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Evolution and Optimization Simulation of Coastal Chemical Industry Layout: A Case Study of Jiangsu Province, China

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Abstract: In the face of geopolitical challenges and climate change, economic progress, safe production, and environmental protection have emerged as important directions for chemical industry development. However, the rational optimization of the chemical industry layout under the backdrop of ecological environmental protection necessitates further exploration. This study explores the evolution and future development direction of the chemical industry layout within the coastal region of Jiangsu Province, China, using the CA–Markov model. The findings reveal a trend of spatial agglomeration growth among coastal chemical enterprises, with Moran's Index increasing from 0.109 in 2007 to 0.206 in 2017. The petrochemical industry, in particular, demonstrated the most significant agglomeration effect, with approximately 52.10% being concentrated in 14 coastal industrial parks in 2017. Under the constraints of the ecological environment and policy guidance, the land area allocated for the chemical industry experienced a reduction of over 10%, further strengthening the emphasis on spatial agglomeration. Chemical industries along Jiangsu's coast have become agglomerated and concentrated near industrial parks and ports. Their spatial distribution and connectivity were mainly influenced by factors such as convenient transportation, the ecological environment, local policies, the distance from residential areas, and industrial agglomeration. Under different scenarios—including natural growth, ecological environment constraints, and policy guidance—chemical industries show diverse spatial patterns. Ecological environmental constraints and policy guidance can provide various intervention methods for the government to promote the optimization direction and focus of the chemical industry layout while minimizing its impact on the ecological environment.

Keywords: chemical industry; CA–Markov model; optimization simulation; coastal development

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1. Introduction

The chemical industry, a cornerstone for economic development, is characterized by high energy consumption, significant pollution, and substantial carbon emissions [1]. Globally, the development of the chemical industry faces numerous constraints, with safety concerns emerging as particularly contentious issues within this sector [2,3]. The high complexity and interdependence of the chemical plant facilities mean that an accident can trigger a cascading effect, resulting in significant casualties, property damage, and pollution [4–6]. Moreover, the climate crisis has been increasingly recognized in recent years as one of the greatest challenges facing human society [7]. Despite being essential materials in contemporary life, the production, utilization, and disposal of chemicals can contribute to environmental degradation, especially through greenhouse gas emissions during manufacturing or waste incineration [8]. Chemical industries, like other carbon–intensive sectors, constitute a multifaceted and diverse group that plays a role in reducing greenhouse gas emissions [9].

China is recognized as one of the world's leading producers and consumers of chemical products [10]. Regarding the product structure within its chemical industry, China has a high proportion of low–value–added and roughly processed chemical products. This results in showing a product structure with a low–end surplus and high–end shortage [11]. In the past, the production technology for these chemical products was relatively outdated, resulting in significant adverse environmental consequences. During this transitional period, there was an urgent need for China to establish a secure and environmentally friendly production structure to meet the requirements of high–quality development. While pursuing economic progress, the Chinese government has increasingly prioritized both production safety and green development [12,13].

Economic development, safe production, and ecological environmental protection are fundamental principles of chemical production. These principles necessitate guidance from industrial policies and regulation from environmental supervision [14]. Therefore, it is particularly important, based on an understanding of the industrial layout, to explore the impact of factors such as industrial policies and environmental supervision on the future layout of the chemical industry. The CA–Markov model can be employed to simulate the future changes in chemical industry land under varying input conditions. This model has traditionally been used for simulating land use/cover change (LUCC) [15]. In recent years, this model has been extended to many aspects of geographic research, including urban expansion/contraction [16], land salinization [17], vegetation change [18], landscape pattern evolution [19], and geomorphic pattern prediction [20]. Generally, chemical industry land is considered part of construction land; however, it can be distinguished in remote sensing images based on the point data of chemical enterprises.

Jiangsu Province, a significant contributor to China's economic development, boasts well–established industries that yield substantial tax revenue annually. Unlike its southern coastal counterparts in Guangdong, Zhejiang, and Fujian, Jiangsu's early economic progress was originally centered along the Yangtze River [21]. However, with the implementation of the central government's "Yangtze River Protection" strategy, there has been pressure on chemical industries along this river to transition, close down, relocate, or transfer operations. The coastal area of Jiangsu Province has emerged as a crucial area for chemical industry relocation [22,23]. While the chemical industry presents opportunities for local economic development, it also poses considerable challenges to local safety production and green development [24]. Thus, this study examines the evolution of the chemical industry layout in Jiangsu's coastal area and applies the CA–Markov model to simulate future development directions under various scenarios. The aim is to provide viable solutions and recommendations for the efficient, safe, and environmentally friendly development of the chemical industry in this region. The paper is structured as follows: Section 2 of the paper primarily introduces data and research methods; Section 3 analyzes the results; Section 4 discusses significant findings; and Section 5 summarizes the main research contributions of this paper.

2. Materials and Methods

2.1. Study Area

China's Jiangsu coastal area, including the cities of Nantong, Yancheng, and Lianyungang, is located at 118.40°~121.944° E and 31.63°~35.121° N, at the intersection of the new national strategies of "One Belt, One Road", Yangtze River Economic Belt and coastal development. It has a land area of 32,500 km^2, accounting for 31.6% of Jiangsu Province (Figure 1). Jiangsu's coastal development started in 2006. The Chinese government approved the "Jiangsu Coastal Area Development Plan" in 2009; since then, the development of the Jiangsu coastal area has been formally upgraded to a national strategy and has achieved remarkable results. By the end of 2022, the resident population of the three coastal cities reached 19.032 million, realizing a GDP of CNY 224.65 billion, accounting for 22.3% and 18.28% of the province, and its comprehensive strength continues to climb. The scale of the manufacturing industry is growing, the chemical industry is booming, and there are about 900 chemical enterprises, accounting for nearly 1/4 of the province. The over–concentration of chemical parks and the presence of numerous scattered chemical enterprises in coastal areas pose a potential threat to achieving high–quality development. Apart from inadequate construction and management levels, the infrastructure was insufficiently developed, and certain chemical enterprises experienced frequent accidents. For instance, the "3−21" explosion incident in Xiangshui, Lianyungang, in 2019 impacted 16 neighboring enterprises and resulted in direct economic losses totaling CNY 1.986 billion.

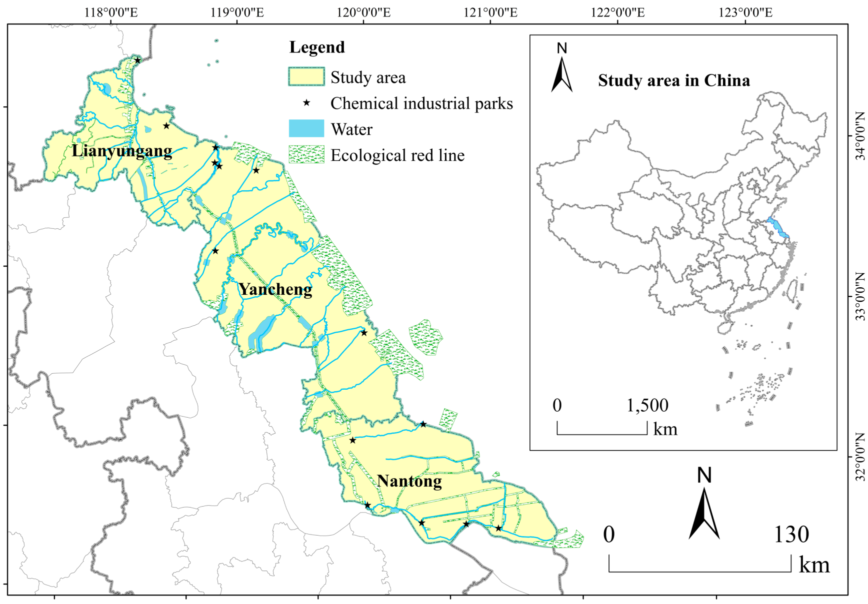


Figure 1. The coastal areas of Jiangsu Province, China.

2.2. *Evolution Measurement*

Mathematical and statistical methods were used to analyze the layout of chemical enterprises, the spatial agglomeration change characteristics, and their layout coercion on the ecological environment since the implementation of the Jiangsu coastal development strategy.

2.2.1. Enterprise Layout

In this study, global spatial autocorrelation was used to analyze the characteristics of the enterprise layout evolution. Global spatial autocorrelation can reflect the spatial correlation of things, which is characterized by Moran's I [25]. The formula is as follows:

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \overline{x})(x_j - \overline{x})}{\left(\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\right)\sum_{i=1}^{n}(x_i - \overline{x})^2} \tag{1}$$

where I is global Moran's I, n is the number of regions calculated, x_i and x_j are the number of enterprises in regions i and j, respectively, w_{ij} is the spatial weight matrix, and $\overline{x}$ is the mean value. Moran's I is between −1 and 1, and the closer the value is to 1, the more it indicates strong spatial agglomeration; when closer to 0, it indicates a spatial random distribution or absence of spatial autocorrelation; less than 0 indicates negative spatial correlation.

2.2.2. Spatial Agglomeration Changes

The kernel density estimation method is an analytical method to measure the degree of agglomeration of the research object in the spatial distribution, which is widely used in the spatial agglomeration analysis based on point data and is used here to estimate spatial agglomeration changes in the chemical industry [25]. For n independently distributed points, the probability density function is assumed to be $f(x)$, and the specific formula is as follows:

$$f(x) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x_i - x}{h}\right) \tag{2}$$

where n is the total number of chemical enterprises, x_i is the number of enterprises in region i, x is the mean value, K is the kernel function, which determines the number of relevant data points used in kernel density computation, and h is the search bandwidth for kernel density computation. The cell size is set to 1 km, the search radius is set to 5 km, and the population field is set to the size of enterprises. The larger the kernel density value is, the denser the enterprise is.

2.2.3. Coercion on the Ecological Environment

Local spatial autocorrelation was used to measure the degree of spatial response between the number of enterprises in the region and the area of the ecological protection red line and to analyze the coercion of the chemical industry layout on the ecological environment. The formula is as follows:

$$I_i^{ap} = Z_i^a \sum_{i=1}^{n} w_{ij} Z_i^p \tag{3}$$

where Z_i^a and Z_i^p are mean–normalized observations, and the spatial weight matrix element w_{ij} is in the row–normalized form. I_i^{ap} represents the product of the number of enterprises in area i and the weighted average of the area of the ecological protection red line, whose value is significantly positive, indicating that the two are positively correlated; on the contrary, they are negatively correlated, and if it is not significant, the two have no clear correlation.

2.3. Optimization Simulation

Based on the qualitative analysis of the factors influencing the layout of the chemical industries, the data of the chemical enterprises were converted into land use data. The CA–Markov model was used to simulate the land use changes in chemical industries under different scenarios, to determine the key development areas in the future after comparative analysis, and to put forward optimization and control countermeasures (Figure 2). The CA–Markov model consists of the factor layer, the cellular automata (CA) layer, and the transition rules [17].

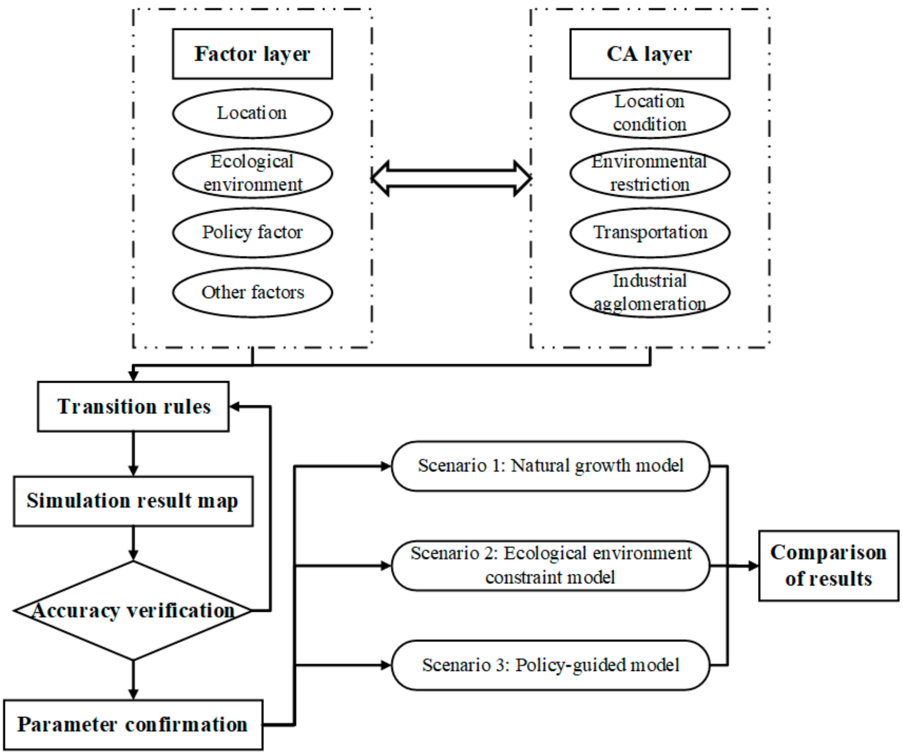


Figure 2. The process of model realization.

2.3.1. Model Construction

(1) Factor layer

The factor layer constitutes the objective environment in which the CA operates. Chemical industries are predominantly characterized by high levels of technology and resource intensity. As a physical industry to produce in geographical space, the location of enterprises is affected by factors such as location conditions, the ecological environment, local policies, distance from residential areas, and industrial agglomeration, which results in the formation of different forms of industrial layout and its spatial connection. Therefore, the factor layer mainly includes location, ecological environment, policy, and other factors (Figure 2).

(2) Cellular automata (CA) layer

CA has a strong simulation ability for spatial changes in complex systems; combined with the Markov model, it has the advantage of long–term prediction, which can improve the prediction accuracy of land use type transformation and effectively simulate the spatial changes in land use [25]. IDRISI 17.0 was used to combine the Markov data chain with the CA to accurately simulate the land use change in the chemical industry. The CA follows the qualifying factors to realize the control of land use–type transformation. The influencing factors of the chemical industry layout mainly include environmental restriction, transportation convenience, the distance from the residential area. and industrial agglomeration [26].

(3) Transition rules

The interrelationships between the factor layer and the CA layer constitute the transition rules for the land use types. The setting of the transition rules is determined by different spatial variables, each of which relates to a corresponding parameter, the size of which determines the role played by the variable in the model.

2.3.2. Scenario Settings

(1) Scenario 1: Natural growth model

In this model, under the condition of constant constraints, the land use change in the chemical industry does not take into account any ecological coercion or environment or industry–related policies.

(2) Scenario 2: Ecological environment constraint model

This model adds ecological environment coercion as a constraint factor in Scenario 1. In order to balance the ecological risk level of each region, the transition rule is set to the ecological environment effect. The higher the level, the more difficult it is to convert to chemical industry land.

(3) Scenario 3: Policy–guided model

This model adds environmental and industry–related policies to Scenario 2 to simulate the policy–guided evolution of the spatial layout of chemical industry land.

2.3.3. Accuracy Verification

The Multi–Criteria/Multi–Objective Decision Wizard module in IDRISI 17.0 was used to create suitability layers for various land use types. The Collection Editor tool was used to package and combine suitable layers into a spatially distributed probabilistic suitability atlas file [19]. Taking the 2012 land use data as the starting year of simulation, the 2012–2017 land use transfer matrix and its suitability atlas were brought in, and the 5 × 5 von Neumann neighborhood structure type was used, with the iteration number set to five to simulate the spatial distribution of land for the chemical industry. Finally, the Kappa coefficient was used to evaluate the accuracy of the model's simulation. Among them, the

Kappa coefficient is the method used to evaluate the classification and simulation accuracy of remote sensing image interpretation, and the specific formula is as follows:

$$I_i^{ap} = Z_i^a \sum_{i=1}^{n} w_{ij} Z_i^p \tag{4}$$

$$P = \frac{\sum_{i=1}^{n} P_i}{N} \tag{5}$$

where P_0 is the overall accuracy of classification, indicating the probability that the classification result of each random sample is the same as the actual data; P is the probability that the extra result due to chance is the same as the actual data; n is the number of land use types; N is the total number of samples; and P_i is the number of samples in which the i land use type is correctly classified. If $Kappa \geq 0.60$, it means the simulation is good.

2.4. Data Sources and Processing

The point data of chemical enterprises involved were mainly derived from economic census data in 2007, 2012, and 2017. The spatial vector data of natural ecological elements such as wetlands, water channels, drinking water sources, and important fishery areas were extracted according to the National Ecological Protection Red Line Planning of Jiangsu Province. The road network data were extracted using Google Earth. The spatial data of centralized residential areas and other spatial data crawled through the network to obtain the points of interest (POI). The data on pollution emissions were mainly derived from the 2007, 2012, and 2017 Environmental Statistics. The 2005, 2010, and 2018 land use data were provided by the Resource and Environment Science and Data Center of the Chinese Academy of Sciences. Socio–economic statistics were obtained from the statistical yearbooks of Lianyungang, Yancheng, and Nantong for the relevant years (Table 1).

Table 1. Research elements and data sources.

Factors	Data Sources
Chemical enterprises	The economic census data in 2007, 2012 and 2017.
Natural ecological elements	National Ecological Protection Red Line Planning of Jiangsu Province
Road network	Google Eart
POI	The spatial data of centralized residential areas and other spatial data
Pollution emissions	The Environmental Statistics data in 2007, 2012, and 2017
Land use	The Resource and Environment Science and Data Center of the Chinese Academy of Sciences.
Socio–economic factors	The statistical yearbooks of Lianyungang, Yancheng, and Nantong

Combine historical high–precision remote sensing satellite images with enterprise location data to outline the contours of businesses in the BIGEMAP software (http://www.bigemap.com). Transform the locations of heavy chemical industry enterprises into data on heavy chemical industry land use. Convert processed heavy chemical industry land into raster layers, overlay with 30–meter land use type data to obtain land use type maps for heavy chemical industry in each city.

3. Results

3.1. Evolution of Chemical Industry Layout

3.1.1. Changes in the Overall Chemical Industry

Coastal chemical enterprises showed spatial agglomeration growth, with Moran's I increasing from 0.109 in 2007 to 0.133 in 2012 and 0.206 in 2017 (Figure 3). Nantong ranked first in quantity, accounting for 52.76% of the total in 2017, and Chongchuan and Rudong in Nantong had the largest number, both exceeding 150. In terms of agglomeration, some regional agglomerations grew rapidly, such as Guanyun in Lianyungang, Binhai, and Dongtai in Yancheng, which doubled 9 times, 8 times, and 5 times, respectively.

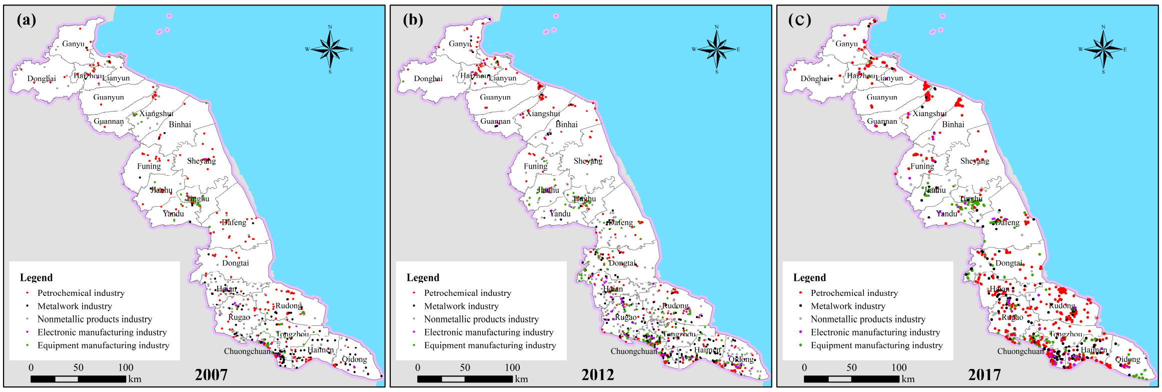


Figure 3. Enterprise distribution map. (**a**–**c**) respectively illustrated the distribution of different types of heavy chemical industries in 2007, 2012, and 2017.

3.1.2. Changes in the Chemical Industry Subsector

Along with the implementation of the coastal development strategy, the chemical industry, especially the petrochemical industry and metalwork industry, in coastal ports tend to be close to the trend of agglomeration (Figure 4). In 2007, high–density areas were mainly concentrated in the south of Chongchuan in Nantong, Gunnan, and the Lingshui junction of coastal areas. In 2012, high–density areas gradually shifted to the coast in an agglomeration trend, and in 2017, they further expanded to the coasts of Gunnan, Lingshui, Binhai, and Rudong, as well as to the coastal and riverine areas of Chongchuan, with a significant increase in spatial agglomeration. From 2007 to 2012, the Lingyun Industrial Zone in Guanyun County, Duigou Port Chemical Industry Park in Guannan County, Ecological Chemical Industry Park in Xiangshui County, Coastal Industrial Park in Binhai Economic Development Zone, and Yangkou Chemical Industrial Park in Rudong County continued to develop, attracting numerous petrochemical enterprises to establish their presence.

The spatial layout of different industries was also different, with the most significant agglomeration effect of the petrochemical industry, about 52.10%, clustered in 14 industrial parks along the coast in 2017, followed by the metalwork industry, 79.65% distributed in Nantong. Since 2012, the electronic and electrical manufacturing industries gradually aggregated from Jianhu District in Yancheng City towards Chongchuan District and Haimen City at the mouth of the Yangtze River. Large and medium–sized enterprises in the equipment manufacturing industry are mainly concentrated in Tinghu District, Yancheng City. As a pillar industry of Yancheng City, Tinghu District is home to numerous large equipment manufacturing enterprises. Due to the elimination of outdated cement capacity in Jiangsu, the number of enterprises in the non–metallic products industry has sharply declined, resulting in a scattered distribution pattern and a lower agglomeration effect.

3.1.3. Coercion on the Ecological Environment

The ecological red line refers to a demarcation line established in ecological conservation and environmental governance. Its primary purpose is to safeguard the integrity of crucial ecological functional areas and important ecosystems, preventing excessive development and pollution. By delineating key areas, the ecological red line aims to achieve the protection of ecosystems and impose restrictions on development and pollution, thus balancing economic development with environmental conservation and ensuring the healthy and sustainable development of ecosystems.

Buffer distances of 100 m, 500 m, and 1000 m are set within the ecological red line (Figure 5). The number of chemical enterprises within each buffer zone generally shows a trend of increasing and then decreasing. Among them, within the 100 m buffer zone, the number of chemical industry enterprises was 137 in 2007, which increased to 254 in 2012 and decreased to 198 in 2017, though the petrochemical industry continued to increase, from 58 in 2007 to 93 in 2017. The trend of enterprises in the buffer zone at all levels is the same. Moran's I of the number of chemical enterprises and the area of the ecological red line protection area was -0.053 in 2017, and the two are negatively correlated.

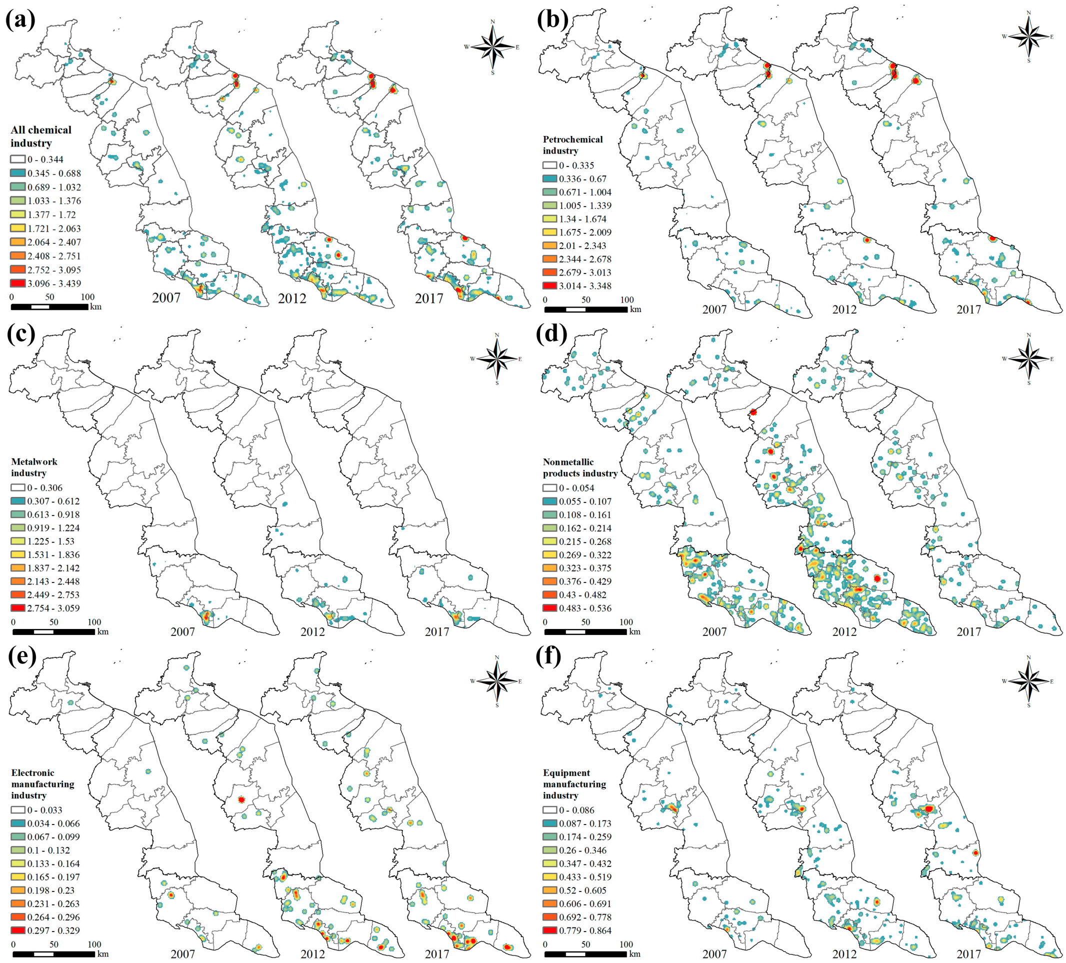


Figure 4. Variation in the kernel density of each chemical industry. (**a**) illustrated the overall changes in the nuclear density of the scale of heavy chemical industries; (**b**–**f**) respectively showed the situations of different types of heavy chemical industries.

Figure 5. Different buffer enterprise locations.

The greater the extent of the ecological red line protection area, the fewer the number of chemical enterprises. The coercion of the chemical industry layout on the ecological environment has been reduced, but the agglomeration pressure in some areas is still large. Enterprises situated in diverse buffer zones are mainly distributed along the water channel and flood storage areas, which continue to increase the pressure on the ecological environment, particularly with regard to the safety of drinking water.

3.2. Optimization Simulation of Chemical Industry Layout

3.2.1. Chemical Industry Layout Influencing Factors

The influencing factors are the basis for conducting the simulation. Chemical industries are mostly technology–intensive and resource–intensive. The spatial distribution and connection of these industries are mainly influenced by factors such as convenient transportation, the ecological environment, local policies, and the distance from residential areas to industrial agglomeration.

The layout of chemical industries near the sea is greatly affected by the transportation conditions of ports, coastlines and waterways. Lianyungang, as the largest seaport in Jiangsu and the eastern bridgehead of the Asia–Europe Continental Bridge, is the main hub port of China's coast and one of the important ports for energy outbound transportation, and an important transshipment port mainly for container transportation. Nantong is adjacent to the mouth of the Yangtze River, with unique conditions for water transportation. Yancheng, despite having less favorable port conditions, boasts four port areas and 91 productive berths. From 2007 to 2017, the total annual cargo throughput and the total container transportation volume of the ports in the three coastal cities increased by 158.13% and 143.56%, respectively. Chemical enterprises in coastal townships increased rapidly, from 199 in 2007 to 605 in 2017. In addition, coastal areas have developed inland waterways, and many inland river ports, and the number of chemical enterprises within a 1 km distance along the river increased from 432 to 609. Jiangsu's coastal chemical industry formed along the "inland waterway distribution axis" and "coastal port distribution axis" distribution pattern (Figure 6).

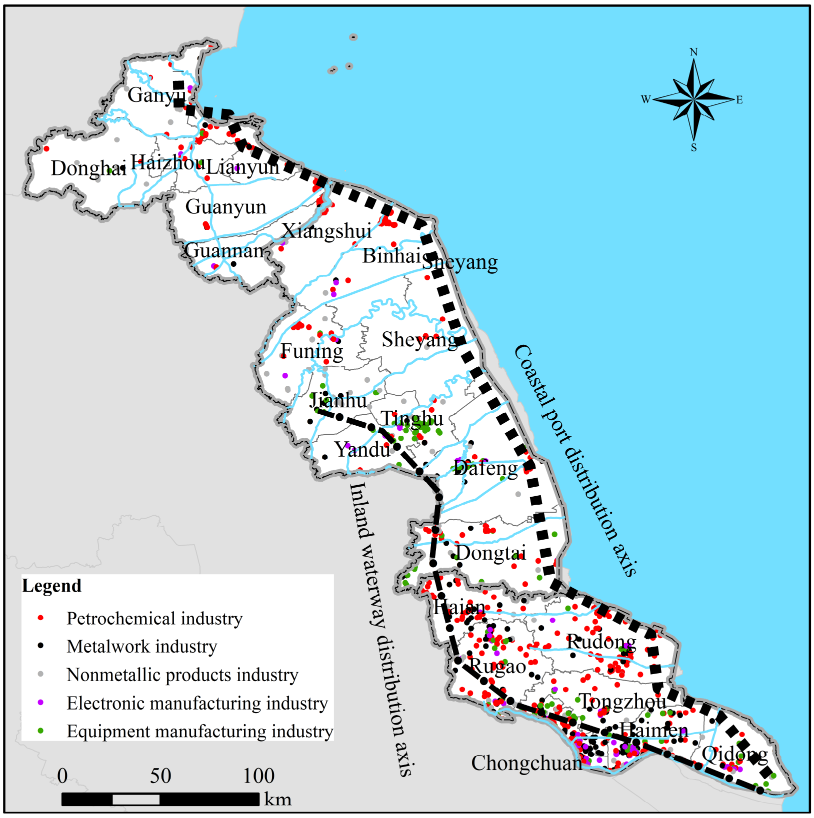


Figure 6. Comparison of industry distribution axis and waterway network.

The ecological environment constraints on the chemical industry layout are mainly realized through relevant policies. The national ecological protection red line planning of Jiangsu Province and the ecological space control area planning of Jiangsu Province require that "the national ecological protection red line is strictly prohibited from all kinds of development activities that do not conform to the positioning of the main function". To mitigate the impact of the heavy industrial layout on ecological space, the land within the national–level ecological protection red line and the ecological space control zone was designated as non–convertible for heavy industrial use. In cases where there was existing heavy industrial land within the region, it was designated for conversion to other land types.

Due to high pollution, chemical industries often need to consider the degrees of resistance that surrounding residents have to their layout. According to the *Jiangsu Province Chemical Park Environmental Protection System Construction Norms*, for a chemical park and residential area isolation bandwidth of no less than 500 m, the park built within the scope and isolation zone should not be planned for the construction of schools, hospitals, residential housing, and other environmentally sensitive targets. Accordingly, 500 m of the residential area is set as a buffer zone. The number of chemical enterprises accounts for 15.88%, of which the petrochemical industry accounts for 10.87%, the metalwork industry accounts for 19.91%, the nonmetallic products industry accounts for 23%, and the electronic manufacturing industry accounts for 38.24%. It can be seen that the number of chemical enterprises within the 500 m buffer zone of the settlement as a whole does not account for a high proportion, and the higher the pollution intensity of the industry, the lower the proportion of the number of enterprises.

Industrial agglomeration is a manifestation of the spatial optimization of productivity. Specifically, the larger the scale of agglomeration, the more conducive it is to encourage the government to increase investment and construction in the infrastructure of agglomeration areas. Therefore, as the degree of agglomeration increases, the probability of converting existing land into chemical industry use also becomes greater.

3.2.2. Simulation Accuracy Verification

The Kappa coefficients of the simulation results of the three cities in 2017 were calculated using the CROSSTAB module of IDRISI software. The accuracy of the overall simulation of Lianyungang is 0.9636, and the accuracy of the chemical industry land is 0.6342. The accuracy of the overall simulation of Yancheng is 0.9756, and the accuracy of the chemical industry land is 0.6130. The accuracy of the overall simulation of Nantong is 0.9733, and the accuracy of the chemical industry land is 0.7718. It can be seen that the model has a good simulation effect in general.

3.2.3. Simulation Scenario Comparison

The CA–Markov model has a higher simulation accuracy at small and medium scales, and there are differences in the development trend of these three coastal cities. Lianyungang, Yancheng, and Nantong are simulated separately, and the land use change in the chemical industry is predicted (Table 2). (a) The indicated area included Ganyu Port Area, Zhewang Industrial Zone, and others; (b) The indicated area encompassed most of the streets in Lianyun District, including Houcheng Street and Zhongyun Street, as well as Lianyun Port Area; (c) The indicated area included Xuxu Street, Guanyun Industrial Zone, and Duigou Port Town in Guannan County.

The fastest growth in the area of land used for the chemical industry between Scenario 1 and Scenario 2 is in Lianyungang, from 6060.06 ha in 2017 to 10,429.5 ha in 2035, with an increase of 72.10%. It was followed by Nantong, which grew from 16,007.13 ha to 23,332.62 ha, with an increase of 45.76%. Yancheng experienced the least growth, growing from 11,386.26 ha to 15,605.12 ha, with an increase of 37.05%. Compared to Scenario 1, Scenario 2 gradually converts chemical industry land in the original high coercion area to other land. The distinction lies in the fact that Lianyungang has gradually transitioned to an area with a lower coercion degree; Nantong has exhibited a notable tendency to shift from the main urban area to the coastal region, and the distribution of changes in Yancheng has been more dispersed.

In Scenario 3, the land area designated for the chemical industry in Lianyungang decreased by 471.57 hectares from 2017 to 2025, with a more evident policy direction towards the increased area. Yancheng decreased to 10,063.23 ha, with a decrease of 11.62% compared to Scenario 2 land use increases in more regular areas as more spatially agglomerative. Nantong decreased from 16,007.13 ha to 15,268.18 ha and further decreased to 15,235.19 ha in 2035, and the spatial layout of chemical industry land in the coastal area was more agglomerative.

In summary, under the natural growth model (Scenario 1), the expansion of the chemical industry land gradually extends outward from the existing foundation. While production capacity can experience rapid growth, the pressure on the ecological environment intensifies. Currently, each main urban area has chemical industries of a certain scale, and the contradiction with resident preferences is expected to become more prominent in the future. Under the constraint of ecological and environmental risks (Scenario 2), the chemical industry has a more balanced spatial layout, but its development path is still unclear. In Scenario 3, environmental and industry–related policies can guide the chemical industry to complete the optimization of spatial layout faster and can reduce the coercive pressure on the ecological environment.

Table 2. Scenario simulation of each city.

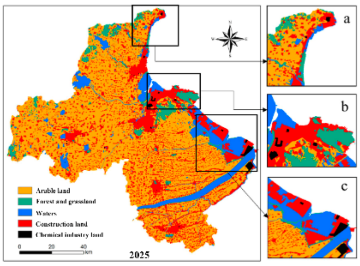
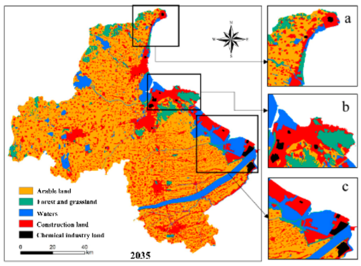
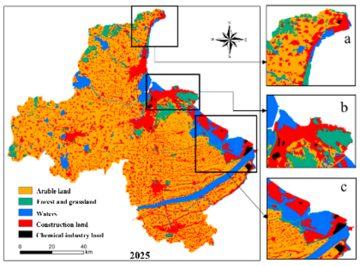
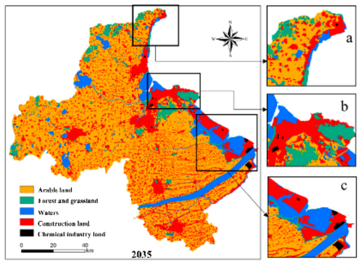
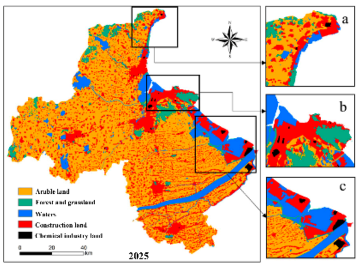
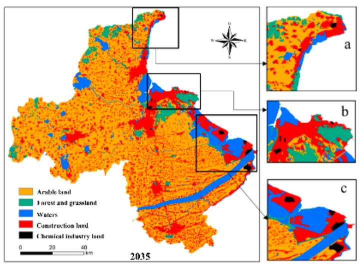
Cities	Scenario	Simulation Results	
		2025	2035
Lianyungang	Natural growth model		
	Ecological environment constraint model		
	Policy–guided model		

Table 2. *Cont.*

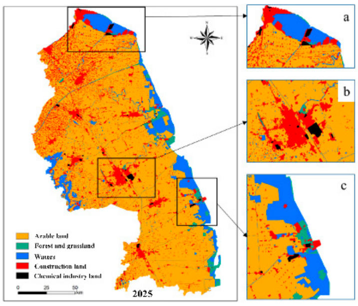
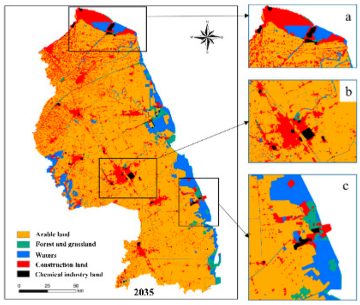
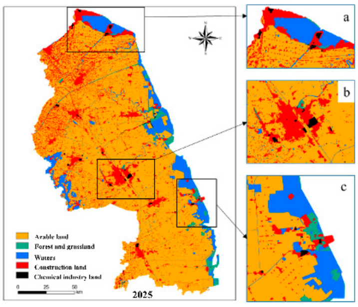
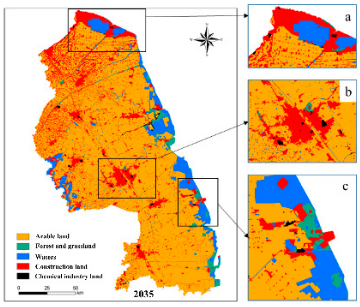
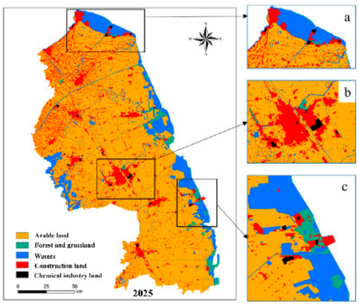
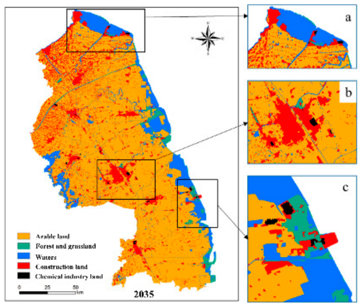
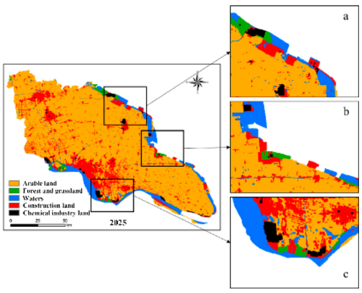
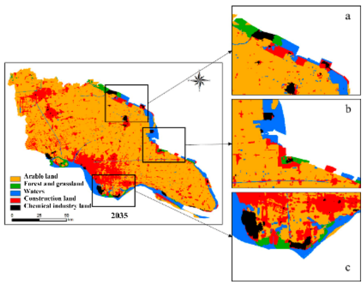
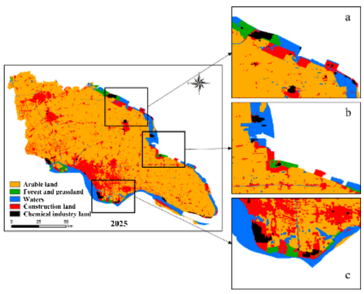
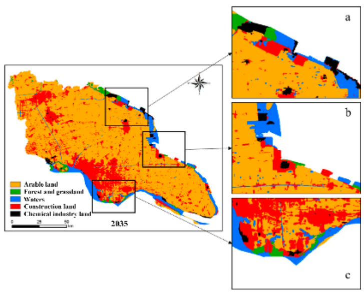
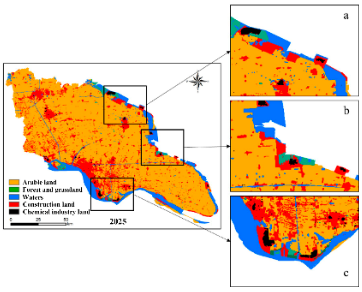
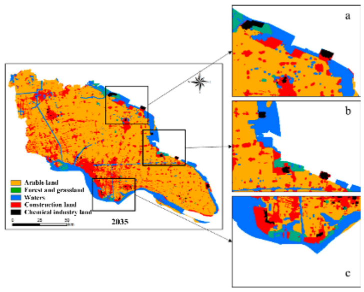
Cities	Scenario	Simulation Results	
		2025	2035
Yancheng	Natural growth model		
	Ecological environment constraint model		
	Policy–guided model		
Nantong	Natural growth model		
	Ecological environment constraint model		

Table 2. *Cont.*

Cities	Scenario	Simulation Results	
		2025	2035
	Policy–guided model		

3.2.4. Future Development Areas for the Chemical Industry

Simulation results show that the coastal port of each city is the future focus of regional development (Figure 7).

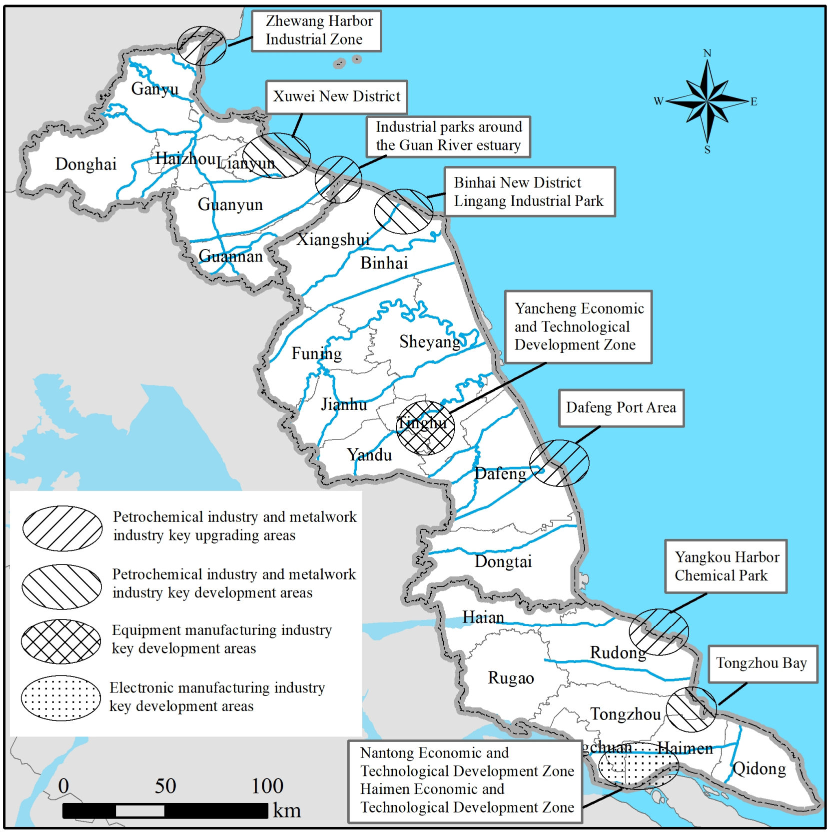


Figure 7. The future development areas of chemical industries.

The Xuwei New District in Lianyungang is one of the seven petrochemical industry bases in China. The Binhai New District in Yancheng is actively developing in four major industrial areas, including the steel industry, high–end equipment manufacturing, the stainless–steel industry, and the biomedical industry. Tongzhou Bay in Nantong links the development of river and sea industries. These areas become the future coastal development areas of the chemical industry. Among them, Xuwei New District, Binhai New District, Lingang Industrial Park, and Tongzhou Bay are the key development areas for the petrochemical industry and metalwork industry. The Zhewang Harbor Industrial Zone, industrial parks around the Guan River estuary, Dafeng Port Area, and Yangkou Harbor

Chemical Park need to be upgraded on the basis of the existing one to reduce pollution emissions. Equipment manufacturing and electronics manufacturing industries have relatively low pollution emissions and can be centralized on an existing basis. The non–metallic products industry does not have a clear concentration area. The *Jiangsu Province three–year implementation action plan to fight air pollution* requires that "the main urban areas within the scope of cement and flat glass and other heavy pollution of the nonmetallic products industry implement their closure or relocation", so the industry should be eliminated with backward production capacity to encourage the development of high–end industries.

4. Discussion

4.1. Evolution of Chemical Industry Layout

The chemical industry has emerged as one of the strongest and largest sectors globally [27]. The pursuit of safe production and green development are important goals, as well as key directions of transformation for this industry. In our case study, we observed the increasing scale of the chemical industry in the coastal area of Jiangsu Province. Concurrently, there is a trend towards clustering within industrial parks and ports. This developmental trajectory aligns with that observed in most coastal chemical industries [28,29].

The evolution patterns of industrial layout primarily explore the dynamic shifts in industrial distribution, with a particular emphasis on inter–regional industrial transfers. Within the Jing–Jin–Ji region and the Yangtze River Economic Belt, it was observed that the transfer paths of the manufacturing industry tend to transition from the developed areas of Beijing, Tianjin, as well as the downstream areas of the Yangtze River towards less developed regions [30,31]. Furthermore, an examination of the manufacturing sector within Guangdong Province reveals that heavy industries such as chemical fiber production and metal smelting are predominantly relocating from the Pearl River Delta region to its peripheral areas [32].

Factors influencing the direction of industrial development are multifaceted and primarily encompass transit trade, location conditions, ecological constraints, and industrial policies [33,34]. The chemical industry has encompassed trends and amplified the intricacy of the supply chain [35,36]. Consequently, China's chemical industry has transitioned from transitioned raw materials to coastal areas [22,24]. Transportation and location factors are becoming more and more important in the chemical industry layout. Given the high energy consumption and pollution characteristics inherent to the chemical industry, ecological environment constraints are unavoidable [37]. Government–driven industrial policy plays a pivotal role in proactively directing the layout of the chemical industry [33].

The simulation of the spatial pattern characteristics exhibited by chemical industries under different scenarios of natural growth, ecological constraints, and policy guidance reveals the multidirectional mechanism of the optimization of the chemical industry's layout. Without considering other factors, the expansion of the chemical industry's layout outward from its original base results in escalating pressure on the ecological environment. Conversely, while accounting for ecological constraints allows for a more balanced spatial layout, it also obscures the development path. However, incorporating policy guidance expedites the optimization of spatial layout and minimizes the environmental impact. The development of heavy industries along Jiangsu's coastal areas necessitates comprehensive enhancement from the following four aspects: "port–industry–city linkage, encouraging the integration of scattered enterprises into industrial parks, intensifying policy guidance, and promoting industrial upgrading." Efforts should be directed towards improving the service level of coastal ports to industrial parks, persistently integrating scattered heavy industrial enterprises into parks, reinforcing policy–guided layouts, and actively fostering high–quality, environmentally friendly heavy industries.

4.2. Simulation of Industrial Layout Optimization

As theories such as the environmental carrying capacity and ecological risk assessment gradually matured, the optimization of industrial layout increasingly required the evaluation of various factors across different zones. However, optimizing industrial layout at a medium scale proved to be spatially challenging, necessitating further exploration for more detailed adjustment schemes. Some studies adjusted the layout of regional industrial land from the perspective of the mutual exclusivity of "production, living, and ecology" [38]. Others have approached this task from a functional zoning perspective, taking into account factors such as the resource and environmental carrying capacity, regional development potential, and current spatial development intensity. These studies have classified regions into optimized, key, and restricted development zones, thereby providing scientific support for industrial layout decisions [39].

In light of the accelerated "Three Zones and One Line" process, some researchers have identified meticulously delineated zones based on ecological protection red lines, environmental quality baselines, and the resource utilization of upper limits. They formulated negative lists for environmental access [40]. By holistically assessing the pressure exerted on resources, the environment, and society in three dimensions, a comprehensive evaluation of the ecological carrying capacity in both the Yangtze River Delta and the Wanjing Urban Belt was undertaken. In conjunction with the intensity of industrial transfer flows, this research offers valuable insights into potential industries suitable for each region [41].

In conjunction with water environmental carrying capacity zoning, a comprehensive analysis was undertaken to assess the sustainable efficiency of various industries. This evaluation was conducted across the following three dimensions: economic benefits, industrial level, and environmental benefits. The primary objective was to optimize the spatial layout of several industrial parks, with a particular emphasis on heavy chemical industries [42]. Serving as a conduit between the industry and the ecological environment, the optimization and adjustment of the industrial layout were instrumental in achieving an equilibrium that fosters both environmental protection and economic development.

4.3. Policy Implications

Economic promotion, safe production, and environmental protection represent pivotal trajectories for the future evolution of the chemical industry. Based on the findings of this study, it is evident that the chemical sector in Jiangsu's coastal region possesses the potential to undergo a comprehensive series of upgrades and transformations.

First, governments in coastal areas can designate key industrial parks based on pre–existing chemical industrial parks. These industrial parks are required to establish rigorous admission standards, safety management measures, and pollution treatment programs, incorporating the experiences of well–developed chemical parks. The government actively participates and guides enterprises within these parks to achieve collaborative construction, management, and infrastructure sharing. This effort aims to facilitate exchanges and advancements among enterprises, fostering the collective development of businesses within the parks.

Second, governments play a pivotal role in guiding the transformation and development of the chemical industry. This involves the integration of small and scattered enterprises into industrial parks, which is a crucial strategy for optimizing the spatial layout of the chemical sector. Environmental regulations and industrial policies are instrumental in directing chemical enterprises to phase out outdated production equipment and excess capacity. They also encourage green innovation within these enterprises and ensure the efficient allocation of capital, labor, raw materials, and other resources [37].

Third, it is imperative to foster intergovernmental cooperation and consultation. This can bolster intraregional collaboration and enhance supply chain resilience both within and between regions, thereby elevating the competitiveness of the chemical industry in Jiangsu's coastal areas. The upstream and downstream sectors of the chemical industry, along with its diverse sub–industries, must engage in the division of labor and cooperative efforts to navigate international geopolitical challenges [38]. In the face of economic, security, and environmental pressures from higher levels of the government, as well as increasing international competition, the division of labor and cooperation in the chemical industry along the coast of Jiangsu Province is conducive to enhancing its competitiveness.

5. Conclusions

In this study, we focused on the coastal area of Jiangsu to examine the evolution characteristics of chemical industry layouts. Utilizing the CA–Markov model simulation, we projected the future trajectory of these layouts under different scenarios. Furthermore, we identified key areas for the future chemical industry layout in three cities along the Jiangsu coast. The primary findings are as follows:

(1) The coastal regions of Jiangsu have witnessed a trend of increased agglomeration within their chemical industries. Despite the reduced impact of the chemical industry layout on the ecological environment, substantial agglomeration pressures continue to prevail in certain areas.

(2) Factors such as transportation, relevant industrial and environmental policies, as well as the willingness of the residents, and the industrial agglomeration degree significantly influence the layout of the chemical industry. The evolution of this industry's layout varies under different circumstances. Under a natural growth model, the expansion of chemical industry land is limited to its original boundaries, leading to increased pressure on the ecological environment. Due to these environmental constraints, the layout of the chemical industry tends to cluster in coastal ports and industrial parks. However, with the guidance of pertinent policies, both the speed and degree of industrial agglomeration are anticipated to experience significant acceleration.

(3) By taking into account a range of factors, including the industrial development foundation, location conditions, ecological constraints, and relevant policies, along with reference to the model's simulation results, we can identify key areas for the chemical industry layout. This offers critical guidance for governmental decision–making processes.

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