Coupling Relationship Among Technological Innovation, Industrial Transformation and Environmental Efficiency: A Case Study of the Huaihai Economic Zone, China

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Abstract: The 14th Five-Year Plan period is a critical period for China to achieve high-quality development. Based on super-efficiency slacks-based measure (SBM) model, grey-related analysis (GRA) and other models, this paper studies the heterogeneity of the coupling relationship among technological innovation, industrial transformation and environmental efficiency in the Huaihai Economic Zone during the period of 2005–2019. In addition, it analyzes the coupling mechanism of single and binary systems to the ternary system, which is of great significance for the collaborative symbiosis among systems. The findings are as follows. 1) The technological innovation, industrial transformation and environmental efficiency (TIE) systems of the Huaihai Economic Zone had significant spatial-temporal heterogeneity. Although their evaluation value fluctuated, the development trends are all positive. Ultimately, technological innovation is characterized by being high in the northeast and low in the southwest around Xuzhou, while other systems are relatively staggered in space. 2) The coupling of TIE systems is in transition, lack of orderly integration and benign interaction. However, the developing trend of interaction is also upward, and a spatial pattern driven by Xuzhou and Linyi as the dual cores has gradually formed. Moreover, the coupling is mostly manifested as outdated technological innovation and industrial transformation. Except for the final coordination of regenerative cities, the other resource types are all in transition. Cities in all traffic locations are still in transition. The overall system interaction of cities on Longhai Line (Lanzhou-Lianyungang Railway) is relatively optimal, and cities on Xinshi Line (Xinxiang-Rizhao Railway) are accelerating toward synergy. 3) The coupling status of TIE systems depends on the development of the single system and the interaction of the binary (2E) system. The coupling is closely related to technological innovation and Technology-Industry system, and is hindered by the inefficient interaction of Technology-Environment system. Specifically, the synergy of regenerative cities is attributed to the advantage of a single system and the effective integration of 2E systems. Beneficial from the advantages of environmental efficiency, the cities on Xinshi Line promote the synergy of the 2E and TIE systems. Therefore, while the Huaihai Economic Zone stimulates the development potential of the single and 2E systems, it is necessary to amplify the superimposition effect of systems in accordance on the basis of resource and location.

Keywords: technological innovation; industrial transformation; environmental efficiency; coupling relationship; heterogeneity

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1 Introduction

A new round of technological revolution and industrial transformation is proceeding vigorously. Against the backdrop of emission peak and carbon neutrality in contemporary China, successfully seizing this major opportunity will become the key to achieving the symbiosis of the system and high-quality development. Therefore, clarifying symbiosis and evolution among the innovation, industry and environment, and thereby revealing the laws of regional differentiation and mutual feedback mechanism, etc. (Guo, 2019), plays a positive role in promoting high-quality regional development (Rui, 2018; Shi and Zhao, 2018). Furthermore, under the influence of COVID-19, combining evolutionary economy, environmental geography, sustainable development, this study systematically explores the interaction mechanism of the innovation-driven, industrial evolution and environmental effects, providing a scientific basis for enhancing sustainable development.

The present research on the relationship among technological innovation, industrial transformation and environmental efficiency is mainly as follows.

First, scholars highlight that technological innovation is the key for industrial upgrading and the driving force for the high-quality development (Freitas et al., 2013; Wang et al., 2015). The comprehensive promotion of industrial transformation from resource-dependent to innovation-driven has gradually been emphasized. The path for innovation under regional characteristics has gradually been proposed. The successful transformation of resource-based areas, such as Ruhr in Germany and Houston in the US, has also proven the driving force of technological innovation (Rui, 2018; Li et al., 2020). Technology promotes industrial upgrading under institutional innovation (Li and He, 2021). Throughout the process, industrial optimization has forced technological innovation. Therefore, the life cycle of technology and industry presents similar ‘S-shaped’ characteristics (Schilling and Esmundo, 2009). The evolution of industry, which is internally determined by innovation, will also continuously promote technological innovation (Du et al., 2021).

Second, industrial optimization is the key path for environmental protection (Li et al., 2019; Fethi and Senyucel, 2021). The transfer of contamination exists in the industrial transition. Under the new economy, the impact of industrial agglomeration on the environment exhibits new characteristics (Liu et al., 2017; Yang et al., 2021). Adjusting the industrial structure can not only increase the proportion of technology- and knowledge-intensive industries, it can also reduce the proportion of high-pollution industries (Zhou and Wang, 2019; Andrée et al., 2019). Governments also encourage technological investment in cleaner production (Liu et al., 2017; Li et al., 2020), so as to control the generation and emission of pollution. When industrial adjustment becomes the key to maintaining growth and promoting emission reduction (Bilen et al., 2008), environmental regulation effectively forces industrial transformation. However, there are obvious differences in the mechanism of regulation on the innovation of different industries, and it is necessary to consider the local endowment and dependence on industry (Pei et al., 2019). Therefore, the synergy between industry and environment is reflected in actively promoting the new industrialization with green ideas (Yang and Wang, 2020), and applying environmental constraints to promote industrial efficiency (Fang et al., 2021).

Third, improving the environment by technological innovation has reached a consensus. According to the Porter Hypothesis, stimulating the effect of ‘innovation compensation’ through technological innovation is the key to achieving pollution reduction and enhancing the competitiveness of enterprises (Rahman and Alam, 2021; Sun and Guo, 2021). Grubb and Ulph (2002) previously showed that, driven by innovation, more advanced technology also becomes greener. Simultaneously, changes in environmental efficiency stimulate the government to induce innovation. Chinese scholars have empirically analyzed the effects of industrial adjustment and technological progress on the environment (Wu et al., 2021; Hao et al., 2021). Therefore, the improvement of regional innovation can effectively reduce carbon emissions, and exert spillover effects on neighboring regions (Fan et al., 2020; Ajibade et al., 2021). Additionally, environmental quality affects the intensity of government control and has an oppressive effect on technological innovation. In other words, relying on green technological innovation will aid in promoting industrial transformation (Ely et al., 2019).

Based on the literature described above, the focus is the system integration of innovation, industry, and environment in the developed regions. Research on the un-
nderdeveloped regions with inter-provincial boundaries and resource-based agglomeration is relatively lacking. In addition, the existing literature mostly focuses on the relationship between innovation, industry and the environment, with particular emphasis on industrial optimization and technological innovation under environmental regulation. However, the current research has neglected the internal interaction of the ternary (TIE) systems of environmental efficiency, technological innovation and industrial transformation. Therefore, the theoretical analysis of the coupling mechanism remains in the exploratory stage. It can be seen that a recognized and unified study framework or analysis paradigm of TIE systems has yet to form.

Therefore, the innovation of this study lies in the following aspects. First, based on the typical region of underdeveloped inter-provincial fringe, the study analyzes the coupling heterogeneity of TIE systems from the spatial-temporal dimension, and explores the mechanism of coupling. Second, it uses the development characteristics of the single system, and interaction law of the binary system to comprehensively analyze the internal coordination mechanism of TIE systems. Third, the study focuses on the perspective of resource and location for analysis, which are closely related to the development and interaction of systems.

Moreover, the significance of this study is as follows. First, the study enriches the content of the coupling of multiple systems and advances the study depth of related theories, such as collaborative innovation and sustainable development. Second, the collaboration of innovation, industry and environment provides a basis for the coordinated development of the Huaihai Economic Zone. This also bears important practical significance for accelerating the process of regional coordination and high-quality development of other resource-based cities and inter-provincial region.

## 2 Mechanism Analysis

The stability and progress of TIE systems are the keys to sustainable development. Based on collaborative innovation, industrial structure and ecological economy, the interaction mechanism is as follows (Fig. 1).

1. Technological innovation is the key to driving the dynamic evolution of comparative advantage and realizing industrial transformation. After industrial upgrading, the benign mechanism will be produced, which will give rise to new technologies. Specifically, technology induces industrial upgrading by influencing demand and supply, and will directly achieve transformation through the renewal of traditional industries (Li and He, 2021). In addition, the important externality of industrial transformation is to continuously stimulate the spillover of knowledge and technology, and this also provides a broad application for innovation (Loorbach et al., 2020).

2. Technological innovation is the fundamental driving force for green ecology. Industrial transformation is capable of reducing the ecological stress caused by economic activities (Fethi and Senyucel, 2021). Innovation and industry interact with environment through innovative collaboration and efficiency improvement (Grubb

![Fig. 1 Coupled framework of technological innovation, industrial transformation and environmental efficiency systems](attachment:image.png)
and Ulph, 2002). Furthermore, green technology promotes the progress of emission reduction and drives the transformation of industries. This, in turn, will inevitably promote the development of industries in the direction of becoming more advanced and ecological, which is conducive to environmental governance (Yang and Wang, 2020).

(3) The environment provides a continuous material and spatial foundation for technological innovation and industrial transformation. A superior environment is conducive to the attraction of talent and the inflow of high-tech industries, and it forces industrial upgrading (Ely et al., 2019). When eco-efficiency fails to meet the requirements, companies often increase investment in pollution control. This results in insufficient innovation motivation and restricts the sustainable development of regulated industries. Naturally, this may in turn produce an innovation compensation effect to promote industrial optimization (Shi and Zhao, 2018; Yang and Wang, 2020).

In summary, systemic development requires the coordinated development of the subsystems under the influence of self-organization and human intervention. This study focuses on system self-organization theory to analyze the internal mechanism of TIE systems.

3 Materials and Methodology

3.1 Study area
The Huaihai Economic Zone is located at the intersection of the Belt and Road and the eastern starting point of the New Eurasian Continental Bridge Economic Corridor. It also forms an important part of the Yangtze River Economic Belt, Yangtze River Delta and Huaihe Ecological Economic Zone (Fig. 2). Therefore, the zone, which acts as a bridge connecting the east-west and north-south economic belts in China, bears the responsibility of opening up to the outside. The zone includes cities such as Xuzhou, Huaibei, Heze, Jining, Linyi, Lianyungang, Shangqiu, Suqian, Suzhou and Zaozhuang, and spans across the four provinces of Jiangsu, Shandong, Henan and Anhui. Most cities regard equipment manufacturing, chemicals, building materials, metallurgy as key industries (Meng et al., 2019). There are four railways that are of great significance to the development of this zone, including the Beijing-Shanghai Railway (Jinghu Line), the Beijing-Kowloon Railway (Jingjiu Line), the Lanzhou-Lianyungang Railway (Longhai Line) and the Xinxiang-Rizhao Railway (Xinshi Line). In the context of innovation, the zone actively develops new energy, promotes energy conservation and implements environmental protection. However, the reliance on resource is evident, and the environment is under pressure. The development of emerging industries there is highly positioned (Cui et al., 2020). As a result, the coordinated development of innovation, industry and environment has attracted widespread attention. In recent years, the zone further emphasized the need to construct a more complete coordination mechanism with open vision and proactive attitude (Ding and Qiu, 2021; Tang and Zhou, 2021).

3.2 Data source
This study takes prefecture-level administrative regions as the unit, with a total of 10 cities, and the study period...
is 2005–2019. The data involved mainly originate from the China City Statistical Yearbook (National Bureau of Statistics of China, 2006–2020), the Jiangsu Statistical Yearbook (Bureau of Statistics of Jiangsu, 2006–2020), the Shandong Statistical Yearbook (Bureau of Statistics of Shandong, 2006–2020), the Henan Statistical Yearbook (Bureau of Statistics of Henan, 2006–2020), the Anhui Statistical Yearbook (Bureau of Statistics of Anhui, 2006–2020). Some missing data in individual years were filled with the method of interpolation. Additionally, the number of papers published draws on the method of Fan et al. (2020), using the CNKI database. This study presets the author unit as a certain city in the advanced search, and retrieves the number of papers published during the study year.

3.3 Methodology

3.3.1 Measurement of technological innovation

(1) Construction of index system

Based on the previous study, this study combines the representativeness and dominance of indicator selection, and considers the unity and accessibility of data (Zhou and Wang, 2019; Li and He, 2021). Additionally, combining the typical characteristics of the Huaihai Economic Zone, an indicator system of technological innovation has been constructed (Table 1), which includes knowledge innovation, technological development capability, and regional service innovation (Wang et al., 2021). Specifically, knowledge is the source of power for innovation. The number of ordinary colleges and universities is selected to measure the development of knowledge platforms. The number of papers published and patent applications directly reflect the output of knowledge innovation. Technological development capability is further divided into the technological subject and technological investment. R&D personnel are the main body of innovation to measure the technological development capability. R&D internal expenditures are used to provide material support and development foundation for technological research, and their proportion of GDP is used as technological investment. Regional service innovation acts as the basic support for innovation. The proportion of education expenditure in public financial expenditure and the number of internet users are selected to measure the regional service innovation.

(2) Entropy weight TOPSIS

Entropy weight TOPSIS is an improvement of the traditional TOPSIS, and it is based on the Entropy method. This method determines the index weight according to the information provided by each evaluation index. Therefore, the relative proximity among each evaluation object and the ideal solution could be ranked. To avoid the influence of the ‘0’ value following the standardization treatment on the subsequent calculation, the data were translated into one unit after being calculated, so that they still bore practical significance. The study mainly used this method to obtain the comprehensive evaluation value of each system. The specific calculation process is detailed in the References section (Zheng et al., 2020).

3.3.2 Measurement of industrial transformation

Most of the existing literature has investigated the industrial transformation from three perspectives (Han et al., 2017): the transformation speed, rationalization and the advanced of industrial structure. Considering evolutionary economic geography (Guo, 2019), integrating existing research and combining the connotation (Guo and Tian, 2021), this study adds industrial path locking and path innovation to measure industrial transformation. In detail, the speed of industrial structure measures the speed of up-

| Table 1 | Evaluation index system of technological innovation |
|---------|---------------------------------------------------|
| **Criterion layer** | **Scheme layer** | **Specific indicators** |
| Knowledge innovation capability | Knowledge platform | Number of ordinary colleges and universities |
| | Knowledge output | Number of patent applications accepted |
| | | Number of papers published |
| Technological development capability | Innovation subject | R&D personnel / person |
| | Innovation investment | R&D internal expenditures as a share of GDP / % |
| Regional service innovation | Governmental support | Proportion of education expenditure in public finance expenditure / % |
| | Other elements | Number of internet users / household |
grading (Qiu et al., 2015); rationalization reflects the degree of coordination between industries and the degree of effective use of resources; the advanced index represents the level of transformation; path locking measures the inertial constraints of industrial transformation; and path innovation measures breakthroughs in the direction (Miao et al., 2018).

(1) Speed and advanced index of industrial restructuring

The speed and advanced index of industrial restructuring refer to the speed of structural change and the process of gradual industrialization of new industries driven by innovation. Drawing on related research (Qiu et al., 2015; Zheng et al., 2020), this study divides the industry into four types: resource-intensive, labor-intensive, capital-intensive and technology-intensive sectors. In addition, it takes the proportion of output value of these four industries as a component of the space vector. The calculation formula used is as follows:

\[
\theta = \arccos \left[ \frac{\sum_{i=1}^{n} (x_{i,j} \times x_{i,0})}{\left( \sum_{i=1}^{n} (x_{i,j}^2)^{1/2} \times \sum_{i=1}^{n} (x_{i,0}^2)^{1/2} \right)^{1/2}} \right] \tag{1}
\]

In the formula, \( \theta \) is the speed of industrial transformation; \( x_{i,j} \) is the proportion of the output value of the resource, labor, capital and technology-intensive industrial sector to the total industrial output value in the study year; and \( x_{i,0} \) represents the proportion in the base year (\( n = 4 \)).

The advanced index \( IH \) refers to the level of industrial structuring. The larger the \( IH \) value is, the more advanced it will be. Based on Formula (1), the formula of the \( IH \) value is as follows:

\[
IH = \sum_{k=1}^{4} \sum_{j=1}^{k} \theta_j \tag{2}
\]

(2) Rationalization

The rationalization of industry is the characterization of the coordination among the three industries and the level of effective utilization of resources (Han et al., 2017). The Theil entropy index can effectively solve the calculation problem of the absolute value with structural deviation degree. The calculation formula used is as follows:

\[
IR = 1 - TL = 1 - \sum_{i} (Y_i/Y) \ln \left( \frac{Y_i/Y}{L_i/L} \right) \quad i = 1, 2, 3 \tag{3}
\]

In the formula, \( IR \) is the rationalization index; \( TL \) is the Theil entropy index; \( Y_i \) and \( L_i \) respectively represent the employees and output value of the \( i \)-th industry; and \( i \) represents the three industries. The larger the \( IR \) is, the more reasonable the industrial structure will be.

(3) Path dependence

As described by Miao et al. (2018), path dependence mainly refers to path locking and path innovation. Based on location entropy, first, the proportion of practitioners per year in resource-based industries (mining, electricity, gas and water production and supply, non-metallic mineral products, metal products, petroleum processing, coking and nuclear fuel processing, ferrous metal smelting and rolling processing) is calculated. Next, path locking is determined by dividing the proportion of total industrial indicators from that of the same indicators throughout the country (China). Path innovation takes a similar approach, based on the data of non-resource industries. The formula used is as follows:

\[
RZI = S_g/S \tag{4}
\]

In the formula, \( S_g \) represents the proportion of practitioners in resource-based or non-resource industries; \( S \) indicates the proportion of practitioners in the corresponding industries throughout the country; and the higher the \( RZI \) is, the more significant the path locking or innovation will be.

3.3.3 Measurement of environmental efficiency

(1) Construction of the environmental efficiency index

Based on the principles of data availability and feasibility, the environmental efficiency is comprehensively measured (Peng et al., 2021). This study originally selects basic elements, such as labor, capital, environmental protection, energy and water resources, as the input indicators. It also selects GDP as the expected output, and the three industrial wastes to characterize environmental pollution, i.e., undesired output (Table 2). In order to improve the accuracy, the results of DEA will be affected by the interrelationship of the indicators. It is also necessary to consider the limitation of the number of cities studied, and the fact that the number of measurement samples is more than twice that of indicators. Important to note is that, the indicators in this study are selected based on weight calculation and model simulation. Finally, the total energy consumption, and energy conservation and environmental protection expenditure are selected as the input indicators; GDP is as...
the expected output; and industrial sulfur dioxide emissions is as the undesired output.

2) Super-efficiency SBM model based on the undesired output

The Data Environment Analysis (DEA) model integrates linear programming technology, and can be used to effectively evaluate the input and output of individual units. In order to compensate for the shortcomings of the traditional model, the study adds undesired output results under the premise of considering slack variables and redundant variables, and uses the SBM model of a non-radial and non-angle. Moreover, to achieve the evaluation of multiple decision-making units, the SBM and super-efficiency DEA are combined, which is known as the super-efficiency SBM model. The specific calculation process is detailed in the References section (Peng et al., 2021).

3.3.4 Measurement of the coupling
(1) Coupling coordination degree model

The concept of coupling originates from physics, and emphasizes the dynamic relationship between different systems. To compensate for the shortcomings of the traditional model, the study adds undesired output results under the premise of considering slack variables and redundant variables, and uses the SBM model of a non-radial and non-angle. Moreover, to achieve the evaluation of multiple decision-making units, the SBM and super-efficiency DEA are combined, which is known as the super-efficiency SBM model. The specific calculation process is detailed in the References section (Peng et al., 2021).

(2) Grey-related analysis (GRA)

This method is the basis of grey system theory. Owing to its ability to evaluate the response with time, it has been widely applied in many fields (Shao et al., 2021; Yang and Chen, 2021). Its basic concept is to measure the degree of correlation between the factors of the systems, so as to determine whether the connections among them are close. The calculation process is described as follows:

Step 1. Normalization of all variables from 0 to 1.
Step 2. From the normalized values, once again a set of gathering values were determined to analyze the behavior of the performance indicators.
Step 3. Grey-related coefficient were generated, which can be used to compare the correlation among the variables. The resolution coefficient of this paper was generally 0.5, and its role was to increase the significance of the difference among the correlation coefficients.

GRA model can offer a clear understanding of the primary and secondary sequence, and the superiority or inferiority relationships among different factors. Therefore, this method was used to study the correlation among systems.

4 Results

4.1 Characteristics of spatial-temporal pattern of technological innovation, industrial transformation and environmental efficiency

This study uses the above method to obtain the comprehensive evaluation value of technological innovation, industrial transformation and environmental efficiency.
The typical years of 2005, 2012 and 2019 are selected, and the evaluation value is divided into high, middle and low levels by Natural breakpoints of ArcGIS.

4.1.1 Spatial-temporal pattern of technological innovation

(1) The development of technological innovation was unstable, the spatial agglomeration radiated by Xuzhou was strengthened, and the administrative barriers were gradually weakened. The evaluation value of technological innovation in the Huaihai Economic Zone was unstable (Table 3), especially in the later period. However, the overall development trend was positive. It can be seen that cities located at the junction of provinces was marginalized in the provinces to which they belonged, resulting in weak technological innovation. However, the gradual narrowing of the gap within the region reflected that with the integration process, administrative barriers were weakened and innovation continued to spill over, especially in technology. In terms of spatial evolution (Fig. 3), the technological innovation in 2005 showed a core-periphery pattern driven by Xuzhou. Among the cities, Zaozhuang and Suqian were at a disadvantage. In 2012, it was still scattered with Xuzhou as the core. The number of low-level cities increased significantly, rising to five. For example, Huaibei declined by 42.42%. In 2019, technological innovation was in a pattern of high in the northeast and low in the southwest. The high in the northeast was mainly due to the advantages of northern Jiangsu and southern Shandong. The number of high-level cities increased from two to four. Among them, Suzhou has risen sharply, and the difference was significantly reduced. The reason is that, Jiangsu and Shandong Province were closely connected with the information network, and had a more innovative economic foundation than the other two provinces. In the process of breaking through the administrative constraints and strengthening the coordination of innovation policies, Xuzhou, as a national innovative city, has shown a radiating and traction role, promoting the first agglomeration development of innovation in northern Jiangsu and southern Shandong, and ultimately achieving regional innovation synergy.

(2) Regenerative cities had significant advantages, and declining and mature cities were on the rise. For dif-

### Table 3 Evaluation value of technological innovation

| City      | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 |
|-----------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Xuzhou    | 0.87 | 0.80 | 0.80 | 0.81 | 0.74 | 0.72 | 0.71 | 0.71 | 0.71 | 0.71 | 0.74 | 0.75 | 0.74 | 0.66 |
| Suqian    | 0.16 | 0.05 | 0.04 | 0.10 | 0.19 | 0.18 | 0.21 | 0.27 | 0.28 | 0.33 | 0.35 | 0.33 | 0.34 | 0.36 | 0.36 |
| Lianyungang | 0.41 | 0.42 | 0.42 | 0.44 | 0.50 | 0.37 | 0.36 | 0.44 | 0.47 | 0.49 | 0.48 | 0.47 | 0.46 | 0.46 | 0.48 |
| Zaozhuang | 0.27 | 0.35 | 0.30 | 0.30 | 0.30 | 0.33 | 0.34 | 0.30 | 0.36 | 0.31 | 0.32 | 0.32 | 0.32 | 0.29 | 0.33 |
| Jining    | 0.58 | 0.55 | 0.52 | 0.52 | 0.52 | 0.51 | 0.51 | 0.48 | 0.48 | 0.50 | 0.53 | 0.55 | 0.55 | 0.54 | 0.52 |
| Shangqiu  | 0.44 | 0.36 | 0.35 | 0.37 | 0.38 | 0.46 | 0.47 | 0.47 | 0.47 | 0.46 | 0.43 | 0.43 | 0.44 | 0.44 | 0.25 |
| Heze      | 0.34 | 0.27 | 0.29 | 0.33 | 0.37 | 0.34 | 0.34 | 0.33 | 0.32 | 0.32 | 0.33 | 0.33 | 0.33 | 0.32 | 0.29 |
| Linyi     | 0.43 | 0.41 | 0.51 | 0.49 | 0.45 | 0.40 | 0.41 | 0.42 | 0.44 | 0.44 | 0.49 | 0.54 | 0.52 | 0.49 |
| Huaibei   | 0.33 | 0.27 | 0.31 | 0.27 | 0.30 | 0.22 | 0.22 | 0.19 | 0.17 | 0.16 | 0.21 | 0.24 | 0.27 | 0.29 | 0.29 |
| Suzhou    | 0.35 | 0.34 | 0.32 | 0.31 | 0.31 | 0.29 | 0.30 | 0.27 | 0.25 | 0.26 | 0.30 | 0.29 | 0.31 | 0.30 | 0.26 |

*Fig. 3 Spatial evolution of technological innovation in the Huaihai Economic Zone*
different resource types, the technological innovation of regenerative cities, which are transformational pioneers, clearly possessed an advantage, showing a steady upward trend. Mature cities were followed by ‘U-shaped’ development, and their technological innovation has gradually been highlighted under the highly dependent on resources. Technological innovation in declining cities was the most disadvantaged, but there was also an upward trend. In recent years, the technological innovation of non-resource-based cities have declined slightly, which reflected the lack of development characteristics. The reason is that, resource-based cities have a development cycle, and it is more urgent to rely on innovation to achieve development.

(3) The advantages of cities on Longhai Line were significant, and the fluctuation of cities on Jingjiu Line has fallen to a disadvantage. From the perspective of traffic location, the technological innovation of cities on Xinshi Line was showing a fluctuating upward trend overall, especially after 2013. The volatility of cities on Longhai Line gradually flattened and had a relative advantage, and it fluctuated around 0.48. Cities on Jinghu Line fluctuated regularly, but there was a downward trend. Cities on Jingjiu Line showed an inverted ‘N’ shape that first rose, then fell; it was the most disadvantaged. The reason for this is that different locations have different impacts on innovation. The outflow of urban human resources on Jingjiu Line was prominent.

### 4.1.2 Spatial-temporal pattern of industrial transformation

(1) The fluctuation of industrial transformation has declined but there has been an upward trend in the later period, and the characteristics of spatial segmentation were significant. The overall industrial transformation shows a decline with large fluctuations (Table 4). Due to the serious industrial isomorphism, the task of industrial transformation in cities was arduous and differentiated. Among the cities, the gap appeared to be widening. Linyi had the largest volatility and was ultimately in a leading position. In terms of spatial evolution (Fig. 4), in 2005, cities with different levels of industrial transformation were scattered. Most of the cities in the middle and high level, including Linyi, Heze, Lianyungang and Suqian, while the agriculture-based Suzhou was the opposite. In 2012, Xuzhou rose significantly. Cities with a high level of industrial transformation were distributed along the junction corridor of provinces. It can be seen that the integration of innovation and industry in Xuzhou has deepened. The development of strategic emerging industries and the ‘four new economies’ has accelerated its industry to upgrade. In 2019, cities with different levels of industrial transformation were segmented in blocks. The number of high-level cities has decreased. Heze and Shangqiu also weakened. The reason is that, the barriers to the flow of factors such as markets and technologies led to a lack of motivation and structural diversification for industrial transformation. Due to insufficient complementarity and blind competition in the region, there was an urgent need to promote the benefit sharing mechanism of industries across administrative regions.

(2) The transformation of regenerative cities was remarkable, and the mature and non-resource-based cities were fluctuating and rising. The industrial transformation of regenerative cities was the strongest, with the highest evaluation value. The level of declining cities

| City       | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 |
|------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Xuzhou     | 0.44 | 0.47 | 0.55 | 0.63 | 0.57 | 0.62 | 0.56 | 0.59 | 0.46 | 0.53 | 0.49 | 0.65 | 0.46 | 0.53 | 0.51 |
| Suqian     | 0.56 | 0.55 | 0.57 | 0.57 | 0.58 | 0.55 | 0.60 | 0.79 | 0.63 | 0.68 | 0.60 | 0.66 | 0.69 | 0.65 | 0.57 |
| Lianyungang| 0.68 | 0.64 | 0.56 | 0.68 | 0.58 | 0.59 | 0.58 | 0.45 | 0.60 | 0.50 | 0.50 | 0.64 | 0.63 | 0.57 | 0.70 |
| Zaozhuang  | 0.43 | 0.43 | 0.51 | 0.66 | 0.61 | 0.45 | 0.40 | 0.49 | 0.26 | 0.32 | 0.39 | 0.56 | 0.38 | 0.50 | 0.34 |
| Jining      | 0.43 | 0.50 | 0.50 | 0.54 | 0.53 | 0.43 | 0.45 | 0.36 | 0.22 | 0.40 | 0.19 | 0.36 | 0.30 | 0.31 | 0.35 |
| Shangqiu   | 0.41 | 0.40 | 0.43 | 0.42 | 0.58 | 0.55 | 0.41 | 0.56 | 0.39 | 0.50 | 0.47 | 0.51 | 0.43 | 0.46 | 0.52 |
| Heze       | 0.67 | 0.65 | 0.66 | 0.73 | 0.70 | 0.65 | 0.63 | 0.62 | 0.62 | 0.62 | 0.62 | 0.61 | 0.56 | 0.54 |       |
| Linyi      | 0.72 | 0.57 | 0.62 | 0.57 | 0.78 | 0.56 | 0.50 | 0.48 | 0.59 | 0.65 | 0.66 | 0.51 | 0.62 | 0.67 | 0.60 |
| Huaibei    | 0.36 | 0.45 | 0.45 | 0.34 | 0.32 | 0.42 | 0.44 | 0.42 | 0.30 | 0.38 | 0.33 | 0.35 | 0.36 | 0.27 | 0.27 |
| Suzhou     | 0.32 | 0.30 | 0.32 | 0.49 | 0.40 | 0.41 | 0.36 | 0.33 | 0.42 | 0.41 | 0.55 | 0.63 | 0.43 | 0.44 | 0.47 |
was in a downward trend. Due to being forced to quickly be free from path dependence, their transformation has changed greatly. Mature cities exhibited a trend of first declining, then fluctuating, but their reliance on resource has disadvantaged the level of transformation. The overall transformation of non-resource-based cities was relatively stable. However, the intensity of transformation has increased following the time and policy requirements in the later period.

(3) Cities on Xinshi Line and Jingjiu Line had significant advantages, while cities on Longhai Line and Jinghu Line were relatively weak but showed an upward trend. Although the industrial transformation of cities on Xinshi Line has declined, overall performance had an advantage. The fluctuations on Longhai Line were gradual, showing an upward trend in the later. Cities on Jingjiu Line have declined in volatility, but have an upward trend in the period of 2018‒2019, and the overall industrial transformation was optimal. The cities on Jinghu Line were the most disadvantaged, but also exhibited a trend of rising later after 2013. The reason is that, industrial optimization effect along the railway has not been fully exerted. Negative effects exist, such as the siphon effect of other cities along Jinghu Line hindering the industrial optimization of cities in the Huaihai Economic Zone.

4.1.3 Spatial-temporal pattern of environmental efficiency

(1) The fluctuation of environmental efficiency was unstable, the differences within the region were significant, and the ecological problems across the border of the administrative region were prominent. The environmental efficiency of the Huaihai Economic Zone fluctuated from 2005 to 2019, and the final evaluation value was lower than the initial stage, but signs of improvement were emerging (Table 5). The flow and diffusion of pollutants make environmental governance show a clear regional trend. Among the cities, the gap first widened and then narrowed, and Xuzhou ultimately gained the upper hand. Regarding spatial evolution (Fig. 5), in 2005, there were more cities with relatively high efficiency. Lianyungang was the best (1.67), and agglomeration highlands were formed near the East Longhai area. In 2012, the environmental efficiency showed a pattern of being high in the middle and low on the left and right sides. Among them, Huaibei was the greatest, reaching 1.75. But for Heze, the conditions for pollution diffusion were poor. Affected by the offset of imported pollution, the improvement in quality was not proportional to its efforts. In 2019, cities in northern Jiangsu and southern Shandong such as Xuzhou and Linyi have formed a high-level ‘V-shaped’ pattern, while Shangqiu, Suzhou and other cities in eastern Henan and northern Anhui had poor environmental efficiency. The reason is that, these cities insist on green development. For example, Xuzhou promoted waste reduction throughout the industry chain, steadily propelled the construction of a ‘waste-free city.’ Linyi established the ecological environment committee and formulated a series of action plans for pollution prevention and control. The zone has not yet achieved cross-regional ecological governance, and it is necessary to continue regional joint prevention and control.

(2) The growth of regenerative cities was significant, and the environmental advantages of declining cities were manifest. The environmental efficiency of regenerative cities has increased significantly after 2015, with an increase of three times. This is mainly due to the advantages of ecological transformation and green technology. Declining cities had the highest value, reaching 1.19. Considering the gradual reduction in pollutant emissions from resource depletion, the control of pollution sources bears a significant direct effect. The mature cities exhibited an ‘M-shaped’ dynamic trend,
which dropped to its lowest in 2019. This is mainly due to the instability brought about by the development model of resource industries. Non-resource-based cities fluctuated relatively smoothly, but began to show a significant decline in 2016.

(3) Cities on Jinghu Line had an advantage, and the development potential of cities on Xinshi Line was highlighted. Cities on Jinghu Line were the highest, with an average value of 1.01. The fluctuations on Longhai Line were relatively flat, but there was also a downward trend eventually. Cities on Jingjiu Line exhibited an ‘M-shaped’ development trend, and fluctuated downward from 2016 to 2019. Although environmental efficiency of cities on Xinshi Line were not ideal, the magnitude of enhancement was highlighted, with an increase of 2.77 times compared with the initial. The reason is that, cities along Jinghu Line had a better foundation for improving the environment, and the economy of Jiangsu and Shandong provinces involved can feed back the ecology. In addition, the potential for improving the ecological efficiency of the remaining railway cities has yet to be tapped.

### 4.2 Heterogeneity of the coupling among TIE systems

#### 4.2.1 Characteristics of time evolution

(1) The coupling continued to be in transition, and the coordinated development trend of active interaction has emerged. The coupling coordination degree of TIE systems in the Huaihai Economic Zone fluctuated at around 0.53 from 2005 to 2019 (Table 6). That is to say, it continued to be in a transitional state. Although the evaluation value was lower in the final stage than the initial, the overall development trend was upward. Because the four provinces where they are located all have their own development priorities for the system, the difference in the zone have expanded. This indicated the existence of development barriers, and there was still a large distance from benign coupling. From 2005 to 2012, the coupling showed a ‘W-shaped’ development trend. The 2012–2019 period fluctuated sharply, and the coupling developed erratically. Xuzhou supported development pattern with new industrialization, and its coupling was the most prominent, hovering at around 0.72. However, Suzhou was the opposite. The increase in the coupling

| City       | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 |
|------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Xuzhou     | 1.24 | 1.05 | 0.70 | 1.20 | 0.60 | 0.68 | 0.79 | 1.00 | 1.10 | 0.77 | 0.57 | 1.11 | 1.30 | 1.05 | 1.47 |
| Suqian     | 0.59 | 0.65 | 0.67 | 0.51 | 0.50 | 0.68 | 0.73 | 0.61 | 0.48 | 0.40 | 0.36 | 0.55 | 0.62 | 0.87 | 0.54 |
| Lianyungang| 1.67 | 1.36 | 1.44 | 1.13 | 1.07 | 1.17 | 1.15 | 1.23 | 1.04 | 1.06 | 0.53 | 1.04 | 0.71 | 0.72 | 0.27 |
| Zaozhuang  | 1.13 | 1.12 | 1.32 | 0.84 | 1.09 | 1.26 | 1.15 | 1.07 | 1.09 | 1.02 | 0.82 | 1.35 | 1.34 | 1.29 | 1.55 |
| Jining     | 0.53 | 0.89 | 0.86 | 1.01 | 1.13 | 1.10 | 1.25 | 1.07 | 1.01 | 0.77 | 0.58 | 0.77 | 0.64 | 1.31 | 0.48 |
| Shangqiu   | 0.48 | 0.59 | 0.64 | 0.88 | 1.21 | 1.04 | 0.58 | 0.70 | 1.21 | 1.29 | 1.72 | 1.07 | 1.04 | 0.82 | 0.38 |
| Heze       | 0.31 | 0.34 | 0.35 | 0.38 | 0.40 | 0.55 | 0.45 | 0.33 | 0.44 | 0.41 | 0.33 | 1.10 | 0.64 | 1.06 | 1.12 |
| Linyi      | 0.22 | 0.24 | 0.23 | 0.23 | 0.17 | 0.22 | 0.23 | 0.21 | 1.08 | 0.20 | 0.15 | 0.25 | 1.16 | 1.25 | 1.32 |
| Huaibei    | 1.00 | 1.19 | 1.18 | 0.38 | 1.38 | 1.99 | 1.59 | 1.75 | 1.70 | 1.83 | 1.30 | 0.61 | 0.60 | 1.12 | 0.54 |
| Suzhou     | 1.09 | 1.09 | 1.14 | 1.27 | 1.30 | 1.15 | 1.12 | 1.21 | 0.80 | 0.58 | 1.01 | 1.03 | 1.18 | 0.88 | 0.38 |
of Linyi was the most significant, particularly in the later period, while Lianyungang was the opposite. The reason is that, due to the limitations of geographical division and administrative barriers, different development ideas lead to evolutionary heterogeneity in the interaction of TIE systems.

(2) Regenerative cities were promoted to synergy, and the interaction of other resource types was disordered. The staged characteristics of resource-based city interaction were prominent. Regenerative cities benefited from the policy support and path innovation, and various systems can be better integrated. Therefore, the coupling of such cities was optimal, which have risen to synergy. The coupling of mature cities was in an ‘M-shaped’ fluctuation, and finally on the verge of imbalance. The decline in the coupling of declining cities was the most apparent. Owing to the exhaustion of resources, the interaction among systems in such cities was disordered. The coupling of non-resource-based cities fluctuated, especially in the later period. It can be seen that such cities urgently need to find the best development path.

(3) The coupling of cities on Longhai Line and Jinghu Line has declined, while other locations have fluctuated upward. The interaction of cities on each railway was characterized by transition. The coupling of cities on Longhai Line was optimal overall, despite the volatility. Especially after 2016, it has shown a significant decline. The volatility and decline of cities on Jinghu Line were significant, and the location advantage has not been brought into play. Although the coupling on Jingjiu Line was at a disadvantage initially, the overall trend was positive. The coupling on Xinshi Line fluctuated greatly, with a ladder-climbing trend in the later stage. It can be seen that while the railway brings positive effects, it may also enhance the imbalance of the region.

### 4.2.2 Characteristics of spatial evolution

The overall performance of the coupling of TIE systems in the Huaihai Economic Zone presented radiation characteristics with Xuzhou as the core (Fig. 6). In the later period, the interaction between northern Jiangsu and southern Shandong tended to be orderly, and eastern Henan and northern Anhui were relatively disadvantaged. It can be seen that due to the constraints of various factors such as administration, interests, and planning, there was spatial heterogeneity in the coupling. Specifically, in 2005, the coupling took Xuzhou and Lianyungang as the traction and distributed horizontally along the East Longhai area. Many cities, such as Jining, Heze and Shangqiu, were in transition, and only Suqian was at a disadvantage. In 2012, the coupling was still dominated by transition types, and Suqian was driven to strengthen. In 2019, due to the construction of ‘Lunan Economic Belt,’ Linyi has achieved a significant enhancement of orderly interaction. Therefore, the coupling evolved into a pattern in which Xuzhou and Linyi were the double agglomeration points, which drove the coupling enhancement in northern Jiangsu and southern Shandong. These indicated that the inter-provincial fringe region with concentrated industrial construction have broken through barriers such as technology and environment, and strengthened cross-provincial coordination. However, cities in eastern Henan and northern Anhui showed imbalance, and in particular Huaibei fell by 28.57%, reflecting the urgency and necessity of their integration into the Huaihai.
Economic Zone.

4.2.3 Type characteristics of the coupling

We sorted out the coupling types of cities, and found the characteristics of the corresponding types of system development. According to the evaluate value of technological innovation, industrial transformation, and environmental efficiency, the system which is at the lowest level or relatively lowest in a certain stage is selected as the system with lagging development. If the three systems are at the same level, then it is regarded as a synchronous development type. The specific results are shown in Table 7.

On the whole, due to administrative barriers, the flow of innovation factors such as knowledge and technology was restricted, and the spillover of technological innovation was seriously hindered, especially in northern Anhui. Specifically, in 2005, cities in imbalance showed a two-way lag in technological innovation and industrial transformation; cities in transition mainly lagged in technological innovation; cities in synergy mostly showed a one-way lag in innovation or industry.

In 2012, cities in imbalance showed obvious lag in environmental efficiency; Suqian, Lianyungang and other cities in transition mostly showed two-way lag, and the impact of technological innovation was prominent; Xuzhou and other cities in synergy were relatively unconstrained by a single system, and the development of each system was relatively synchronized. In 2019, Huaibei, Shangqiu and other cities in imbalance mainly showed two-way lag mainly in technological innovation; Zaozhuang and other cities in transition had various types of system lag, and most of them lag in industrial transformation; cities in synergy developed relatively comprehensively. For example, the industrial transformation of Xuzhou has already been successful, and the synergy of systems of Linyi has been improved. The reason is that, cities in imbalance were mainly the backward areas of northern Anhui, and the lack of innovative development foundation hindered the interaction with other systems. Cities in transition have gradually turned into a lag in industrial transformation. It can be seen that despite the enhancement of innovation and

Fig. 6 Spatial evolution of coupling coordination degree of technological innovation, industrial transformation and environmental efficiency systems in the Huaihai Economic Zone

Table 7 Development type of the coupling of technological innovation, industrial transformation and environmental efficiency systems

| City     | 2005                        | 2012                        | 2019                        |
|----------|-----------------------------|-----------------------------|-----------------------------|
| Xuzhou   | Synergy (Industry lagging)  | Synergy (Environment lagging) | Synergy (Industry lagging)  |
| Suqian   | Imbalance (Technol & Environment lagging) | Transition (Innovation & Environment lagging) | Transition (Synchronous development) |
| Lianyungang | Synergy (Innovation lagging) | Synergy (Synchronous development) | Transition (Environment lagging) |
| Zaozhuang | Transition (Innovation & Industry lagging) | Transition (Innovation lagging) | Transition (Innovation & Industry lagging) |
| Jining   | Transition (Synchronous development) | Transition (Industry lagging) | Transition (Industry & Environment lagging) |
| Shangqiu | Transition (Synchronous development) | Transition (Innovation & Environment lagging) | Imbalance (Innovation & Environment lagging) |
| Heze     | Transition (Innovation & Environment lagging) | Transition (Innovation & Environment lagging) | Transition (Innovation & Industry lagging) |
| Linyi    | Transition (Innovation & Environment lagging) | Imbalance (Environment lagging) | Synergy (Synchronous development) |
| Huaibei  | Transition (Innovation & Industry lagging) | Transition (Innovation & Industry lagging) | Imbalance (Innovation & Industry lagging) |
| Suzhou   | Transition (Innovation & Industry lagging) | Transition (Innovation & Industry lagging) | Imbalance (Innovation & Environment lagging) |
environmental protection, the function of industrial optimization has not been fully exerted. Cities in synergy mainly benefited from the coordinated and orderly development of various systems, which was driven by innovation.

4.3 Reasons for the coupling of TIE systems

According to the model of coupling coordination degree, the coupling between the two systems was calculated, which was named 2E system in this study. To facilitate ease of understanding, the naming of 2E system was simplified: technological innovation and industrial transformation (Technology-Industry), industrial transformation and environmental efficiency (Industry-Environment), technological innovation and environmental efficiency (Technology-Environment) system. Simultaneously, with the aid of GRA model, the closeness and influence of every individual system and 2E systems to TIE systems were quantified (Table 8). Therefore, the internal mechanism of coupling was analyzed in detail. On the whole, enhancing the development power of each element and each system, starting from the internal governance of each 2E system, is the key to the benign interaction of TIE systems.

4.3.1 Analysis of the reasons for the interaction of the whole zone

(1) The revitalization of technology and other elements and the enhancement of each single system laid the foundation for the coordination of the system. From a single system perspective, among the correlations with the coupling of TIE systems, the grey-related coefficient to technological innovation was the highest, followed by industrial transformation. Influenced by the development focus of each administrative region, the zone had the characteristics of unbalanced elements and heterogeneity of regional basis, resulting in different performances of correlation among the coupling of TIE systems and each single system. From 2005 to 2012, cities attached great importance to increasing investment in technology and promoting green technology. The enhancement of innovation elements has greatly promoted the advancement and path innovation of the industry, and stimulated the interaction. From 2012 to 2019, the correlation among each single system and the coupling of TIE systems increased, and the highest grey-related coefficient hovered between technological innovation and industrial transformation. Increased environmental efficiency had a greater impact on overall interaction. It

Table 8 Grey-related coefficient among the coupling of technological innovation, industrial transformation and environmental efficiency systems

| Year | Grey-related with a single system | Grey-related with 2E system |
|------|---------------------------------|-----------------------------|
|      | Technological innovation | Industrial transformation | Environmental efficiency | Technology-Industry | Industry-Environment | Technology-Environment |
| 2005 | 0.54 | 0.54 | 0.51 | 0.65 | 0.65 | 0.60 |
| 2006 | 0.60 | 0.55 | 0.53 | 0.52 | 0.53 | 0.38 |
| 2007 | 0.63 | 0.61 | 0.55 | 0.65 | 0.61 | 0.46 |
| 2008 | 0.59 | 0.54 | 0.64 | 0.58 | 0.58 | 0.52 |
| 2009 | 0.68 | 0.63 | 0.61 | 0.68 | 0.60 | 0.55 |
| 2010 | 0.63 | 0.66 | 0.61 | 0.75 | 0.68 | 0.49 |
| 2011 | 0.58 | 0.61 | 0.51 | 0.65 | 0.59 | 0.46 |
| 2012 | 0.54 | 0.52 | 0.43 | 0.60 | 0.51 | 0.46 |
| 2013 | 0.62 | 0.52 | 0.52 | 0.72 | 0.32 | 0.49 |
| 2014 | 0.61 | 0.50 | 0.48 | 0.63 | 0.51 | 0.50 |
| 2015 | 0.66 | 0.67 | 0.57 | 0.68 | 0.55 | 0.50 |
| 2016 | 0.55 | 0.66 | 0.61 | 0.68 | 0.67 | 0.55 |
| 2017 | 0.60 | 0.52 | 0.54 | 0.75 | 0.48 | 0.59 |
| 2018 | 0.60 | 0.65 | 0.59 | 0.62 | 0.51 | 0.50 |
| 2019 | 0.73 | 0.65 | 0.62 | 0.60 | 0.50 | 0.48 |
can be seen that inter-provincial administrative barriers have been gradually broken down, and elements such as capital, knowledge, and talents have been continuously integrated. Innovation has accelerated the penetration of the industry, and knowledge innovation and industrial sophistication have increased the promotion of system interaction. Simultaneously, this zone gradually no longer pursued the speed of transformation, but focused on the quality of transformation and comprehensive innovation. Therefore, the basis for enhancing the collaboration of TIE systems is to promote the development of a single system. This also reflects that technological innovation is the key to fully driving system interaction.

(2) The inefficient interaction of Technology-Environment system and the functional superposition of other 2E systems affected the coupling of TIE systems. Based on the binary system, the coupling development of TIE systems in the Huaihai Economic Zone was closely related to the coupling situation of each 2E system and their superimposed functions (Fig. 7). Table 8 showed that the coupling of TIE systems had the highest correlation with the coupling of Technology-Industry system, but was significantly restricted by the coupling of the Technology-Environment system. Viewed in stages, from 2005 to 2012, the coupling coordination degree of TIE systems fluctuated between the 2E systems and increased slightly. Its fluctuation situation was most consistent with the fluctuation of the coupling of Technology-Industry system. Although the Technology-Environment system had poor interaction, it was moderated by the strong interaction of other 2E systems. From 2012 to 2019, the coupling of TIE systems fluctuates unsteadily, which was most consistent with the fluctuation in the coupling of the Technology-Industry system. The interaction of each 2E system was strengthened. The strong interaction of Industry-Environment and Technology-Industry systems maintained a positive pulling effect, while Technology-Environment system inhibited the interaction of TIE systems. It can be seen that, due to the existence of planning barriers, the time sequence of the interactive development of 2E systems was different, and the lack of benign resonance among systems affected the coupling of TIE systems.

4.3.2 Analysis of the reasons for the interaction from different resource types

From Fig. 8 and Table 8, it can be seen that the reasons for the coupling of TIE systems in cities with different resource types were heterogeneous. Except the coupling of regenerative cities benefited from the orderly development of systems, other types of cities were all restricted by the development of single system or 2E systems. In particular, the lack of technological innovation had a significant negative impact on the coupling of declining cities and non-resource-based cities.

(1) For regenerative cities coupled to synergy, it benefited from the orderly integration of a single system and the enhanced interaction of each 2E system. These cities successfully freed from resource dependence. They also bear the technical conditions to cultivate emerging industries, and innovation chain, industrial chain and ecological chain are deeply integrated. The high-intensity industrial transformation in 2005–2012 intensified the coupling of the 2E system from transition to synergy. Particularly, the coupling of Industry-

![Fig. 7](image-url)  The coupling coordination degree of technological innovation, industrial transformation and environmental efficiency systems in the Huaihai Economic Zone
Environment system increased by 21.82%. In the later stages, technological innovation and environmental efficiency were enhanced, which strengthened interaction of the 2E system. However, the timing difference of the coupling of the 2E system was enlarged, and Industry-Environment system fluctuated greatly, which in turn led to fluctuations in the coordination of TIE systems.

(2) For mature cities that were on the verge of imbalance, the contradiction between resource dependence and the environment resulted in a mismatch in system development. This type is in the period of prosperity of resource-based industries, and the industry is strongly dependent, which has caused the contradiction between environmental pollution and economic development to intensify. The environmental efficiency slipped from 0.81 to 0.43, causing it to be out of synchronization with innovation and industry. These have led to a prominence of disorder in the coupling of TIE systems. The coupling of each 2E system fluctuated significantly, and there was a phenomenon of slipping to disorder. In particular, the interlaced and disordered development of each 2E system from 2012 to 2019 was more significant.

(3) For declining cities that continued to be at a disadvantage, the lack of technological innovation and industrial transformation curbed the exertion of environmental benefits. The development of technological innovation and industrial transformation in such cities was not sufficient to curb the decline, and it was difficult to exert its due environmental benefits. In particular, the early-stage disadvantages of innovation were in sharp contrast with environmental efficiency, thereby leading to disorderly development of Technology-Environment system. Hence, the interaction of TIE systems was hindered. Subsequently, R&D investment increased, technological innovation increased by 25%, and the interaction of Technology-Industry and Industry-Environment systems was stimulated to increase. However, it was difficult to quickly realize the integration and penetration of technological innovation and the other two systems in the short term.

(4) For non-resource-based cities with declining coupling, the lack of endowments such as innovation and resource has implicated the interaction of all the 2E systems. Due to the lack of resource endowment, such cities need the promotion of innovation. However, technological innovation and environmental efficiency were at a disadvantage, thereby implicating the decline of the coupling fluctuations of each 2E system. The early-stage coupling of Technology-Environment system significantly lagged behind other systems, while the later-stage environment and innovation continued to decline. The coupling and oscillation of each 2E system were significant, which severely weakens the interaction of TIE systems. Overall, the lag in innovation of such cities has hindered the interaction of TIE systems.

4.3.3 Analysis of the reasons for the interaction from different traffic location

From Fig. 9 and Table 8, it can be seen that the reasons for the coupling of TIE systems at different transportation location have varied widely.

(1) For cities on Jinghu Line accompanied by fluctu-
Fig. 9 Interactive relationship among systems of different traffic location in the Huaihai Economic Zone

Discussion

First, this article draws on and integrates existing research, so as to scientifically and reasonably measure the interaction and decline, the lag of industrial transformation and technological innovation systems weakened the interaction among systems. Most cities of the railway were old industrial bases, and were not strong in independent innovation and industry optimization. Due to the ‘siphon’ of the developed region, these cities were mostly reduced to energy warehouses and hindered the industrial upgrading. Technological innovation has not been able to continuously meet the requirements of industrial transformation, and the transformation was significantly lagging. This has caused the fluctuation of Industry-Environment system. Therefore, the lag which is dominated by innovation leads to poor interaction of TIE systems.

(2) For cities on Longhai Line with optimal interaction but declining, the single system was relative stable, but Industry-Environment system was chaotic in the later stage. These cities were actively integrated into the Belt and Road, and the development of the single system was relatively stable, especially technological innovation system. Technology-Industry and Technology-Environment systems were both fluctuating and increasing, and thus promoting interaction. The benign interaction of Industry-Environment system from 2005 to 2012 was even more advantageous. From 2012 to 2019, the environmental efficiency systems declined. This in turn led to large fluctuations in Industry-Environment, weakening and disrupting the interaction of TIE systems.

(3) For cities on Jingjiu Line that got rid of disadvantages and gradually improved, the optimization and integration of industry and environment drove the coupling among systems. The comprehensive benefits and interaction of the north-south line have been continuously enhanced. Industrial transformation has gradually become better, and environmental efficiency has also continued to rise. The interaction of Industry-Environment system and TIE systems were enhanced. However, after 2016, the long-term weakening of innovation led to a weakening of Technology-Environment interaction, and the gap with other 2E systems widened. Fortunately, the interaction between industry and environment was significantly enhanced, resulting in an increase in the coupling of TIE systems compared with the beginning.

(4) For cities on Xinshi Line from transition to synergy, the efficient development of systems such as environmental efficiency supported the synergy. The substantial increase in environmental efficiency affected the interaction of systems, while the fluctuation of the coupling of each 2E system was consistent with TIE systems. In particular, in the later period, the interaction of Industry-Environment system fluctuated significantly, which stimulated the overall interaction. The coupling of Technology-Industry and Technology-Environment was affected by the efficient development of subsystems, so it ultimately led to the enhancement of the synergistic effect.

5 Discussion

First, this article draws on and integrates existing research, so as to scientifically and reasonably measure
the spatial-temporal evolution of technological innovation, industrial transformation and environmental efficiency systems in the Huaihai Economic Zone. Based on the study of Qu et al. (2015), the contradiction between resources and development is further revealed. Evaluation value of each system provide conclusive evidence that Xuzhou is the primary economic core and radiative center of the Huaihai Economic Zone (Meng et al., 2019). Furthermore, although the pollution caused by industrialization in the zone has improved, the problem remains prominent (Shen et al., 2018; Zang et al., 2020). As Tang and Zhou (2021) previously confirmed, the environmental efficiency fluctuated significantly. For the technological innovation system, Freitas et al. (2013) emphasized knowledge and technology capability. The regional service innovation has been added in the study, so as to analyze the shortcomings of the innovation in the later stage. Furthermore, in addition to commonly using industrial rationalization and advancement to measure industrial transformation, drawing on the work of Boschma and Frenken (2011), we added industrial path dependence and path innovation based on the perspective of evolutionary economic geography. However, due to the limitation of data availability, the scale based on the two-digit industry is relatively macro. In the future, it can be further explored and analyzed based on three- or four-digit industry data and case studies, and the correlations among different industries will be included.

Second, although there have been few direct studies performed on the measurement of the coupling among TIE systems, some relevant studies exist. For example, Yang and Wang (2020) analyzed the interaction and evolution of collaborative innovation, industrial structure and eco-efficiency in the Yangtze River Delta, noted that the spatial-temporal differentiation was obvious, and emphasized that the overall interaction was negatively affected by the incoordination of systems; Lu et al. (2017) and Ely et al. (2019) discussed the dynamic relationship among industrial agglomeration, technological innovation and environmental pollution, emphasizing the diversified fluctuations driven by the innovation; Du et al. (2021) explored the interaction of environmental regulation, green technology innovation and industrial upgrading. All of these observations show that innovation, industry and environment have complex internal connections. Furthermore, the coupling of ternary system is mostly the study of the spatial-temporal development based on the coupling coordination degree model (Wang et al., 2021), which lacks the use of the GRA model for multi-level analysis (Shao et al., 2021). The study combines two models to carry out coupling research on the underdeveloped zone, then analyzes the interactive characteristics of systems from the perspectives of location and resource.

Third, this study explored the internal mechanism of the coupling of TIE systems in the Huaihai Economic Zone. Drawing on the work of Lu et al. (2017), which emphasized the internal governance of each 2E system, we also combined the evolution of a single system. Therefore, the co-analysis of the coupling mechanism by using the single system and 2E systems has enriched the previous research (Grubb and Ulph, 2002). The present study has also confirmed that industry, innovation, ecology and their interaction are important for sustainable development (Yang and Wang, 2020; Sun et al., 2020). Simultaneously, it is emphasized that the uneven development of science, education, industry and the environment has led to the heterogeneity of economic synergy. Therefore, the construction of a synergy mechanism in each system must be strengthened (Ding and Qiu, 2021), especially transition governance strategies (Loorbach et al., 2020). Additionally, Zhou et al. (2020) also confirmed that the zone must promote high-quality synergy among systems according to location and resource. In practice, according to current research, the evolution model of TIE systems may be more diverse and complex (Andrée et al., 2019; Rahman and Alam, 2021). We need to continuously clarify the coupling mechanism among the evolution of TIE systems in this zone.

6 Conclusions and Suggestions

This study constructed the index system of technological innovation, industrial transformation and environmental efficiency, and measured the coupling of the system. In addition, the evolution law of the coupling of TIE systems was analyzed. All these are of great significance for the high-quality and coordinated development in the Huaihai Economic Zone.

6.1 Conclusions

(1) The technological innovation, industrial transforma-
tion and environmental efficiency showed significant spatial-temporal heterogeneity, but had basically similar development trends. Technological innovation was high in the northeast, and low in the southwest. Industrial transformation and environmental efficiency were relatively staggered in space. Regenerative cities showed higher innovation and industrial advantages, while cities on Jinghu Line of industrial transformation exhibited the opposite trend. Declining cities had superior environmental efficiency, and cities on Longhai Line had strong technological innovation. It also can be seen that, due to the existence of administrative barriers, the development of each system was not identical.

(2) Overall, the coupling of TIE systems was in transition, but the developing trend was positive. The spatial pattern driven by the dual cores of Xuzhou and Linyi has emerged. In addition, regenerative cities and cities on Longhai Line had the best interaction with TIE systems, while mature cities had the opposite effect. The interaction of TIE systems in the Huaihai Economic Zone was disordered and complicated, and it was a gradual process to move toward synergy.

(3) The coupling of TIE systems is a comprehensive result of the development of a single system and the interaction of 2E systems. Relatively, the coupling had a strong correlation with the system of technological innovation and Technology-Industry. For the entire zone, the lack of innovation motivation and the disorderly interaction of the Technology-Environment system were crucial to the coupling. Additionally, the advantages of a single system of regenerative cities, and the 2E system formed by them significantly promoted the coupling, while declining cities showed the opposite. The coupling of cities on Jinghu Line were constrained by industrial upgrading. The cities on Xinshi Line were promoting their synergy due to environmental advantage. Therefore, according to the location and category, the efficient development of each subsystem, and the synchronization and ordering of the 2E system are the basic condition for improving the coupling of TIE systems.

6.2 Suggestions
(1) Enhance innovation capabilities. The Huaihai Economic Zone should focus on optimizing the soft and hard environment for innovation, and effectively link knowledge and technological. It should also actively deploy the innovation chain, guide the flow of innovative elements to environmentally friendly industries. Among them, Xuzhou strengthened the radiation of innovation and played the role of regional growth pole. Mature cities such as Suzhou should seek to attract talent and promote innovative R & D and services. In addition, cities on Jinghu and Longhai Lines should make full use of advantageous locations to absorb advanced knowledge and technology.

(2) Promote industrial transformation. The zone should optimize industrial policies to promote the modernization of the industrial chain. It should also actively undertake industrial transfer of the Yangtze River Delta. Regenerative cities such as Xuzhou should cultivate emerging industries and improve the industrial ecology. Mature cities should extend the industrial chain with distinctive characteristics and advanced technologies. Declining cities should break path dependence, introduce new industries, and promote structural diversification. Based on providing energy for other cities on Jinghu Line, the cities on this line should focus on the optimization of traditional industries and the introduction of advanced industries.

(3) Improve ecological quality. The Huaihai Economic Zone, which is dominated by industry, should strengthen green technological innovation, formulate targeted environmental regulations, build a green ecosystem, and maintain a good environment for innovation and industry. Among these cities, declining cities should focus on the hidden environmental hazards, strengthen the application of green technology, and cultivate new economic growth points. Regenerative cities should also continue to strengthen the construction of environment-friendly cities.

(4) Produce the synergistic amplification effect of TIE systems. The zone should take the ecological construction of the industrial chain as a foothold, proceed from the perspective of industrial agglomeration, and propose innovative and differentiated development plans based on regional characteristics. By breaking down administrative barriers, the zone can promote a new leap to co-construction in the ‘Huaihai Model’, and ensure the coupling in a healthy and orderly way.

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