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Analysis of coupled coordination and spatial interaction effects between manufacturing and logistics industries in the Yellow River Basin of China

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ABSTRACT

The coupled and coordinated development of the manufacturing and logistics industries has become an inevitable choice for achieving high-quality development in both sectors. In this study, we focused on nine provinces located in the Yellow River Basin and analyzed panel data from 2010 to 2021. Our analysis, based on the super-efficient SBM-undesirable model, revealed that the coupling and coordination efficiency between the two industries in the region is moderate, with significant regional disparities. Additionally, using the Global Moran's I and the local Moran's I, we tested the spatial autocorrelation of the two industries and analyzed their spatial interaction effect using SDM. The study reveals that the manufacturing and logistics industries in the Yellow River Basin exhibit moderate coupling and coordination efficiency with significant regional variations. We found that the logistics industry plays a more supportive role in the manufacturing industry, particularly in Henan and Shandong provinces. Spatial spillover effects in terms of informationization, openness to the outside world, and energy consumption are more significant, while infrastructure investment does not exhibit significant spatial interaction effects. Based on our findings, we propose relevant development strategies for the two industries.

1. Introduction

The concept of "high-quality development" was first proposed by China in 2017. Promoting coordinated regional development is one of the main elements of high-quality development, which is manifested in the coordination between urban and rural areas, regions and industries, and the coordinated development of real economy and finance, real economy and real estate, manufacturing and modern service industries, so as to maintain effective supply and stable growth on this basis. The Yellow River Basin, spanning three regions in eastern, central and western China, is a crucial economic belt along the land-based "Silk Road," playing a pivotal role in promoting the "Belt and Road" initiative and coordinated regional development. The manufacturing industry serves as the power source for high-quality development in the Yellow River Basin and is essential for technological innovation, industrial transformation, and upgrading. Meanwhile, the logistics industry provides new impetus for integrated, specialized, and sustainable development of advanced manufacturing. As the two industries are complementary and interdependent, promoting their coupled and coordinated

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development is crucial for enhancing the core competitiveness of the manufacturing industry, building an advanced logistics hub system, and achieving high-quality coordinated development in the region.

At present, China's trend towards integrating the manufacturing and logistics industries is becoming stronger, and a new development pattern of "risk-sharing and benefit-sharing" is gradually emerging. However, it is worth noting that the level of integration and development between these two industries is still not high enough, as mentioned in the "Implementation Plan for Promoting the Deep Integration and Innovative Development of the Manufacturing and Logistics Industries" (NDRC [2020] No. 1315) issued by the National Development and Reform Commission in August 2020. The Yellow River Basin, which comprises nine provinces, including Qinghai and Sichuan, faces challenges due to various factors such as geographical location, resource endowment, development status, and policy environment, and has become a key area of concern for addressing the issue of imbalanced and insufficient development in China. Moreover, the overall development level of the manufacturing industry in each province in the basin exhibits a "ladder-like" pattern, with an unbalanced evolution of industrial structure. The logistics industry in the downstream region of the Yellow River Basin has better internal coordination, and the overall development trend is "wave-like", with Shandong's logistics industry being more mature and developing earlier, while Shaanxi and Henan are in the rapid development stage. However, the logistics industries in Ningxia and Gansu are lagging behind in terms of overall development level [1]. Therefore, the unbalanced and uncoordinated development between the manufacturing and logistics industries in the Yellow River Basin is still an issue that needs to be addressed. Exploring the coupled and coordinated relationship and spatial interaction effects between the two industries in the Yellow River Basin is of great practical significance in promoting their deep integration, implementing the strategy of high-quality development, transforming and upgrading China's industrial structure, and forming a new development pattern.

The research results on the coupled and coordinated development of manufacturing and logistics industry mainly include the following three aspects. (1) The research objects mostly focus on the nationwide coupled and coordinated development of the two industries [2], and some scholars select typical regions and provinces as research objects, such as the Yangtze River Economic Belt [3], East China [4], Guangxi Province [5] and Heilongjiang Province [6], which play a guiding role in the coupled and coordinated development of the two industries. (2) Most of the studies are on linkage efficiency measurement and coupling coordination analysis. Scholars started from linkage efficiency or coordination degree measurement; and explored the spatial correlation characteristics of the two industries based on the assessment of the coordinated development level of manufacturing and logistics industries, and some scholars examined the effect of the agglomeration level of the two industries on the manufacturing industry [7,8]. Most studies show that the linkage efficiency of manufacturing industry and logistics industry is low and does not achieve good coupling and coordinated development [9], and spatially it shows the characteristics of low-low agglomeration as the main and high-high agglomeration as the supplement [10]. (3) The research methods are mainly based on DEA method, Coupling Coordination Degree Model, and Gray Correlation Analysis. Data Envelopment Analysis (DEA) has good applicability in assessing the efficiency of linkage and integration development of two industries [11,12], coupling coordination model is more used to analyze the coupling and coordination relationship between manufacturing and logistics industries [4], and Gray Correlation Analysis focuses on empirical analysis of correlations [13]. However, spatial econometric analysis is gradually and widely used to explore the spatial and temporal characteristics and evolution law of the integration development of two industries [14,15], which is more recognized by scholars.

In a comprehensive view, the research on the coupled and coordinated development of the manufacturing and logistics industry has been gradually enriched, but there are still some shortcomings that need to be addressed. With the enhancement of the strategic status of the Yellow River basin, the studies for the Yellow River basin mainly focus on ecological efficiency [16], green low-carbon development [17,18], water resources [19], etc., and relatively few studies on the efficiency of industrial development, optimization of industrial structure configuration and deep integration and innovation development between industries in the region. Furthermore, most existing studies on the coordinated development of manufacturing and logistics industries have focused on efficiency measurement and coordination analysis, without exploring the interaction effect of the two industries from a spatial perspective. To address this gap, this study utilizes the super-efficient SBM-undesirable model to measure the coupled coordination efficiency of manufacturing and logistics industries in nine Yellow River provinces from 2010 to 2021 in the time dimension. Additionally, the Global Moran's I index and the Spatial Durbin Model are used to analyze the spatial dimension of manufacturing and logistics industries in the Yellow River basin, and to examine the spatial correlation and regional interaction effects between these industries. Based on the findings of this study, relevant countermeasures and suggestions are proposed to provide valuable references for the industrial transformation and upgrading, and high-quality development in the Yellow River Basin. Overall, this study aims to fill existing gaps in the literature and contribute to a better understanding of the coupled and coordinated development of manufacturing and logistics industries in the Yellow River basin.

2. Research methodology and indicators

2.1. Data Envelopment Analysis

Data Envelopment Analysis (DEA) is a non-parametric method that utilizes convex analysis and linear programming to evaluate the relative effectiveness among Decision Making Units (DMUs). This method has significant advantages in evaluating the effectiveness of multiple inputs and multiple outputs. One of the most significant benefits of DEA is that it does not require the estimation of parameters in advance. Instead, it carries out efficiency evaluation by replacing the production function with an envelope, which enhances the objectivity of the evaluation, simplifies the algorithm, and reduces errors. Another advantage of DEA is that the evaluation results are independent of the selection of indexes, which largely eliminates the influence of subjective factors and human errors on the evaluation results. As a result, the evaluation results are highly robust and objective. Due to these benefits, the DEA method is widely used in the field of efficiency measurement and decision analysis. In summary, DEA is a powerful non-parametric method for evaluating the relative effectiveness of DMUs, and it has significant advantages over other methods. Its objectivity, simplicity, and robustness make it an excellent choice for efficiency measurement and decision analysis in various fields.

2.1.1. Input-BCC model

The traditional models used in DEA include the CCR model, BCC model, Super-DEA model, SBM model (Slack-Based Measure), and EBM model (Epsilon-Based Measure). In the context of evaluating the efficiency of manufacturing and logistics industries in nine provinces along the Yellow River in China, it is important to consider the potential variability of coupling and coordination efficiency, which may result in increasing, constant, or decreasing scale payoffs. To address this, the research study in question employs the Input-BCC model with variable scale payoffs, which is a DEA model commonly used in such analyses. Through this approach, the researchers aim to accurately evaluate the development efficiency of the manufacturing and logistics industries in the selected provinces over a period of ten years, from 2010 to 2021.

Suppose there are n DMUs within the evaluation system, and each DMU has m inputs and s outputs, where x_{ij} represents the i-th input of the j-th DMU, y_{rj} represents the r-th output of the j-th DMU, and j represents the linear combination coefficient of each DMU. Where DMU_k is the k-th decision unit evaluated, x_{ik} represents the i-th input of DMU_k, y_{rk} represents the r-th output of DMU_k, and represents the relative efficiency value of the evaluated decision unit DMU_k, which is modeled as follows.

$$
\begin{aligned}
& Min\ \theta \\
& s.t. \sum_{j=1}^{n} \lambda_j x_{ij} \leq \theta x_{ik} \\
& \sum_{j=1}^{n} \lambda_j y_{rj} \geq y_{rk} \\
& \sum_{j=1}^{n} \lambda_j = 1 \\
& \lambda_j \geq 0, i = 1, 2, ..., m;\ r = 1, 2, ..., s;\ j = 1, 2, ...n
\end{aligned} \tag{1}
$$

In model (1), the DMU $(x = \sum_{j=1}^{n} \lambda_j x_{ij}, y = \sum_{j=1}^{n} \lambda_j y_{rj})$ is considered as a virtual ideal DMU, whose input is no greater than the input of the evaluated DMU_k and output is no less than the output of DMU_k, which constitutes the production frontier of the evaluation system, and the distance of the evaluated DMU from the production front represents its relative efficiency value. When $\theta = 1$, DMU_k is called “DEA efficient” or “optimistic efficient”; when $0 \leq \theta < 1$, DMU_k is called “DEA inefficiency” or “optimistic inefficiency”.

2.1.2. Super-efficient SBM-undesirable model

When evaluating the coupling and coordination efficiency of the manufacturing industry and logistics industry, it is important to consider the support and driving efficiencies between the two industries. To systematically evaluate the support efficiency of the logistics industry to the manufacturing industry, indicators of the logistics industry are used as inputs, while indicators of the manufacturing industry are used as outputs. Conversely, to systematically evaluate the driving efficiency of the manufacturing industry to the logistics industry, indicators of the manufacturing industry are used as inputs, while indicators of the logistics industry are used as outputs. However, the evaluation process may reveal unexpected output indicators that cannot be accounted for using traditional DEA models. To address this issue, the research study in question utilizes the SBM model proposed by Tone (2001), which can account for unexpected output factors. The SBM model aims to achieve more expected output or less unexpected output by using fewer resources. By employing the SBM model, the researchers hope to obtain a more accurate evaluation of the efficiency of the manufacturing and logistics industries in the selected provinces along the Yellow River.

Furthermore, as radial DEA models, both the traditional CCR and BCC models only account for equal scaling down (or up) of all input (or output) indicators when evaluating inefficient decision-making units (DMUs), which is not realistic. This is because labor and capital are the core input indicators when evaluating the efficiency of manufacturing or logistics industries, and substitution effects often occur between them. Thus, equal scaling down of both labor and capital input quantities is not a feasible solution. In contrast, the slack-based measure (SBM) model relaxes the assumption of “equal improvement of input/output factors” in traditional radial CCR and BCC models, and measures the inefficiency of both inputs and outputs from a non-oriented perspective. This approach avoids the efficiency bias caused by neglecting one aspect of inputs or outputs in radial DEA models.

Although the SBM model shows strong applicability to the coupling and coordination efficiency of manufacturing and logistics industries, it is still prone to the situation that “multiple DMUs are DEA effective and cannot effectively differentiate efficiency” for a total of 99 evaluated decision units in 9 provinces from 2010 to 2021. To address this issue, this paper employs the super-efficient SBM-undesirable model to evaluate the coupling and coordination efficiency of manufacturing and logistics industries in the nine provinces of the Yellow River Basin during 2010–2021. The model used is as follows.

$$Min\ \rho = 1 + \frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{ik}}$$
$$s.t.\ \sum_{\substack{j=1\\ j\neq k}}^{n} x_{ij}\lambda_j - s_i^+ \leq x_{ik}$$
$$\sum_{\substack{j=1\\ j\neq k}}^{n} y_{rj}\lambda_j \geq y_{rk} \tag{2}$$
$$\lambda_j, s_i^-, s_i^+ \geq 0, i = 1,2,...,m;\ r = 1,2,...,s;\ j = 1,2,...n$$

In equation (2), ρ is the coupling efficiency value of manufacturing and logistics; s_i^- and s_i^+ are slack variables, when $\rho \geq 1$, it means that the evaluated decision unit DMU_k is "DEA effective", when $0 \leq \rho < 1$, it means that the decision unit DMU_k is "non-DEA effective".

2.2. Spatial econometric analysis

2.2.1. Spatial econometric model

Combing the existing related literature reveals that spatial econometric analysis is widely used in the fields of exploring spatial correlation among subjects, spatial evolutionary characteristics and spatial interaction effects. Elhorst (2010) proposed three classical spatial econometric models, including the Spatial Durbin Model (SDM), the Spatial Lag Model (SLM) and Spatial Error Model (SEM), which are modeled as follows.

Spatial Lag Model (SLM):

$$y_{it} = \alpha_{it} + \rho W y_{it} + x_{it}\beta_{it} + \varepsilon_{it} \tag{3}$$

2.2.2. Spatial error model (SEM)

$$y_{it} = \alpha_{it} + x_{it}\beta_{it} + u_{it}, u_{it} = \lambda W u_{it} + v_{it} \tag{4}$$

Spatial Durbin Model (SDM):

$$y_{it} = \alpha_{it} + \rho W y_{it} + W x_{it}\gamma_{it} + x_{it}\beta_{it} + \varepsilon_{it} \tag{5}$$

In equations (3)–(5), where y_{it} represents the explanatory variable, W_{it} represents the spatial weight matrix, X_{it} represents the explanatory variable, ε_{it} and v_{it} denote random error terms with mean 0 and variance σ^2; ρ and γ is the spatial lag parameter. The spatial Durbin model (SDM) incorporates the characteristics of spatial lagged model (SLM) and spatial error model (SEM), contains the spatial errors of SLM and SEM, and incorporates the explanatory variables into its regression model, explores the spatial effects between the explanatory variables and the two explanatory variables, and is more suitable for exploring the interactive effects of the coupled and coordinated development of manufacturing and logistics industries in the Yellow River basin in space.

2.2.3. Spatial weight matrix construction

Compared with traditional econometric models, the setting of spatial weight matrix directly affects the spatial correlations, of is a necessary way to study the spatial effects. The methods of setting up spatial weight matrix are mainly divided into two categories: adjacency matrix and inverse distance matrix. In order to reflect the social objective facts and more accurately describe the spatial interaction between the coupling and coordination efficiency of manufacturing and logistics in the Yellow River Basin, this paper constructs a spatial geo-economic distance matrix with the following formula.

$$W1 = \begin{cases} {}^{1}/{d_{ij}}\ i \neq j \\ 0\ i = j \end{cases} \tag{6}$$

$$W2 = W1 * diag\left(\frac{\overline{y_1}}{\overline{y}}, \frac{\overline{y_2}}{\overline{y}}, \cdots \frac{\overline{y_n}}{\overline{y}}\right) \tag{7}$$

In equation (6), where d_{ij} denotes the distance between region i and region j. In this paper, we use the latitude and longitude of each province to calculate the geographical distance between regions. In equation (7), $\overline{y_i}, i = 1, 2, \cdots n$ denotes the GDP per capita of each region i during the study period; $\overline{y}$ denotes the average value of GDP per capita of each region during the study period.

2.3. Indicator system and variable descriptions

2.3.1. Indicator system

The establishment of an indicator system is crucial to ensure the validity and reliability of research findings. In this study, we have drawn on the works of Chu Yanchang [12], Dong Qianli [15], and Shangguan Xu-Ming [18], and have taken into account the principles of green development and driving factors for technological innovation. Specifically, we have included R&D investment, level of informationization, degree of openness to the external environment, energy consumption, and carbon dioxide emissions into the input-output index systems of the manufacturing and logistics industries. Detailed information can be found in Tables 1 and 2.

2.3.2. Data sources and variable descriptions

This study focuses on the manufacturing and logistics industries in nine provinces located in the Yellow River Basin during the period of 2010–2021. The data related to relevant indicators is obtained from various sources such as China Statistical Yearbook (2011–2021), China Energy Statistical Yearbook (2011–2021), and statistical yearbooks of each province (2011–2021). The missing data is supplemented by using the difference method.

(1) Explained variables

The value added of the industry is a comprehensive indicator used to measure the level and quality of industrial development, which can reflect the overall value of the industry. In this study, the value added of the logistics industry and the value added of the manufacturing industry are used as explanatory variables to measure the development level of the two industries in each province of the Yellow River Basin, in accordance with the strategic deployment of "high-quality development".

(2) Explanatory variables

To investigate the spatial interaction effect between the manufacturing and logistics industries in the Yellow River Basin, this study selected the explanatory variables based on the previous selection of variables. Specifically, when using the value added of the logistics industry as the explanatory variable, the explanatory variables of the manufacturing industry's indicator system were used to examine the spatial effect of the manufacturing industry on the development level of the logistics industry. Conversely, when using the value added of the manufacturing industry as the explanatory variable, the explanatory variables of the logistics industry's indicator system were used to examine the spatial effect of the logistics industry on the development level of the manufacturing industry. The spatial interaction effect between the two industries in the Yellow River Basin was explored by combining the results of both analyses. The details are shown in Table 3.

3. Analysis of results

3.1. Relative efficiency analysis

Using the Input-BCC model, the relative efficiency of the manufacturing and logistics industries in the Yellow River Basin was measured using DEAP2.0 software, and the results are presented in Figs. 1 and 2 below.

From the relative efficiency of the two industries in the Yellow River Basin, the development level of manufacturing industry is higher than that of logistics industry. The development efficiency of logistics industry fluctuates more during 2010–2021, while the overall development efficiency of manufacturing industry is at a higher level, but the stability of manufacturing industry decreases over time.

As shown in Fig. 1, the comprehensive efficiency of the logistics industry in the Yellow River Basin fluctuates between 0.800 and 1.000. The efficiency fluctuates less during 2010–2013 but more during 2014–2021. However, the overall efficiency of the logistics industry in the Yellow River Basin has been gradually improving over time, and the gap between regions has also narrowed. The logistics industry in Inner Mongolia, Shaanxi, Qinghai and Sichuan provinces shows relatively stable and high comprehensive efficiency, while the logistics industry in other provinces has been fluctuating mainly from 2013. This may be attributed to the rapid

Table 1
Manufacturing input and output indicator system.

First-level indicators	Second-level indicators	Third-level indicators
Input indicators	Total fixed assets of manufacturing industry	Stock of fixed assets of manufacturing industry
	Manufacturing labor input	Number of employees in manufacturing industry
	Energy consumption of manufacturing industry	Energy consumption of various terminals in manufacturing industry
	R&D investment in manufacturing industry	R&D expenditure in manufacturing industry
	Informationization level of manufacturing industry	Informationization infrastructure
	Degree of openness to the outside world	Total import and export of manufacturing industry
Output indicators	Manufacturing industry value added	Manufacturing industry value added
	Technological innovation	Number of patent applications
	Main business income of manufacturing industry	Main business income of manufacturing enterprises

Table 2
Logistics industry input and output indicator system.

First-level indicators	Second-level indicators	Third-level indicators
Input indicators	Total fixed assets in logistics industry	Fixed assets stock in logistics industry
	Labor input in logistics industry	Number of employees in logistics industry
	Logistics network mileage	Total number of highway and railroad mileage
	Energy consumption of logistics industry	Energy consumption of various terminals in logistics industry
	Investment in R&D in logistics industry	Investment in scientific and technological R&D in logistics industry
	Informationization level of logistics industry	Informationization infrastructure
Output indicators	Value added in logistics industry	Value added in logistics industry
	Cargo turnover	Total cargo turnover of road and railroad transportation modes
	Carbon dioxide emissions	Carbon dioxide emissions in logistics operation

Table 3
Variable selection and variable names.

Variable category	Variable	Variable name
Explained variables	lnwlyzjz	Value added in logistics industry
	lnzzyzjz	Manufacturing industry value added
Explanatory variables	lnwlygdzc	Total fixed assets in logistics industry
	lnwlyldl	Labor input in logistics industry
	lnwlywllc	Logistics network mileage
	lnwlynyxh	Energy consumption of logistics industry
	lnwlyxxh	Informationization level of logistics industry
	lnwlyeyht	Carbon dioxide emissions
	lnhwzzl	Cargo turnover
	lnzzygdzc	Total fixed assets of manufacturing industry
	lnzzyldl	Manufacturing labor input
	lnzzynyxh	Energy consumption of manufacturing industry
	lnzzyyftr	R&D investment in manufacturing industry
	lnzzyxxh	Informationization level of manufacturing industry
	lndwkf	Degree of openness to the outside world
	lnjscx	Technological innovation
	lnzyywsr	Main business income of manufacturing industry

Note: The prefix "ln" indicates the natural logarithm.

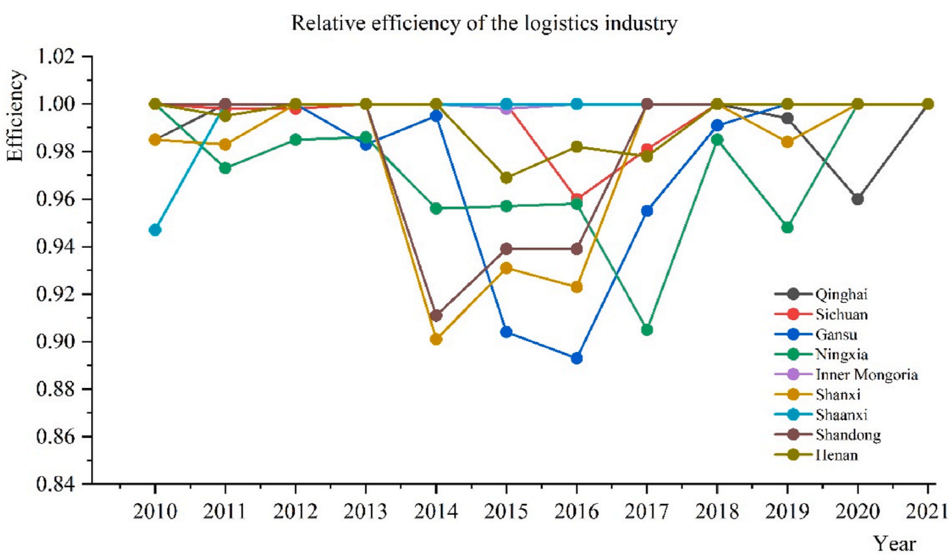

Fig. 1. Relative efficiency of the logistics industry.

development of the logistics industry in recent years, leading to an imbalance in the industrial structure and irrationality in input and output. In particular, the rapid development of the logistics industry in the lower reaches of the Yellow River has overlooked the balance of industrial structure, leading to a decline in the overall efficiency.

From Fig. 2, most of the comprehensive efficiency of manufacturing industry is between 0.900 and 1.000, and the overall

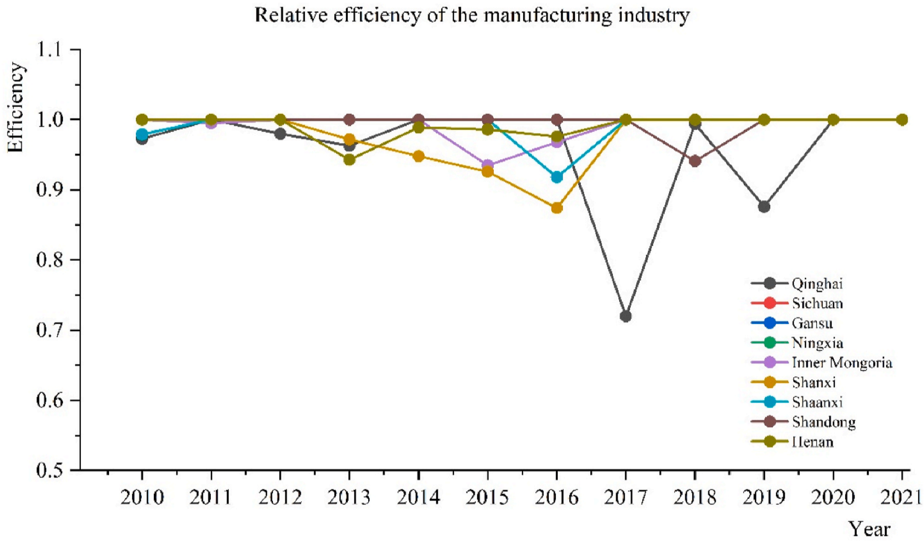

Fig. 2. Relative efficiency of the manufacturing industry.

fluctuation is small. Qinghai, Inner Mongolia, Shanxi, Shaanxi and Henan have lower levels of comprehensive manufacturing efficiency, with Qinghai Province falling below 0.750 in 2017, with the greatest fluctuations. The development efficiency of all other regions has been rising over time. The comprehensive manufacturing efficiency of Sichuan, Gansu, Ningxia and Shandong is at a high level, and its efficiency value remained above 0.950 during 2010–2021. It shows that the development efficiency of the manufacturing industry in the Yellow River Basin is at a good level, and the difference between regions is small. From the overall perspective, the comprehensive efficiency of manufacturing and logistics in the Yellow River Basin shows that the development of logistics industry is lagging behind.

3.2. Coupling efficiency analysis

3.2.1. Logistics-manufacturing coupling efficiency analysis

Based on the super-efficient SBM-undesirable model, using logistics industry indicators as inputs and manufacturing industry indicators as outputs, the Mydea1.0.5 software is used to measure the support efficiency of logistics industry to manufacturing industry and explore the impact of logistics industry on the development of manufacturing industry, and the measurement results are shown in Fig. 3.

Based on the analysis of Fig. 3, the comprehensive efficiency of several provinces in China shows stable or fluctuating patterns over time. The provinces of Henan, Shandong, Sichuan, Gansu, and Inner Mongolia show stable comprehensive efficiency from 2010 to 2013. However, the comprehensive efficiency of Shaanxi, Qinghai, Shanxi, and Ningxia fluctuates significantly during this period. From 2014 to 2016, the comprehensive efficiency of the upper Yellow River region fluctuates significantly, while the middle and lower reaches of the Yellow River region show stable and high comprehensive efficiency. In the period 2017–2021, the comprehensive efficiency of Qinghai and Gansu lags behind, while the comprehensive efficiency of other regions fluctuates but remains high. Overall, the three radar charts suggest that the support role of the logistics industry to the manufacturing industry has improved from 2014 to 2021. This indicates that the coordination and interaction between the logistics industry and the manufacturing industry have been strengthened. The input and output of the logistics industry have a catalytic effect on the development of the manufacturing industry.

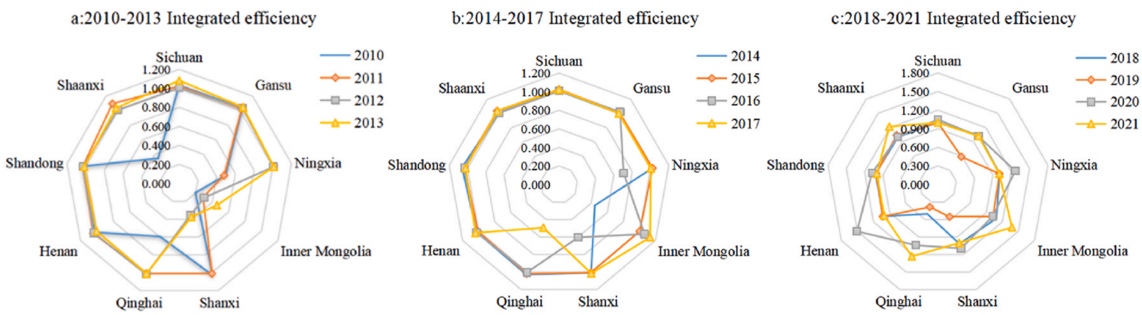

Fig. 3. Logistics - manufacturing integrated efficiency radar chart in 2010–2021.

In this paper, the mean values of the comprehensive efficiency of the logistics -manufacturing industry from 2010 to 2021 are ranked, and the coupled and coordinated efficiency of the two industries in each province is compared and analyzed from the time dimension, and the results are shown in Table 4.

From the results, Henan (1.064) and Shandong (1.031) have the highest combined efficiency means, followed by Sichuan (1.023), and the efficiency values of these regions are DEA valid. On the other hand, the mean efficiency values of Shaanxi (0.987), Gansu (0.986), Ningxia (0.920), Qinghai (0.861), and Shanxi (0.838) fall within the range of 0.800–1.000. The differences in the mean efficiency values of these regions are relatively small, and they are generally at an average level. The lowest mean value is in Inner Mongolia (0.784) in the upper reaches of the Yellow River. The overall downstream regions have higher combined logistics-manufacturing efficiency than the middle and upstream regions. This is due to the different degrees of development of logistics industry along the Yellow River and the differences in the effects of logistics industry inputs and outputs on the manufacturing industry. The efficiency of logistics industry supporting manufacturing industry in Henan and Shandong is at the top of the Yellow River basin, and their developed logistics industry can better serve the manufacturing industry and promote the integration of the two industries. For regions with lower efficiency values, the development level of logistics industry is low and lacks geographical advantages. The logistics service capacity in the middle and upper reaches of the Yellow River lags behind the demand of manufacturing industry in the region and cannot effectively serve the manufacturing industry, making the integration of the two industries relatively backward.

3.2.2. Manufacturing-logistics coupling efficiency analysis

Similarly, using manufacturing industry indicators as inputs and logistics industry indicators as outputs, the driving efficiency of manufacturing industry to logistics industry is measured by MyDEA1.0.5 software, and the measured results are shown in Fig. 4.

According to the findings presented in Fig. 4, the combined efficiency of manufacturing and logistics in the Yellow River Basin exhibited fluctuation during the period of 2010–2013. From 2014 to 2016, there were significant fluctuations in the regions of Ningxia, Qinghai, and Shanxi, while three other regions, namely Henan, Shandong, and Shaanxi, stabilized at a lower level. Between 2017 and 2021, the efficiency of the manufacturing industry driving the logistics industry increased progressively over time, except for Shaanxi. The reason for this disparity can be attributed to the more developed logistics and manufacturing industries in Shandong and Henan, which, in the process of rapid development, overlooked the drive of the manufacturing industry towards the logistics industry. This oversight resulted in the emergence of an unreasonable industrial structure, leading to significant fluctuations in the coupling efficiency of the manufacturing industry and the logistics industry. A comprehensive analysis using three radar charts indicated that the coupling and coordination efficiency of the manufacturing industry and logistics industry has been steadily increasing over time.

According to the ranking of the average value of the comprehensive efficiency of the manufacturing-logistics industry from 2010 to 2021, the coupling and coordination efficiency of the two industries in each province is compared and analyzed from the time dimension, and the results are shown in Table 5.

Based on the results presented in Tables 5 and it can be observed that Inner Mongolia (1.097), Gansu (1.096), Qinghai (1.043), and Sichuan (1.016) have the highest mean combined efficiency values, and these values are DEA effective. Following these provinces, Shanxi (0.994), and Ningxia (0.944) have mean efficiency values between 0.900 and 1.000, and their combined efficiency is DEA invalid, but at a relatively higher level. On the other hand, the middle and lower reaches of the Yellow River, namely Henan (0.625), Shandong (0.462), and Shaanxi (0.452), have lower mean values. The overall combined efficiency of the manufacturing and logistics industries in these regions is lower than that in the upper reaches. This indicates that the more developed the manufacturing and logistics industry is, the less the manufacturing industry drives the logistics industry. The reason for this could be attributed to the fact that the manufacturing demand in the upstream areas of the Yellow River is smaller compared to the middle and downstream areas, and the gap between the development level of manufacturing and logistics is smaller in the upstream areas. Meanwhile, the areas with larger manufacturing demand tend to overlook the logistics operation mode, resulting in weaker driving effects on the logistics industry, particularly in the downstream areas of the Yellow River.

3.3. Analysis of spatial interaction effects

3.3.1. Spatial autocorrelation analysis

To further analyze the spatial correlation between the coordinated development of manufacturing and logistics in the Yellow River

Table 4
The logistics-manufacturing combined efficiency results.

Province	Year												
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	平均值
Henan	1.026	1.047	1.039	1.005	1.022	1.006	1.027	1.037	1.023	1.026	1.507	1.000	1.064
Shandong	1.034	1.031	1.028	1.015	1.061	1.033	1.037	1.022	1.021	1.011	1.079	1.000	1.031
Sichuan	1.033	1.024	1.005	1.083	1.013	1.025	1.010	1.022	1.005	1.001	1.050	1.000	1.023
Shaanxi	0.346	1.095	1.009	1.036	1.012	1.036	1.007	1.034	1.001	1.037	1.006	1.219	0.987
Gansu	1.037	1.023	1.036	1.046	1.002	1.014	1.022	1.001	1.031	0.587	1.017	1.020	0.986
Ningxia	0.495	0.479	1.008	1.012	1.021	1.023	0.707	1.004	1.010	1.007	1.265	1.006	0.920
Qinghai	0.594	1.007	1.017	1.010	1.030	1.020	1.004	0.493	0.502	0.384	1.039	1.231	0.861
Shanxi	1.028	1.009	0.352	0.375	1.009	1.007	0.604	1.016	1.015	0.552	1.094	1.000	0.838
Inner Mongoria	0.196	0.290	0.302	0.458	0.446	1.003	1.063	1.132	1.089	1.026	1.022	1.380	0.784

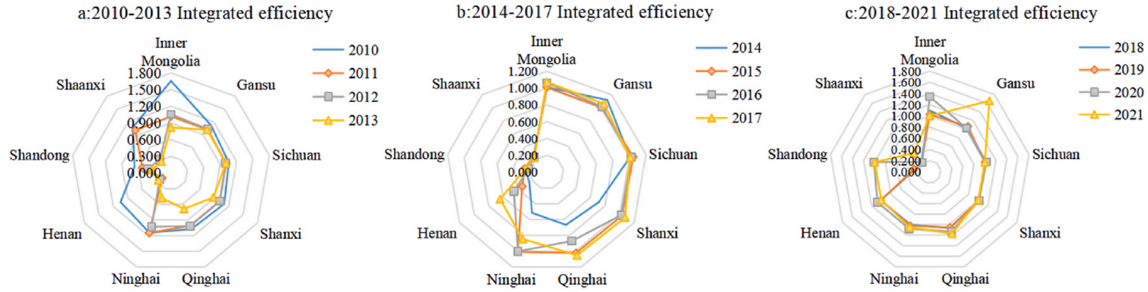

Fig. 4. Manufacturing-logistics integrated efficiency radar chart in 2010–2021.

Table 5
The manufacturing-logistics combined efficiency results.

Province	Year												
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	平均值
Inner Mongoria	1.655	1.016	1.054	0.821	1.010	1.009	1.061	1.072	1.096	1.024	1.345	1.000	1.097
Gansu	1.122	1.019	1.033	1.014	1.120	1.007	1.019	1.060	1.022	1.061	1.019	1.658	1.096
Qinghai	1.075	1.010	1.015	0.686	0.667	1.022	0.871	1.053	1.063	1.054	1.130	1.871	1.043
Sichuan	1.060	1.013	1.001	1.007	1.005	1.046	1.019	1.006	1.008	1.000	1.030	1.000	1.016
Shanxi	1.109	1.015	1.016	0.882	0.714	1.035	1.023	1.077	1.019	1.019	1.017	1.000	0.994
Ningxia	1.142	1.146	1.033	0.480	0.515	1.010	1.003	0.844	1.001	1.024	1.079	1.049	0.944
Henan	1.048	0.180	0.234	0.264	0.241	0.339	0.453	0.643	1.016	1.009	1.078	1.000	0.625
Shandong	0.667	0.521	0.428	0.352	0.265	0.267	0.222	0.255	0.266	0.287	1.013	1.000	0.462
Shaanxi	1.071	1.000	0.311	0.268	0.247	0.239	0.234	0.235	0.239	0.223	0.215	1.138	0.452

Basin, the global Moran's I was used to represent the global spatial autocorrelation between the regional manufacturing and logistics industries for the explanatory variables. According to the results in Table 6, the global Moran's I of the Yellow River Basin all have positive values and basically pass the significance test with 95% confidence level. It can be seen that the coupled and coordinated development of the manufacturing and logistics industries in the Yellow River Basin provinces has a global positive correlation. At the same time, the global Moran's I of logistics industry in the Yellow River Basin is growing in general, and the positive spatial interaction of logistics industry between provinces and regions is increasing. The overall Moran's I of manufacturing industry is mainly stable above 0.500, which indicates that the spatial interaction of manufacturing industry in the Yellow River basin is relatively stable. These results can be explained by the increasing frequency of inter-regional trade and information exchange, leading to an increase in the quantity of goods circulation and acceleration of speed. The increased spatial correlation of logistics industry becomes an inevitable result, while the spatial correlation of manufacturing industry remains more stable.

The local Moran's I of industry value added of manufacturing and logistics in the Yellow River basin in 2021 was used to represent the spatial autocorrelation between a province and its neighboring provinces, as shown in Figs. 5 and 6. The results show that almost all provinces do not show significant agglomeration. In contrast, there is an obvious low-low agglomeration in both logistics and manufacturing industries in Inner Mongolia, indicating that the development level of logistics industry in the region is low, and the development level of logistics industry in its neighboring regions is also low. There is an obvious high-low agglomeration in the logistics industry in Sichuan Province, indicating that there is a negative spatial autocorrelation in the development of the logistics industry between regions. The above results indicate that there is a spatial agglomeration characteristic of manufacturing and logistics industry in the Yellow River Basin of China, but the performance is not significant.

3.3.2. Spatial econometric model selection test

In this paper, based on the spatial correlation between manufacturing and logistics industries in the Yellow River Basin, parameter estimation is conducted for the relevant variables of the two industries. After LM test, the statistics LM-lag, Robust LM-lag and Robust LM-error passed the 5% significance level test, and the spatial econometric model was chosen to explore the spatial interaction between manufacturing and logistics industries with better effect. The LR test results showed that the data samples in this paper were more suitable for analysis using SDM. The original hypothesis was rejected from the 1% significance level by the Hausman test, so fixed effects were chosen to explore. Due to space limitations, the test results are not shown in this paper.

3.3.3. Analysis of Spatial Durbin Model results

The regression analysis of the spatial Durbin model using Stata software was conducted for the temporal fixed, spatial fixed, and spatio-temporal fixed effects, respectively. From the estimation results, it can be seen that the likelihood function values of the spatio-temporal fixed effects for both manufacturing and logistics industries are the largest, 116.386 and 102.468, respectively. Therefore, the spatio-temporal fixed effects are analyzed in this paper, and the results are shown in Table 7.

In the spatial Durbin model, which contains a spatial lag term as the dependent variable, it turns out that the coefficient of the

Table 6
Moran's I and P values for manufacturing and logistics in the Yellow River Basin provinces, 2010–2021.

Indicator	Variable	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Moran's I	Value added in logistics industry	0.389	0.379	0.385	0.408	0.418	0.423	0.417	0.423	0.449	0.457	0.566	0.512
	Manufacturing industry value added	0.541	0.536	0.54	0.541	0.543	0.545	0.543	0.55	0.565	0.567	0.451	0.045
P-value	Value added in logistics industry	0.019	0.022	0.02	0.016	0.013	0.013	0.014	0.013	0.01	0.008	0.009	0.490
	Manufacturing industry value added	0.005	0.006	0.006	0.006	0.005	0.005	0.005	0.004	0.003	0.003	0.003	0.005

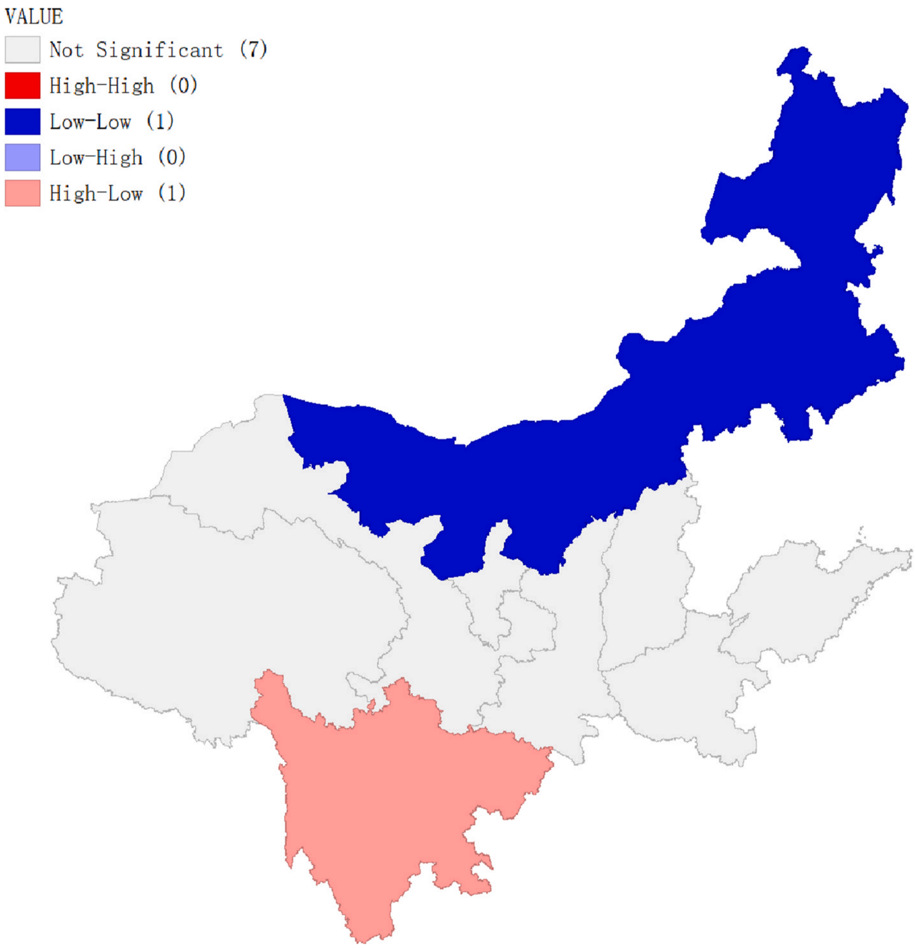

Fig. 5. The local spatial autocorrelation cluster of logistics industry.

spatial lag term of the explanatory variables is obviously not 0. Changes in the independent variables in one region may affect the fixed effect results, and the surrounding areas in turn may have other effects on the region. Therefore, the regression coefficients in Table 7 above cannot accurately describe the true marginal effects of the independent variables, and their spatial effects are decomposed to estimate their direct, indirect and total effects, and the results are shown in Table 8.

Combining the results in Tables 7 and 8 and it can be seen that.

(1) Direct effect analysis

From the manufacturing industry, the direct effects of the degree of openness of the manufacturing industry (0.135) and energy consumption of the manufacturing industry (−0.430) passed the significance test with 99% confidence level, indicating that the degree of openness of the manufacturing industry has a promotional effect on the development of the logistics industry in the region, and the energy consumption of the manufacturing industry has a significant inhibitory effect on the logistics industry in the region. The direct effects of fixed assets in manufacturing industry (0.118) and the level of informationization in manufacturing industry (0.089) passed the significance test with 95% confidence level, indicating that the investment in fixed assets in manufacturing industry and the improvement of informationization level help the development of logistics industry in this region. The influence of other factors on the logistics industry is not significant, and from the overall perspective, the driving effect of manufacturing industry on the development of logistics industry in the region is not yet obvious.

From the perspective of logistics industry, the direct effects of the level of informationization of logistics industry (0.551), carbon dioxide emission of logistics industry (−0.254), and passed the significance test with 99% confidence level, indicating that there are significant direct effects of these influencing factors on the development of the two industries in the region. The level of informationization of logistics industry has a positive effect on the development of the region's manufacturing industry. On the contrary, carbon dioxide emissions and the development of manufacturing industry in the region both have a negative relationship, and the increase of carbon dioxide emissions will naturally affect the ecological level of the local industry and thus have a negative effect. The direct effects of network mileage of logistics industry (−0.920) and cargo turnover of logistics industry (0.246) pass the significance

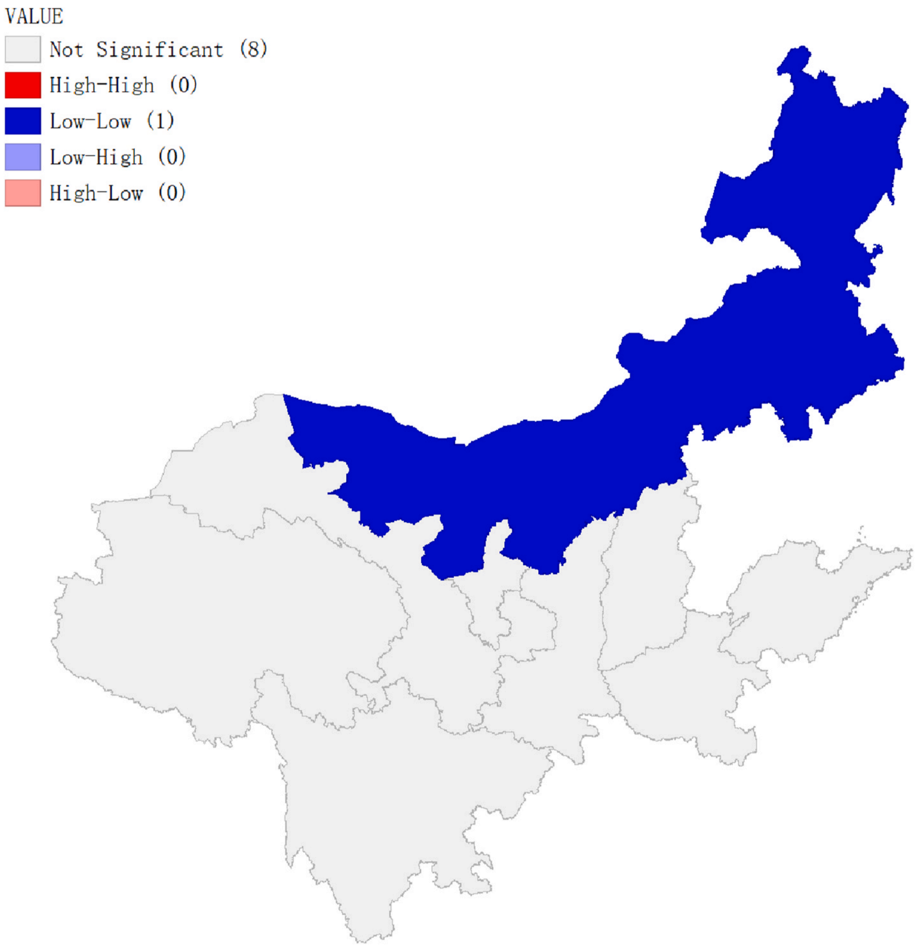

Fig. 6. The local spatial autocorrelation cluster of manufacturing industry.

Table 7
Estimation results of the Spatial Durbin Model.

Industry	Variable	Space fixed	Time fixed	Space-time fixed
Manufacturing Industry	lnzzygdzc	0.168***	−0.213	0.121*
	lnzzyldl	0.013	0.231	0.099*
	lnzzynyxh	−0.553***	−0.205	−0.458***
	lnzzyyftr	−0.058	0.125	−0.215
	lnzzyxxh	0.203***	−0.385***	0.083
	lndwkf	0.145***	0.036	0.164***
	lnzzyzjz	−0.975	0.238	−0.140*
	lnjscx	0.052	−0.270***	−0.007
	lnzyywsr	0.012	−0.102	0.106
Logistics Industry	lnwlygdzc	−0.007	0.034	−0.0246
	lnwlyldl	−0.017	0.106*	−0.0347
	lnwlywllc	−0.788*	0.611***	−0.8144*
	lnwlynyxh	0.017	−0.200***	0.0255
	lnwlyxxh	0.505***	−0.385***	0.5072***
	lnwlyeyht	−0.257***	0.439***	−0.2361***
	lnhwzzl	0.160	0.404***	0.2637***
	lnwlyzjz	0.096	0.031	0.0735

Note: *p < 0.1; **p < 0.05; ***p < 0.001.

test with 95% confidence level, and the direct effect of logistics network mileage is negative, which may be due to the underutilization of logistics network or insufficient resources. While the direct effect of logistics industry cargo turnover is positive, which indicates that the increase of logistics industry cargo turnover can improve the efficiency of manufacturing industry. On the whole, the logistics

Table 8
Decomposition of spatial effects.

Industry	Variable	Direct effect	Indirect effect	Total effect
Manufacturing Industry	lnzzygdzc	0.118**	0.028	0.146*
	lnzzyldl	0.081*	0.119	0.200**
	lnzzynyxh	−0.430***	−0.134	−0.565***
	lnzzyyftr	−0.031	0.075	0.044
	lnzzyxxh	0.089**	−0.045	0.044
	lndwkf	0.135***	0.214***	0.349***
	lnzzyzjz	−0.128*	−0.877	−0.215
	lnjscx	−0.001	−0.605	−0.061
	lnzyywsr	0.086	0.176*	0.261***
Logistics Industry	lnwlygdzc	−0.021	−0.050	−0.072
	lnwlyldl	−0.036	−0.026	−0.061
	lnwlywllc	−0.920**	3.484***	2.564***
	lnwlynyxh	0.023	0.048	0.071
	lnwlyxxh	0.551***	−0.987***	−0.437**
	lnwlyeyht	−0.254***	0.524	0.270
	lnhwzzl	0.246**	0.530**	0.776***
	lnwlyzjz	0.0516	0.446**	0.498**

Note: *$p < 0.1$; **$p < 0.05$; ***$p < 0.001$.

industry has a weak role in supporting the development of the manufacturing industry in the region.

(2) Indirect effect analysis

From the perspective of manufacturing industry, the indirect effect of the degree of opening up of manufacturing industry to the outside world (0.214) passed the significance test with 99% confidence level, and the indirect effect of the main business income of manufacturing industry (0.176) passed the significance test with 90% confidence level. Only two variables passed significance tests with different levels of significance, indicating that the manufacturing industry in the region has a weak effect on the development of the logistics industry in neighboring regions. However, the indirect effects of the main business income of the manufacturing industry and the degree of openness to the outside world are significantly positive, indicating that the increase in the output value of the manufacturing industry can significantly drive the logistics industry in the neighboring regions.

From the perspective of logistics industry, the indirect effects of network mileage of logistics industry (3.484) and the level of informationization of logistics industry (−0.987) passed the significance test with 99% confidence level. The indirect effects of cargo turnover (0.530) and value-added of logistics industry (0.446) passed the significance test with 95% confidence level. It indicates that the network mileage, cargo turnover and value-added of logistics industry are positively related to the development of manufacturing industry in the adjacent area, but the level of informationization has not yet been perfected and still shows a negative effect on the development of the two industries. Compared with the manufacturing industry, the positive spatial spillover effect of the logistics industry is more obvious.

4. Research findings and policy recommendations

4.1. Research findings

The level of coupled and coordinated development between the manufacturing and logistics industries in the Yellow River Basin from 2010 to 2021 was evaluated using the DEA and SDM methods, and the spatial interaction effects between regions in the two dimensions were analyzed. The main conclusions are: (1) The level of coupling and coordination between the manufacturing and logistics industries in the Yellow River Basin is moderate, with the logistics industry playing a greater supporting role to the manufacturing industry than the driving role of the manufacturing industry to the logistics industry. This is especially true for the two regions of Henan and Shandong in the lower reaches of the Yellow River. (2) There is a spatial correlation between the manufacturing industry and the logistics industry in the Yellow River Basin, but the level of spatial correlation between the two industries is low. This suggests that the development level of the manufacturing and logistics industries in the Yellow River Basin is not only related to the development level of the two industries within the region, but also to the development level of the two industries in neighboring regions. (3) The overall spatial interaction effect between the manufacturing and logistics industries in the Yellow River Basin is not significant. The degree of openness and main business income of the manufacturing industry has a significant positive effect on the development of the logistics industry in other regions. The positive spatial spillover effect of cargo turnover and added value of the logistics industry is more pronounced. However, the level of informationization in both industries is not yet well-established and both show a negative spatial effect.

Since the 13th Five-Year Plan period is a period of rapid economic development in China, this paper selects the data since the 13th Five-Year Plan period and the data of the five years before the 13th Five-Year Plan for comparison and analysis. This paper compares the data since the 13th Five-Year Plan period with the data in the five years before the 13th Five-Year Plan to investigate the development of the manufacturing and logistics industries in the Yellow River Basin. At the same time, considering the availability and accuracy of data, this study only analyzes the sample data of nine provinces in the Yellow River Basin from 2010 to 2021, which may have a weak impact on the research results and reduce the prospective of the study.

4.2. Policy recommendations

Based on the findings of the previous study, the following policy recommendations are suggested.

(1) Adopt a holistic and differentiated industrial development strategy. Consider the Yellow River Basin as a whole, plan as a whole, coordinate regionally, and promote the flow of logistics and production factors among regions. Based on the characteristics and development status of different areas in the Yellow River Basin, leverage strengths and complement weaknesses, and promote the coordinated development of manufacturing and logistics industry according to local conditions. The lower reaches of the Yellow River region focus on the high-quality development of manufacturing and logistics industry, and actively provide technical, talent, and financial support to the middle and upper reaches of the Yellow River region. The middle and upper reaches of the Yellow River should combine their own resource advantages, improve the urbanization level, focus on increasing the basic investment of the two industries, and promote the coordinated development of the two industries.
(2) Improve the structure of the industry itself and promote industrial upgrading. Enhance the degree of agglomeration and modernization of the logistics industry, guide the logistics industry to gather the scattered enterprise resources, advanced technology and high-end talents together to form a specialized and modernized logistics industry, and effectively improve the service capacity and quality of the logistics industry. Particularly, the logistics demand in the middle and upper reaches of the Yellow River is more scattered, and the economy is relatively backward. Therefore, vigorously improving the degree of concentration of the logistics industry in the middle and upper reaches of the Yellow River and comprehensively promoting high-quality development will be more effective. Take manufacturing enterprises as the main body, strengthen the outsourcing of manufacturing logistics, increase the connection between manufacturing industry and logistics industry, save the logistics cost of enterprises, focus on the core business of enterprises, provide more high-quality productive services, and further strengthen the driving effect of manufacturing industry on logistics industry.
(3) Establish the exchange platform between the two industries and improve the level of informationization. Build an efficient information communication and connection platform, build "one-to-one", "one-to-many" and "many-to-many" industrial relations, reduce information asymmetry, strengthen the interaction and cooperation between the manufacturing industry and the logistics industry in the Yellow River Basin, and improve the logistics industry. The interaction and cooperation between the manufacturing industry and the logistics industry in the Yellow River Basin, improve the integration and standardized service capacity of the logistics industry to meet the specialized and multi-level logistics needs of the manufacturing industry; and realize the coordinated development of the manufacturing industry and the logistics industry among the provinces in the Yellow River Basin.

Author contribution statement

Aifeng Song: Conceived and designed the experiments; Wrote the paper.
Yifan Liu: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.
Xue Zhao: Performed the experiments.
Xindie Liu: Analyzed and interpreted the data.
Dongling Bai: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

Data availability statement

Data included in article/supp. material/referenced in article.

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Declaration of competing interest

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

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