Research on the Coordination Relationship of Transportation, Regional Economy and Eco-environment in Urban Agglomerations

Liangsheng Zhao, Changfeng Zhu, Jie Wang, and Linna Cheng

Abstract—**This study explores the coupling coordination mechanisms among transportation, regional economy, and eco-environment (TREEE) in urban agglomerations (UAs). We propose an integrated framework combining rough set theory (RST), a combined weighting method based on game theory (CWMGT), and an improved coupling coordination degree model (ICCDM). Applying this RST-CWMGT-ICCDM framework to panel data from the Yangtze River Delta Urban Agglomeration (YRDUA), we analyze TREEE development trends, coupling interactions, and spatiotemporal coordination dynamics, and identify critical influencing factors. Results show that RST-driven index screening increases the coupling coordination degree (CCD) explanatory power by 5.6%, and ICCDM is 13.2% more accurate than conventional methods. These advances suggest that the new framework provides theoretical support for the study of TREEE coordination in UAs. This study will offer decision-making references for promoting the coordinated development of TREEE in UAs and achieving the goal of high-quality, sustainable UAs development.**

Index Terms—**Urban Agglomerations (UAs), Improved Coupling Coordination Degree Model (ICCDM), Rough Set Theory (RST), Transportation, Regional Economy, Eco-environment.**

I. Introduction

As China's urbanization shifting toward a development model led by urban agglomerations (UAs), UAs have become the primary driver of new urbanization in China [1]. UA integration refers to regional integration guided by UAs, including economic integration, transportation integration, and infrastructure integration [2][3][4]. Within UAs, the efficient flow of resources and industrial collaboration among cities fosters economic integration [5]. Transportation infrastructure improves intercity accessibility [6], strengthens urban connectivity, and facilitates the reallocation of economic resources. The transportation, regional economy, and eco-environment (TREEE) of UAs form a complex, interconnected system. The coordinated development of TREEE is essential for optimizing the spatial layout of urbanization and advancing high-quality economic growth.

Manuscript received May 29, 2024; revised April 16, 2025.

This work was supported in part by the National Natural Science Foundation of China (No.72161024) and "Double-First Class" Major Research Programs, Educational Department of Gansu Province (No.GSSYLXM-04).

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However, as UAs continue to expand, issues such as environmental pollution, traffic congestion, and wealth polarization are becoming increasingly severe. These challenges have raised concerns about the future development prospects of UAs [7][8]. Specifically, rapid urbanization has created significant pressure on the eco-environment and has disrupted people's lifestyles [9]. On the one hand, transportation is a major contributor to environmental pollution. Despite ongoing investments in transportation infrastructure, traffic congestion remains unresolved. This has led to debates over whether further transportation investments are justified [10][11]. On the other hand, the ecological impacts of rapid economic growth remain controversial. It is unclear whether such growth has caused irreversible damage to the environment [12].

As a developing country, China's rapid economic growth has historically relied on environmental degradation [13]. In response, the Chinese government has implemented strong policies, such as carbon peaking and carbon neutrality goals, which have significantly advanced environmental protection efforts. Some scholars argue that economic growth at a certain stage can positively impact the environment. This raises the question: Has China reached the turning point of its Environmental Kuznets Curve (EKC) [14]? In UAs, economic growth initially accelerates eco-environmental pollution. However, at a certain stage of development, industrial restructuring and increased investment in environmental governance may reverse this trend, leading to positive environmental outcomes. Transportation, while a key driver of economic growth, is also a major source of air pollution. Balancing the relationship among TREEE in UAs is critical for achieving coordinated development. Further research is needed to address this challenge.

Scholars have extensively studied the interactions among TREEE. These studies mainly focus on three areas.

First, regarding transportation and regional economy, research shows that transportation infrastructure enhances urban accessibility and promotes sustainable regional economic development [15][16]. There exists a complex interaction between regional economic resilience and transportation infrastructure [17]. Additionally, a two-step process has been proposed to evaluate the economic and environmental impacts of new railway construction [18]. To describe the coupling relationship between transportation and the economy, scholars have integrated the coupling coordination degree model (CCDM) with methods such as nonlinear autoregressive analysis [19], the scissors difference method [20], and DEA cross-efficiency [21]. These approaches have opened up new research avenues.

Second, as green living concepts gain increasing prominence, the interaction between transportation and the environment has attracted significant attention. For instance, studies have examined CO_2 emission efficiency in China's transportation sector using the EBM DEA model and the spatial Durbin model (SDM) [22]. Others have explored the asymmetric impacts of different transportation modes on environmental pollution using the nonlinear autoregressive distribution lag (NARDL) model [23]. The full life cycle method has also been used to analyze the negative environmental impacts of transportation infrastructure [24].

Third, research on regional economy and eco-environment has gained considerable interest. For example, a zoning method based on ecological and economic indices was used to calculate the coupling coordination degree (CCD) of ecology and economy in Sichuan Province [25]. Principal component analysis (PCA) and CCDM were applied to study the coordination between Shanghai Port's economic development and the urban eco-environment [26]. Studies on the Yangtze River Delta have revealed significant regional differences in its economy and eco-environment [27]. Another study investigated the dynamic relationship between economic growth, road transportation, and environmental quality and concluded that road infrastructure promotes economic growth, while urbanization negatively affects environmental quality [28].

In summary, scholars have explored the relationships among TREEE from various perspectives and using diverse methods. However, limited literature comprehensively examines the mutual influences and interactions within the TREEE system. A search using "TREEE" as a keyword in the Web of Science core database has revealed fewer than 300 relevant core papers in recent years. Research on the coordinated development of TREEE from the perspective of UAs is even scarcer. The research hotspots and fields of TREEE are illustrated in Fig.1 and Fig.2. Key research topics include energy, urbanization, CO_2 emissions, and research on China. Despite these efforts, research on TREEE remains fragmented. The primary research fields include Environmental Sciences, Green Sustainable Science Technology, and Environmental Studies. Notably, the number of publications in transportation science and technology has increased in recent years. Given these gaps, it is highly significant to integrate the transportation system into existing studies on the relationship between regional economy and eco-environment. This approach will help clarify the impacts of transportation on both economic and environmental systems.

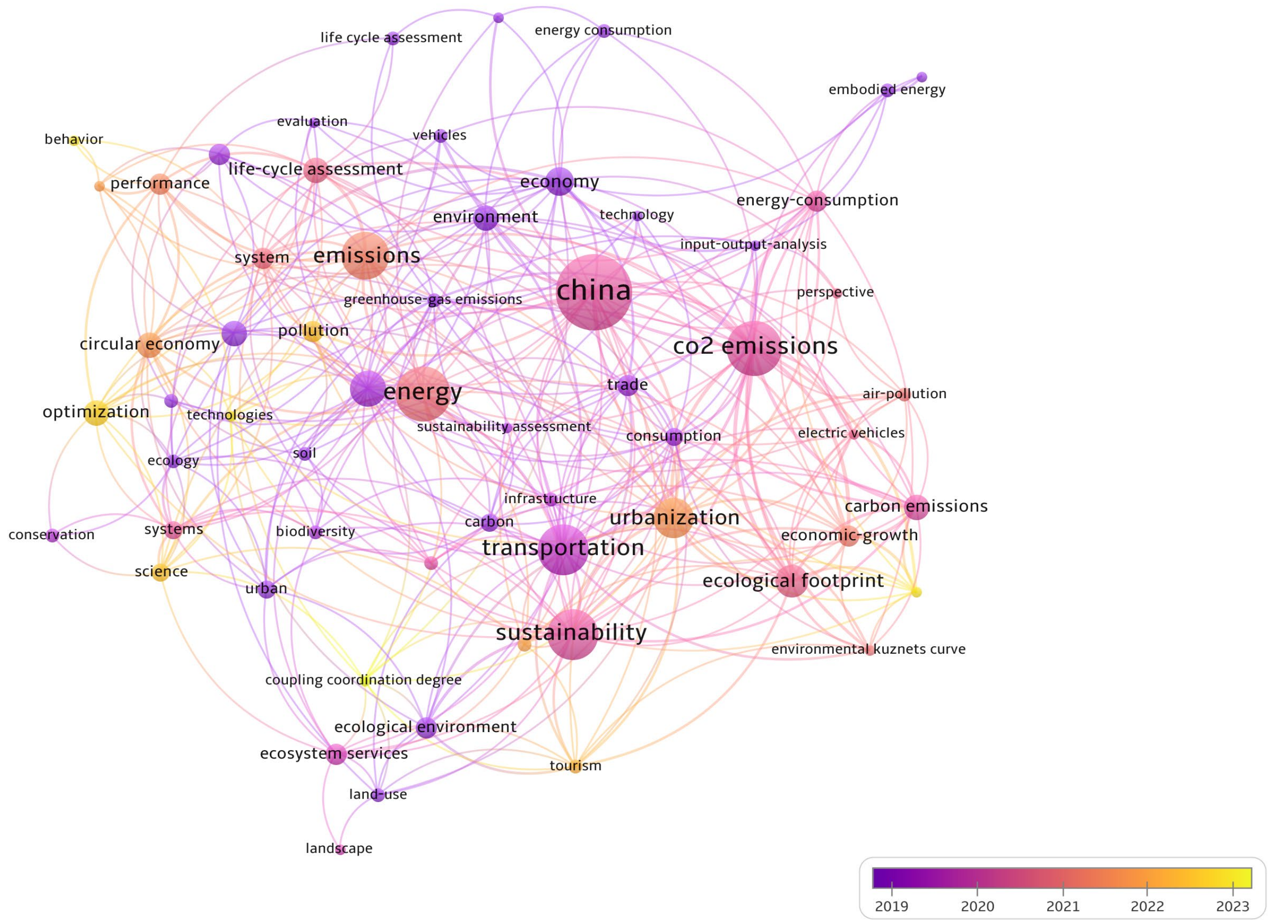


Fig.1. Research hotspots of TREEE.

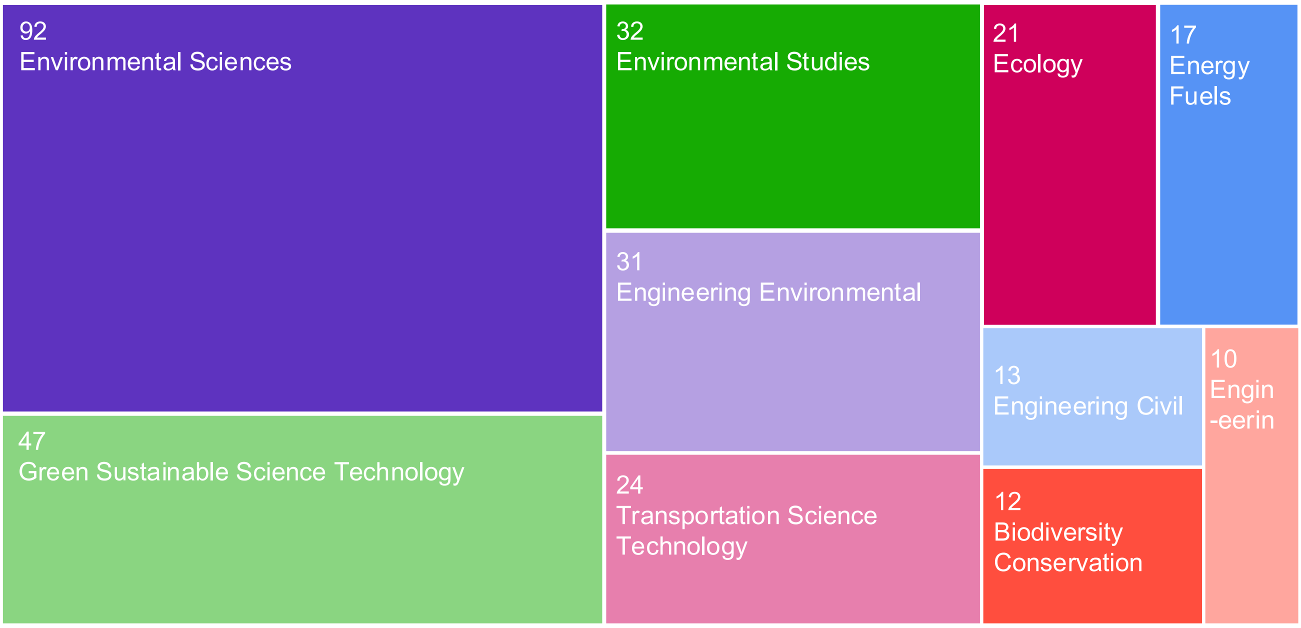


Fig.2. Research fields of TREEE.

Based on the above analysis, this paper makes the following contributions: (1) Rough set theory (RST) is introduced to screen for redundant indices and construct a scientifically robust evaluation index system. (2) The combined weighting method based on game theory (CWMGT) is applied to allocate weights, addressing the limitations of single-weight methods and reducing results' uncertainty. (3) The traditional CCDM has been improved. The contribution coefficient of the model is determined by the comprehensive development index rather than being subjectively assigned. Building on these theoretical advancements, this study constructs a novel UA coordination research framework, termed the RST-CWMGT-ICCDM. Finally, the obstacle degree model (ODM) is introduced to identify and analyze key factors influencing UA development.

The remainder of this paper is structured as follows: Section II introduces the evaluation index system. Section III outlines the research methods. Section IV describes the study area and presents the results. Section V discusses the accuracy of the proposed model. Finally, Section VI concludes the paper and puts forward the problems to be further studied.

II. INDEX SYSTEM

The TREEE system is a complex and extensive system comprising numerous interrelated factors. Which includes transportation, environmental, and economic development, are interdependent and exhibit intricate interactions. To accurately characterize the coordinated development relationship among these three systems, we constructed a multi-level and multi-dimensional index system. The system includes 26 indices across six dimensions: transportation capacity, transportation scale, economic structure, economic scale, environmental pollution, and environmental governance. The TREEE index system is illustrated in Fig. 3.

Obviously, these index data are easy to obtain. The index data were collected from statistical yearbooks, national economic and social development statistical bulletins, and the China Urban Statistical Yearbook. Due to missing data for some indices, the exponential smoothing method was used to estimate these values. The resulting data were then standardized using the min-max scaling method. The specific equations are provided in equations (1) and (2).

$$\text{Positive indicators}: x_{ij}^{+} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)} + 0.001 \quad (1)$$

$$\text{Negative indicators}: x_{ij}^{-} = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)} + 0.001 \quad (2)$$

Where, x_{ij} is the value of index j in year i, $\max(x_j)$ and $\min(x_j)$ are the maximum and minimum values of index j, respectively.

III. RESEARCH METHODS

A. Rough Set Theory

In studying the coordinated development of UAs, the number of indices does not guarantee accuracy. Instead, the index system must prioritize interpretability for the research object. Redundant indices may distort evaluation results by misrepresenting the target system. To address this, we employ RST, which was developed by Polish scientist Z. Pawlak. RST enables data analysis without prior knowledge and eliminates redundant information through attribute reduction. This process retains essential data characteristics while maximizing information preservation [29]. Given its broad applicability and operational simplicity, RST is adopted for index screening. Key definitions of RST are outlined below.

(1) Comprehensive evaluation system

Define the coordination relationship comprehensive evaluation system $S = (U, C, V, F)$, where $U = \{x_1, x_2, \cdots, x_n\}$ is a non-empty finite object set, such as the year, $C = \{c_1, c_2, \cdots, c_m\}$ is the conditional attribute set, i.e. the unreduced indices in TREEE system. V is the set of attribute values. $f: U \times A \to V$ is the information function.

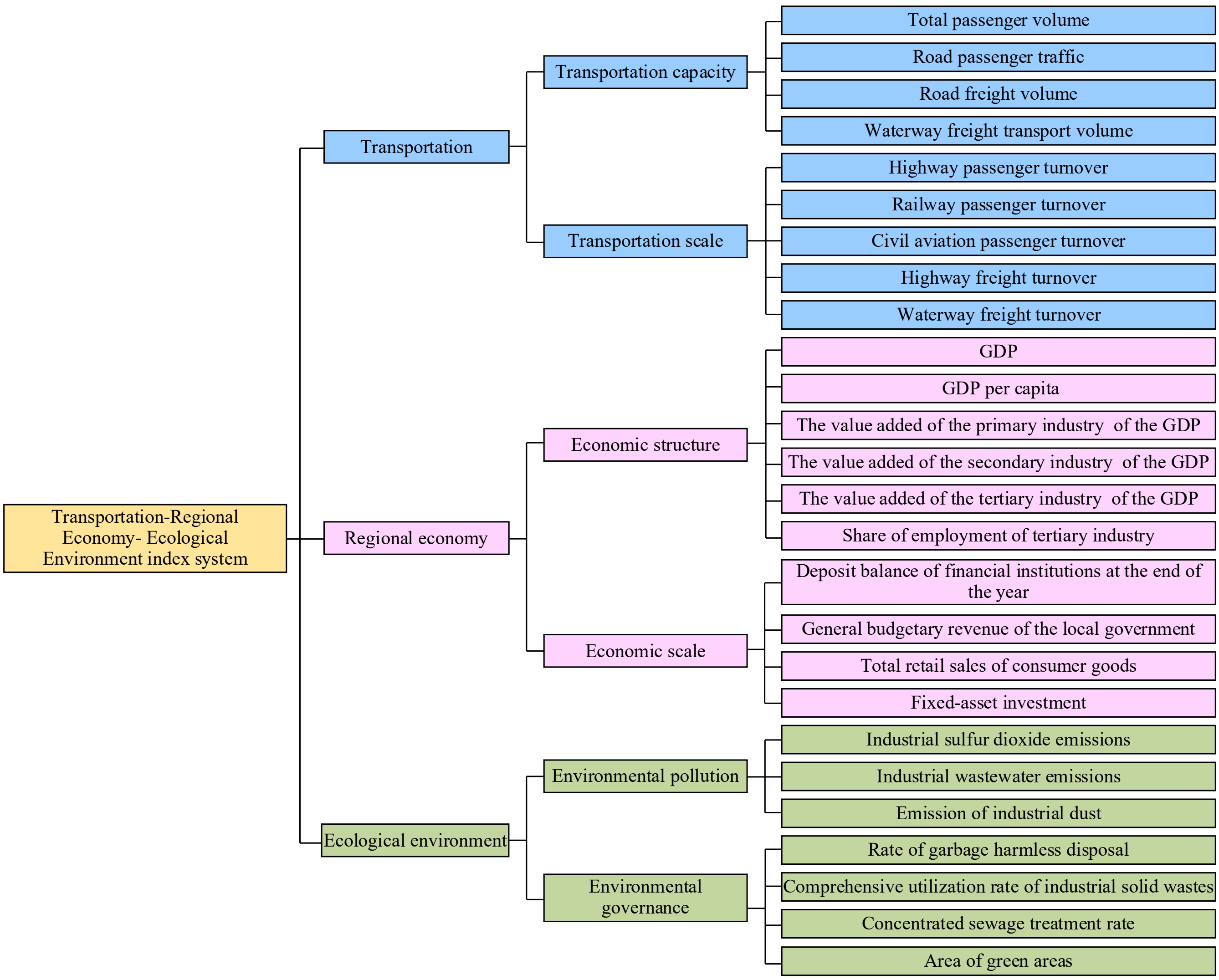


Fig.3. TREEE index system.

(2) Discernibility matrix and discernibility function [30]

Let $c_k(x_j)$ be the value of sample x_j on attribute c_k, the discernibility matrix of system S is $M=\left[m_{ij}\right]_{n\times n}$, and the elements of row i and column j of discernibility matrix are

$$m=\begin{cases} a_k \in C \wedge c_k(x_i) \neq a_k(x_j), C(x_i) \neq C(x_j) \\ \varnothing, C(x_i)=C(x_j) \qquad i,j=1,2,\cdots,n \end{cases} \tag{3}$$

The discernibility function is

$$f(s)=\wedge\left\{\vee m_{ij}, 1\le j<i\le n, m_{ij}\neq\varnothing\right\} \tag{4}$$

Where, $\wedge$ represent conjunction operation, $\vee$ represent disjunctive operation.

(3) Reduction and kernel

Let $Q\subseteq C$, if Q is independent and $\text{Ind}(Q)=\text{Ind}(C)$, then Q is called a reduction of the equivalence relation family C, and is denoted as $\text{Red}(C)$.

The steps for index reduction based on RST are as follows.

Step 1: Establish the raw index system by selecting the corresponding indices as the attribute set.

Step 2: Discretize data by normalizing and discretizing the original index data according to the method in reference [31], yielding a discrete data table.

Step 3: Build the discernibility matrix for the indices using equation (3).

Step 4: Calculate the discernibility function for the indices using equation (4).

Step 5: Reduce the indices by applying the absorption law to the discernibility function, thereby obtaining the reduced set of indices.

Taking the regional economy system as an example, the indices are reduced based on RST. Define the object set $U=\{1,2,\cdots,12\}$, where 1-12 represents the years. Attribute set $C=\{a,b,\cdots,j\}$, where a - j represents the indices of the regional economy system. The discernibility matrix of the indices of the regional economy system is shown in Tab.1.

TABLE I
DISCERNIBILITY MATRIX OF THE INDICES OF THE REGIONAL ECONOMY SYSTEM

U	1	2	3	4	⋯	12
1	$\varnothing$					
2	g	$\varnothing$				
3	bg	b	$\varnothing$			
4	$abgi$	$abgi$	ai	$\varnothing$		
⋮	⋮	⋮	⋮	⋮	⋱	
12	$abcghij$	$abcghij$	$abcghij$	$abcghij$	⋯	$\varnothing$

The discrimination function of the regional economy system index can be obtained from equation (4).

$$\begin{aligned} f(s) &= g \wedge (b \vee g) \wedge (a \vee b \vee g \vee i) \wedge \cdots \wedge j \wedge f \\ &= g \wedge (a \vee i) \wedge b \wedge h \wedge j \wedge f \end{aligned}$$

The reduced index set $\mathrm{Red}(C) = (a, b, f, g, h, i, j)$, that is, the final indices of the regional economy system are GDP (*a*), GDP per capita (*b*), the share of employment of tertiary industry (*f*), deposit balance of financial institutions at the end of the year (*g*), general budgetary revenue of the local government (*h*), total retail sales of consumer goods (*i*), and fixed-asset investment (*j*). Similarly, the final indices of the transportation system and eco-environment system can be obtained.

B. Combined Weighting Method Based on Game Theory

The key to multi-attribute decision-making is determining the weights of various indices. To avoid one-sided characterization of research indices from traditional single weighting methods, first use the entropy method [32] and the CRITIC method [33] to determine two sets of weights, W_{1j} and W_{2j}. Then, apply the CWMGT to fully retain information from both methods and obtain the final comprehensive weight. The CWMGT principle is finding a compromise between the two weight sets to optimize index weighting. The specific calculation process is as follows.

Minimize the deviation between the comprehensive weight W_j and the objective weights W_{1j} and W_{2j}

$$\begin{cases} \min \left\| W_j^T - W_{1j} \right\|_2 \\ \min \left\| W_j^T - W_{2j} \right\|_2 \end{cases} \tag{5}$$

The system of linear equations corresponding to the first derivative condition of equation (5) is

$$\begin{bmatrix} W_{1j}W_{1j}^T & W_{1j}W_{2j}^T \\ W_{2j}W_{1j}^T & W_{2j}W_{2j}^T \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix} = \begin{bmatrix} W_{1j}W_{1j}^T \\ W_{2j}W_{2j}^T \end{bmatrix} \tag{6}$$

Find the solution (α_1, α_2) of equation group (6), and normalize it.

$$\alpha_i = \alpha_k \Big/ \sum_{k=1}^{2} \alpha_k \tag{7}$$

The objective weight vector is linearly combined using a linear combination method to obtain the comprehensive weight vector W_j

$$W_j = \alpha_1 W_{1j} + \alpha_2 W_{2j} \tag{8}$$

C. Improved Coupling Coordination Degree Model

The CCDM is an effective method for measuring the overall balanced development of a region. The coupling degree (CD) reflects the interaction and influence between different systems of UAs, while the CCD measures the coordination state between these systems. However, in the traditional CCDM, the contribution coefficient of each system is subjectively determined by the decision-maker, despite the dynamic nature of the actual situation. To better align with the development patterns of UAs, this paper improves the contribution coefficient using the comprehensive development index [34]. The calculation method for the ICCDM is as follows.

$$U_{ki} = \sum_{j=1}^{n} W_j y_{ij} \tag{9}$$

$$C_i = \frac{3\sqrt[3]{U_{1i}U_{2i}U_{3i}}}{U_{1i} + U_{2i} + U_{3i}} \tag{10}$$

$$\beta_{ki} = \frac{U_{ki}}{\sum_{k=1}^{3} U_{ki}} \tag{11}$$

$$T_i = \sum_{k=1}^{3} \beta_{ki} U_{ki} \tag{12}$$

$$D_i = \sqrt{C_i T_i} \tag{13}$$

Where, U_{ki} is the comprehensive development index of system k in year i, C_i is CD, β_{ki} is the contribution coefficient of system k, T_i is the comprehensive coordination index in year i, D_i is the CCD in year i.

The classification of CCD aids in identifying the development stage and coordination status of UAs. From the coordination level perspective, the CCD shows a wide numerical span initially but a limited change range in the later stage of development. To better reflect the actual situation of UAs, this paper subdivides the CCD into seven levels and three development periods. The criteria for classifying the CCD of UAs are presented in Tab.2.

TABLE II
DIVISION CRITERIA OF CCD IN UAS

CCD	Coordination level	Development period
[0.0,0.3)	Serious imbalance	Imbalance decline period
[0.3,0.4)	Moderate imbalance	
[0.4,0.5)	Slight imbalance	Transitional adjustment period
[0.5,0.6)	Reluctant coordination	
[0.6,0.7)	Moderate coordination	Coordinated development period
[0.7,0.8)	Good coordination	
[0.8,1.0]	High coordination	

D. Obstacle Degree Model

To enable UAs to formulate and adjust policies related to TREEE more precisely, we employ the ODM to assess the obstacle degree of each index and identify barriers to the coordinated development of the three systems. The obstacle degree is calculated using equation (14).

$$O_{ij} = \frac{I_{ij} W_j}{\sum_{j=1}^{n} I_{ij} W_j} \tag{14}$$

Where, O_{ij} is the obstacle degree of the index j in the year i, I_{ij} is the index deviation degree, indicating the difference between the actual value of each index and the optimal target value, $I_{ij} = 1 - y_{ij}$, y_{ij} is the value after the standardization of the raw data, factor contribution is calculated by index weight W_j.

Based on the above research methods, the newly proposed framework for studying the coordination of UAs, namely RST-CWMGT-ICCDM, is illustrated in Fig.4.

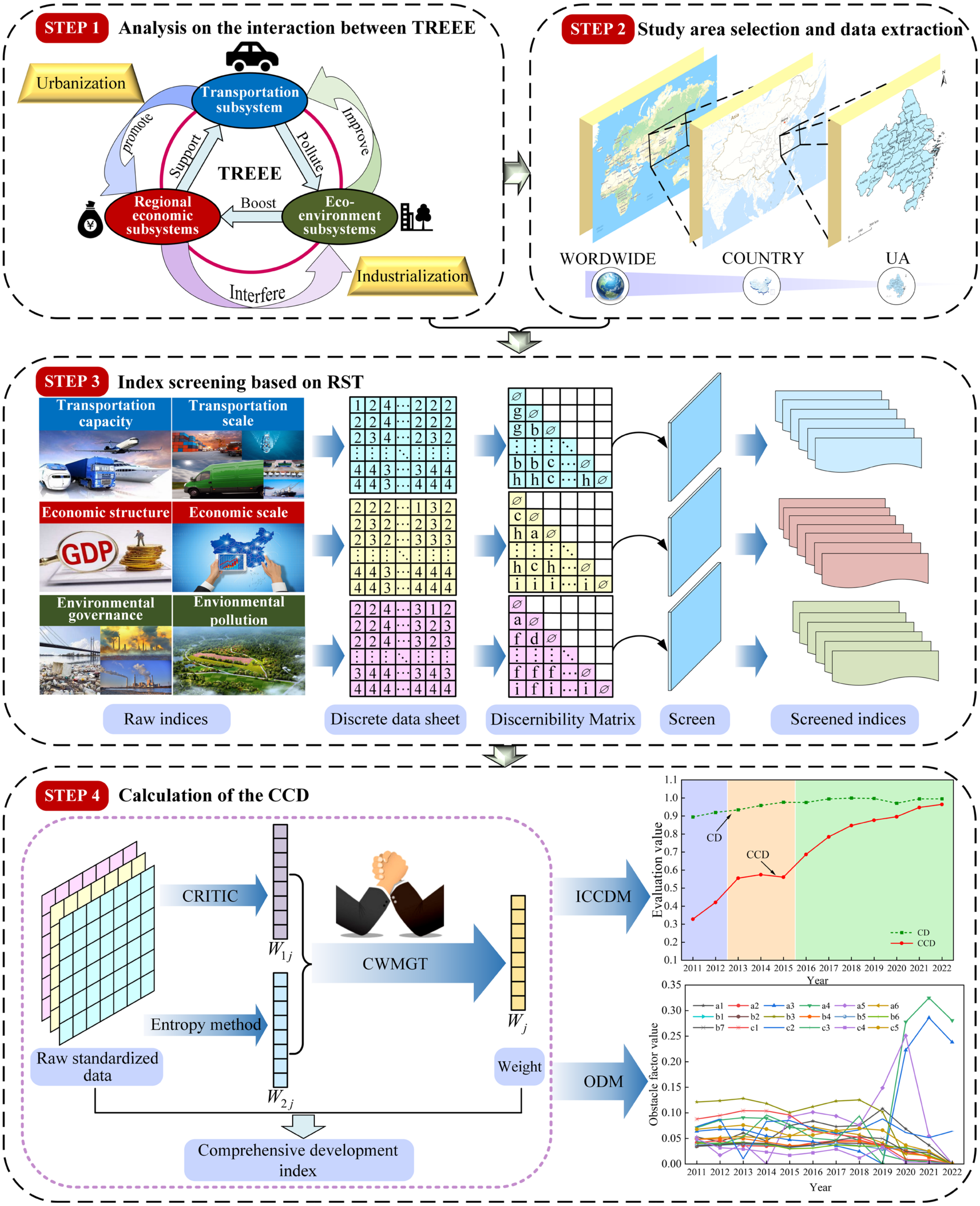


Fig.4. Research framework of RST-CWMGT-ICCDM.

IV. Study Area and Results

A. Study Area

The selection of the YRDUA as the study area is primarily based on two reasons. First, the YRDUA is China's only super UA ranked among the world's top six, boasting a 2023 GDP of 30.5 trillion yuan (about 24% of China's total). Its economy is rapidly growing, with pronounced development issues and urgent need for governmental reform. Second, the YRDUA possesses China's most comprehensive transportation system, featuring an integrated road, rail, water, and air network that facilitates index system construction and data collection.

As outlined in the integrated regional development plan for the Yangtze River Delta, the YRDUA covers 27 cities, and its geographical location is shown in Fig.5.

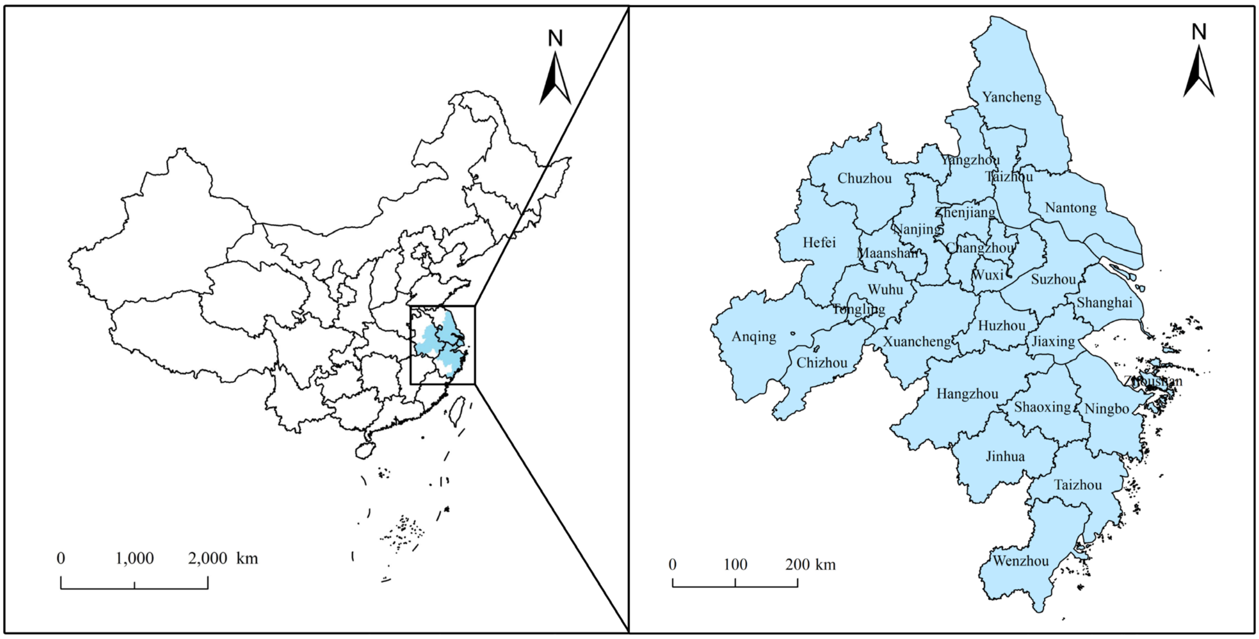


Fig.5. Geographical location of YRDUA.

TABLE III
REDUCED INDEX SYSTEM AND ITS WEIGHT.

Target tier	Criterion tier	Index tier	Property	W_{1j}	W_{2j}	W_j
Transportation	Transportation capacity	Road freight volume	Positive	0.176 6	0.144 2	0.154 6
		Waterway freight transport volume	Positive	0.124 8	0.116 8	0.119 4
	Transportation scale	Railway passenger turnover	Positive	0.146 9	0.200 0	0.183 0
		Civil aviation passenger turnover	Positive	0.218 6	0.212 7	0.214 6
		Highway freight turnover	Positive	0.145 9	0.210 2	0.189 6
		Waterway freight turnover	Positive	0.187 2	0.116 1	0.138 9
Regional economy	Economic structure	GDP	Positive	0.124 0	0.084 1	0.098 2
		GDP per capita	Positive	0.107 4	0.094 2	0.098 9
		Share of employment of tertiary industry	Positive	0.266 7	0.391 3	0.347 2
	Economic scale	Deposit balance of financial institutions at the end of the year	Positive	0.130 6	0.085 7	0.101 6
		General budgetary revenue of the local government	Positive	0.106 9	0.118 3	0.114 3
		Total retail sales of consumer goods	Positive	0.127 0	0.095 1	0.106 4
		Fixed-asset investment	Positive	0.151 6	0.131 2	0.138 4
Ecological environment	Environmental pollution	Industrial sulfur dioxide emissions	Negative	0.287 8	0.188 9	0.251 7
		Industrial wastewater emissions	Negative	0.230 7	0.199 4	0.219 3
		Emission of industrial dust	Negative	0.155 9	0.268 3	0.196 9
	Environmental governance	Concentrated sewage treatment rate	Positive	0.102 7	0.201 8	0.138 8
		Area of green areas	Positive	0.222 9	0.144 2	0.194 2

TABLE IV
COMPREHENSIVE DEVELOPMENT INDEX AND CCD.

Year	U1	U2	U3	C	D	Degree of coordination	Coordination type	Development type
2011	0.161 1	0.051 0	0.082 2	0.894 4	0.327 6	Imbalance decline	Moderate imbalance	Economy lag
2012	0.235 2	0.085 8	0.186 9	0.919 4	0.420 4	Imbalance decline	Slight imbalance	Economy lag
2013	0.260 9	0.175 5	0.433 3	0.933 8	0.554 8	Transitional adjustment	Reluctant coordination	Economy lag
2014	0.449 8	0.261 9	0.233 3	0.958 0	0.574 3	Transitional adjustment	Reluctant coordination	Environment lag
2015	0.222 4	0.380 7	0.321 5	0.976 0	0.560 6	Transitional adjustment	Reluctant coordination	Environment lag
2016	0.332 7	0.472 9	0.578 8	0.974 9	0.686 6	Coordinated development	Moderate coordination	Environment lag
2017	0.561 2	0.565 8	0.705 4	0.994 3	0.784 0	Coordinated development	Good coordination	Environment lag
2018	0.720 6	0.679 7	0.749 7	0.999 2	0.846 9	Coordinated development	High coordination	Economy lag
2019	0.689 3	0.771 9	0.836 1	0.996 9	0.876 4	Coordinated development	High coordination	Transportation lag
2020	0.537 6	0.850 8	0.966 1	0.970 5	0.895 7	Coordinated development	High coordination	Transportation lag
2021	0.766 3	0.936 2	0.972 6	0.994 7	0.947 1	Coordinated development	High coordination	Transportation lag
2022	0.795 2	1.000 0	0.981 1	0.994 8	0.964 2	Coordinated development	High coordination	Transportation lag

B. *Reduced Index and Weight*

According to the RST, we reduce the indices of each system and obtain a total of 18 TREEE indices for the YRDUA. Then, we use the entropy method and CRITIC method to determine two sets of weights respectively. Finally, the comprehensive weight is determined by the CWMGT. The reduced index system and corresponding weights are shown in Tab.3.

C. *Analysis of Comprehensive Development of YRDUA*

Combined with the RST-CWMGT-ICCDM framework proposed in this paper, we analyze the TREEE results of the YRDUA from 2011 to 2022. The comprehensive development index and CCD of TREEE for the YRDUA are presented in Tab.4.

Fig.6 shows the changing trend of the comprehensive development index.

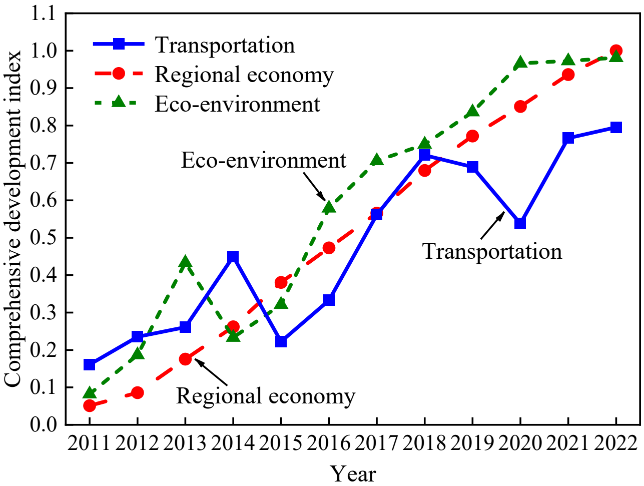


Fig.6. Change trend of comprehensive development index.

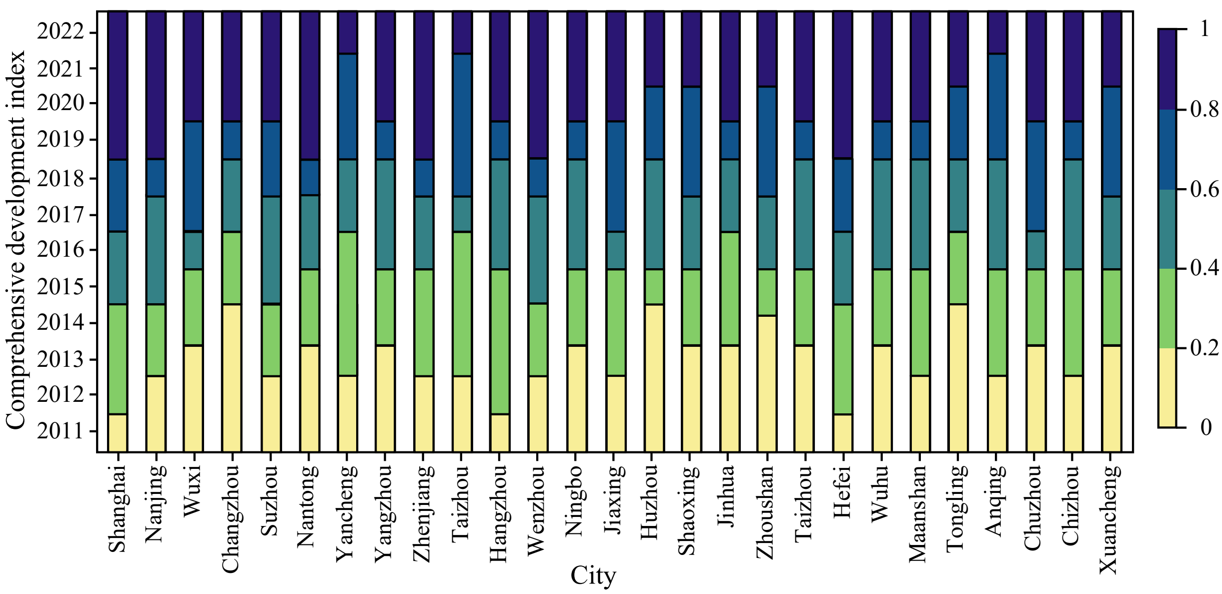
Overall, this index for the three systems of TREEE in the YRDUA grew from 2011 to 2022, despite different growth patterns. Specifically, transportation increased from 0.1 611 to 0.7 952, regional environment increased from 0.0 510 to 1.0 000, and eco-environment increased from 0.0 822 to 0.9811.

The comprehensive development index of the regional economy system has consistently grown over the past 12 years, with a gradual deceleration in the growth rate during the later stages of development. The specific numerical value increased from 0.051 in 2011 to 1.000 in 2022, indicating that the YRDUA possesses strong economic resilience and vitality, with all economic indices peaking in 2022.

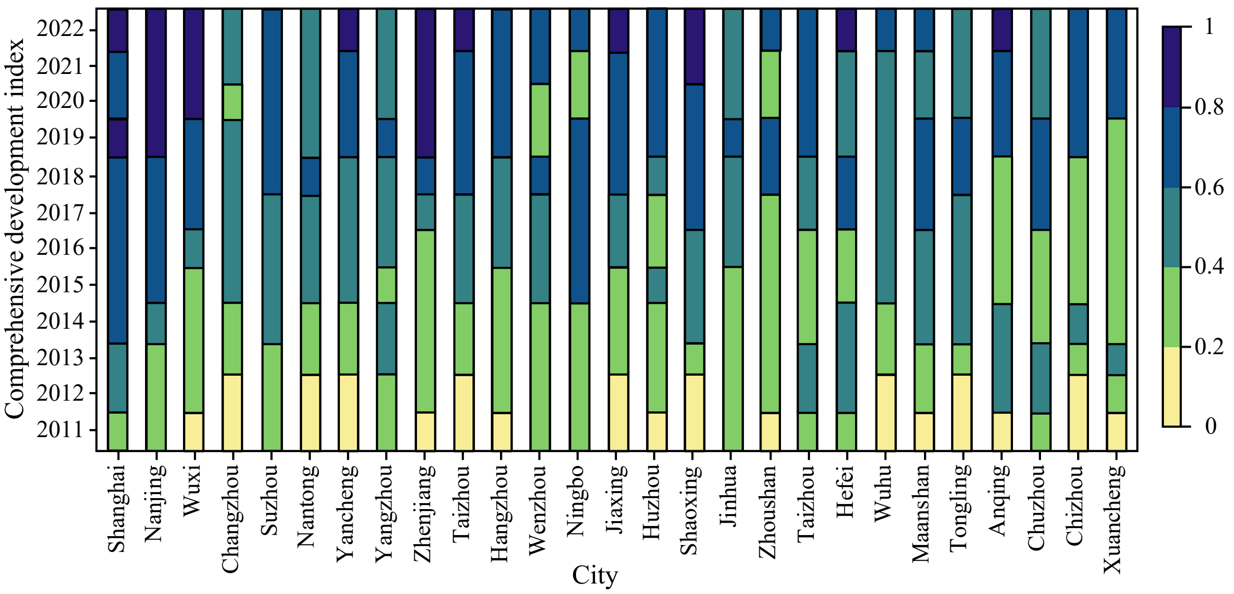
The development index of the transportation system shows a fluctuating upward trend from 2011 to 2022, divided into three periods:

- ■ **2011-2014:** Stable growth before policy impacts.
- ■ **2015-2019:** The comprehensive development index dropped sharply in 2015 due to statistical-caliber changes, but the transportation industry still developed rapidly. Since 2016, YRDUA cities promoted public transport development through low-carbon, fast, and efficient policies, spurring industry growth. In 2019, a 13.4% year-on-year decrease in highway freight turnover slightly reduced the transportation comprehensive development index.
- ■ **2020-2022:** The 2020 COVID-19 impact severely disrupted the transportation industry, causing index values to plummet. By 2021, the situation improved, and indices returned to pre-pandemic levels.

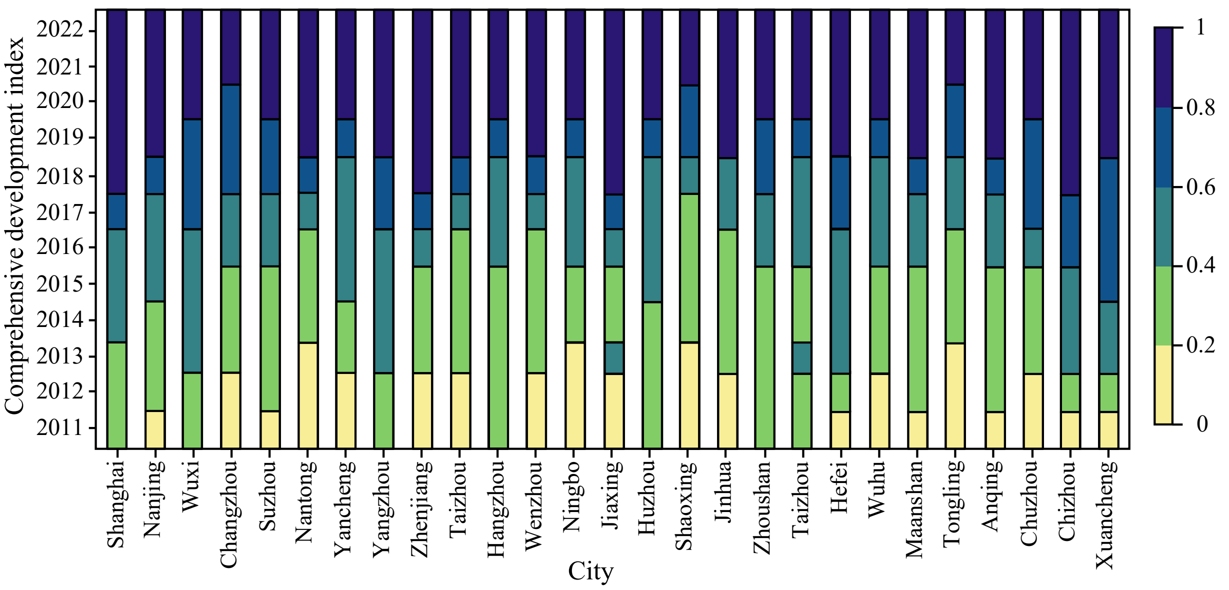
The development index of the eco-environment system rose, fell, and then rose again from 2011 to 2022. Between 2011 and 2013, it grew rapidly. In 2014, industrial dust emissions and transportation volume surged, causing the index to drop. Starting in 2015, government supervision and joint pollution control in key areas spurred rapid eco-eco-environment system development. The YRDUA's case shows that economic growth can coexist with eco-environmental progress. China's economy will long remain a strong force for eco-environment advancement.



(a) Comprehensive development index of the regional economy of YRDUA.



(b) Comprehensive development index of transportation of YRDUA.



(c) Comprehensive development index of eco-environment of YRDUA.

Fig.7 Value of TREEE comprehensive development index of YRDUA.

Note: the first Taizhou is located in Jiangsu Province, and the second Taizhou is located in Zhejiang Province.

Fig.7 presents the comprehensive development index values of TREEE within the YRDUA. From an urban perspective, the comprehensive economic development index of cities in the YRDUA has shown a gradual growth trend over time, without any abrupt numerical jumps or drops. Although there are significant differences in the economic volume of each city, the differences in the comprehensive economic development index are not pronounced, and the economic development trend of each city remains positive.

The cities in the YRDUA generally have a low comprehensive transportation development index, indicating room for enhancing the transportation structure and scale. Additionally, the development levels of different cities are highly uneven. As shown in Table 3, despite the relatively low weight of waterway freight transport volume and turnover, there are significant city-to-city differences in waterway freight transport volume due to varying geographical locations. For instance, Shanghai's waterway freight turnover in 2022 was nearly 50,000 times that of Jinhua.

The eco-environment in the YRDUA has seen continued overall development, yet some cities, like Jiaxing, Taizhou, and Wuhu, witnessed fluctuations in certain years. From the perspective of eco-environmental indices, the annual emissions of industrial wastewater and dust are inconsistent and show significant city-to-city differences. Moreover, eco-environmental development is greatly policy-influenced.

In summary, while the YRDUA's eco-environment has improved overall, certain cities have faced fluctuations. These fluctuations stem from inconsistent industrial wastewater and dust emissions as well as significant policy impacts on eco-environmental development.

D. Spatiotemporal Evolution Analysis of CCD in YRDUA

D.1 Analysis of time series evolution of CCD in YRDUA

Using the RST-CWMGT-ICCDM method based on the comprehensive development index of three systems, the CD and CCD of TREEE in the YRDUA are calculated. Fig.8 shows their change trends.

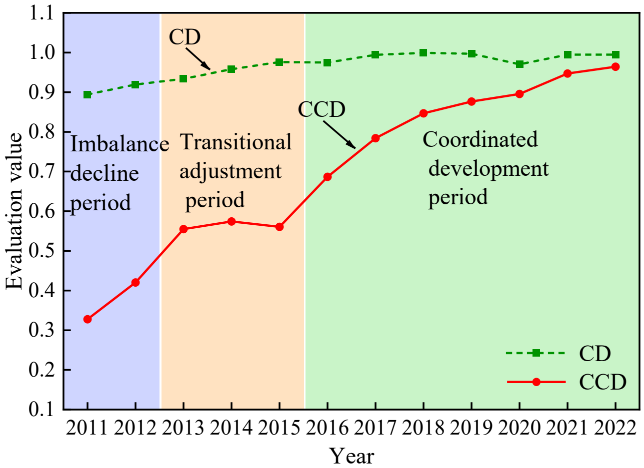


Fig.8. Change trend of CD and CCD.

From the CD evolution perspective, the YRDUA's three-system CD has mostly been above 0.9, except for 0.8944 in 2011, indicating a good coupling state. A CD closer to 1 means stronger system interaction, suggesting a deep and close relationship within the YRDUA's TREEE.

From the coordinated development perspective, the YRDUA's CCD evolution has three stages. From 2011 to 2012, the YRDUA was in an imbalance decline period, during which the regional economy lagged behind transportation and eco-environment development. From 2013 to 2015, during the transitional adjustment period, the factors limiting the YRDUA's coordinated development transformed from the regional economy to the eco-environment and then to transportation. The regional economy became China's most dynamic after the YRDUA's economic structural adjustment. Since 2016, the CCD has exceeded 0.6, and the three systems of the study area have entered a stage of coordinated development, while the short-board effect of transportation has begun to emerge.

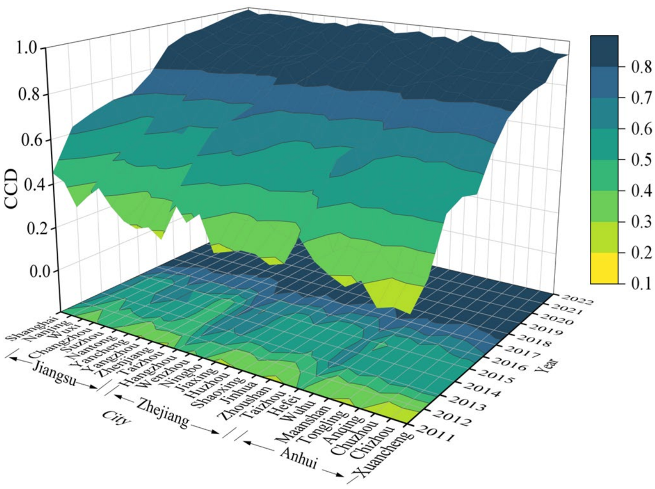


Fig.9 CCD values of TREEE in the YRDUA.

Fig.9 presents the CCD values of TREEE within the YRDUA. Overall, each city's CCD has transitioned from moderate imbalance to high coordination, yet there are significant regional differences in the sequence and extent of this development. Shanghai performs the best, with Jiangsu and Zhejiang Provinces following closely. In contrast, Anhui Province lags behind the other regions in CCD development.

Specifically, Shanghai, the central city of the YRDUA, has a high urbanization rate and strong economic vitality, giving it absolute advantages in economy, transportation, and environment. Cities in Jiangsu Province, such as Nanjing, Suzhou, and Wuxi, have achieved balanced TREEE development without short-board constraints. Zhejiang Province boasts super ports like Ningbo Port and Zhoushan Port, which provide significant water transport advantages. However, these transportation advantages have not driven the coordinated development of the eco-environment and economy. Anhui Province, a strong industrial province in China, has an eco-environment system that has become a short board restricting its coordinated development. Notably, through industrial transformation and upgrading in recent years, Anhui Province has become the region with the fastest-growing CCD in the YRDUA.

D.2 Analysis of spatial evolution of CCD in YRDUA

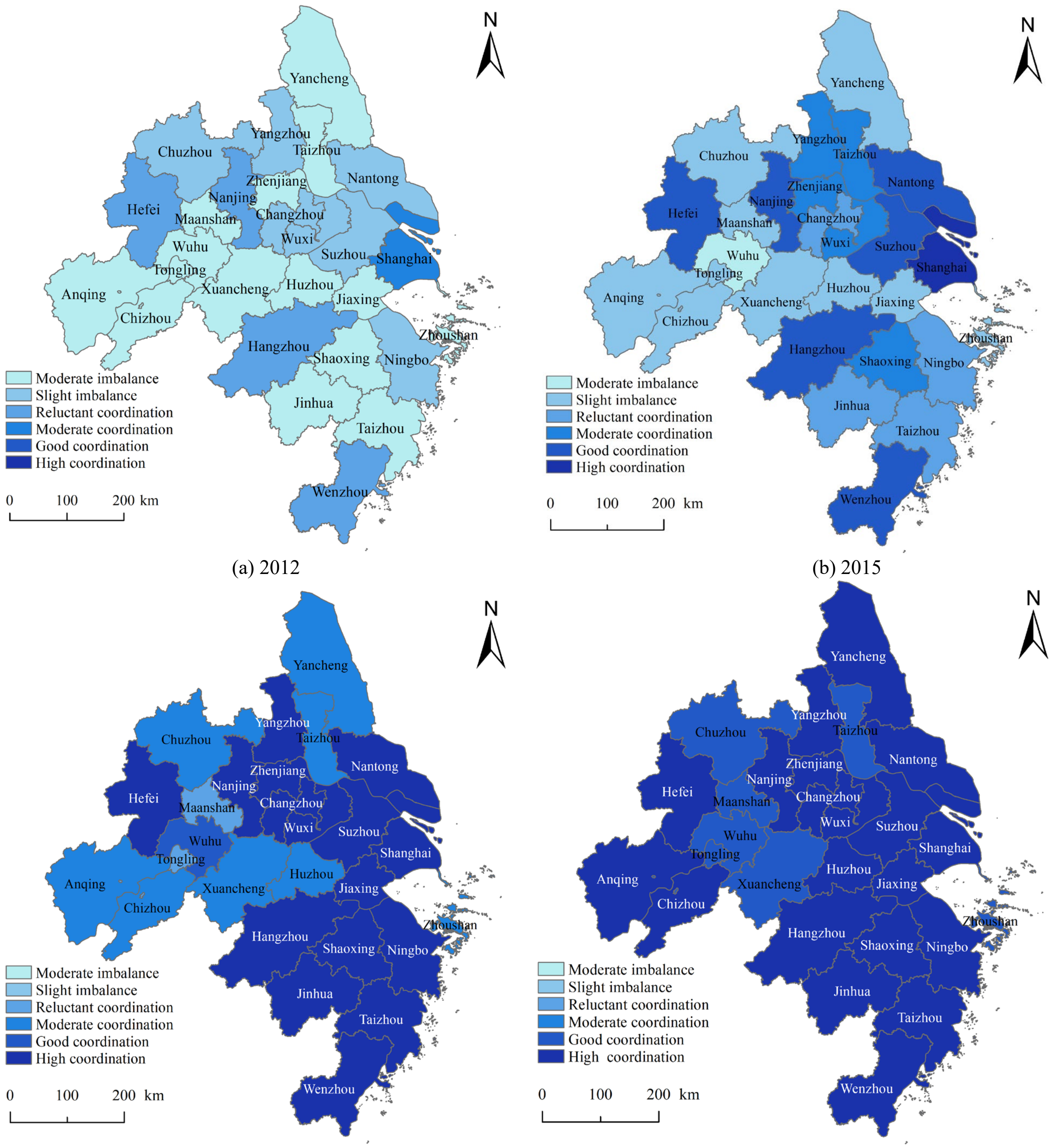
To further explore the spatiotemporal evolution characteristics of the coupled and coordinated development of TREEE in the YRDUA, ArcGIS 10.7 was utilized to visualize the CCD of each city in 2012, 2015, 2018, and 2021. These years represent the most significant numerical changes. The spatial evolution of CCD is depicted in Fig.10.

In 2012, except for Hefei, Nanjing, Hangzhou, and Wenzhou, which had reached a reluctant coordination level, and Shanghai, which was at a moderate coordination level, the remaining cities were in a moderate imbalance stage, indicating an overall low development level. This is because cities with high coordination levels are typically municipalities directly under the central government, provincial capitals, or prefecture-level cities with large economic volumes. Cities with dominant economic volumes also tend to have relatively high coordination. In 2015, most cities were in the stage of reluctant coordination, and the coordination displayed a high-value area with Shanghai as the core. The radiating-driven effect of Shanghai was evident, along with a positive spillover effect. By 2018, most cities had entered the stage of good and high coordination. Spatially, the southeast YRDUA exhibited better CCD than the northwest, with clear regional differentiation.

In 2019, the *outline of the integrated regional development of the Yangtze River Delta* was released, elevating the YRDUA's integration to a national strategy. The YRDUA seized this opportunity to enhance interaction and coordination among its metropolitan areas. By 2021, most cities had reached the high coordination stage, and the CCD gap between the southeast and northwest had narrowed.

D.3 Obstacle factor analysis

The obstacle degree of each index affecting coordinated development is depicted in Fig.11, where a1–a6 represents six indices of the transportation system, b1–b7 represents seven indices of the regional economy system, and c1–c5 represents five indices of the eco-environment system.



(a) 2012 (b) 2015

(c) 2018 (d) 2021

Fig.10. Spatial evolution of CCD.

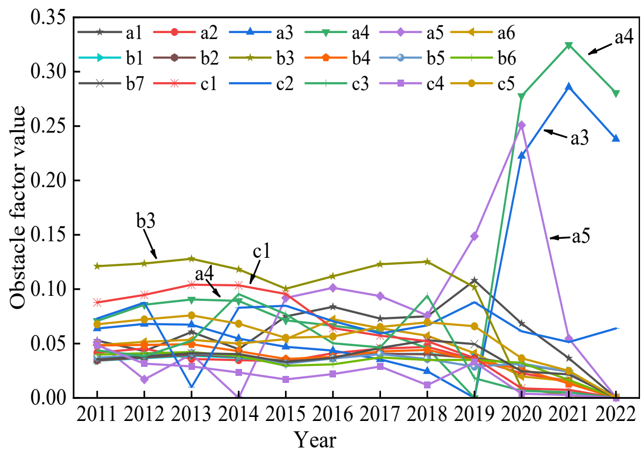


Fig.11. Obstacle degree of each index affecting coordinated development.

Before 2018, the main factors hindering the coupling and coordinated development of the YRDUA were the share of employment in the tertiary industry (b3), industrial sulfur dioxide emissions (c1), and civil aviation passenger turnover (a4). From 2019 to 2022, the primary obstacle factors shifted to the transportation system, including railway passenger turnover (a3), civil aviation passenger turnover (a4), and highway freight turnover (a5). These three indices are the main reasons why the YRDUA's transportation system lags behind the regional economy and eco-environment systems. In the next few years, relevant departments need to strengthen policy guidance, focus on these key factors hindering the coordinated development of the YRDUA, and comprehensively promote its integrated and high-quality development.

V. Discussion

A. Impact of Indices on Results

We used RST to screen and retain only the useful indices. To test the impact of this screening, we divided the results into two groups: one with unscreened data and one with screened data. We then compared these groups using analysis of variance (ANOVA) to assess each index's influence on the problem. A significant between-group difference indicates the index has a strong explanatory ability.

TABLE V
RESULTS OF THE HOMOGENEITY TEST OF VARIANCE

Term	Difference	Sum of squares	Degree of freedom	Mean square	P value
After screening	Inter group	143	11	13	0.00
	Within group	0	0	--	--
	total	143	11	--	--

The variance homogeneity test assesses whether the fluctuations in each group's data exhibit significant differences. As shown in Tab.5, the samples before screening do not universally show significance after screening, making ANOVA appropriate for these data.

TABLE VI
EFFECT MEASURE

Term	SSB	SSW	SST	Partial η^2
After screening	0	143	143	1.00

As shown in Tab.6, the results demonstrate that SSB is smaller than SSW, and the two groups of indicators produce significantly different outcomes. Furthermore, the indices screened by RST exhibit stronger explanatory power, with an approximate increase of 5.6%.

B. Impact of ICCDM on Results

To validate the superiority of the newly proposed RST-CWMGT-ICCDM - based UAs coordination research model, we compared the traditional CCDM results with those from the RST-CWMGT-ICCDM model.

The TREEE comprehensive development index calculated by using the traditional CCDM is shown in Fig 12.

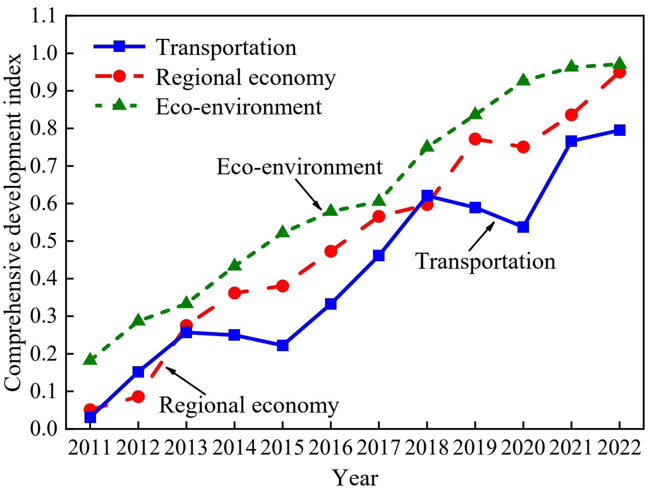


Fig.12. Trend of TREEE comprehensive development index by CCDM.

By comparing Figure 6 and Figure 12, it can be found that the development indices obtained from the traditional CCDM and the RST-CWMGT-ICCDM method have similar changing trends. However, Figure 12 indicates that the traditional CCDM yields results showing independent development of the three TREEE systems in the YRDUA, but it fails to reveal the mutually reinforcing and constraining relationships between these systems.

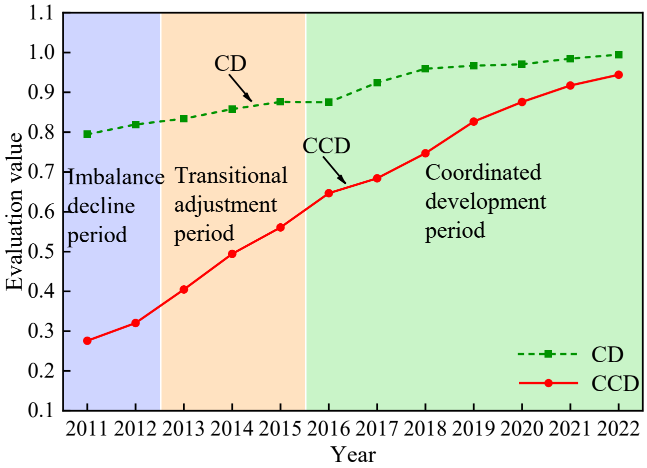


Fig.13. The changing trend of CD and CCD based on CCDM.

When the contribution coefficients of TREEE are set to 0.333, Fig 13 shows the CD and CCD based on the traditional CCDM. The lower CD value indicates that the TREEE interaction relationship obtained through the traditional CCDM is not significant. The results of dividing the development period of CCD based on the traditional CCDM and RST-CWMGT-ICCDM are consistent, but the overall coordination degree of YRDUA obtained by the traditional CCDM is relatively low. This is attributed to different methods for determining TREEE contribution coefficients. Compared with the traditional CCDM, the accuracy of ICCDM is improved by 13.2%.

In summary, the model based on RST-CWMGT-ICCDM is more accurate and in line with the actual situation when studying the coordination relationship of UA.

VI. Conclusion

The TREEE of UAs is a complex system of mutual influence and interaction. This paper treats the three as a whole and systematically analyzes their coordinated development. Based on the RST, CWMGT, and ICCDM, this paper constructs the RST-CWMGT-ICCDM coordination relationship research model of UA. The validity of the new model is verified by an example of the development law and spatio-temporal evolution characteristics of YRDUA. The main conclusions are as follows.

(1) RST in fuzzy mathematics removes redundant indices by screening, which significantly enhances the explanatory power of CCD. Compared to the results without RST, this explanatory power has seen a 5.6% improvement.

(2) CWMGT combines the strengths of the entropy method and CRITIC method, enhancing model robustness.

(3) The ICCDM dynamically calculates the contribution coefficients of TREEE using the comprehensive development index. This overcomes the shortcoming of the

traditional CCDM, which treats the three TREEE systems as equally important.

(4) The YRDUA case proves the advantages of the new RST-CWMGT-ICCDM model proposed in this paper. Specifically, the adoption of ICCDM improves result accuracy by 13.2%.

(5) The YRDUA case shows a strong correlation between CCD and urban economic development levels. That is, more developed economies have closer industrial interactions and higher coordinated development degrees. YRDUA's development has passed the EKC turning point, where the economy begins to positively impact the ecological environment.

(6) The RST-CWMGT-ICCDM model proposed in this paper has broad applicability. Future research will explore coordination between other systems besides TREEE and between different regions, such as metropolitan areas and other specific regions.

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