	0.823	1.789	0.677	1.740	0.558	1.703	0.784	1.672	0.637
	2015	1.807	0.789	1.819	0.581	1.795	0.307	1.732	0.300	1.937	0.010
	2020	1.756	0.864	1.748	0.814	1.574	0.406	1.771	0.131	1.381	0.342
Technology dimension	2010	1.758	0.924	1.836	0.435	1.867	0.098	1.313	0.201	1.703	0.383
	2015	1.774	0.918	1.812	0.453	1.866	0.084	1.525	0.186	1.815	0.125
	2020	1.813	0.836	1.821	0.560	1.864	0.343	1.920	0.013	1.618	0.630

dimension first increases and then decreases, and the spatial difference widens. The east-west and southeast–northwest subdimensions of the government dimension show the same trend as the omnidirectional subdimension, with the southeast–northwest spatial difference being the largest. For the technology dimension, the number of omnidirectional subdimensions gradually increases, indicating that the spatial differences in the technology dimension are decreasing (Fan et al., 2014). The south–north direction of the technology dimension shows a relatively rapid increase in the number of subdimensions, and its spatial difference continues to decrease. The number of subdimensions in the southeast–northwest direction shows a trend of first increasing and then decreasing; this direction remains the most important source of spatial differences. Therefore, the spatial differences between the GTIE–CE and the market, government and technology dimensions show different evolution trends. In general, the most important spatial differences are reflected in the southeast–northwest direction.

Figure 2 shows the evolutionary results of kriging interpolation of the spatial variance function of the GTI of construction enterprises in China and the social, governmental and technology dimensions. The high-value areas of GTIE–CE from 2010 to 2020 were concentrated in Hainan Province and Guangdong Province, while the central and western regions were low-value areas in this period. Overall, the GTIE–CE decreased from the southeast to the northwest during the study period. For the market dimension, the spatial structure from 2010 to 2020 did not obviously transform, the coastal areas of Fujian Province, Zhejiang Province, Jiangsu Province, Shandong Province and Shanghai Municipality were high-value areas that gradually spread inland, and there was an obvious circular structure. The market dimensions gradually decreases from east to west over the period studied. The government dimension showed a significant change in its spatial structure from 2010 to 2020, with two high-value zones in the Guangdong and Zhejiang Provinces and the Shanghai and Jiangsu Provinces in 2010. In 2015, the high-value zones were concentrated on the east coast of China, including the Shandong, Jiangsu, Zhejiang, and Anhui Provinces. However, in 2020, the spatial structure of the government dimension exhibited spatial characteristics similar to those in 2010. Overall, the development of the spatial structure of the government dimension decreases from the southeast coastal region to the northwest. The technology dimension had a similar spatial structure in 2010 and 2015, with the high value of the southeastern coastal region transferring inland in a northwest direction. However, in 2020, the technology dimension formed two high-value regions in Jiangsu Province and Guangdong Province. Overall, the technology dimension decreased from the southeast to the northwest during the study period. In summary, the spatial structure of the

GTIE–CE is similar to that of the government, technology and market dimensions. Therefore, the PVAR model is further applied in this study to explore the interaction relationships among these parameters.

Dynamic response relationship between GTIE-CE and the factors affecting different dimensions

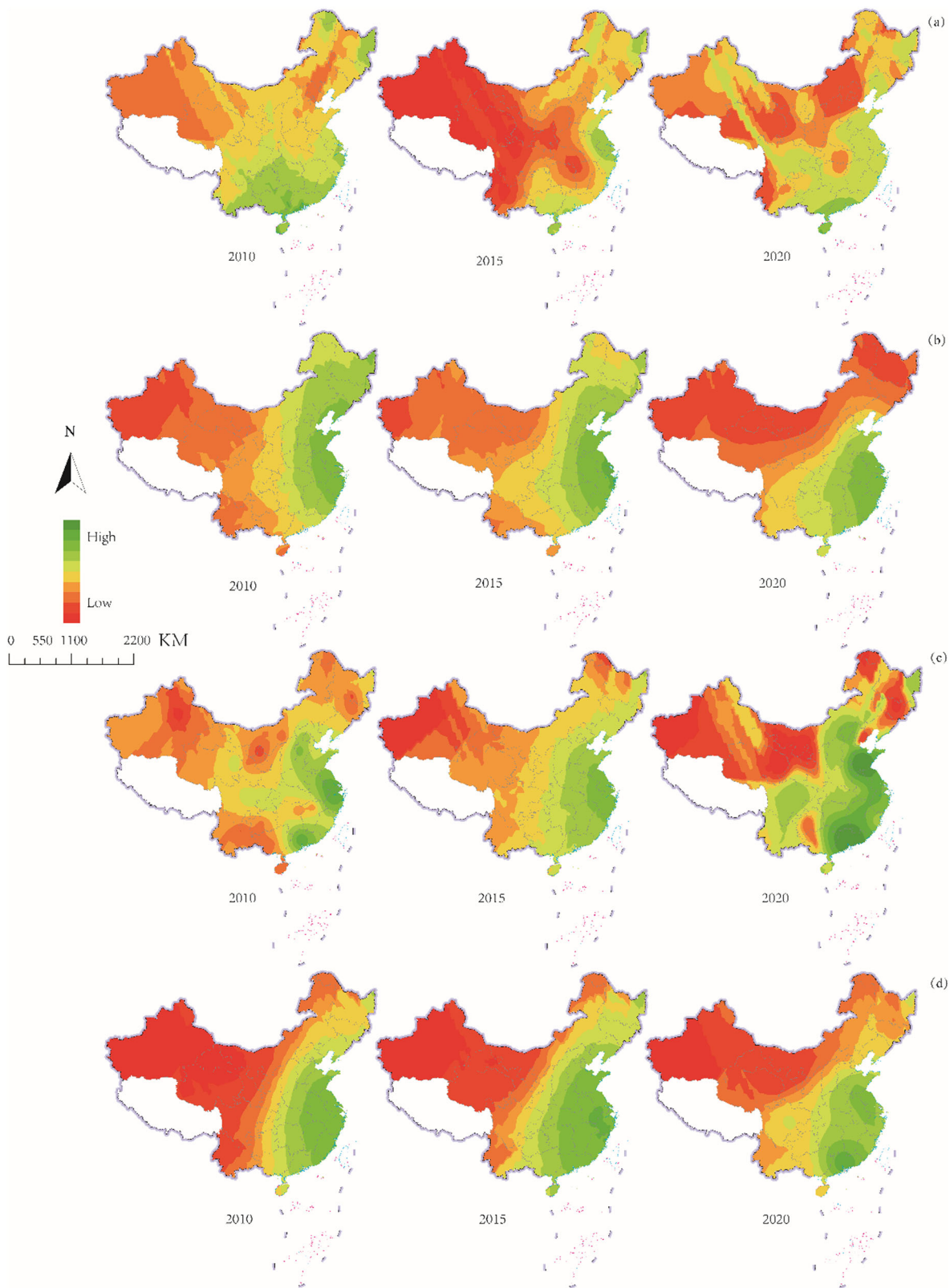
*Smoothness test and model lag selection.* In this study, a PVAR model is constructed to test the interactions between the GTIE–CE and the market, government and technology dimensions. To avoid the pseudoregression phenomenon, a smoothness test is performed on the GTIE–CE and the market, government and technology dimensions. Table 7 shows the results of the tests for each variable, GTIE–CE, Market dimension, Government dimension and Technology dimension all passed the LLC test and ADF-fisher test.

Furthermore, the optimal lag order of the PVAR model is given in Table 8. The optimal lag order of the PVAR model is determined to be 1st order based on the Akaike information criterion (AIC), Bayesian information criterion (BIC), and Hannan–Quinn information criterion (HQIC) criteria.

*Granger causality test.* Granger causality test can analyse the causal relationship between different variables, which helps to intuitively reveal the direction of the development of the variables and the mechanism of the interaction between the variables. In this study, Granger causality test is used to analyse the interaction relationship between GTIE–CE and market, government and technology dimensions, and the results of Granger causality test are given in Table 9. Therein, bidirectional causality exists between the GTIE–CE and the market dimension. The market dimension promotes the improvement in GTIE–CE, while the improvement in GTIE promotes market development. At both times, unidirectional causality exists between the government dimension and the GTIE–CE, and the government dimension can promote the improvement in the GTIE–CE. The market dimension and the technology dimension have a two-way causal relationship; market development promotes the progress of technology, and the improvement in technology also improves the market environment.

*Impulse response analysis.* To further explore the interactive correspondence between the variables, by Monte Carlo simulation, shock correspondence plots between the variables are obtained. The impulse response analysis results of the variables are given in Fig. 3. The market dimension has a negative impact on GTIE–CE in period 1 but a positive impact in period 2, and





**Fig. 2** Kriging interpolation evolution of the spatial variance function of GTIE-CE in China. **a** Results of Kriging Interpolation for GTIE-CE. **b** Results of Kriging Interpolation for Market Dimension. **c** Results of kriging interpolation for the government dimension. **d** Results of Kriging Interpolation for Technical Dimensions.

there is a lag in the promotion effect of the market dimension on GTIE-CE. The government dimension has a significant positive effect on GTIE-CE in period 1, but in the following periods, the effect gradually weakens and approaches 0. This finding shows

that the government dimension contributes significantly to the promotion of GTIE-CE in the short term. For the market dimension, under the impact of the government dimension, the market dimension shows a significant positive response in periods

Table 7 Smoothness test results.			
Variable	Levin, Lin, and Chu (LLC) test	Augmented Dickey-Fuller (ADF)-Fisher test	Conclusion
GTIE-CE	−7.9196***	7.8661***	Smooth
Market dimension	−8.0303***	13.4129***	Smooth
Government dimension	−13.9859***	13.9178***	Smooth
Technology dimension	−5.7613***	22.7827***	Smooth
***represent significance levels of 1%.			

Table 8 Optimal lag order of the PVAR.			
Lag	AIC	BIC	HQIC
1	−8.88153*	−7.06899*	−8.15369*
2	−8.53181	−6.3274	−7.64359
3	−7.75464	−5.07695	−6.67215
*represent significance levels of 10%.			

1–3, while the technology dimension has the same impact on the market dimension. This result suggests that both the government dimension and the technology dimension have significant positive effects on the market dimension. For the technology dimension, under the impact of the government dimension, the technology dimension shows a significant positive response in period 1, which indicates that the government dimension facilitates the technology dimension.

**Robustness tests.** To ensure the validity of the PVAR model and the impulse response results, a robustness test of the PVAR model is conducted with reference to Baek’s study (Baek et al., 2018). Figure 4 shows the results of the robustness test. The test results show that the eigenvalues of the dynamic matrices in the PVAR model are within the unit circle; thus, the model results are robust.

Discussion

In this section, the evolution trends and mechanisms of GTIE–CE are further discussed.

**Trends in the evolution of GTIE–CE.** By exploring the spatial evolution characteristics of the GTIE–CE with respect to the government, technology and market dimensions, it is revealed that the GTIE–CE with respect to the government, technology and market dimensions has significant spatial heterogeneity, revealing that the coastal region is generally better than the inland region. Moreover, its evolution is characterized by a gradual tendency to spread towards the northwestern inland area from the southeastern coastal area. The regional heterogeneity of the GTIE of Chinese regional enterprises has been confirmed by most studies (Gao et al., 2021). Unlike past empirical studies, it is discovered that the GTIE–CE first forms a high-value region in the Pearl River Delta and Yangtze River Delta and then gradually spreads to the surrounding areas and drives the development of the GTIE–CE in the vicinity. Meanwhile, the evolution trend of the influencing factors of the technology and government dimensions also proves this viewpoint. the evolution trend of the technology dimension from 2010 to 2020 is decreasing from the southeast coastal region to the northwest inland, and in 2020, the technology dimension has formed two high-value regions in Jiangsu Province and Guangdong Province. After the reform and opening up, the Pearl River Delta and Yangtze River Delta regions are more likely to absorb international technological and financial resources due to the geographic advantages of the coastal regions,

and then spread to the inland regions after forming rich technological accumulation (Ma et al., 2024). The government dimension shows two high value zones in 2010 and 2020, centred on Guangdong Province and Zhejiang Province, Shanghai and Jiangsu Province. The Pearl River Delta and Yangtze River Delta, the regions with the highest concentration of technological and economic resources in China, are more likely to be used as pilot regions to test the applicability of relevant policies, and are also favoured by more policy resources. Moreover, due to their special geographical location, the Pearl River Delta and Yangtze River Delta regions are able to enjoy the benefits of the open-door policy more directly, and the government dimension has formed an evolutionary trend with the Pearl River Delta and Yangtze River Delta as the high-value regions and spreading to the surrounding areas (Guo et al., 2024). This study finds that the spatial and temporal evolution characteristics of the influencing factors of the market, government and technology dimensions are consistent with the spatial and temporal evolution characteristics of GTIE–CE, which all show the characteristics of forming a high value region in the Pearl River Delta and Yangtze River Delta and gradually spreading from the Southeast Coastal Region to the Northwest Inland Region, which reflects the spillover effect of the economy and technology. Therefore, these regions are the key drivers of GTIE–CE in the entire Chinese region. The possible reasons for this phenomenon are that the regional geographical advantages, the complete technology and innovation system, and the national policy support contribute to its GTIE. In addition, resource differences in various regions cause regional heterogeneity in the GTIE–CE (Cai et al., 2024). The geographical situation and development status of different regions determine that different regions have distinct resources (Zhao et al., 2023). Therefore, in the development of the GTIE–CE, the resources and development status of a particular region should be considered according to the characteristics of different regions to complement each other to improve overall efficiency (Silvestre and Dalcol, 2009). GTIE–CE gradually spreads from the southeastern coastal region to the northwestern inland region. We can fully exploit the contributions of high-efficiency regions and the advantageous resources of different regions by building a cooperative and innovative platform to promote the overall enhancement of GTIE–CE.

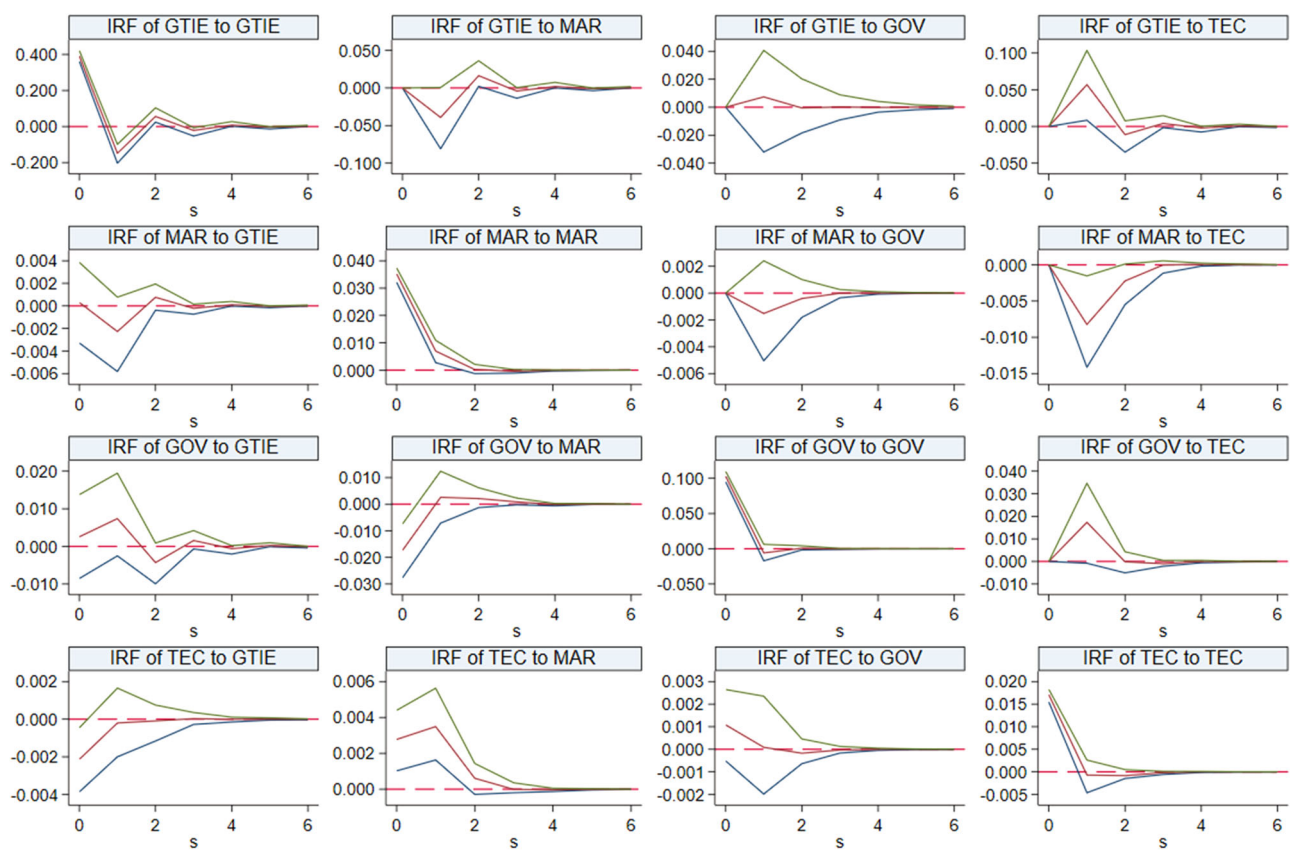
Mechanisms of the GTIE–CE

*Mechanisms of the market dimension and GTIE–CE factors.* By examining the dynamic response relationships among GTIE–CE and the market, government and technology dimensions, it is revealed that the market dimension has a negative impact on GTIE–CE in impact period 1 but has a positive impact in period 2. The conclusions of existing studies on the mechanism through which the market dimension influences the GTIE of enterprises remain controversial. Some scholars believe that market factors such as the degree of openness to the world, industrial structure, and green finance have a significant role in promoting GTIE–CE (Liu et al., 2022). Moreover, the optimization of the market environment can promote the flow of innovation resources in the

**Table 9 Granger causality test.**

Equation	Chi2	Prob>chi2	Conclude
Granger reasons for the GTIE not being the market dimension	2.8518	0.091	Rejection of the original hypothesis*
Granger reasons for the GTIE not being the government dimension	0.0307	0.861	Acceptance of the original hypothesis
Granger reasons for the GTIE not being the technology dimension	3.8405	0.050	Rejection of the original hypothesis**
Granger reasons for the market dimension not being the GTIE	3.4020	0.065	Rejection of the original hypothesis*
Granger reasons for the market dimension not being the government dimension	0.2625	0.608	Acceptance of the original hypothesis
Granger reasons for the market dimension not being the technology dimension	4.0487	0.044	Rejection of the original hypothesis**
Granger reasons for the government dimension not being the GTIE	2.9803	0.084	Rejection of the original hypothesis*
Granger reasons for the government dimension not being the market dimension	0.0365	0.848	Acceptance of the original hypothesis
Granger reasons for the government dimension not being the technology dimension	3.2238	0.073	Rejection of the original hypothesis*
Granger reasons for the technology dimension not being the GTIE	0.1210	0.728	Acceptance of the original hypothesis
Granger reasons for the technology dimension not being the market dimension	6.4849	0.011	Rejection of the original hypothesis**
Granger reasons for the technology dimension not being the government dimension	0.0124	0.911	Acceptance of the original hypothesis

\*\*and \*represent significance levels of 5 and 10%, respectively.

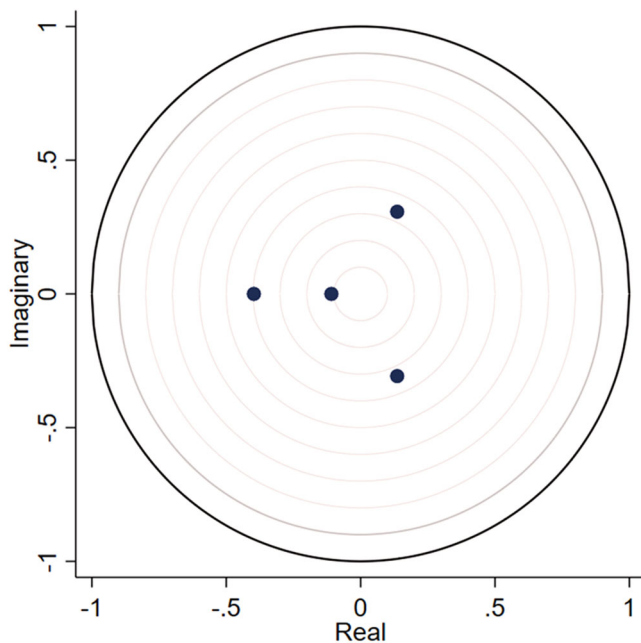


**Fig. 3 Impulse-response analysis.** Errors are 5% on each side generated by the Monte Carlo simulation with 200 reps. MAR market dimension, GOV government dimension, and TEC technology dimension.

industry, thus improving the GTIE of enterprises (Li and Zeng, 2020). Other scholars believe that excessive openness and marketisation will have a crowding out effect on green R&D funds, which is not conducive to enhancing GTIE (Lv et al., 2020). Unlike the results of some existing studies, we find that the market dimension has a lagging effect on the promotion of GTIE-CE; that is, the optimization of the market environment cannot immediately promote the improvement in GTIE. The possible reason for this delay is that the change in the market is reflected in the profit and resource acquisition of enterprises, and enterprises cannot immediately adjust to this change. Asymmetric innovation theory suggests that China's unique market is

characterised by a large and uneven market. The unbalanced market affects the profits and resources created by GIT for enterprises, and in the face of changes in the market environment, enterprises can't immediately make adjustments, enterprises need a certain amount of time to adapt to the changes in the market environment, resulting in a lag in the market dimension for the promotion of the GTIE-CE (Chen et al., 2024). Furthermore, through the expansion of openness to the world, foreign capital and technological resources can be introduced, and the spillover and diffusion benefits of green technology can enhance the GTIEs of local enterprises (Lv et al., 2021). The findings of this study confirm this conclusion, with the difference that marketisation





**Fig. 4 Robustness test of the PVAR model.** The test results show that the eigenvalues of the dynamic matrices in the PVAR model are within the unit circle; thus, the model results are robust.

does not produce an immediate facilitating effect in this study. It takes time for construction firms to collect and integrate knowledge when introducing external technology and capital before they GTIE can increase (Liu et al., 2022). Because of the lagging effect of the market dimension on GTIE-CE, the promotion of GTIE-CE through the market requires a long-term plan. Nevertheless, the market dimension can positively affect GTIE-CE.

**Mechanisms of the government dimension and GTIE-CE factors.** The government dimension has a remarkable impact on the GTIE-CE during period 1 that gradually diminishes and approaches zero in the following periods. Thus, the government can significantly promote GTIE-CE, but the government dimension does not have a long-term promotion effect. Many studies on the effect of the government dimension on GTIE have been conducted. Most scholars believe that the government can guide enterprises to increase investment in GTIE through the new system while sharing the cost; therefore, government policy significantly promotes the GTIE (Liu et al., 2022). This study confirms this conclusion. Moreover, this finding is consistent with the asymmetric innovation theory, which involves the characterization of the strong government system while innovating Chinese firms; according to this theory, the government can impose direct and mandatory constraints on enterprise behaviour. Existing studies have concluded that environmental pressures and innovation incentives imposed by the government on firms positively contribute to the importance of GTI and GTIE (Gao et al., 2018). However, the government does not have a long-term effect on GTIE according to this study, potentially because government regulations can significantly constrain the behaviours of enterprises in a short period. However, this doesn't lead to long-lasting innovation resources for enterprises. Resource orchestration theory suggests that the integration of enterprise resources and knowledge absorption capacity can help enterprises improve the efficiency of developing innovative products. Government policy support can provide support for GTI for a certain period of time, but it can't improve the resource acquisition and

knowledge integration ability of enterprises in the long run (Liao et al., 2024). Moreover, GTI requires long-term technological accumulation and resource investment, and an innovative technological development system and a perfect industrial structure can have a long-term impact on the improvement in the GTIE of enterprises (Kai et al., 2020). To improve the GTIE-CE, the role of the government should not be ignored. The development of industry standards and the funding of green R&D by enterprises can promote enterprises to invest additional resources in green technology R&D, and new industry standards can help enterprises bring the results of GTIE to the market.

**Mechanisms of the technology dimension and the GTIE-CE factors.** For the technology dimension, its impact on the market dimension shows a significant positive response in periods 1–3. Thus, the technology dimension has a significant positive effect on the market dimension. However, for the GTIE-CE, the market dimension and the GTIE-CE do not pass the Granger causality test; therefore, the market dimension cannot have a significant effect on the GTIE-CE. Moreover, this study shows that the technology dimension has a significant positive effect on the market dimension. Strengthening the input of the technology dimension can indirectly promote GTIE-CE. Asymmetric innovation theory suggests that the scenario of a weak technological regime prevails among Chinese enterprises. When GTI results enter the market, they are easy to be learnt, imitated or even copied by other enterprises, which results in innovative enterprises investing a lot of R&D resources but failing to obtain the expected market returns, which is not conducive to the enhancement of enterprises' GTIE (Wei et al., 2016). In Addition, investment in technical resources can promote the standardization of the technology market and strengthening the protection of intellectual property rights can effectively guarantee the transformation of green technological innovation, thus promoting GTIE-CE (Li et al., 2024). Furthermore, a standardized and efficient technology market helps enterprises acquire new technologies, integrate green knowledge and production technology and promote the output of green innovation (Samuel et al., 2024).

## Conclusions and implications

**Conclusions.** In this study, the changes in GTIE-CE in China are revealed and the interaction relationships between GTIE-CE and the market, government and technology dimensions in China are analysed using the PVAR model. The main conclusions are as follows:

- (1) GTIE-CE is regionally heterogeneous in China, with an evolutionary trend of spreading from high-efficiency regions to surrounding areas. Specifically, the GTIE-CE in China gradually spreads to the surrounding areas after the formation of high-efficiency regions in the Pearl River Delta and Yangtze River Delta. Therefore, fully exploiting the effects of high-efficiency regions and forming complementary resources with different regional advantages can help reduce the regional heterogeneity of the GTIE-CE, which is key to realizing the green transformation of Chinese construction enterprises.
- (2) Although the market dimension positively contributes to GTIE-CE, the effect is delayed. The market dimension itself does not promote GTIE-CE in a short period, but a combination of the market dimension and the government dimension can produce an increasingly significant positive effect. To promote GTIE-CE, the role of the market dimension should not be ignored. By creating a favourable market environment and upgrading the existing industrial structure, we can actively promote GTIE-CE and help to



improve the problems of high energy consumption and high emissions in the construction industry.

- (3) Although the government dimension significantly contributes to the improvement in the GTIE–CE, this effect has a time limit. Specifically, it is difficult to rely on only the government dimension to have a long-term promotion effect on GTIE–CE. The government dimension helps early green transformation of construction enterprises, and the government's role in guiding the behaviour of enterprises is an important factor driving the green transformation of construction enterprises. A combination of government and market dimensions can have a long-term effect on the GTIE–CE.

**Implications.** This study provides the following managerial and policy insights for improving GTIE–CE:

First, GTIE–CE is regionally heterogeneous in China, and there is an evolutionary trend in which the Pearl River Delta and Yangtze River Delta regions are high-efficiency regions that are spreading in all directions. Due to the significant regional heterogeneity in the GTIE–CE in China, the government should promote the common progress of construction firms in different regions by constructing a synergistic mechanism for innovation in construction enterprises. Governments should facilitate exchanges of technological and innovation resources between low-efficiency and high-efficiency regions to accelerate the diffusion of GTIE. Meanwhile, existing green innovation incentive policies should be integrated, and dispersed resources for innovation subsidies and technological incentives should be consolidated through the establishment of special innovation funds, so as to provide innovation funding support for enterprises with the willingness and ability to innovate. In addition, the government can provide perfect information technology services for innovative enterprises and strengthen the exchange of GTI in various regions by building an innovation information platform. It helps to fully exert the diffusion role of high-efficiency regions and realise the balanced development of GTIE–CE.

Second, the government dimension significantly promotes the improvement of GTIE–CE, therefore, constructing a policy system in which environmental policy and innovation policy are coordinated with each other and innovating the existing environmental policy tools is the key to improving the GTIE–CE. For regions with low GIE, the government should innovate the existing construction industry chain policy. The aim is to integrate enterprises in different industry chains to jointly carry out green innovation, share the uncertain risks in the green innovation process and achieve efficient allocation of innovation resources. For regions with high GIE, the government can formulate cooperation and innovation policies in different regions, widely absorb low-efficiency regions and small and medium-sized private enterprises, guide enterprises in various regions to carry out green technology research and development through high-efficiency regional enterprises, accelerate the degree of industrial agglomeration in low-efficiency regions, and cultivate new green innovation agglomerations.

Third, the market dimension has a positive role in promoting the GTIE–CE. Therefore, the government and state-owned enterprises should give full play to the role of promoting the GTIE, create the atmosphere of GTI in the market through the leadership of the government and the active response of state-owned enterprises, and set up GTI demonstration enterprises to call for more enterprises to actively invest in GTI. Moreover, the government and state-owned enterprises should give full play to the role of promoting the GTIE. While the government actively plays its own role, the market should also be fully exploited.

Governments are required to build an active market management system and introduce policy tools to constrain the behaviour of enterprises and enhance GTIE–CE. The government can create an open market atmosphere and allow enterprises to make flexible decisions according to market conditions. In addition, the government should strengthen the management and regulation of the introduction of foreign investment, formulate appropriate open-door policies according to the economic level, industrial development status and GIE of different regions, and guarantee the high quality of the introduction of foreign investment by raising the threshold of foreign investment entry.

**Limitations and future perspectives.** Similar to most studies, this study has several limitations. First, we only reveal the spatial evolution mechanism of GTIE–CE from the government, market and technology dimensions, but we have yet to consider the interaction effects of different governmental subjects, market sizes and technology levels. Future research can involve analyses of the interaction effects of different influencing factors on the GTIE–CE on this basis. Second, we have only measured the GTIE–CE from the perspective of inputs and outputs and have not considered the inputs of intangible resources, such as the organisational management system, into the GTIE process. Therefore, future research can involve optimizations of the GTIE–CE measurement system by quantifying the input of intangible resources such as the organisational management of enterprises. Third, the data in this study mainly come from the statistical yearbooks issued by the state, and due to the limitations of data acquisition, some indicators cannot be included in the GTIE–CE measurements. For future research, scholars can obtain relatively detailed data through field visits and interviews to accurately measure the GTIE–CE.

### Data availability

The datasets used and analysed in the current study are available in the editorial section of the National Bureau of Statistics at <http://www.stats.gov.cn/>. The data include input-output efficiency indicators of GTI in construction enterprises and influences of the market, government and technology dimensions of the GTIE–CE.

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## Author contributions

Xingwei Li: conceptualization, methodology, writing - original draft, supervision, project administration. Xiang Liu: methodology, validation, formal analysis, investigation, resources, data curation, writing - original draft, writing - review & editing, visualization

## Competing interests

The author declares no competing interests.

## Ethical approval

Our study was not medical research nor employed any experiments on humans. Hence, according to the Declaration of Helsinki, the ethical issue should not be a problem in our study. Furthermore, the gathered information is strictly confidential and anonymous and is only used for research purposes. Hence, no ethical approval was needed by the author.

## Informed consent

This article does not contain any studies with human participants performed by any of the authors.

## Additional information

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