



Dynamic evolution and spatial–temporal disparities decomposition of high-quality economic development in China

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Abstract

High-quality economic development (HQED) in China is an important embodiment for adapting new normal of economy and implementing new concept of sustainable development. Accurately portraying the evolution trajectory of China's HQED and tracing sources of its spatial–temporal disparities are of great significance for promoting balanced and healthy economic development. Since the evolution of HQED is dynamic and motivated by the need for continuously monitoring the time-varying process of HQED, we develop a functional high-quality economic development index (HQEDI(t)) in the context of functional data analysis. We use the functional ANOVA to examine the significance of disparities between regions, in terms of static absolute level and dynamic development potentials, based on the continuous measurement of provincial HQED. The extended functional Dagum Gini coefficient is also used to decompose the overall and structural inequality of China's HQED. The results show the following. (1) The overall level of China's HQED has been steadily increasing, and innovation efficiency is the leading factor for improvement of China's HQED. (2) Uneven development between regions exists only at the absolute level and grow velocity of HQED, but it is not significant in acceleration. (3) The overall regional disparities of China's HQED show a downward trend, and inter-regional disparities dominate the inequality of HQED. We make a contribution to the idea of a dynamic framework for evaluating HQED and provide guidance for policy-making authorities to formulate target development policies.

Keywords High-quality economic development · Functional data analysis · Dynamic evolution · Spatial–temporal disparities decomposition

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1 Introduction

Since entering the twenty-first century, China's economy has made remarkable achievements. From 2000 to 2020, the total of China's GDP increased from RMB 9,906.6 billion to RMB 1,013,567 billion, ranking from the sixth to the second in the world (Deng et al., 2022; Xie et al., 2022). Then, China's average contribution ranks the first in the world in 2020 (Lu and Wu, 2022). However, behind the rapid economic development is the sacrifices of interests, such as environmental pollution, widening urban–rural disparity, low production efficiency, and unbalanced regional development (Abbass et al., 2022; Li et al., 2016; Nie & Jian, 2020). At present, severe constraints on environment and resources, and unbalanced development between regions and urban and rural areas have become key problems that need to be solved urgently in China's economic development (Zhou et al., 2020). The report of the 20th National Congress of the Communist Party of China (CPC) once again pointed out that China's economy has shifted from the stage of high-speed growth to the stage of high-quality development, and high-quality development has become the new direction of China's economic development in the future. In order to achieve high-quality economic development (HQED), China has put forward a series of important conclusions, such as unwaveringly implement the new development concept of innovative, coordinated, green, open and shared development, and promote high-quality development. Therefore, the new development concept has become the internal requirement of China's economic transformation to high-quality development (Tang et al., 2019). How to measure the HQED level of China? Which areas should China focus on developing in the future? What should China focus on in the future? All these are key issues that need to be addressed in the process of HQED in China.

High-quality economic development (HQED) is the coordinated and unified sustainable development of economic, political, cultural, social and ecological civilization (Liu et al., 2021; Wang & Tang, 2022). Sustainable development was first proposed in the World Commission on Environment and Development (WCED) in 1987. It can be interpreted as development that meets the needs of the present without endangering future generations (Amjad et al., 2022; Zakari et al., 2022). The theory of sustainable development emphasizes the overall coordination and unity of the complex relationship among ecology, economy and society. As a result, fairness, sustainability and commonality are the three principles of sustainable development (Huang et al., 2022; Awan et al., 2022). The Chinese government has explored and practiced the theory of sustainable development. For example, the sustainable development strategy was formally written into the economic construction plan in 1995. Then, the 15th National Congress of the Communist Party of China confirmed it as one of the strategies of China's modernization construction. The comprehensive, coordinated and sustainable scientific outlook on development is the sublimation of the connotation of sustainable development. The report to the 18th National Congress of the Communist Party of China put forward the grand blueprint for building a beautiful China. In the following decade, China has been committed to the practice of sustainable development. Insist on quality first, efficiency first, promote the development of economy, efficiency, quality change and dynamic change to become the development direction of China's economic future.

As we all know, HQED has the dual advantages of maintaining ecological balance and promoting sustainable economic development (Tian et al., 2018; Zhou et al., 2020). From the time dimension, the high-quality development level of China's economy always changes dynamically with time, rather than a fixed value over a period of time. Then, how to construct a relatively complete economic high-quality development index for comprehensive

measurement and analysis? How to test the regional differences of high-quality development level of Chinese economy based on static absolute level and growth potential, and then investigate the sources of regional disparities? This study is conducive to the better integration of the connotation of HQED and the theory of sustainable development. Secondly, it reveals the current situation of regional disparities of HQED and improves the mechanism analysis and exploration of regional disparities theory. It is helpful to analyze the status quo of China's HQED, including capturing the characteristics of spatial and temporal disparities, so as to provide reference for the government decision-making departments to formulate timely and targeted development policies.

Up to now, many scholars have conducted extensive research in China's HQED, which focus on the following two aspects. One of them is focused on measurement of China's HQED, including the measurement object and measurement method. Specifically, Wei and Li (2018) argued that evaluation system of HQED should comprehensively consider all aspects of economic development. They systematically constructed a measurement system for HQED in China and measured three regions in China via the entropy weight method. Ma et al. (2019) proposed an evaluation system of China's HQED indicators using five subsystems: efficient, high-quality demand, efficiency and sustainability, economic stability, and openness to the outside world. They measured HQED of each provinces using the equal-weight assignment method. Moreover, Nie and Jian (2020) developed a system of HQED indicators based on the quality of the products and services, economic performance, social performance, ecological performance, and economic operation. Using the vertical and horizontal pull-out grade approach, they simultaneously measured the HQED of the provinces and three regions. Zhang et al. (2020) constructed an index system for HQED from three levels: enterprise, industry, and region. This system included innovation, green, openness, sharing, efficiency, and risk prevention. And it measured HQED of manufacturing enterprises in Dongguan City using expert scoring method. Considering the relationship between indicators and dimensions, Jiang et al. (2021) used SMI-P model to comprehensively evaluate HQED and found out the main factors affecting the improvement of the HQED level by using the obstacle degree model. In general, the existing literature methods, including entropy weight method, equal-weight assignment method, vertical and horizontal pull-out grade method and expert scoring method, measure the trend of HQED from a static perspective, ignoring information that changes from year to year. Moreover, when constructing the composite index of HQED, the existing methods can only characterize HQED at specific discrete points in time. Therefore, we think it is necessary to solve this problem from the perspective of continuous dynamics.

The measuring of regional disparities is the second important topic on China's HQED. The existing methods include regression decomposition method, coefficient of variation method, Thiel index, Gini coefficient, and Dagum Gini coefficient. Specifically, Yamamoto (2008) used coefficient of variation method, Gini coefficient, and Theil index to measure regional disparities in the USA and Rodriguez and Ezcurra (2010) proposed a combination of coefficient of variation method and Theil index to measure regional disparities. Qu and Liu (2021) and Sun et al. (2020) both conducted a comprehensive test of regional disparities in China's HQED. They used decomposition method of regression equation, and they examined main sources of regional disparities in the process of China's HQED. Guo et al. (2020) combined Thiel index with spatial data to uncover spatial disparities. Li and Lei (2021) revealed the regional disparities in China's HQED and their convergence characteristics with the help of analytical methods such as the Theil index, catch-up degree and coordination degree. Gini index and its decomposition were used to delineate regional disparities of spatial distribution (Long et al., 2019; Zhang et al., 2020; Liu et al., 2021; Dai

et al., 2022). In recent studies, geographical weighted regression model has also become a common method to explore regional disparities (Deng et al., 2022; Xie et al., 2022). Overall, the existing approaches only focus on the absolute level, and they have not considered dynamic growth potential perspective to examine variability of HQED, failing to explore intrinsic information of HQED.

Although the existing literature has laid foundation for measurement of China's HQED, there are still three shortcomings. First, from regional perspective, the existing literatures often take three or four major regions, which show certain limitations and fail to reflect spatial characteristics of China's regional HQED. Second, by nature, HQED is a continuous, dynamic change process. It can lead to problems, such as loss of information or distortion of model estimates, to measure China's HQED in fixed-frequency observation time points when using composite index with static assignment of equal weights. Third, there are few assessments of regional inequalities in dynamic development potentials; instead, most tests of regional disparities remain at static absolute levels. This leads to a failure to comprehensively and systematically examine regional disparities in HQED and the spatially dimensional sources of regional disparities.

In light of the aforementioned problems, it is essential for China's HQED to accurately portray dynamic trajectory and capture patterns of intra- and inter-regional disparities in functional data analysis (FDA). Firstly, as a useful method for analyzing repeatedly observed data, FDA was introduced by Ramsay and Silverman (2005). It can extract information from function sets, which transform repeated measurements of individuals as smooth functions (Shang, 2017; Tsay, 2016). And then, it can comprehensively consider the change pattern of growth potential energy with the help of the first and second derivative curves (Ruiz-Medina et al., 2014). What is more, it has been applied in various fields, such as energy security (Wang et al., 2020), genetic association research (Reimherr et al., 2014), water quality index model (Li et al., 2017), pattern recognition in computer graphics (Zipunnikov et al., 2011). It should be noted that creating a dynamic index in FDA is thought to be doable (Wang et al., 2020). This confirms its potential in the field of the dynamics of HQED.

In view of the necessary of dynamic measurement of HQED, we portray the evolution trajectory of China's HQED and trace sources of its spatial-temporal disparities in this paper. To be specific, first of all, we establish a high-quality economic development indicator system consistent with the connotation of the new normal of the economy, to accurately portray high-quality economic development index curve. Then, we employ the functional ANOVA to examine the significance of regional disparities of HQED, including absolute levels and dynamic growth potentials. Finally, by using the functional Dagum Gini coefficient, we measure the dynamic evolution of regional disparities in China's HQED and quantitatively trace the sources of disparities in HQED. The following are the innovations of this paper: (1) we discuss the evolution trajectory of HQED from eight economic regions in China, breaking the limitation of previous research based on only three or four regions. (2) HQEDI(t) established in this paper can measure the evolution trend of HQED based on dynamic weights. (3) we enrich the research perspective on the disparities test of HQED based on the static absolute level and the speed level. (4) we dig the disparities sources of HQED from the perspective of time variability and clarify the dynamic change process of the dimensions of the disparities sources.

In light of the dynamic time-varying nature of China's HQED, this paper contributes in developing a functional framework to continuously quantify the time-varying evolution and to trace the source of the spatial-temporal disparities in China's HQED. In contrast to existing studies on measuring the static level of HQED upon discrete data, the proposed

functional framework is particularly useful for identifying the dynamically evolving law of HQED in the context of continuous curves. To the best of our knowledge, our work is first introducing FDA to investigate the dynamics in the development of China’s high-quality economy. In terms of China’s provincial high-quality economic development data from 2000 to 2020, we aim to portray the continuous trajectories of provincial HQED evolution and trace the sources of spatial–temporal disparities in China’s HQED from both static and dynamic perspectives. Thus, the empirical results could provide accurate and real-time decision-making references for further improving HQED in China. The remaining part of this paper are as follow. Section 2 describes regions division and indicators system. Section 3 shows method used in this paper. The results are showed in Sect. 4. Section 5 elaborates discussion. Section 6 conducts the paper and puts forward relevant policy recommendations. Figure 1 shows the theoretical framework in this paper.

2 Conceptual framework

2.1 Definition and indicator system of HQED

Fundamentally, achieving HQED in the new era is the requirement of a modern economic power (Quan, 2018). HQED not merely to meet people’s aspirations, but also emphasize the improvement of goods and services quality, input–output efficiency, and economic

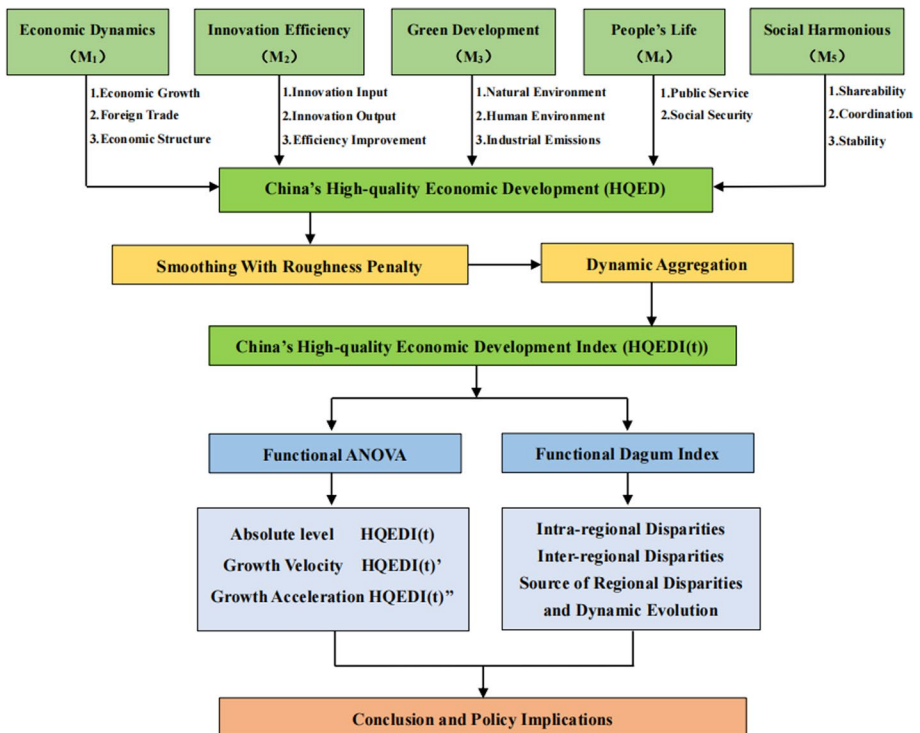


Fig. 1 Theoretical research framework

benefits (Guo et al., 2020). A new era, according to Ren and Li (2018), demands us to give up the old model of economic growth centered on quantity. Then, HQED mandates that we attach the critical importance of new ideas, emphasize the driving force's effect, and travel the path of civilized growth.

In this paper, in light of the indicator selection method of Wei and Li (2018), connotation of HQED theory, and China's own pattern, we define HQED as a model that covers five dimensions, including economic dynamics, innovation efficiency, green development, people's life, and social harmony. As a result, we construct a HQED index system including 5 dimensions, 14 elements, and 36 indicators. To be specific, economic dynamics are the material foundation for China's HQED. It is reflected in three aspects of economic growth, foreign trade, and economic structure in this paper. Innovation efficiency is a constraint factor, determining velocity, efficiency and sustainability of development (Zhang & Huang, 2020). It is necessary for HQED to strengthen scientific and technological innovation and production efficiency. Then, three indicators, including innovation input, innovation output, and efficiency improvement, are selected for this dimension in this paper. Green development is necessary, as destruction of environmental carrying capacity and aggravation of pollution will hinder HQED. Therefore, it is essential for us to conserve resources and advocate green development. For this dimension, the indicators of natural environment, human environment and industrial emissions are selected. What is more, dimensions of people's life are the reflection of people's basic subsistence and living conditions, which involve clothing, food, housing, transportation, education, and medical care. In this paper, we consider two aspects of public services and social security, and we propose seven indicators to measure dimensions of people's life. Three features of sharing, coordination, and stability are reflected in this paper as three ways that social harmony mirrors HQED's internal criteria. As can be seen in Table 1, the five dimensions impact and interact with one another to form an indicator system for calculating China's HQED.

2.2 Measurement region and data description

For a long time, China's HQED has focused on four regions: East, Central, West and Northeast. Due to the vast territory of China, it is a country with obvious regional disparities, which leads to development status of each region varies greatly ().The previously regional divisions no longer adopt the development of new era. In this paper, we divide into eight economic regions, according to regional division proposed by Development Research Center of the State Council. The specific division shows the following: (1) Northeast region (NE), including Heilongjiang, Jilin, and Liaoning. (2) North Coast region (NC), including Beijing, Tianjin, Hebei, and Shandong. (3) East coast region (EC), including Shanghai, Jiangsu, and Zhejiang. (4) South coast region (SC), including Fujian, Guangdong, and Hainan. (5) The middle Yellow River region (HH), including Shanxi, Shanxi, Henan, and Inner Mongolia. (6) The middle Yangtze River region (CJ), including Anhui, Jiangxi, Hubei, and Hunan. (7) Southwest region (SW), including Guangxi, Chongqing, Yunnan, Guizhou and Sichuan. (8) Northwest region (NW), including Xinjiang, Gansu, Qinghai, and Ningxia. Considering difficulty of obtaining data in Tibetan, it is not included in this paper. As a result, we use panel data between 2000 and 2020 from 30 provinces in China. Among them, the data used for land productivity and urban-rural income coordination level are from China Rural Statistical Yearbook. The number of beds in medical and health institutions are obtained from China Health and Family Planning Statistical Yearbook. Other basic indicators are all from China Statistical Yearbook.

Table 1 Indicator system of HQED

Dimension	Element	Indicator	Description	Attribute	Source
Economic Dynamics (M ₁)	Economic Growth	Economic growth rate (M ₁₁)	Final GNP/Base GNP	+	Chen et al., (2020a, 2020b)
		Rationalization of industrial structure (M ₁₂)	Rationalization Index of industrial structure	-	Wei and Li (2018), Lv and Cui (2020)
		Advanced industrial structure (M ₁₃)	Advanced index of industrial structure	+	Wei and Li (2018), Lv and Cui (2020)
Foreign Trade	Foreign Trade	Openness to foreign investment(M ₁₄)	Actual utilization of FDJ/GDP	+	Wei and Li (2018), Lv and Cui (2020)
		Openness to foreign trade(M ₁₅)	Total import and export trade /GDP	+	Guo et al. (2020), Chen et al., (2020a, 2020b)
Economic Structure	Economic Structure	The proportion of tertiary industry (M ₁₆)	Share of tertiary industry output in regional GDP	+	Guo et al. (2020), Hieckel (2019)
		Urbanization rate(M ₁₇)	Urban population/Total population	+	Wei and Li (2018)
		R&D funding intensity(M ₂₁)	R&D expenditure/GDP	+	Wei and Li (2018), Guo et al. (2020)
Innovation Efficiency (M ₂)	Innovation Input	R&D personnel investment intensity(M ₂₂)	Number of R&D personnel/Total employees	+	Hieckel (2019), Lv and Cui (2020)
		Number of domestic invention patents granted(M ₂₃)	Number of domestic invention patents granted	+	Lv and Cui (2020), Chen et al., (2020a, 2020b)
Innovation Output	Innovation Output	Technology market turnover share(M ₂₄)	Technology market turnover/GDP	+	Chen et al., (2020a, 2020b), Wei and Li (2018)
		Energy consumption per unit of output value(M ₂₅)	Comprehensive industrial energy consumption/Gross industrial output value	-	Wang and Gong (2018), Lv and Cui (2020), Wei and Li (2018)
		Capital productivity(M ₂₆)	GDP/ Social fixed asset investment	+	Wei and Li (2018), Lv and Cui (2020)
Efficiency improvement	Efficiency improvement	Labor productivity(M ₂₇)	GDP/ Number of employees in society	+	Wei and Li (2018), Lv and Cui (2020)
		Land productivity(M ₂₈)	Total grain production/Total cultivated land area	+	Lv and Cui (2020), Guo et al. (2020)

Table 1 (continued)

Dimension	Element	Indicator	Description	Attribute	Source
Green Development (M ₃)	Natural Environment	Greenery ownership rate in built-up areas(M ₃₁)	Total green area of built-up area/ Total population	+	Guo et al. (2020),
		Coverage rate of nature reserves(M ₃₂)	Area of nature reserve/Area of jurisdiction	+	Yu et al. (2021), Long and Ji (2019)
Human Environment	Human Environment	Comprehensive utilization rate of solid waste(M ₃₃)	Comprehensive utilization of general industrial solid waste/General industrial solid waste generation	+	Guo et al. (2020), Long and Ji (2019)
		Investment intensity of environmental pollution control(M ₃₄)	Total investment in environmental pollution control/GDP	+	Wei and Li (2018), Lv and Cui (2020)
Industrial Emissions	Industrial Emissions	Wastewater discharge per unit of output value(M ₃₅)	Wastewater discharge/GDP	-	Wei and Li (2018), Lv and Cui (2020)
		SO ₂ emissions per unit output value(M ₃₆)	Total sulfur dioxide emissions/Gross industrial output value	-	Wei and Li (2018), Lv and Cui (2020)
		CO ₂ emissions per unit output value(M ₃₇)	Total carbon dioxide emissions/ Gross industrial output value	-	Guo et al. (2020)

Table 1 (continued)

Dimension	Element	Indicator	Description	Attribute	Source
People's Life (M_4)	Public Service	Public transport vehicles per 10,000 people(M_{41})	(Total number of buses / Total population of the area)*10,000	+	Guo et al. (2020), Chen et al., (2020a, 2020b)
		Number of beds in medical institutions per capita(M_{42})	Health technicians/Total population	+	Yu et al. (2021), Chen et al., (2020a, 2020b)
	Social Security	Number of health technicians per capita(M_{43})	Health technicians/Total population	+	Guo et al. (2020), Chen et al., (2020a, 2020b)
		Number of public toilets per 10,000 people(M_{44})	(Total number of public toilets / Total population of the area)*10,000	+	Guo et al. (2020), Chen et al., (2020a, 2020b)
Social Security	Investment intensity in education(M_{45})	Financial expenditure on education/ regional GDP	+	Long and Ji (2019), Wei and Li (2018)	
	Basic medical insurance fund share of expenditure(M_{46})	Basic medical insurance fund expenditure as proportion of regional GDP	+	Yu et al. (2021), Li and Wang (2020)	
	Basic endowment insurance fund share of expenditure(M_{47})	Basic pension insurance fund expenditure as a proportion of regional GDP	+	Yu et al. (2021), Li and Wang (2020)	

Table 1 (continued)

Dimension	Element	Indicator	Description	Attribute	Source
Social Harmonious (M ₅)	Shareability	Regional income sharing level(M ₅₁)	GDP per capita by province / GDP per capita nationwide	+	Wei and Li (2018), Lv and Cui (2020)
		Regional consumption sharing level(M ₅₂)	Consumption level of residents by province / National average consumption level	+	Wei and Li (2018), Lv and Cui (2020)
Coordination	Urban and rural income coordination level(M ₅₃)	Urban-rural income ratio	Urban-rural income ratio	-	Li et al. (2021), Guo et al. (2020)
		Urban and rural consumption coordination level(M ₅₄)	Comparison of urban and rural consumption levels	-	Wei and Li (2018), Lv and Cui (2020)
Stability	The proportion of workers' compensation(M ₅₅)	The proportion of workers' compensation	The proportion of workers' compensation	+	Yu et al. (2021), Chen et al., (2020a, 2020b)
		Unemployment rate of residents(M ₅₆)	Registered urban unemployment rate	-	Chen et al. (2021), Wei and Li (2018)
		Population mortality rate(M ₅₇)	Population mortality rate	-	Lv and Cui (2020), Guo et al. (2020)

3 Methodology

3.1 Data smoothing with roughness penalty

Within the framework of functional data analysis (FDA), each indicator of high-quality economic development is considered as smoothed curves rather than discrete ordered observations. Then, the noisy observations y can transform a smooth function $x(t)$, that is $y = x(t) + \varepsilon(t)$, where $\varepsilon(t)$ satisfies Gaussian distribution assumption of i.i.d, $E\varepsilon(t) = 0; \text{var}(\varepsilon(t)) = \sigma^2, t$ represents year observed by provinces. (Ramsay & Silverman, 2005; Wang et al., 2020). Throughout the paper, t without the limits of integration refers to year observed by provinces. Motivated by the presence of noise or measurement errors and the non-smooth characteristics of observed data, we need smooth data to eliminate interference of noise. Generally speaking, the common method of curve reconstruction is the basis function expansion.

In terms of the idea that functional data can be seen as combinations of basis functions (Ramsay & Silverman, 2005), we use a series of known optimal functions $\phi = \phi(t) = \{\phi_1(t), \phi_2(t), \dots, \phi_k(t)\}^T$ to construct curves, i.e., $x(t) = \sum_{k=1}^K c_k \phi_k(t) = c^T \phi(t) = c^T \phi$, where c is estimated coefficient on Hilbert space. In general, B-spline basis and Fourier basis are two kinds of basis functions commonly used in functional data analysis. The difference is that the former fits periodic data, while the latter can handle complex fluctuation data. In this paper, we use B spline basis to fit high-quality economic development (HQED) curves. At the same time, in order to fit data and avoid information loss, we can introduce PENSSE(λ) based on minimize the residual sum of squares, as shown in formula (1).

$$\text{PENSSE}(\lambda) = \sum_j (y - x(t_j))^2 + \lambda \int (D^2x(t))^2 dt \tag{1}$$

where λ is smoothing parameter, $D^2x(t)$ represents the second derivative of $x(t)$. Obviously, the choice of penalty parameters is critical. Graven (1979) proposed generalized cross-validation method (GCV) to determine penalty parameter, which is superior to traditional cross-validation methods in solving overfitting problem. The method is usually expressed as

$$\text{GCV}(\lambda) = \left(\frac{N}{N - \text{df}(\lambda)} \right) \left(\frac{\text{PENSSE}(\lambda)}{N - \text{df}(\lambda)} \right) \tag{2}$$

where $\text{df}(\lambda) = \text{trace}(S_{\phi, \lambda})$ is degree of freedom, smoothing matrix $S_{\phi, \lambda} = \phi(\phi^T \phi + \lambda R)^{-1} \phi$, rough penalty matrix R is a $K \times K$ matrix, $R_{jk} = \int_T \phi_j''(s) \phi_k''(s) ds$, and N represents sample size. The effective premise of this method is that the number of selected basis functions is optimal, and then, the same penalty is imposed on each independent variable. However, when multivariable problems are involved, if the same penalty is added to all variables, some variables will be punished for negligence or insufficient punishment, and the optimal fitting effect cannot be obtained. To solve this problem, the original GCV method is extended to a dual-parameter approach, to obtain optimal number of basis functions and smooth parameters. The variable is defined as

$$GCV(\lambda_i, K_i) = \left(\frac{N_i}{N_i - df(\lambda_i, K_i)} \right) \left(\frac{PENSSE(\lambda_i, K_i)}{N_i - df(\lambda_i, K_i)} \right) \tag{3}$$

By adjusting (λ, K) to minimize $GCV(\lambda_i, K_i)$ to weigh relationship between degree and smoothness, the optimal number of functions and penalty parameters are adaptively selected according to the fluctuation characteristics of data. It reduces potential disturbances due to subjective determinations and enables a more accurate portrayal of HQED curves. According to Eqs. (1–3), it can be seen that each indicator is reconstructed to handle the anomalies of missing data and non-equally spaced sampling, and to provide possibility of examining dynamic potentials of velocity and acceleration from a continuous perspective.

3.2 Dynamical aggregation via functional information entropy weight

The problem of multidimensional indicator assignment is an important part of constructing high-quality economic development index. The entropy method, one of objective assignment methods, has been multiplied in social sciences field. It overcomes the problem of thinking and subjectivity of traditional assignment methods, but inevitably has its limitations. Because it defines fixed weights, ignoring the information of index weights changing over time and updating. In order to describe the trend of index change over time, we develop a functional index method. The steps of functional index method are as follows.

Step 1: Standardization of indicator functions. We use this step to eliminate differences in scale and attributes of original indicators.

The normalized formula for positive indicator is:

$$X_{ijk}(t) = \frac{x_{ijk}(t) - x_{jk}^{\min}(t)}{x_{jk}^{\max}(t) - x_{jk}^{\min}(t)} \tag{4}$$

The normalized formula for negative indicators is:

$$X_{ijk}(t) = \frac{x_{jk}^{\max}(t) - x_{ijk}(t)}{x_{jk}^{\max}(t) - x_{jk}^{\min}(t)} \tag{5}$$

where i represents province, j represents indicator, k represents indicator dimension, and t represents time. $x_{ijk}(t)$ denotes its normalized value, i.e., $x_{ijk}(t) \in [0, 1]$.

Step 2: Calculate the weight of standardized indicator. Denote $p_{ijk}(t)$ as the weight of the j -th index in the k -th dimension for the i -th province in t year. The formula is

$$p_{ijk}(t) = \frac{X_{ijk}(t)}{\sum_{i=1}^n X_{ijk}(t)} \tag{6}$$

Step 3: Calculate functional information entropy of each indicator within each dimension. If $p_{ijk}(t) = 0$, then $p_{ijk}(t) \ln p_{ijk}(t) = 0$ is defined. The information entropy $e_{jk}(t)$ of the j -th indicator function within the k -th dimension in t year is calculated as

$$e_{jk}(t) = -\frac{1}{\ln n} \sum_{i=1}^n p_{ijk}(t) \ln p_{ijk}(t) \tag{7}$$

It shows that the larger information entropy of indicator function indicates, the smaller the dispersion degree, i.e., the smaller information represented, the greater relative importance of indicator.

Step 4: Calculate indicator function weights within the dimension. The weight $w_{jk}(t)$ of the j -th indicator within the k -th dimension is calculated as follows.

$$w_{jk}(t) = \frac{1 - e_{jk}(t)}{\sum_{j=1}^m (1 - e_{jk}(t))} \tag{8}$$

Step 5: Synthesize the index function of each dimension based on weighted summary of $w_{jk}(t)$. Denote $E_{ik}(t)$ as the index function of the k -th dimension of the i -th province, and calculate as formula (9).

$$E_{ik}(t) = \sum_{j=1}^m (w_{jk}(t)X_{ijk}(t)) \tag{9}$$

Step 6: Calculate the composite index of high-quality economic development (HQEDI(t)). Taking $E_{ik}(t)$ as the object, functional entropy weight $W_k(t)$ of the composite index of M dimensions is calculated based on Eqs. (6)-(8). Given the differences in the number of indicators in different dimensions, HQEDI_{*i*}(*t*) is calculated as

$$HQEDI_i(t) = \sum_{k=1}^M \pi_k W_k(t) E_{ik}(t) \tag{10}$$

Considering whether the dimensional weight is reasonable or not is directly related to credibility of HQEDI(t), we draw on the practice of the Asian Development Bank and expand it. In Eq. (10), $\pi_k = m_k / \sum_{k=1}^M m_k$ is used to reflect the importance disparity of each dimension, due to different number of indicators. And we enhance robustness of HQEDI_{*i*}(*t*) measurement results.

3.3 The ANOVA test for functional data

Similar to variance analysis of discrete data, functional variance analysis is mainly used to compare whether multiple groups of function curves obey the same distribution. That is, to compare whether there is a significant difference in the mean between the groups. In this paper, we treat the eight regions as different groups and compare whether there are significant differences in their level of high-quality economic development. Consistent with the discrete analysis of variance, we believe that the differences between the mean values of the curves of each group mainly come from two aspects: one is the information that reflects the differences between different groups; the other is random error caused by external factors such as observation measures and environment. The process of testing the difference of high-quality economic development level in eight regions is as follows:

First, we define the category labels $i, i = 1, 2, \dots, g$, then assuming that the sample size of each group is N_i , and define the j th function curve of the i th group $x_{ij}(t), i = 1, 2, \dots, g; j = 1, 2, \dots, N$. Then, we construct a test statistic to test the difference in the mean of the curve. The specific steps of constructing the statistic are as follows:

Step 1: Let us make our null hypothesis $H0 : \bar{x}_1(t) = \bar{x}_2(t) = \dots = \bar{x}_g(t)$, i.e., the mean values of the samples are equal.

Step 2: We calculate differences between groups and within groups, and define $MSR_i(t)$ and $MSE_{ij}(t)$,

$$MSR_i(t) = \|\bar{x}_i(t) - \bar{x}_..(t)\|^2 / (g - 1) \tag{11}$$

$$MSE_{ij}(t) = \|x_{ij}(t) - \bar{x}_i(t)\|^2 / (N - g) \tag{12}$$

Step 3: We give the test statistic $F_N(t)$,

$$F_N(t) = \frac{\sum_{i=1}^g MSR_i(t)}{\sum_{i=1}^g \sum_{j=1}^{N_i} MSE_{ij}(t)} = \frac{\frac{1}{g-1} \sum_{i=1}^g N_i \|\bar{x}_i(t) - \bar{x}_..(t)\|^2}{\frac{1}{N-g} \sum_{i=1}^g \sum_{j=1}^{N_i} \|x_{ij}(t) - \bar{x}_i(t)\|^2} \tag{13}$$

where $\|x(t)\| = (\int x^2(t)dt)^{1/2}$, $\bar{x}_i(t) = (\overline{x_i(t_1)}, \dots, \overline{x_i(t_T)})^T$, $\bar{x}_..(t) = (\overline{x_..(t_1)}, \dots, \overline{x_..(t_T)})^T$. Based on the above symbol representation, the equivalent form of Eq. (12) is

$$V_N = \sum_{i < j}^g N_i \|\bar{x}_i(t) - \bar{x}_j(t)\|^2 \tag{14}$$

The critical values under the significance level were calculated, respectively, $P_{H_0}\{F_N > F_{N,\alpha}\} = \alpha$, $P_{H_0}\{V_N > V_{N,\alpha}\} = \alpha$. By comparing the actual value with the critical value, we can judge whether to reject the null hypothesis.

3.4 Functional Dagum Gini coefficient decomposition

Dagum (1997) developed a new tool to decompose Gini coefficient to identify and interpret corresponding components, which has been successfully applied to investigate regional disparities. In light of the dynamic evolution trend of regional disparities of HQED, we extend traditional Dagum-Gini coefficient method in the context of FDA. The specific steps are as follows. Let G denotes the number of regions divided in China, n denotes the number of provinces in China, and $n_u(n_v)$ denotes the number of provinces in the $u(v)$ -th region. The total Dagum Gini coefficient $G(t)$ of China’s HQED can be calculated.

$$G(t) = \frac{\sum_{u=1}^G \sum_{v=1}^G \sum_{h=1}^{n_u} \sum_{r=1}^{n_v} |HQEDI_{uh}(t) - HQEDI_{vr}(t)|}{2n^2HQEDI(t)} \tag{15}$$

In Eq. (15), $HQEDI_{uh}(t)(HQEDI_{vr}(t))$ gives the HQED level of province $h(r)$ in the $u(v)$ -th region, and $HQEDI(t)$ shows the overall economic quality development index. The Gini coefficient $G_{uu}(t)$ in a certain region (such as u region) is expressed as:

$$G_{uu}(t) = \frac{\sum_{h=1}^{n_u} \sum_{r=1}^{n_u} |HQEDI_{uh}(t) - HQEDI_{ur}(t)|}{2n_u^2HQEDI_u(t)} \tag{16}$$

where $HQEDI_{uh}(t)(HQEDI_{ur}(t))$ indicates HQED of the $h(r)$ -th Province in u region.

The Gini coefficient $G_{uv}(t)$ between regions (such as region u and region v) is expressed as:

$$G_{uv}(t) = \frac{\sum_{h=1}^{n_u} \sum_{r=1}^{n_v} |HQEDI_{uh}(t) - HQEDI_{vr}(t)|}{n_u n_v (HQEDI_u(t) + HQEDI_v(t))} \tag{17}$$

In view of decomposition method of Dagum Gini coefficient, overall Gini coefficient is decomposed into:

$$G(t) = G_w(t) + G_{nb}(t) + G_t(t) \tag{18}$$

$G_w(t)$ represents the contribution of intra-regional disparities, $G_{nb}(t)$ means the contribution of inter-regional disparities, and $G_t(t)$ represents the contribution of intensity of trans-variation. The intensity of transvariation contribution represents impact of the overall gap, which is caused by the existence of cross and overlap effects in various regions. When $G_t(t) = 0$, it indicates that there is no cross term in various regions with HQED levels. The calculation formula of each part is as follows:

$$G_w(t) = \sum_{u=1}^G G_{uu}(t) p_u s_u \tag{19}$$

$$G_{nb}(t) = \sum_{u=2}^G \sum_{v=1}^{u-1} G_{uv}(t) (p_u s_v + p_v s_u) D_{uv} \tag{20}$$

$$G_t(t) = \sum_{u=2}^G \sum_{v=1}^{u-1} G_{uv}(t) (p_u s_v + p_v s_u) (1 - D_{uv}) \tag{21}$$

where $p_u = n_u/n$ represents proportion of provinces quantity in the u -th region, $s_u = n_u HQEDI_u(t)/n HQEDI(t)$ indicates the proportion of HQED level in the u -th region, and $\sum_{u=1}^G \sum_{v=1}^G p_u s_v = 1$. $G_{uv}(t)$ is disparity of HQED between the u -th region and the v -th region. D_{uv} is the relative HQED level between region u and region v . Specifically, assuming that HQED of region u is higher, we define the integral sum of HQED of provinces in region u higher than that of provinces in region v ; otherwise, it is a reverse disparity.

4 Empirical results

4.1 Identification of smoothing parameters

There is no doubt that the selection of smoothing parameters and iteration times has been an important part of data smoothing. According to the method in Sect. 3.1, we use R package “fda” (5.5.1) to smooth HQED curves. The B-spline basis function is selected, and optimal smoothing parameter λ and number of basis functions K are determined according to the minimization dual-parameter $GCV(\lambda, K)$ criterion. However, considering that fitting residuals should obey a normal distribution with zero mean and limited variance, we apply Jarque–Bera tests on the results of 36 indicators for 30 samples, respectively. The results are shown in Table 2.

It is necessary to impose penalty function independently, since a comparison with original data shows that the frequency and range of fluctuations of 36 indicators vary greatly. Comparing results of parameter selection in Table 2, we discover that curves, such as the

Table 2 The result of optimal parameter selection

Indicator	$GCV(\lambda, K)$	$(\log\lambda)_{opt}$	K_{opt}	J-B test (p -value)	Indicator	$GCV(\lambda, K)$	$(\log\lambda)_{opt}$	K_{opt}	J-B test (p -value)
M_{11}	36.0621	-1.45	15	0.4806 (0.7864)	M_{34}	2.885747	-0.85	17	3.4478 (0.1784)
M_{12}	302.5863	-2.25	19	2.9160 (0.2328)	M_{35}	84.58178	1	6	0.4955 (0.7803)
M_{13}	0.1452	-1.7	12	0.4751 (0.7886)	M_{36}	9.315583	-0.95	14	2.1986 (0.3331)
M_{14}	0.0011	-0.9	14	0.2126 (0.8992)	M_{37}	0.002589	-1	13	0.7724 (0.6796)
M_{15}	0.0384	-1.25	12	3.5427 (0.2246)	M_{41}	45.60431	0.3	13	2.0872 (0.2956)
M_{16}	47.9365	-2.75	14	1.3943 (0.4980)	M_{42}	49.6251	-0.05	10	0.3712 (0.8306)
M_{17}	4.9083	-2.4	19	2.8460 (0.2453)	M_{43}	485.4754	0.8	5	1.2952 (0.5233)
M_{21}	1.99435	-0.2	12	0.5105 (0.7747)	M_{44}	2.56051	-0.2	10	0.7589 (0.6842)
M_{22}	3.17735	-6.35	18	0.3813 (0.8453)	M_{45}	3.629804	-0.75	16	0.8051 (0.6686)
M_{23}	5,248,306	-4	17	0.9856 (0.3837)	M_{46}	0.482688	-3.5	16	1.1873 (0.3721)
M_{24}	0.00011	-0.95	8	0.2686 (0.8743)	M_{47}	2.581569	-7.05	18	0.5899 (0.7446)
M_{25}	0.10768	-2.6	16	2.8519 (0.2336)	M_{51}	0.026386	-2.3	12	1.2226 (0.5457)
M_{26}	0.43494	-3.95	16	2.5428 (0.2610)	M_{52}	0.024866	-0.9	17	2.7603 (0.2515)
M_{27}	34,308,146	-2.1	20	2.8460 (0.2453)	M_{53}	0.621596	-3.15	19	0.0360 (0.9822)
M_{28}	1.1273	1	11	0.9566 (0.6198)	M_{54}	0.517722	-0.45	12	0.4574 (0.7956)
M_{31}	16.95992	-1.7	11	0.7241 (0.6962)	M_{55}	0.002175	-0.9	19	1.3943 (0.4980)
M_{32}	14.06365	-1.95	19	0.9660 (0.9538)	M_{56}	0.838547	-1.3	8	2.7762 (0.2418)
M_{33}	875.5688	1	6	2.5428 (0.2610)	M_{57}	1.747085	-0.5	17	1.2986 (0.6745)

proportion of health technicians per capita, can be accurately reconstructed using fewer basis functions and smaller penalties. However, labor productivity, for example, requires more basis functions and larger penalties to highlight its dominant trend because of its fluctuation range. What is more, the J-B test results show that fitting residuals obey a normal distribution and satisfy the priori assumption, based on penalized smoothing parameters determined by minimizing $GCV(\lambda, K)$.

4.2 Functional high-quality economic development index (HQEDI(t))

In terms of smoothing results in Table 2 and functional entropy weight method proposed in Eqs. (4) - (10), we construct the HQEDI(t) with the inter-provincial indicators data between 2000 and 2020. Figure 2 shows functional entropy weight curves of each indicator in five dimensions. We give a functional entropy weight curve for each dimension, with fluctuations over time rather than constants. This is different from previous research weights. Each indicator weight is not averaged based on the number of indicators in the dimension, but is automatically and flexibly assigned according to data information. This verifies the importance and necessity of continuous dynamic weighting. As further explained in Fig. 2, we can find that in the dimension of economic vitality and people’s life, each index has no significant leading factor. On the contrary, in the dimension of social harmony, the level of regional consumption sharing is the most important factor. The principal contradiction facing China today is that between the people’s desire for a better life and unbalanced and inadequate development. Export, investment and consumption have always been known as the three driving forces of China’s economic growth, and the prosperity of the consumption industry has promoted the sustained, healthy and stable development of the economy. Therefore, it is clearly pointed out in the 14th Five-Year Plan that we should fully stimulate regional consumption potential and deduce high-quality economic development. As a result, Beijing, Tianjin, Shanghai, Guangdong and Chongqing became the first five major international consumer cities in China.

Meanwhile, in order to examine dynamic evolution process of China’s HQED from perspective of these dimensions, we draw functional entropy weights in five dimensions. As can be seen from Fig. 3, it shows functional entropy weights for five dimensions of HQED between 2000 and 2020. We find that the indicators and dimension entropy weights of China’s HQED change during the over observation period.

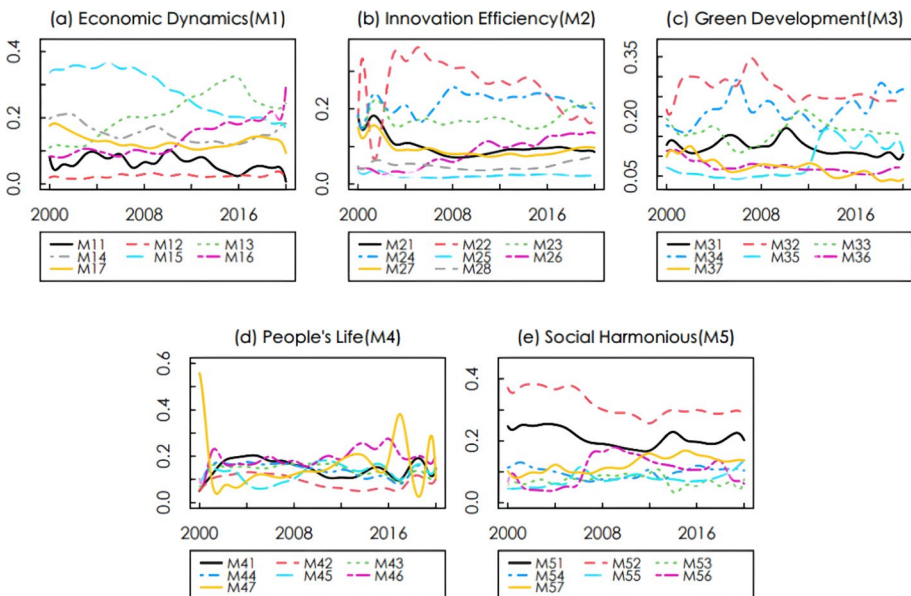


Fig. 2 Weight curves of indicators in five dimensions

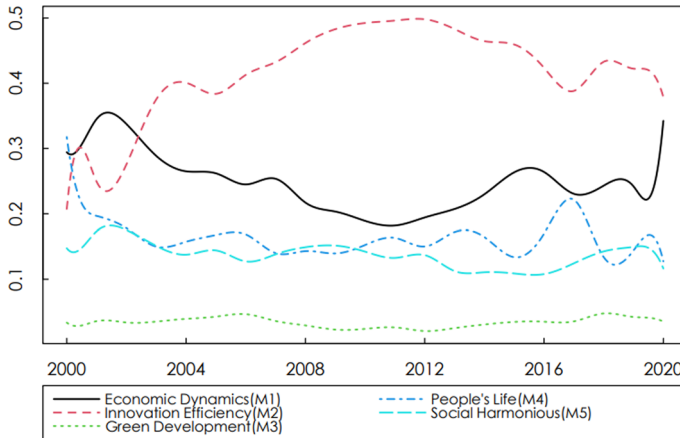


Fig. 3 Weight curves of five dimensions

Specifically, the general trend of dimension changes is as follows: innovation efficiency > economic dynamics > people's life > social harmony > green development. We find that economic dynamics remain an important factor in determining the level of headquarters in China, but not the dominant factor. This is an interesting finding. In contrast, functional entropy weight of innovation efficiency is concentrated in [0.215, 0.493], and it always higher than the other four dimensions after 2003, showing an increasing trend. China's economy is in a critical stage of transforming growth mode, optimizing economic structure, and transforming growth momentum (Ma et al., 2019). Quality first and benefit priority have become important criteria for measuring development. Innovation efficiency is the first driving force for China's HQED, and this verifies the result of Chen et al., (2020a, 2020b). As a result, innovation efficiency provides new growth space for China's HQED. In the future, China will promote reform in quality and efficiency through innovation.

In order to portray spatio-temporal evolution pattern of China's HQED and explore characteristics of regional development, we construct high-quality economic development index curve (HQEDI(t)). Figure 4 shows the mean curve of high-quality economic development index in eight major regions of China and the national average curve. The gray curve is the actual high-quality development index curve of each province. Furthermore, Fig. 5 gives the trajectory of HQEDI(t) for each province in China's eight regions. We find that, overall, HQEDI(t) is primarily distributed between [0.05, 0.075]. The overall level is not high, but it shows a steady growth trend, indicating that China's HQED is generally improving. In particular, China's economy has paid more attention to high-quality development and accelerated its growth rate since 2017, and thus, its development level has been significantly improved. From the perspective of eight regions, on one hand, the average value of HQEDI(t) shows an increasing trend, and then, this trend is obvious in the later period. On the other hand, we find that the regional average high-quality development level presents two distinct distinctions. Among them, the coastal areas are higher than the national average level, while the Yangtze River, the middle reaches of the Yellow River, the northwest and the southwest are lower than the national average; in addition, the northeast area is close to

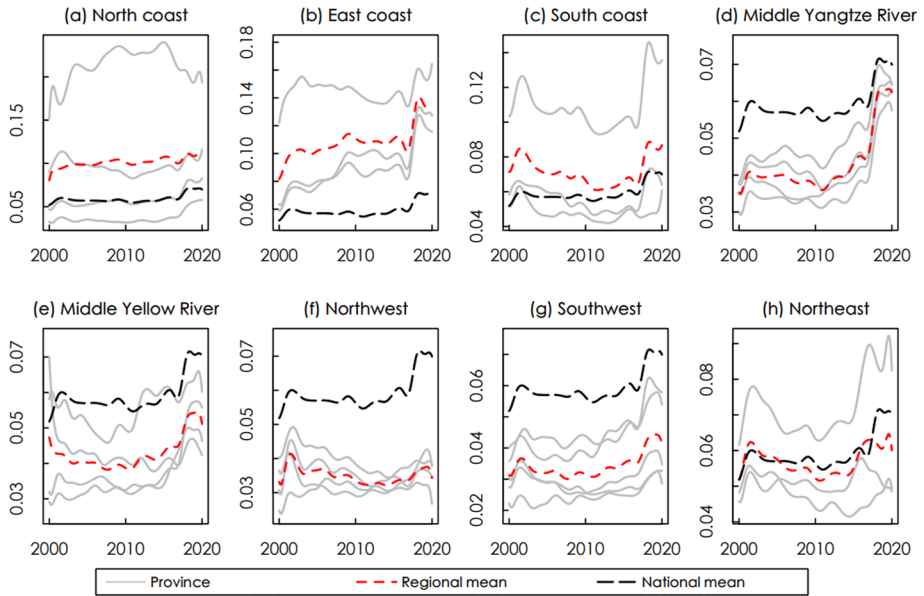


Fig. 4 National, regional, and provincial HQEDI(t) curves in China

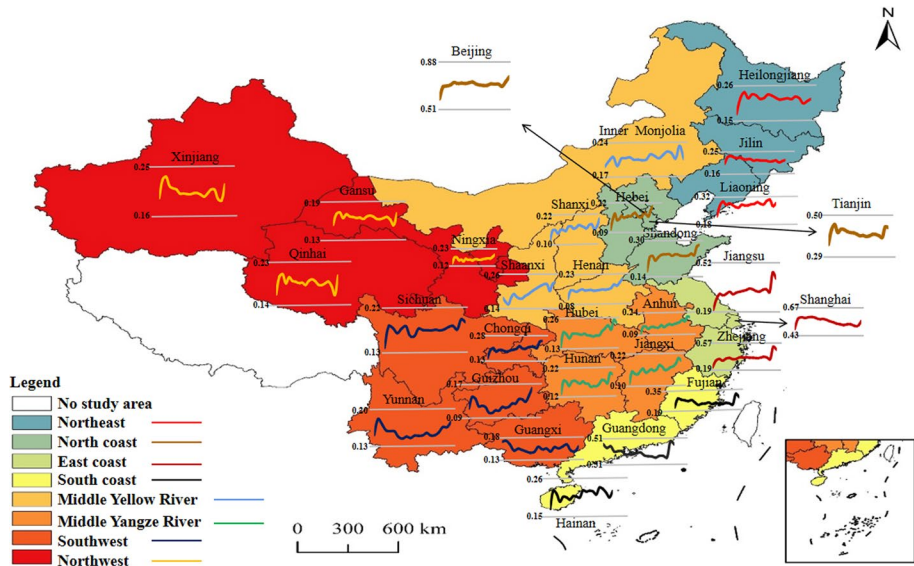


Fig. 5 Geographic distribution of China's HQED

the national level. A similar conclusion can be found in Guo et al. (2020). In general, China's HQED shows a decreasing spatial distribution pattern of “east coast—north coast—south coast—northeast—middle reaches of Yangtze River—middle reaches of Yellow River—southwest—northwest.”

4.3 Static and dynamic disparity test of HQED via functional ANOVA

In order to further test whether there is a significant difference between the static absolute level and dynamic potential energy of China's HQED in the eight regions, functional ANOVA is used to test the index curve of HQED. Considering that the bootstrap method can simulate unknown distribution through a large number of put-back resamples, the probability of rejecting the null hypothesis that the means of HQEDI(t) are equal can be calculated. The result of 300 cycles from the original sample can be shown in Fig. 6a–f. From the absolute level, in Fig. 6 a and d, it is roughly found that the average value of national and eight regional HQEDI(t) is different in value, while the fluctuation trend is roughly same. When the significance level is 5%, the P-value is 0.0033 in Fig. 6d, indicating that there are significant disparities in the absolute level of HQEDI(t) in eight regions. In Fig. 6b and e, there are significant disparities in the velocity of HQEDI(t), since the P-value is 0.03 at the 5% significance level. Similarly, we find that disparity of acceleration of HQEDI(t) in eight regions is not significant at the 5% level, with P-value is 0.14 in Fig. 6c and f. Although China has implemented development policies, the HQED level of eight regions has achieved growth, and there is still a gap between the absolute level and growth velocity of HQEDI(t), due to the differences in energy and resources.

4.4 Regional disparities decomposition of HQED

In Sect. 4.3, we examine regional differences in absolute level and growth rate of HQEDI(t) in China. It is very necessary to dig into the internal source behind this difference by the functional Dagum Gini coefficient decomposition. In this section, we construct the Dagum

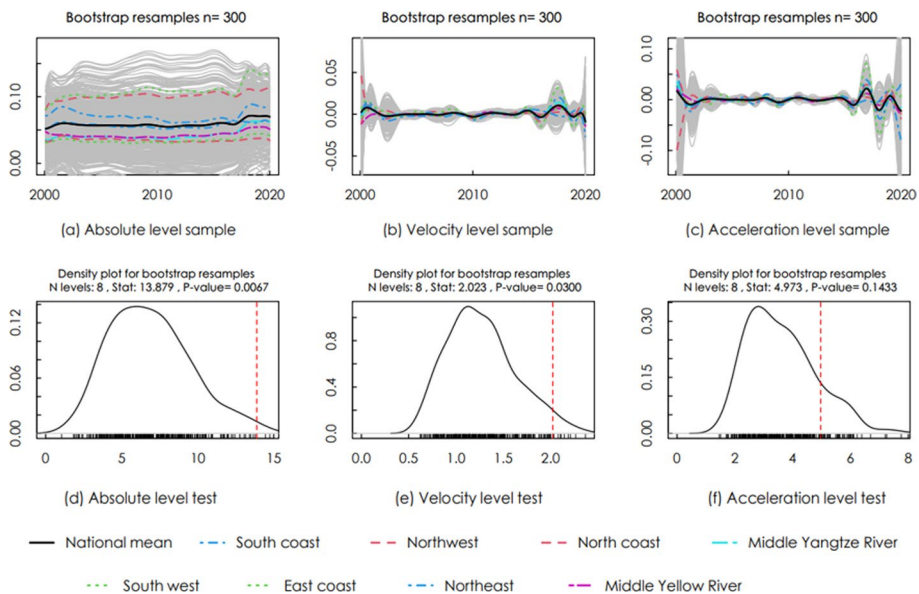


Fig. 6 Functional ANOVA test for regional disparities in absolute level, velocity and acceleration of HQEDI(t)

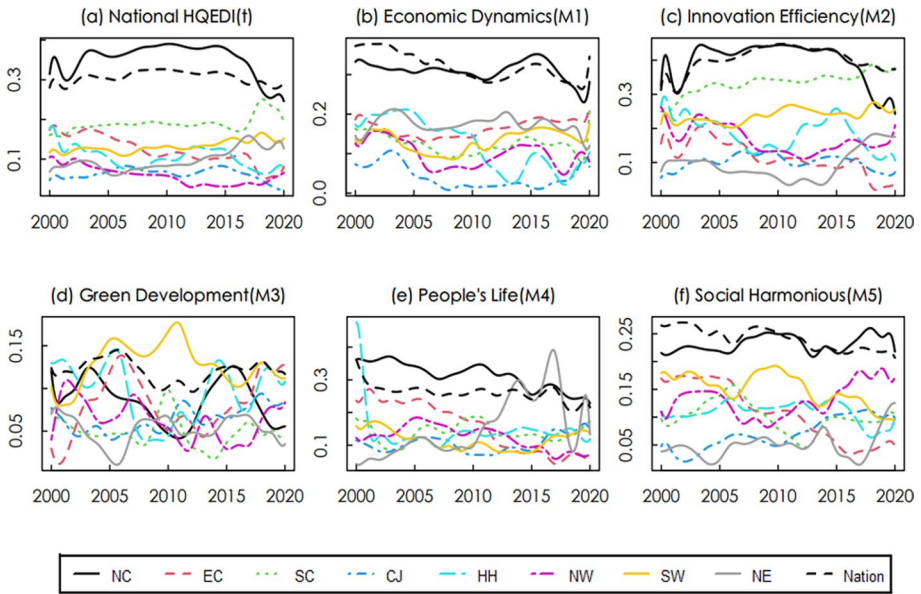


Fig. 7 The dimensional sources for intra-regional disparities

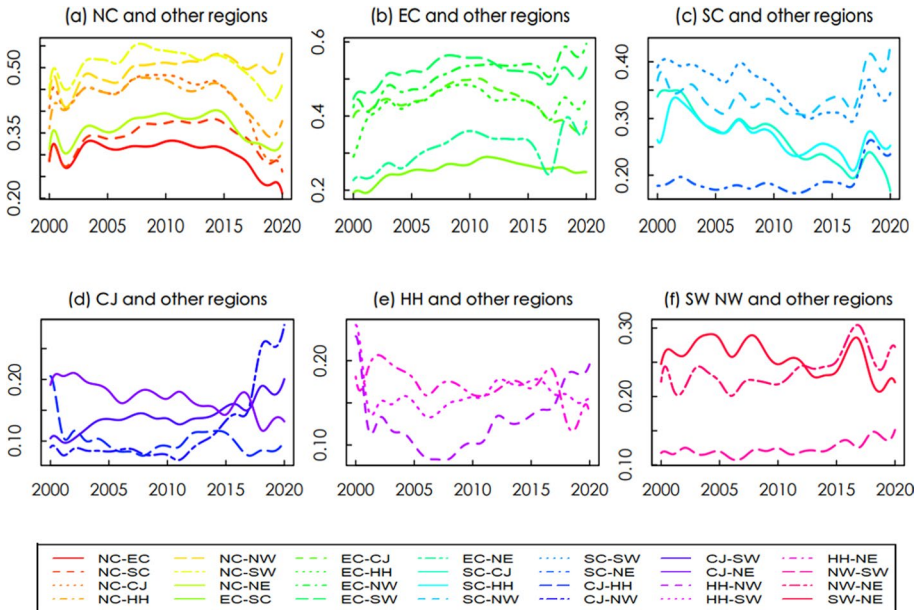


Fig. 8 The dynamic evolution of inter-regional disparities

Gini coefficient curve to analyze the dynamic evolution and internal causes of the difference in the level of high-quality economic development in China from 2000 to 2020. The results are as in Figs. 7, 8 and 9.

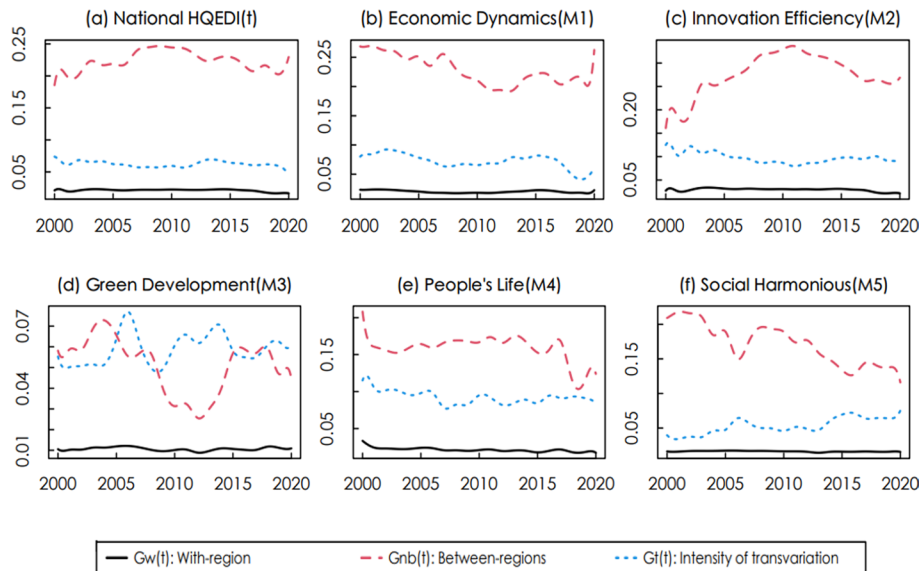


Fig. 9 The disparity decomposition of Gini coefficient in five dimensions

Intra-regional disparities and dynamic evolution.

According to the expression of the calculated Gini coefficient curve, Fig. 7 shows the continuous trajectory of intra-regional differences of HQEDI(t) based on Gini coefficient decomposition in eight regions of China under the global dimension and five dimensions. As shown in Fig. 7a, the overall HQED level in China varies significantly, with Gini coefficient between [0.285, 0.325]. From the perspective of dynamic evolution, the overall regional disparities in China's HQED show a trend of decline in fluctuation, which means that the overall regional coordination of HQED is gradually improving. Figure 7b–f shows the decomposition results of HQEDI(t) in five dimensions in eight regions based on Gini coefficient. From the perspective of intra-regional disparities in China's eight regions, first of all, Gini coefficient in north coast region is the highest, with intra-regional disparity significantly higher than that of the other seven regions, followed by south coast region, while disparity in the northwest region is the smallest. This verifies that the northern coastal areas account for the largest proportion in the national level of HQED, which has been pointed in Fang et al. (2021). Then, we notice that the situation of northeast, south coast, and southwest regions is different from that of the other five regions, showing an upward trend. This means that disparities among provinces in the Northeast, south coast, and Southwest regions are gradually increasing. What is more, we find that the disparities within Southwest China are the most prominent in the dimension of green development, which is a new finding in this paper. During the 10 years from 2005 to 2015, it showed a significant increase trend, and the disparities within the region were significantly higher than that in other regions. In contrast, intra-regional disparities are at a lower level in the dimension of people's living. Surprisingly, from 2005 to 2015, Northeast China had the smallest intra-regional disparities in innovation efficiency and social harmony dimension, but after 2015, Northeast China showed an increasing trend. Meanwhile, in combination with the historical background, we further explore the reasons of such dimensional differences in

the discussion section. In view of this, Chinese government should pay attention to distinguishing deep-seated reasons for formation of regional disparities when formulating the strategy for coordinated HQED.

Inter-regional disparities and dynamic evolution.

Based on the overall HQED level curve, we further explore its regional disparities in eight regions, and the specific results can be found in Fig. 8. In Fig. 8a–f, we find that there are significant differences in terms of the inter-regional Gini coefficient. On the whole, through the three figures in the first row of Fig. 8, we find that the disparities between the east, north and south coasts and southwest regions are significant, while the differences between coastal areas are not significant, geographical factors may be a factor restricting the HQED of inland areas. What is more, we can also find that the disparities between the northwest and southwest regions are not significant, showing a trend of increasing differences after 2015. Furthermore, the disparity between the north coast region and the southwest region shows a fluctuating downward trend, while the disparity with the northwest region shows a gradual upward trend. The disparities between the southeast coast regions and the southwest region are gradually narrowing, while the disparity in the northwest region is gradually increasing. In addition to the sharp increase in regional disparity between the middle Yangtze River and the southwest, most of regional disparities show a downward trend, which verifies that the level of coordinated development among regions is increasing. We will analyze the reasons behind it in detail in the following discussion section.

Source of regional disparities and dynamic evolution.

Furthermore, according to the theory of Dagum (1997), we decompose the national average level of HQED into intra-regional and inter-regional disparities in the overall dimension and the five dimensions, so as to reveal the sources of China's HQED regional disparities. As we can be seen, Fig. 9 shows disparity decomposition results of Gini coefficient. On the whole, the regional disparities in China's HQED mainly come from the inter-regional disparity, with the range of variation between [0.18, 0.25]. Similar conclusions can be found in Lv et al. (2020). At the same time, we find that the contribution of intra-regional disparity and inter-regional intensity of transvariation are close with a low level, indicating that they are not the main reasons caused regional disparity. Therefore, in order to solve regional disparity in HQED, it is necessary to reduce inter-regional disparity and promote coordinated China's economy.

From the perspective of five dimensions, the overall disparity decomposition is generally similar to HQED of China's, including economic dynamics, innovation efficiency, people's life and social harmony. The inter-regional disparity contributes the largest, while intra-regional disparity and inter-regional intensity of transvariation contribute a small share. In addition, we find that the contribution ratio of regional disparity decreases over time in the dimensions of people's lives and social harmony. However, since 2002, the proportion of regional differences increase sharply in the dimension of innovation efficiency and become stable after 2015. Specially, the curve of inter-regional disparity has an "inverted U" shape in the dimension of green development, with the turning point at around 2012. The reason may be that various regions pursued high-speed economic growth, which brought air pollution and environmental damage. After 2012, China no longer unilaterally pursued quantitative growth with a high GDP growth rate, but changed to pursue high-qualitative development. Although green development has been gradually advocated, it is worth noting that the degree of green development in different regions is not the same.

5 Discussion

In view of the above results, we combine the current situation and policy to further discuss and analyze the reasons. In essence, HQED is a continuous process that changes over time. In this paper, the traditional index model is expanded, and the functional HQED index model is innovatively constructed, which has been improved in the interpretation of results. In contrast to previous static studies (Ma et al., 2019; Long et al., 2019; Jiang et al., 2021; Dai et al., 2022), we convert the discrete observational indicator data into smooth curve functions by using smoothing techniques in FDA. As a result, we can capture the dynamic changes of each indicator at a time interval by constructing HQEDI(t). In addition, static weights can hardly reflect the changes in the relative importance of different dimensions over a long period of time (Wang et al., 2020). The weights constructed in this paper are data-driven dynamic weights that change over time, and the weight allocation of dimensions can be reasonably adjusted to ensure the scientific and robust results. Meanwhile, in terms of the whole research results, as shown in Figs. 4 and 7, the intra-regional and inter-regional disparity are dynamically changing rather than fixed coefficient values. This may be different from the results of HQED measurement and disparity decomposition based on discrete panel data (Li & Lei, 2021; Sun et al., 2020).

Results show that the overall level of HQED in China has steadily improved, and the regional average HQED presents two distinct distinctions. Among them, the coastal areas are higher than the national average level, while the Yangtze River, the middle reaches of the Yellow River, the northwest and the southwest are lower than the national average. It shows a spatial decreasing distribution pattern of “coastal regions > northeast region > middle reaches of the Yangtze River > middle reaches of the Yellow River > western regions.” This confirms the existing research that inland geographical factors may be a major factor restricting HQED (Li et al., 2016; Yuan et al., 2022). Since the reform and opening-up, China has taken action in implementing the unbalanced development strategy in coastal regions, which has injected vitality into rapid development of coastal regions (Zhang & Huang, 2020). In contrast, although west regions are also supported by many large-scale strategies, HQED is correspondingly low (Guo et al., 2020). The root may be a series of reasons, such as their late development, lack of capital, and brain drain. At the same time, China is a vast country with an uneven distribution of population and natural resources (Tian et al., 2018; Zhou et al., 2020). The material and cultural foundations resulting from historical development, including natural and human factors, undoubtedly bring about dynamic disparities in regional development. As a result, government should formulate development policies in various regions with local conditions and tilt more development resources to less developed areas.

Additionally, the overall disparity in China's HQED is large, but shows a downward trend in fluctuation. This confirms the findings of existing studies (Liu et al., 2021; Lv & Cui, 2020). The report of the 20th National Congress of the Communist Party of China again pointed out that China's economy has shifted from the stage of high-speed growth to the stage of high-quality development, and HQED has become the new direction of China's economic development in the future (Xie et al., 2022). As a result, disparity in the overall level of HQED between regions is narrowing. Then, the intra-regional disparity in the northern coastal areas is significantly higher than those in other areas. The northern coastal region includes Beijing, Tianjin, Hebei and Shandong provinces. As a super city in China, Beijing is far ahead in terms of its comprehensive strength. It has a solid economic foundation, strong scientific and technological innovation capacity, profound

cultural and educational heritage, and considerable political resources. In contrast, Hebei has lower HQED level due to its weak scientific and technological innovation and industrial efficiency. This deviation leads to the imbalance of development within the northern coastal areas. What is more, from 2005 to 2015, Northeast China had the smallest intra-regional difference in innovation efficiency and social harmony dimension, but after 2015, it showed an increasing trend. The economy of Northeast China has developed rapidly, since it was used as the base of China's heavy industry. In the context of industrial transformation, Northeast China is committed to the overall structural transformation and emphasizes coordinated development, so the HQED in the past 10 years is relatively balanced (Ren & Li, 2018). The rapid development of trade in Liaoning relies on the advantages of coastal ports, and the HQED of the three provinces in Northeast is gradually increasing.

Based on the results of the inter-regional disparities in eight regions, it is worth paying further attention to the fact that disparities between three coastal regions and southwest region have shown a decreasing trend in recent years, while disparities with northwest region have been rising year by year. Due to own location factors and objective conditions, the southwest and northwest regions still have many weak links in HQED. In recent years, growth momentum of the southwest region has been significantly stronger than that of the northwest region (Deng et al., 2022). Among six state-level new areas in western China, the southwest region accounts for 2/3 (Zhang, 2022). Northwest region has been caught in the development dilemma of double disadvantage in industrial structure and competitiveness. In contrast, the southwest region has been developing rapidly, with strong tourism industry and rational industrial layout.

6 Conclusions and policy recommendations

Accurately portraying the evolution trajectory of China's HQED and tracing sources of its spatial–temporal disparities are of great significance for promoting balanced and healthy economic development. First, we construct a functional high-quality economic development index (HQEDI(t)), which is used to measure the dynamic weight of high-quality economic development level in the past two decades under the background of FDA. Subsequently, we use functional ANOVA to test whether there are significant differences in the absolute level, velocity and acceleration of HQEDI(t) in each region. Then, with the help of functional Dagum Gini coefficient, we trace sources of intra-regional and inter-regional disparities in HQED. Compared with the traditional index method, we vary flexibly with the number of indicators contained in the dimensions, and we balance the information adequacy among dimensions using penalty parameters. Thus, different conclusions can be found in this paper:

(1) Based on the dynamic weight level of constructing the high-quality economic development index, the dimension proportion show a distribution pattern of “innovation efficiency > economic dynamics > people's life > social harmony > green development.” In terms of geographical area, China's HQED shows a decreasing distribution pattern of “coastal regions—northeast—middle Yangtze River—middle Yellow River—west regions.” (2) There are regional disparities in China's HQED. A significant regional imbalance exists only in the absolute level and velocity of HQED, but not in its acceleration. (3) The overall regional disparities of China's HQED show a downward trend, and inter-regional disparities are the dominant factor in the overall regional disparities. (4) What is more, the disparities between three coastal regions and northwest region are the most

significant, while the disparities in the north coast region are the most prominent. For the North Coast region, intra-regional disparities in the innovation efficiency dimension are major. For Southwest China, green development is the biggest driving force for high-quality and balanced economic development.

Given that the results of dynamic evolution and spatial characteristics in China's HQED, we offer the following advice. (1) Given the dominant position of innovation efficiency dimension in HQED, the government should continue to adhere to innovative development and enhance synergy, effectiveness, and equity of development, in order to guarantee strength and space for reforms in other dimensions. (2) Due to a large difference in HQED of China's eight regions and the low overall development level, China should concern the issue of HQED, including optimize industrial layout, focus on efficiency and innovation, expand employment surface, balance residents' income, and improve social security mechanism. (3) The inter-regional disparities are main source of regional disparities in HQED, and the disparities between three coastal regions and northwest region are relatively large. Government should formulate development policies in various regions according to local conditions and tilt more development resources to less developed areas. Regions should take advantage of their strengths and leverage the platform of national HQED strategy to achieve a new situation of coordinated regional development.

Compared with the existing studies, the approach in this paper has the following advantages: (1) Using functional entropy weight method to objectively determine the relative importance changes of different dimensions and indicators; (2) A penalty parameter that varies flexibly with the number of indicators contained in each dimension is adopted to balance the information adequacy among all dimensions; (3) additional information is provided, such as growth potential energy to measure the HQED; (4) data constraints are relaxed to measure the trajectory of the HQED level in real time. Although we provide a novel approach for dynamically portray China's regional HQED, some practical extensions call for future research. Functional convergence model can be further used to track the evolution path of HQED, explore its coordinated development process, and then, study its absolute convergence and conditional convergence properties under control variables. Secondly, in the context of spatial functional data analysis, if geographical location weighting matrix can be considered to establish a spatial functional regression model, it is an interesting topic to explore the factors leading to regional differences from the perspective of spatial heterogeneity.

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Data availability The datasets generated or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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