Revealing The Synergistic Development Mechanism of Digitalization and Greenization in Chinese Cities: Based on The Haken Model

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Abstract. To promote the coordinated development of digitalization and greenization and provide strong support for the high-quality development of China's economy and society, this paper uses panel data of 281 Chinese cities from 2012 to 2022 to measure the "dualization synergy" level of digitalization and greenization of Chinese cities from a systemic synergy perspective. Firstly, the paper acquires data through existing research literature, the Chinese government's work reports, and statistical results from third-party institutions, and successfully constructs an index system for evaluating the levels of digitalization and greenization. Then, it analyzes the degree of synergy through the Haken model to better capture this complex mechanism and provide more detailed synergy analysis results. Finally, it concludes that the development of the "dualization synergy" system in cities shows a good upward trend year by year and gradually forms a coordinated development model that shifts from digitalization dominance to greenization dominance. Therefore, cities should promote the "dualization synergy" development based on local conditions, make up for the objectively existing regional differences, and promote the "dualization synergy" to a higher level through overall coordination and advancement. The innovation of this study lies in its application of the Haken model's analytical framework based on the theory of collaborative systems to reveal the dynamic interaction mechanism between greenization and digitalization at different development stages in the "dualization synergy" system.

Keywords: Digitization, Greenization, Dualization Synergy, Haken Model.

1. Introduction and literature review

The essence of " dualization synergy " is to realize the mutual promotion and deep coordination of digitalization and greenization in various fields of economic production and life through digitalization enabling greenization and greenization leading digitalization, so as to effectively promote the high-quality development of China [1]. At the beginning, the two were relatively independent, but now they gradually form an interactive pattern of "digitalization enables greenization, and greenization drives digitalization" : digital technology promotes green development by improving management efficiency and industrial upgrading, while the demand for green transformation forces digital infrastructure investment and technological innovation [2,3]. The two are neither completely separate nor completely overlapping, and the primary and secondary relationships need to be harmonized to explore how digital transformation can achieve green benefits while boosting productivity and economic development. It is of key significance to study the coordination level and the interaction mechanism of the two at the city level to optimize the implementation of policies and strengthen the overall promotion. This approach can address the phenomenon that during the initial exploration period of China's " dualization synergy ", there were significant differences between greenization and urbanization [4].

Centering on the important topic of urban "dualization synergy" development, existing studies have mainly discussed it from the following three aspects:Firstly, in terms of level measurement, most of the existing studies use the coupling coordination degree model to explore the collaborative development level of "double-information synergy" at different levels and in different industries by constructing the index system of digitalization and greenization respectively [2,5,6]. Some scholars

also constructed a system of "integrated development of information and industrialization" to measure the development level of "coordinated development of information and industrialization" [6]. This part of research finds that in terms of spatial distribution, the development levels of the coordination of information and industrialization in all provinces and regions reflect the distribution pattern of "high in the eastern region, low in the central and western regions," and there are obvious differences in the development levels of all regions.Secondly, at the level of evolution trend, Jiali Zhao (2024) used kernel density estimation and spatial autocorrelation analysis methods [7] to explore the spatio-temporal evolution characteristics of the development level of the urban "coordination of information and industrialization" in central China. Shihua Hu (2022) found through the spatial convergence model [8] that in the long run, the development degree of China's "coordination of information and industrialization" will tend to a steady state level. All these studies show that the development level of the synergy of information and industrialization in Chinese cities has shown a gradual improvement in recent years. These studies provide the research basis for the analysis of spatio-temporal evolution at the city level in this paper.Thirdly, for the research on the influencing factors of digitalization and greenization, most of the current research focuses on the one-way effect of digitalization or greenization, and most of them use spatial econometric models and other methods to identify the driving factors of regional digitalization and greenization. Zongbing Deng (2024) conducted an in-depth analysis of the driving mechanism of regional differences in their coupling and coordination from the perspective of social network relations [9]. From this perspective, at the current stage of development, the " dualization synergy " is faced with the task of further strengthening the overall coordination and overall promotion among cities.

Existing studies predominantly employ the coupling coordination degree model, which fails to adequately capture the evolving dominant-subordinate dynamic between digitalization and greening across development stages. This paper applies the Haken model from a systems synergy perspective to identify the primary-secondary relationships within the "dualization synergy" system, measure the coordinated development level of urban digitalization and greening, and thereby clarify the current status of China's "dualization synergy" development.

2. Digitization and greenization research design based on Haken model

2.1. Index system construction

In order to comprehensively evaluate the digitalization and greenization level of cities, this study builds digitalization and green evaluation index system based on existing literature and theoretical framework, respectively, from seven dimensions of digital infrastructure, digital economic development, digital environment, green production, green life, green ecology and green innovation. The data adopted below are sourced from the website of the National Bureau of Statistics of China and the statistical yearbooks of various provincial governments in China.

In terms of digitalization, referring to relevant literature [1,6,7], a digitalization evaluation system is constructed from three dimensions, mainly composed of seven subdivision indicators from three dimensions: digital infrastructure construction, digital economy development, and digital environment (as shown in Table 1). The construction of digital infrastructure is the foundation of digital development, and the number of mobile phone users per 100 people at the end of the year and the number of Internet broadband access users per 100 people are selected as the representative by referring to previous studies. The development of digital economy is the main carrier of digitalization, which is reflected by the per capita telecom business income, digital financial inclusion index and the proportion of the number of employees in the information transmission, software and information technology service industry in the total number of employees at the end of the year. The development of digital financial inclusion is measured by the digital financial inclusion Index released by the Digital Finance Research Center of Peking University. At the same time, the external environment is also an important factor to improve the digital level of the city. Therefore, in the dimension of digital

environment, this paper selects the word frequency related to digitalization in the government work report and the digital invention patents per 10,000 people in the city for characterization.

In terms of greenization, with reference to relevant literature [4,5,6,8], an evaluation system of nine subdivided indicators in four dimensions is constructed, including green production, green life, green governance and green innovation (as shown in Table 1). Green production is an important part of the construction of green city, green production refers to the goal of energy saving, consumption reduction, pollution reduction, the implementation of the whole process of industrial production pollution control, to minimize the amount of pollutants produced a comprehensive measure. In this paper, SO2 discharge per unit GDP output value and wastewater discharge per unit GDP output value were selected for characterization at the pollution discharge level, and sewage treatment rate was selected for characterization at the pollution control level. In terms of green life, per capita consumption of standard coal, per capita ride times of public buses (electric vehicles), harmless treatment rate of household garbage and green space coverage rate of built-up areas were selected to characterize. In the dimension of green governance, the government's governance of green can be reflected by the government's attention to green, so this paper selects the word frequency related to green in the government work report for characterization. The green innovation dimension is characterized by selecting green invention patents per 10,000 people in cities.

Table 1 Digital and green evaluation index system

	First level index	Second level index	Indicator specification	Units	Trait
Digitization level	Digital infrastructure	Number of Internet broadband access users	Number of households with Internet access/registered population	Households / 100 people	+
		Number of mobile phone subscribers	Number of mobile phone users/registered population	Households / 100 people	+
	Digital economy development	Digital industrialization	Telecommunications traffic revenue	Ten thousand yuan/person	+
		Industrial digitization	Digital Financial Inclusion Index		+
		Information talent reserve	Employment in information transmission, software and information technology services/total employment	%	+
	Digital environment	Digital policy	Government reports word frequency	Frequency	+
		Digital technology innovation	Digital invention patent	Number of units/10,000	+

				peopl e	
Greenization level	Green production	Pollution discharge	SO2 emissions per unit of GDP	Ton/t en thous and yuan	-
			Discharge of wastewater per unit of GDP	Ton/t en thous and yuan	-
		Pollution control	Sewage treatment rate	%	+
	Green life	Energy consumption level	Per capita annual standard coal consumption	Tons/ perso n	-
		Green travel	Per capita number of bus (electric) trips per year	Frequ ency	+
		Pollution control	Harmless treatment rate of household garbage	%	+
		Greenization index	Green space coverage in built-up areas	%	+
	Green governance	Government concern	Government reports word frequency	Frequ ency	+
	Green innovation	Number of patents	Number of green patents	Piece s/10, 000 peopl e	+

2.2. Basic principle of Haken model

2.2.1 Entropy weight method

In order to eliminate the interference of subjective factors, this paper uses entropy weight method to calculate the comprehensive score, and assigns weights to each index according to the variation degree of each index value, so as to avoid the deviation of evaluation results caused by human factors. The calculation steps are as follows: firstly, the dimensionless processing of each index is carried out; secondly, the specific weight of the index, the redundancy of information entropy and the weight of the index are calculated; finally, the comprehensive score of the index is obtained by weighting.

2.2.2 Haken model

Haken model is an important model proposed by Hermann Haken to analyze the order degree of complex systems [10]. Through the deep understanding of the system state and dynamic feedback mechanism, the Haken model can better capture this complex two-way feedback in the analysis, so as to provide more detailed collaborative analysis results. It is assumed that there are two subsystems in a dynamic system: the order parameter q1 and the variable q2 governed by it. The evolution of the system is mainly dominated by the slow variable, namely the order parameter q2, and has an impact on the fast variable q2. The construction process of the specific model is as follows:

① Hypotheses are proposed and corresponding evolutionary equations are constructed. In this system, specific equations of motion need to be satisfied:

$$q_1^{'}=-\gamma_1 q_1-aq_1q_2 \quad (1)$$

$$q_2^{'}=-\gamma_2 q_2+bq_1^2 \quad (2)$$

where q1 and q2 are the derivation function of the state variable to the time, -γ1, -γ2, a and b are the control parameters, -γ1, -γ2, also known as the damping coefficient, a and b are also known as the strength coefficient of the interaction of the two subsystems.

② Solve the parameter values of the evolution equation. To determine the order parameter q1 of the system, it is necessary to judge whether the equation meets the adiabatic approximation condition($|\gamma_2| \gg |\gamma_1|$ and $\gamma_2>0$). If it does not meet this assumption, it is necessary to return to the initial step to re-determine the order parameter of the system.This condition indicates that when q2 is removed instantaneously, q1 has no time to change, making q2 equal to 0:

$$q_2=\frac{b}{\gamma_2}q_1^2 \quad (3)$$

③ Find the system evolution equation and potential function. At this time, it is the order parameter, and the system evolution equation is obtained:

$$q_1=-\gamma_1 q_1-\frac{ab}{\gamma_2}q_1^3 \quad (4)$$

Perform the integral operation on the opposite number to obtain the potential function of the system:

$$v=\frac{1}{2}\gamma_1 q_1^2+\frac{ab}{4\gamma_2}q_1^4 \quad (5)$$

④ in order to better understand the synergistic effect of digitization and greenization, we made the following improvements to the system evolution equation: First, since the physical equation is set for continuous random variables, the time scale of the data in this study is divided into years, showing discrete characteristics, so it is discretized [10]. Second, due to the initial application of Haken model in the field of physics, there are some defects in the use of economic and social research. Digital greenization is an inherent system of cities. In order to better reflect the synergistic effect of urban digitalization and greenization, this paper improves it by adding a constant term. The improved model is as follows:

$$q_{1(t)}=(1-\gamma_1)q_{1(t-1)}-aq_{1(t-1)}^2+c_1 \quad (6)$$

$$q_{2(t)}=(1-\gamma_2)q_{2(t-1)}+bq_{2(t-1)}^2+c_2 \quad (7)$$

3. Level measurement of urban "dualization synergy"

3.1. Model construction and order parameter identification

According to the basic principle of Haken model, digitization index and greenization index are taken as variables, DIG represents digitization index and GRE represents greenization index. In this paper, the model hypothesis is proposed, and the model motion equation is constructed in stages and relevant parameters are solved to judge whether the model hypothesis is valid and order parameters are obtained. The motion equation was obtained by EVIEWS10.0 software. As shown in Table 2, No. 1 is the result of the whole sample, No. 2 is the result of the sample from 2012 to 2016, and No. 3 is the result of the sample from 2017 to 2022.

Table 2 Estimation results of Haken model

Number	Assumption	Equation	Information	Conclusion
1	q_1=GRE	$q_1=0.990433q_{1(t-1)}+0.0208q_{1(t-1)}q_{2(t-1)}+0.0029$ (***) (***)	γ_1=0.009567	The equation is established. Model hypothesis is valid. Greenization is an order parameter.
			γ_2=0.079219	
	q_2=DIG	$q_2=0.920781q_{2(t-1)}++0.111364q^2_{1(t-1)}+0.027379$ (***) (***)	a=-0.02082	
			b=0.111364	
2	q_1=DIG	$q_1=0.968607q_{1(t-1)}+0.0624919q_{1(t-1)}q_{2(t-1)}+0.02$ (***) (***)	γ_1=0.031393	The equation is established. Model hypothesis is valid. Digitization is an order parameter.
			γ_2=0.054267	
	q_2=GRE	$q_2=0.945733q_{2(t-1)}+0.088391q^2_{1(t-1)}+0.011530$ (***) (***)	a=-0.06249	
			b=0.088391	
3	q_1=GRE	$q_1=0.970296q_{1(t-1)}+0.072192q_{1(t-1)}q_{2(t-1)}+0.003$ (***) (***)	γ_1=0.029704	The equation is established. Model hypothesis is valid. Greenization is an order parameter.
			γ_2=0.119755	
	q_2=DIG	$q_2=0.880245q_{2(t-1)}+0.16682q^2_{1(t-1)}+0.03479$ (***) (***)	a=-0.07219	
			b=0.16682	

The results of the whole sample show that γ_1=0.009567, γ_2=0.079219, a=-0.02082, b=0.111364. The evolution equation can be obtained as follows:

$$\dot{q_1}=-0.009567q_1+0.029268q_1^3 \quad (8)$$

Further, the potential function is:

$$v=0.0047835q_1^2-0.007317q_1^4 \quad (9)$$

If q1 is equal to 0, three steady-state solutions of the potential function can be obtained. If $\gamma_1\gamma_2$ab<0, then $q_1^{'}=0$, $q_1^{''}=\sqrt{-\frac{\gamma_1\gamma_2}{ab}}$, $q_1^{'''}=-\sqrt{-\frac{\gamma_1\gamma_2}{ab}}$. When $\gamma_1\gamma_2$ab>0, there is only a unique zero solution. The three steady-state solutions of the potential function are: $q_1^{'}=0$, $q_1^{''}=0.571674$, $q_1^{'''}=-0.571674$, three stable points of system evolution can be obtained by substituting three solutions of the potential function into the system potential function equation. However, in the actual economic analysis, the state parameters of the order parameters are all greater than zero, so the stability point of the urban "dualization synergy" system is v*(0.571674,0.000782). The distance between any state parameter

point A of the system and the stable point determines the state of the system, so the system state evaluation function is:

$$d=\sqrt{(q-0.571674)^2+(v-0.000782)^2} \quad (10)$$

The larger the d value is, the farther the state point of the system is from the stable point, the lower the synergy score is; otherwise, the higher the synergy score is. In order to facilitate the follow-up study, the synergy score is processed in a positive way.

3.2. Analysis of the current situation of "dualization synergy" in Chinese cities

Based on the aforementioned research findings, in the process of urban "dualization synergy", greenization transformation served as the order parameter dominating the evolution of the urban " dualization synergy " system during the sample research period. However, in different development stages of the actual socio-economic context, digitalization and green transformation play varying dominant roles. During certain phases, digitalization may emerge as the order parameter governing the system, while in other periods green transformation might take precedence. As shown in Table 2 results, a pivotal change occurred in the order parameter of the urban " dualization synergy " system in 2017. During the 2012-2016 research period, digitalization functioned as the order parameter. However, from 2017 to 2022, the order parameter shifted to green transformation. This transition can likely be attributed to the formal implementation of the Environmental Protection Law of the People's Republic of China in 2017, along with the initiation of multiple pollution prevention and control action plans. Under this policy background, Chinese cities demonstrated significantly accelerated progress in green transformation compared to digital advancement, marking the entry of the " dualization synergy " system into a green transformation-dominated era.

The research shows that $\gamma_1 > 0, \gamma_2 > 0$. That means the coordinated development of urban greenization and digitization in China presents a phased feature. In the early stage (2012-2017), the two formed a two-way mutual promotion relationship, and digitalization and greenization achieved synergistic growth through mutual promotion. However, on the whole, the dual-integration collaborative system has not yet formed an orderly development mechanism, mainly due to the unbalanced regional development, the weak economic foundation of some cities and the shortage of technical talents, which makes it difficult to take into account both green and digital development [9].

With the promotion of the Digital China strategy (2018-2022), the role of digitalization in promoting greenization has been significantly enhanced. Digital technology has effectively promoted the improvement of green production levels by optimizing resource allocation, improving production efficiency and reducing energy consumption. This phased transformation shows that, driven by policy guidance and pilot projects, the in-depth application of digital elements has become an important force driving the green transformation [11].

4. Research conclusions and prospects

Based on the panel data of 281 cities in China from 2012 to 2022, this study reveals the dynamic law of the " dualization synergy " of Chinese cities by constructing the digital and green indicator system and applying the Haken model. The study found that the level of coordinated development of digitalization and greenization across the country showed a trend of continuous improvement, and the vast majority of cities achieved significant growth. As a system order parameter, greenization plays a leading role in the overall coordination process, but the primary and secondary relationship between digitalization and greenization has dynamic evolution characteristics, and their interaction provides a new perspective for understanding the complex mechanism of " dualization synergy ".

In view of the current development status, it is suggested to strengthen the core position of green transformation at the national level, consolidate its function of order parameters by strengthening the innovation and application of green technology, and support digital incentive policies to guide the collaborative transformation of government and enterprises to form a dual benign interactive system.

Local governments need to establish a differentiated promotion path, set up a " dualization synergy " test ground in combination with regional characteristics, dynamically evaluate the primary and secondary weights of digital and green elements, and maximize development effectiveness through precise policies.

Due to the limitation of data quality, the current research has not been able to analyze the inter-regional synergy differences in depth. In the future, the mechanism of " dualization synergy " in different regions can be explored to provide a basis for formulating spatial adaptation policies.

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