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Research on Efficiency Coupling Coordination Feature Model of Digital Economy Based on Multi-Objective Machine Learning Algorithm

Xiaochong CUI*, Shili GE

Abstract: Based on the coupled coordination development theory, the evaluation feature system of the coupled coordination system is first established according to the principle of feature selection, and the feature system of the digital economy subsystem is constructed from the three dimensions of digital infrastructure, digital application development and digital development environment, and its weight is determined by comprehensive evaluation method and entropy method. Secondly, the original machine learning particle swarm optimization algorithm is improved, including the improvement of infrastructure, digital application development, and digital development environment. Then, the method is combined with the dynamic multi-objective technology, the clustering method is selected as the objective function, the background difference method is used to design the digital economy efficiency coupling coordination feature model and rules, and the dynamic multi-objective optimization diagnosis model of improved particle swarm is established to achieve the optimization of the digital economy efficiency coupling coordination feature model. Finally, through the grey correlation analysis method, the paper analyzes the specific factors and degrees that affect the coordinated development level of digital economy and real economy.

Keywords: coupling coordination; digital economy efficiency; grey correlation analysis; multi-objective machine learning algorithm

1 INTRODUCTION

The digital economy relies on the Internet information platform and has no high requirements for geographical location, regional development level and human resources level. It can break through the limitations of space and expand the boundaries of the exchange and circulation of production factors, thus establishing a better domestic value chain, deepening international cooperation and improving status in the world [1]. Therefore, it is of great significance both theoretically and practically to study the impact of digital economy on the ability of regional coordinated development under the new development pattern.

In the field of digital economy, few scholars have linked digital economy with the ability of regional coordinated development, and discussed the function curve and transmission mechanism of the two [1-4]. The correct identification of the coupling mechanism between the development of digital economy and the real economy is a prerequisite for achieving high-quality economic development. At the same time, on this basis, a series of related issues such as whether the two can actively coordinate development in the integration process, what is the level of their coordinated development, and what are the key factors affecting their coupled and coordinated development, are further explored [5]. This has an important role and help for accurately measuring the development level of the digital economy and the real economy, grasping the situation of economic and social development, and promoting coordinated economic development. At the same time, it has an important practical role for rapidly revitalizing the vitality of economic development after the current epidemic, and planning the coordinated development layout of the digital economy and the real economy to promote high-quality economic development.

In this paper, an improved particle swarm dynamic multi-objective optimization diagnosis method is proposed. The traditional multi-objective optimization coupling and coordination of digital economy efficiency clustering method cannot adapt to the dynamic change of time or environment, so this paper takes the clustering method K-means algorithm and fuzzy clustering algorithm as the two objective functions of the dynamic multi-objective optimization model, and defines the background difference method to design environmental change factors and rules. The dynamic multi-objective particle swarm optimization (PSO) is analyzed and improved to construct the efficiency coupling coordination feature model of digital economy. Based on the research results and the actual situation, some suggestions are put forward for how to further coordinate the development of digital economy and real economy and jointly promote high-quality economic development.

2 RELATED WORK

The definition of digital economy has become more and more perfect, but different scholars have different emphasis on the understanding of the connotation of digital economy. In this regard, many domestic scholars have put forward their own unique views on the construction of digital economy characteristic system, and the evaluation system of digital economy characteristic built on this basis is also different. They believe that although the direct method is effective in measuring the digital economy, its operability is poor [6], so they adopt the comparison method, and the development level of the digital economy is divided into three aspects: digital foundation, digital application and digital innovation. Through all-factor digital transformation and innovative application of information technology, the economic form can be promoted to be more and more efficient, fair and unified [7]. Therefore, the digital economy is measured through three aspects: network effect, innovation effect and factor effect. According to the national science, technology and digital development strategy, the characteristic system of digital economy is divided into digital infrastructure, digital media, digital education scale and digital consumption power based on several aspects [8, 9]. They selected the digital economic environment and digital infrastructure as characteristics, and at the same time, considering that the research object was the countryside, they also included the digital improvement of life and the digital transformation of agriculture into the characteristic system to fill the gap in the investigation of the digital economy in the rural field [10]. It can be seen that for the digital economy, various scholars build a feature system based on their own understanding of the digital economy from different perspectives to fill the gap in the feature system of the digital economy. Although the established feature systems have different focuses, different scholars have found that there are significant regional differences in the development level of digital economy. It is believed that according to the development degree of digital economy [11], it can be divided into three tiers, among which the first tier includes Beijing-Tianjin-Hebei city cluster, Yangtze River Delta City cluster and Pearl River Delta City cluster, while the next tier is mostly in the radiation circle of the first tier. It is found that the four regions and the five economic zones are decreasing in spatial order in the east, middle and west, and the development of coastal areas is higher than that of inland areas, while the development level of digital economy in most regions is at a low level and has remained stable for a long time [12]. Through exploratory spatial data analysis and nuclear density estimation, it is found that the development of digital economy shows a decreasing trend from east to west, and the development of neighboring provinces also shows the same trend [13]. Meanwhile, compared with 2013, the overall development level in 2018 was improved, and the relative gap between regions was narrowing [14]. It can be seen that the development of digital economy varies greatly between regions, with the eastern region generally developing well and the western region not developing well.

It is believed that the digital economy brings new development opportunities to the real economy by transforming the dynamic mechanism of economic growth [15]. Later, the research on digital economy and real economy provided theoretical support [16]. Based on the perspectives of market, organization, human resource management and tourism policy, the paper theoretically explained the relevant impact of digital economy on the tourism industry [17, 18], studied the data of G7 countries (G7 Summit), and found that digital economy played an important role in promoting technological innovation [19]. It is believed that the impact of digital economy on the real economy starts from individual enterprises, spreads from industrial clusters to the digitalization of the economic system, and then expands its impact through the transformation of nine economic models [20]. When studying the deep integration and development of digital economy and real economy, it is found that current economic integration presents three characteristics: the acceleration of industrial digital transformation, the reverse penetration of industrial structure and the transformation of consumption and production in the form of integration. Therefore, it is believed that in the future, the research and development of common digital technologies should be strengthened to realize the digitalization of the whole industrial chain [21]. It is found that although the overall coupling and coordination level of digital economy and real economy development in the Yangtze River Economic Belt shows an upward trend, the overall level is not high, and most provinces and cities are above the imbalance level, and there are obvious regional differences [22]. From the gray correlation degree, it is found that digital economy has a greater impact on the coupling and coordination degree of provincial economy, and has a significant spatial external spillover effect on surrounding areas [23]. Spatial metrology is used and the differences between regions are increasingly expanding, which is embodied in the semi-enclosed spatial differentiation pattern with high and low integration areas as the periphery [24]. The degree of economic coupling and coordination among provinces continues to deepen, and there is a big gap in the digital economy index of different regions. Digitalization and networking are the main factors determining the development of digital economy, but compared with the real economy, the development of digital economy in most provinces is lagging behind [25]. Listed entities find that the development of digital economy and the scale of inefficient investment of real enterprises show an "inverted U" shape, which has an asymmetric impact on the investment efficiency of real enterprises. Meanwhile, the development of digital economy can integrate the advantageous production factor resources between regions [26]. It can be seen that there are few papers on the coupling coordination degree between the two economies, and there is still a certain gap in the research of the coupling coordination relationship between the two economies.

In the early stage, it mainly focuses on the content related to regional development differences. He believes that the main reason for the imbalance of regional development is that different regions have different attractions to economic industries due to their inherent characteristics [27]. Some regions have attracted a large amount of capital by relying on their advantages such as geographical location, geomorphic features and traffic level, and these capitals have created greater advantages for them [28, 29]. As a result, the richer the rich are, the more obvious the gap between regional economic aggregates is. To sum up, many scholars at home and abroad have conducted in-depth studies on digital economy [30], regional coordinated development ability and the internal relationship between the two. These studies have great reference value for this paper and provide reliable theoretical support for the empirical test and even the writing of the article. Compared with more mature foreign theoretical research, domestic scholars have not formed a mature and stable research system on digital economy and regional coordinated development ability, and it is still in the initial stage, and the research depth and breadth are also limited by the research time. At present, most domestic researches on the impact of digital economy on regional coordinated development ability focus on the direct effect and the transmission mechanism of some specific intermediary variables, and ignore the influence of core explanatory variables on the explained variables at different stages of development and the spatial effect.

3 RESEARCH ON THE DEVELOPMENT LEVEL AND INFLUENCE CHARACTERISTICS OF EFFICIENCY COUPLING AND COORDINATION OF DIGITAL ECONOMY

The efficiency and coordinated development of digital economy is an inevitable prerequisite for high-quality economic development. In the process of continuous integration of digital economy and real economy, the coupling and coordinated development level reflects the effective enthusiasm of integration to a certain extent. Through the gray correlation degree analysis model, the key factors affecting the coupling and coordinated development of digital economy and real economy are analyzed to achieve high-quality economic development. The research frame diagram is shown in Fig. 1.

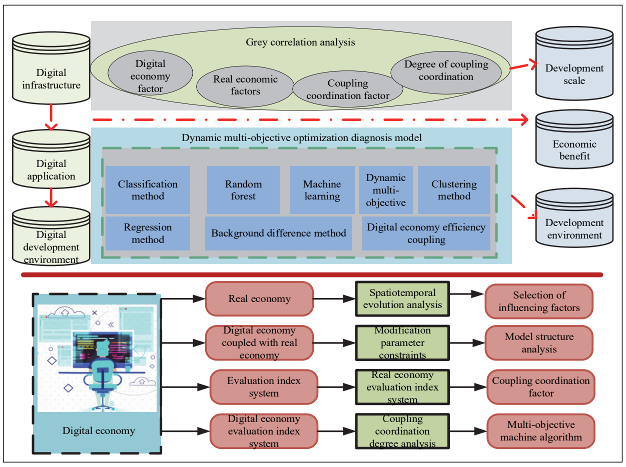

Figure 1 Research framework of digital economy coupling coordination based on multi-objective machine learning

3.1 Construction of Coupling and Coordination Model of Digital Economy Efficiency

Based on the capacity coupling coefficient model in physics, the coupling degree model of multiple systems can be generalized:

$$C_n = C(c, f(u,v)) / \prod (u_i + u_j)^n \tag{1}$$

Where, C_n is the coupling degree; $f(u, v)$ is a function of two system variables. The coupling degree C_n is between 0 and 1, and the coupling degree of digital economy and real economy is calculated as follows:

$$C = 2\sqrt{U_1 U_2} / (U_1 + U_2) \tag{2}$$

Among them, U_1 represents the development level of digital economy; U_2 represents the development level of the real economy.

A single measure of the coupling degree of two systems by coupling degree will appear false phenomenon, it will still show a highly coupled state, at this time the high coupling degree will no longer have practical significance. Therefore, it is necessary to increase the degree of coordination based on the coupling degree model, which is expressed as:

$$\begin{cases} D = (C \times T)^{0.5} \\ T = aU_1 + bU_2 \end{cases} \tag{3}$$

where, $a = b = 0.5$. The value of coupling coordination degree D can generally be divided into four levels, as shown in Tab. 1.

Based on the measurement of the development level of the digital economy and the real economy, the coupled coordination feature system is constructed by integrating the characteristics of the development system of the digital economy and the development system of the real economy, as shown in Tab. 2.

Table 1 Classification of coupling coordination degree

Coupling coordination range	Coupling coordination level	Coupling coordination range	Coupling coordination level
[0, 0.4]	Borderline disorder	(0.6, 0 .8]	Intermediate coordination
(0.4, 0.6]	Primary coordination	(0.8, 1]	Advanced coordination

Table 2 Coupling coordination feature system

Coupled system	First-order feature	Second-order feature
Digital economy system U1	Digital infrastructure	Internet penetration rate X_1
		Number of domain names X_2
		Internet broadband access port X_3
		Mobile phone penetration X_4
		Optical cable density X_5
		Number of websites per 100 companies X_6
		The proportion of enterprises with e-commerce transactions X_7
	Digital application development	The proportion of employees in the information industry X_8
		E-commerce sales X_9
		Total telecom business per capita X_{10}
		Digital Financial Inclusion Index X_{11}
	Digital development environment	Internal expenditure of R&D funds X_{12}
		R&D personnel equivalent to full-time equivalent X_{13}
Real economy system U2	Development scale	The value added of the real economy as a proportion of GDP Y_1
		The total amount of consumer goods accounted for Y_2
		The proportion of employees in the real economy is Y_3
	Economic benefit	The proportion of profits of industrial enterprises above designated size Y_4
		Per capita disposable income Y_5
		Proportion of local enterprise income tax in local tax revenue Y_6
	Development environment	Proportion of R&D expenditure in main business income of industrial enterprises above designated size Y_7
		The development of market intermediary organization and the legal system environment
		Increase in social financing Y_9

The entropy method is used to determine the weight of digital economy and real economy characteristic system. The core of the idea of entropy weight method is to judge the amount of information carried by data according to the degree of data dispersion. The more discrete the data, the more information carried, the higher the weight will be given, and the smaller the weight will be. The steps are as follows, for positive features x:

$$x(i,j) = \frac{x(i,j) - x_{\min}(j)}{x_{\max}(j) - x_{\min}(j)} \tag{4}$$

For reverse features:

$$x(i,j)=\frac{x_{\max}(j)-x(i,j)}{x_{\max}(j)-x_{\min}(j)} \tag{5}$$

Calculate the entropy of the j-th feature:

$$e_j=-k\ln_{i-1}^{n}p_{ij}\ln(p_{ij}),\ j=1,\ 2,\ ...,\ m \tag{6}$$

Calculate the weight of each feature d:

$$w_j=\frac{d_j}{\sum_{j=1}^{m}d_j},\ j=1,\ 2,\ ...,\ m \tag{7}$$

3.2 Coupling and Coordination Analysis of Digital Economy Efficiency

In order to further study the coordination level of five subsystems of regional coordination development ability, a coupling coordination degree model is introduced. The calculation equation is:

$$D=\sqrt{C\times U},U=rX \tag{8}$$

D represents the coupling coordination degree of different systems, and U represents the comprehensive evaluation index of subsystems weighted according to specific weights. r represents the weight coefficient of each subsystem, $r = 0.2$.

The weight of the calculated index is calculated to obtain the comprehensive evaluation results of the regional coordinated development ability of each region in each year. In addition, the comprehensive evaluation index of the regional coordinated development ability of each region is calculated to measure the regional coordinated development ability of each region. The radar chart is drawn according to the annual geometric average calculation results, as shown in Fig. 2.

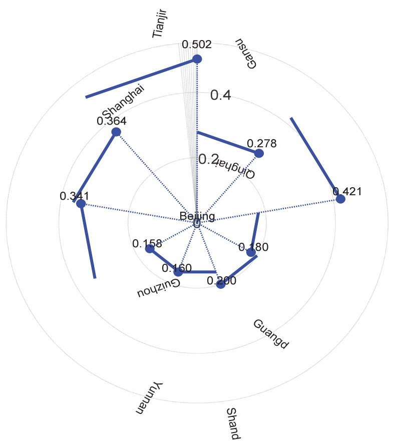

Figure 2 Characteristic radar map for comprehensive evaluation of regional coordinated development capacity in various regions

It can be seen that on the whole, the average annual comprehensive evaluation index of Beijing's regional coordinated development ability reached 0.502, ranking first. It was followed by Shanghai and Tianjin with an average annual composite index of 0.364 and 0.341 respectively. The lowest ability of regional coordinated development is Gansu Province, with an average annual composite index of 0.158. Other regions with low capacity for regional coordinated development include Qinghai Province, Guizhou Province and Yunnan Province. It is not difficult to find that the high index areas are mostly distributed in the east and southeast, which often have convenient transportation networks, superior geographical location and economic development level. The low index areas are often distributed in the western, northwestern and other underdeveloped areas. According to the above regional division, the average of the five system coordination degrees of each region is calculated, as shown in Tab. 3 below.

Table 3 Average value of system coordination degree of coordinated development capacity of each region

Whole country	East	Middle	West
0.41	0.43	0.39	0.36
0.42	0.44	0.40	0.38
0.43	0.45	0.41	0.39
0.45	0.47	0.42	0.40
0.46	0.48	0.44	0.42
0.49	0.51	0.46	0.44
0.51	0.53	0.48	0.46
0.52	0.55	0.49	0.48
0.53	0.56	0.50	0.48
0.55	0.58	0.52	0.50

By observing the calculation results of coupling degree and coupling coordination degree of various provinces, we can find that the coupling degree of regional coordinated development ability of various provinces and cities is at a relatively high level, which indicates that there is a relatively close interaction relationship among the five subsystems of economic development, public service, people's life, infrastructure and ecological environment. In terms of coupling coordination degree, the coordination degree among subsystems is not high. The mean value of the five system coupling coordination degrees in each region is 0.414, and the value is greater than the mean value in 12 regions; the mean value of the coupling coordination degrees in each region is 0.551, and the value is greater than the mean value in 11 regions. From the perspective of data distribution, the average of regional coupling coordination degree data is larger than the median, showing a right-skewed distribution, more low-score data, and more regions at a relatively low coordination degree level. From the numerical point of view, with the passage of time, the coordination of the five sub-systems of regional coordination development ability has been gradually improved, and the overall coordination level has been greatly improved.

Specifically, the coupled and coordinated development of provinces and cities in different regions is further analyzed, as shown in Fig. 3. It can be intuitively seen from the figure that the provinces and regions in the eastern region can be roughly divided into two categories, above the average level of coupling and coordination development and below the average level. Provinces and cities that have been higher than the average level are Guangdong, Zhejiang, Beijing, Shanghai and Jiangsu, among which Guangdong has always occupied a leading position in general, and the coupling and coordinated development level of Beijing and Zhejiang is basically the same, maintaining relatively stable development. Although the coordinated development level of Shanghai and Jiangsu is lower than the first three, its development speed is faster than that of the same kind, reaching more than 0.75. The level of development is basically the same, and will soon reach the stage of high-level coordinated development. Fujian and Shandong have achieved leapfrog development, and the coupling coordination degree is about 0.62, in the intermediate stage of coordinated development, and later reaches more than 0.7, which is expected to break through the next level to achieve further coordinated development. The other provinces and cities include Liaoning, Hebei and Hainan, whose development has been below the average level, and Liaoning and Hainan have been in the primary stage of coordinated development.

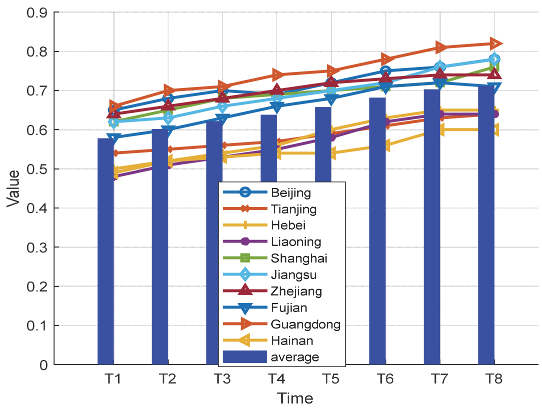

Figure 3 Changes in the development trend of regional coupling and coordination in eastern provinces

In general, in the eastern region, Guangdong, Beijing, Jiangsu and Shanghai are at the leading development level and perform the most prominent in the coupling and coordinated development of digital economy and real economy. The rapid growth of the coordinated development level of Jiangsu and Shanghai indicates that the integration process of digital economy and real economy has been deepened, and the coupling and coordinated development has been accelerated. Maintaining the current growth trend is expected to surpass Guangdong and Beijing, and the development situation is improving, which can play an example role in the whole country and is worth learning from.

The change of the coupling and coordination development trend of provinces and cities in the central region is shown in Fig. 4. As can be seen from the figure, the starting point of the coupled coordinated development level in the central region is not superior, only Hubei has reached the national average level, and other provinces and regions have not reached the national average level, and the central region is in the primary stage of coordination. With the development, the gap between the development levels of provinces begins to appear, except Jilin Province, all the other provinces and regions have entered the intermediate coordination stage and developed rapidly. The proportion of provinces and cities above the average level has reached 62.5%, the average coupling coordination degree has reached 0.6581, and the gap with the eastern region has been narrowing, showing a catch-up development trend.

As shown in Fig. 5, the development trend of the coupled and coordinated development of provinces and regions in the western region is more prominent in Shaanxi and Sichuan, which are basically above the national average level. The coupled and coordinated development level of Sichuan Province reached 0.7, achieving a leapfrog breakthrough. In the same year, except Inner Mongolia, Tibet and Xinjiang, all other provinces and cities reached the intermediate stage of coordinated development. However, the proportion of provinces and cities reaching the national average level is only 41.67%, less than half, and most provinces in the western region have a low level of coordinated development of digital economy and real economy, most of them are below the national average level, and there is still a lot of room for progress. However, in Fig. 5, from the perspective of the overall development trend, the progress signal, provinces and regions from a low starting point rapid development, in 8 years to achieve leapfrog development and primary coordinated development stage, and the coupling coordination degree is mostly concentrated between 0.45 and 0.55, except for some provinces and regions that have entered the intermediate coordination stage, the growth trend is rapid.

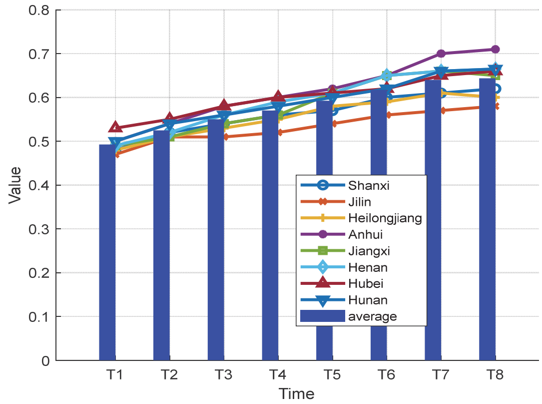

Figure 4 Changes in the development trend of regional coupling and coordination in central provinces

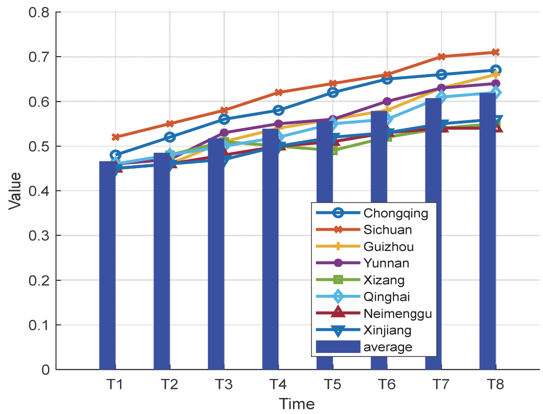

Figure 5 Change of coupling coordination trend of provinces and regions in western

4 DIGITAL ECONOMY EFFICIENCY COUPLING COORDINATION FEATURE MODEL FOR DYNAMIC MULTI-OBJECTIVE MACHINE LEARNING

4.1 Dynamic Multi-Objective Machine Learning Optimization Model

In the application of dynamic multi-objective optimization, the background difference method is selected to judge the environmental change. Firstly, some pixels of the obtained digital economy efficiency coupling feature are randomly selected, and then the difference operation is applied to the original pixel matrix and the current pixel matrix of the monitoring object. If the difference result is greater than the given threshold, the background environment changes; otherwise, the background environment does not change.

$$sRuler = pre\operatorname{Im}g - now\operatorname{Im}g \begin{cases} > \lambda \\ \leq \lambda \end{cases} \tag{9}$$

In the equation, λ represents the threshold value, which changes according to the different test functions. In the test, we consider the complexity of the actual environment, determine the size of the threshold through multiple experiments, and introduce the first-in-first-out principle of the queue algorithm to achieve the optimal algorithm.

The variable w is a parameter that can ensure that the particle is in the normal motion state, and the value of w directly affects the particle speed and the solution effect. If. If the value increases, the spatial threshold of particle finding solution increases. If the value of w decreases, the solution may fall into local optimal. Therefore, by optimizing the value of w in the particle iteration process, the particle has a larger search space in the initial period, and then decreasing the value of w to slow down the particle speed, so that the particle can find and select the local solution and global solution well, and better adapt to the needs of actual changes. Define k as the algebra of the current moment in particle evolution and $K_{\max}$ as the maximum algebra of particle runtime at time t:

$$w = w_0 - (\sin k - \frac{1}{2}) + \frac{k}{K_{\max}} \tag{10}$$

The sinusoidal function is used to dynamically adjust the solution range of particle flight. Because improper value of w will cause the algorithm to fall into local optimal, it is necessary to restrict its change. In the iterative process, the value of w needs to be controlled within a certain range to ensure the effectiveness of particle solution. In this paper, by introducing the expression of variable k, the adaptation value conforming to the sine change is obtained, and then it is solved. Variable can avoid the inertial factor due to the rapid increase in particle algebra caused by its own speed of the situation occurred.

In combination with the above analysis, the nearest neighbor method is used to define the variation factors. The core of the nearest neighbor method is to determine the final classification by solving the class of the samples closest to the samples to be tested. At time t, when processing the t-th digital economy efficiency coupling feature, mutation operation is used to improve the diversity of particles for possible pixel misjudgment. Here we introduce the KNN (k-nearest neighbors) algorithm, through the KNN algorithm calculation, to solve a particle in the nearest neighbor and as the offspring of every particle. If the number of solutions in the solution set is r, r variant particles will be solved.

$$g_i(x) = \min_k (x - x_i^k),\ k = 1, 2, ..., N_i \tag{11}$$

4.2 Influencing Factors of Coupling coordination are Analyzed Based on Grey Relational Degree

First of all, dimensionless processing should be carried out on the data to eliminate the impact of large dimensional differences. Generally, initial value and averaging are adopted to eliminate dimensionality processing. Here, averaging is adopted for processing. Then, the standardized data is used to find the correlation coefficient of each impact indicator for each year.

Initializing means dividing all the data in each column of a matrix $\boldsymbol{X}$ by the initial value of that column, that is, the value of the first row. This method is suitable for steadily increasing or decreasing data.

$$y_{ij} = \frac{x_{ij}}{x_{1j}} \tag{12}$$

Averaging means dividing all the data in each column of a matrix $\boldsymbol{X}$ by the mean of that column, and this method is suitable for data with no obvious trend.

$$y_{ij} = \frac{x_{ij}}{\frac{1}{m}\sum_{i=1}^{m} x_{ij}} \tag{13}$$

Table 4 Grey correlation degree of digital economy coupling and coordinated development of provinces and cities

District	X_1	X_2	X_3	X_4	X_5
Peking	0.847	0.725	0.818	0.934	0.915
Tianjin	0.750	0.755	0.747	0.931	0.786
Hebei (Province)	0.817	0.731	0.845	0.973	0.746
Shanxi (Province)	0.828	0.531	0.824	0.958	0.875
Inner Mongolia	0.786	0.717	0.842	0.964	0.673
Liaoning (Province)	0.850	0.742	0.842	0.939	0.696
Ji Lin	0.842	0.636	0.783	0.939	0.823
Amur River	0.784	0.642	0.739	0.942	0.672
Shanghai	0.830	0.658	0.862	0.913	0.823
Jiangsu (Province)	0.800	0.737	0.821	0.966	0.852
Zhejiang (Province)	0.822	0.715	0.828	0.952	0.814
Anhui (Province)	0.759	0.729	0.816	0.945	0.762
Fujian (Province)	0.808	0.563	0.824	0.924	0.743
Jiangxi (Province)	0.754	0.593	0.831	0.942	0 .703
Shandong (Province)	0.823	0.684	0.782	0.991	0 .774
Henan (Province)	0.795	0.673	0.813	0.965	0 .885
Hubei (Province)	0.823	0.684	0.802	0 .954	0 .786
Hunan (Province)	0.783	0.708	0.843	0.942	0 .822
Kwangtung	0.862	0.843	0.756	0.914	0 .753
Guangxi	0.802	0.713	0.793	0 .946	0 .754
Hainan (Province)	0.752	0.708	0.736	0.974	0 .792
Chongqing	0.795	0.712	0.796	0 .961	0 .843
Four)l!	0.783	0.773	0.782	0.952	0 .814
Less expensive l, l	0.784	0.584	0.801	0.973	0 .927
Yunnan (Province)	0.785	0.618	0.798	0.974	0.733
Xizang	0.722	0.802	0.703	0.942	0.952
Shaanxi (Province)	0.808	0.665	0.792	0 .953	0.823
Gansu (Province)	0.707	0.629	0.814	0.962	0.903
Qinghai (Province)	0.976	0.973	0.973	0.992	0.977
Ningxia	0.715	0.692	0.716	0.934	0.610
Xinjiang	0.837	0.786	0.823	0.965	0.813
Mean value	0.803	0.707	0.806	0.956	0.805

The grey correlation degree of each evaluation object is:

$$a_i = \sum_{i=1}^{m} w_j r_{ij} \tag{14}$$

The results of the grey correlation degree between the digital economy indicators and the coupling and coordinated development level obtained by calculation are shown in Tab. 4. As can be seen from the results in the table, except for the tenth indicator, the total amount of telecom business per capita, the grey correlation degree between the other indicators and the coupled coordinated development level is basically above 0.7, which is a strong correlation level, indicating that all indicators of the development of the digital economy have a strong influence on the coupled coordinated development level.

Suppose that the cell variable X has an independent and equally distributed sample x_1, x_2, ..., x_n, then the one-dimensional kernel density estimate of the density function $f(x)$ of the variable x follows the distribution is:

$$f(x)=\frac{1}{n}\sum_{j=1}^{n}\frac{1}{h}K\left(\frac{x-x_j}{h}\right) \tag{15}$$

5 SIMULATION VERIFICATION

In order to ensure the accuracy of experimental data, this paper tests each function 20 times and calculates the average extreme value and statistical variance. The selected function set, such as the result of function f, begins to converge rapidly after 45 iterations and begins to approach the optimal solution after 83 iterations. At this time, other algorithms are still fluctuating and converge to the optimal solution when iteration reaches 92 times, and other algorithms still fail to obtain the optimal solution at the end of iteration, as shown in Fig. 6.

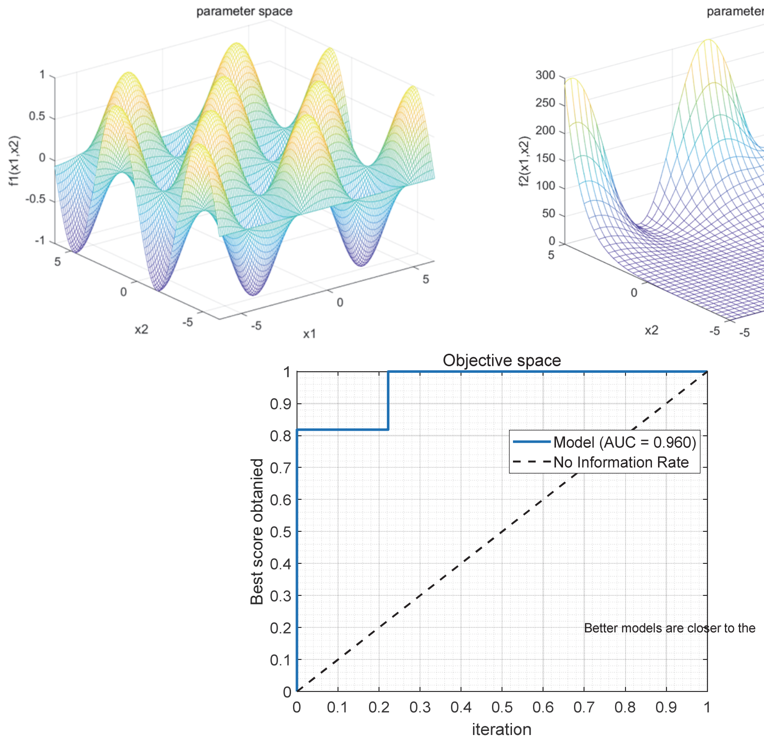

Figure 6 Test results of the three methods on the f1 and f2 functions

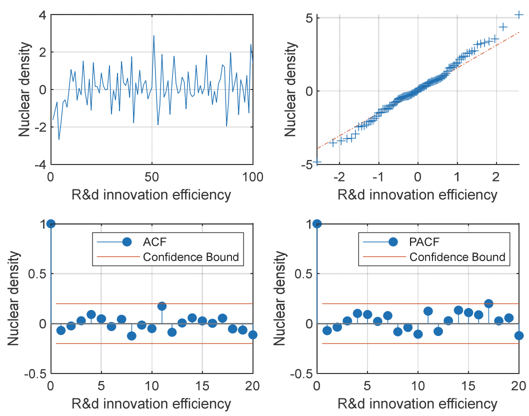

Figure 7 Kernel density estimation of digital economy efficiency

In order to more clearly show the distribution state and dynamic evolution trend of digital economic efficiency in the sample interval of the country and the three regions, this paper analyzes it by using kernel density estimation method. The nuclear density distribution is shown in Fig. 7.

Before the empirical analysis begins, the correlation between the core explanatory variable and the explained variable is first described, as shown in Fig. 8.

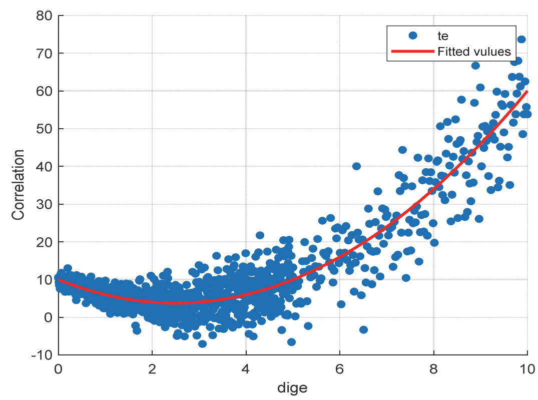

Figure 8 Scatter plot of digital economy development and digital economy efficiency

As shown in Fig. 8, the horizontal axis represents the development level of digital economy, the vertical axis represents the calculated efficiency of digital economy, and the scatter point represents the corresponding coordinates of various provinces and cities within the sample interval. Through the position and direction of the scatter point, a straight line inclined to the upper right can be fitted. This means that with the improvement of the development level of regional digital economy, the efficiency of digital economy also has a trend of improvement, and the two show a positive correlation.

The spatial and temporal evolution characteristics of the coupling coordination degree of the five systems of regional coordination development capability were analyzed by using the nuclear density estimation method. In this paper, the nuclear density estimation curves of the country and the eastern and western regions in 2012, 2015, 2018 and 2021 were drawn from four periods. The results are shown in Fig. 9 below.

From a national perspective, the coupling coordination degree kernel density curve of the five sub-systems of regional coordination development capability from 2012 to 2021 shows a gradual shift to the right, indicating that the coupling coordination degree of the five systems gradually increases over time, that is, the multi-dimensional coordinated development of economic development, public service, people's life, infrastructure and ecological environment is constantly promoted. The height of the main peak of the nuclear density curve increased significantly in 2018 but dropped to the original level in 2021. On the whole, there was no significant change in the data dispersion degree of the coupling coordination level of regional coordination development capability, that is, the inter-provincial gap did not change much.

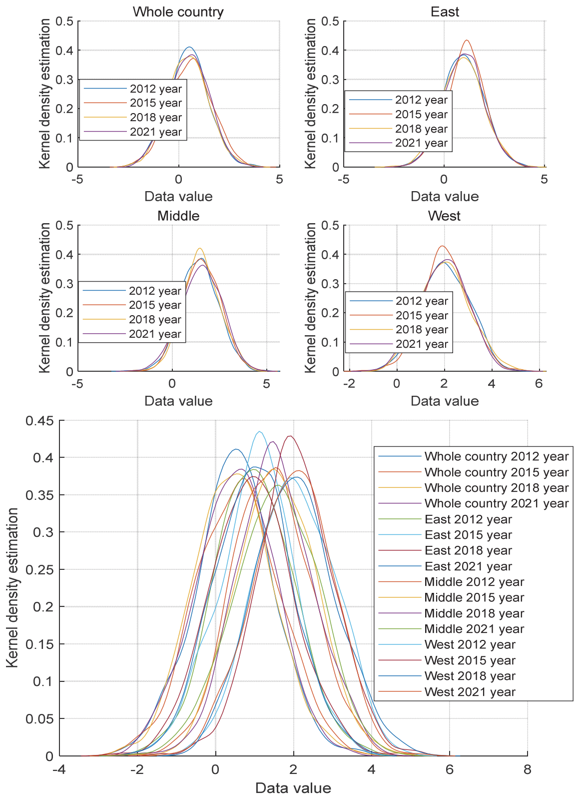

Figure 9 Kernel density map of coupling coordination degree in each region

The process of seeking the optimal solution for the coupled characteristic parameters of digital economy efficiency based on multi-objective machine learning method is shown in Fig. 10. It can be seen from the figure that the selection of different parameters has a great impact on the result.

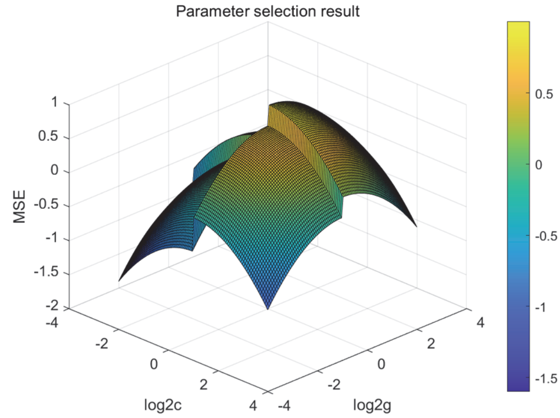

Figure 10 Multi-objective machine learning method to optimize the coupling feature parameters of digital economy efficiency

To sum up, all sub-indicators of the development of the digital economy and the real economy are strongly correlated with the gray correlation degree of the coupled coordinated development level, which all affect the coordinated development of the digital economy and the real economy to varying degrees, among which the major influencing degrees are the level of digital infrastructure and digital application development, which mainly belong to the secondary indicators. It shows that the development of the digital economy mainly affects the coupling and coordination level with the development of the real economy from these two aspects. Among them, the level of digital infrastructure is the cornerstone of the development of the digital economy, while the development of digital application, which is mainly the digitalization of the industry, is mainly to help enterprises to carry out financing and capital allocation, and inject vitality into the real economy enterprises. Therefore, its contribution to the level of coordinated development coupled with the real economy is greater.

6 CONCLUSION

The development level of digital infrastructure, the development of digital applications and the scale and benefits of real economy development are the keys to the development level of coupling and coordination. Through the gray correlation degree analysis, it is concluded that all digital economy indicators and real economy indicators are strongly correlated with coupled and coordinated development. Among them, digital economy indicators mainly reflect the level of digital infrastructure development and digital application development, and real economy indicators mainly reflect the scale and benefits of physical development. It shows that in the process of integrated development of digital economy and real economy, digital infrastructure, digital application development and the scale and efficiency of real economy are the keys to promote the coupled and coordinated development. In this paper, the dynamic multi-objective technology is used to take machine learning algorithm as the objective function, and seek more excellent solutions in the function, and the background difference method is introduced into the particle swarm optimization algorithm to design the environmental change factors and rules, so as to build the coupled coordination feature model of digital economy efficiency. By testing the digital economy efficiency data set, the experimental results show that compared with the single objective optimization algorithm, the model obtains more quantity, high-quality and uniformly distributed frontier solution sets, and gives each recognition result, proving that the model proposed in this paper has better efficiency and accuracy in diagnosing the coupled features of digital economy efficiency. As the theoretical knowledge is relatively weak, the problem mining and countermeasures and suggestions can be further thought and explored. The next step should be to vigorously develop digital industrial clusters, accelerate the upgrading of industrial structure in various regions, and build a new pattern of coordinated regional development. For the eastern region and the regions with high regional coordinated development capacity at this stage, it is necessary to give full play to the radiating effect of the digital economy as much as possible, encourage cross-regional enterprise cooperation and industrial division of labor, promote the complementarity of regional production factors, and promote the high integration of digital technology and real industry, so as to narrow the development differences between regions and achieve regional coordinated development.

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Contact information:

Xiaochong CUI
(Corresponding author)
School of Economics,
South-Central Minzu University,
Wuhan Hubei, 430074, China
E-mail: chongxiaocui0716@163.com

Shili GE
College of Information and Management Science,
Henan Agricultural University,
Zhengzhou Henan, 450046, China