

Coupling and Coordinated Development of the Digital Economy and Economic Resilience in the Pearl River Delta under the Background of a Unified National Market

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Abstract

Against the backdrop of China's ongoing efforts to build a unified national market, the coordinated evolution of the digital economy and economic resilience has become central to regional high-quality development. Using panel data for nine cities in the Pearl River Delta from 2012 to 2022, this study constructs evaluation indicator systems for the digital economy and economic resilience, and applies the entropy weight method, coupling coordination model, obstacle degree model, and spatial visualization to examine their development levels, coordination dynamics, spatiotemporal patterns, and key constraints. The results show that both systems improved over the study period, with faster and more volatile growth in the digital economy and steadier gains in economic resilience. Spatially, both systems show a core-periphery pattern, with the three subregions of Shenzhen–Dongguan–Huizhou, Guangzhou–Foshan–Zhaoqing, and Zhuhai–Zhongshan–Jiangmen forming an increasingly distinct spatial gradient in the later years. High-value digital economy areas are concentrated in Guangzhou, Shenzhen, and nearby cities, while economic resilience shows a more stable hierarchy, with manufacturing-based cities such as Foshan and Dongguan gradually catching up and peripheral cities improving more slowly. Coupling coordination also improved overall, though with periodic fluctuations, and the improvement in coordination was mainly associated with the simultaneous rise in the comprehensive development levels of the two systems. The main obstacles to the digital economy are employment in knowledge-intensive service industries and per capita telecommunications business volume, whereas those to economic resilience are R&D expenditure, industrial structure coordination, and patents granted per 10,000 people. These findings suggest the need for differentiated policies that strengthen the capacity of lagging areas, align digital development with resilience building, and reinforce regional resilience through innovation investment and structural upgrading.

Keywords

digital economy, economic resilience, coupling coordination, obstacle factors, pearl river delta, unified national market

1. Introduction

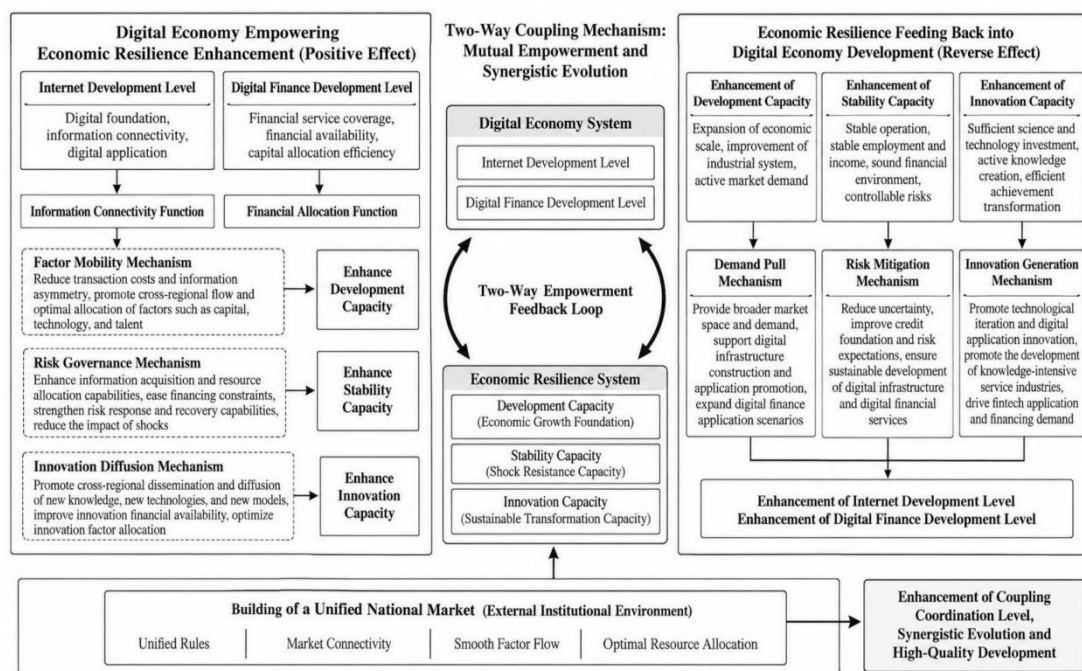
The establishment of a united national market is one of the institutional arrangements that will smoothen internal circulation and create a new development pattern. The essence of the approach is to eliminate local protectionism and market segmentation and facilitate the free movement and optimal distribution of goods and factors of production over a larger scale [1]. Under these conditions, the digital economy, which is based on the circulation of data elements, platform connectivity, and information diffusion, may partially weaken the market segmentation and increase the degree of market integration, and therefore be regarded as an important technological tool in the construction of a unified national market [2]. Economic resilience is the total ability of a regional economy to withstand shocks, absorb disturbances, recover and adapt, and transform and upgrade itself, and it is one of the key bases that ensure the steady performance and sustainable growth of the regional economy [3]. Current literature has already provided quite diverse findings regarding the conceptual definition, indicator measurements, and mechanisms of the digital economy [4-9] as well as the conceptualization, measurement, and determinants of economic resilience [3,10-13]. Nevertheless, there are not many works that would fit the context of building a unified national market into some common analytical perspective of the digital economy and economic resilience, and the issue of how unified rules, market connectivity, and smooth factor flow impact their joint development is not well discussed. Simultaneously, the study of the interaction coordination between the digital economy and economic resilience in the Pearl River Delta is not very deep, particularly the lack of overall recognition of its spatiotemporal evolution features and critical restrictions.

Within the framework of developing a unified national market, there is a constant increase in unified regulations, interconnected markets, fluid movement of factors, and effective distribution of resources, and the issues of interregional market segmentation, transaction costs, and misallocation are slowly resolved [14], which reinforces the foundation of two-way interaction between the digital economy and economic resilience. In terms of positive impacts, the Internet and digital finance development levels, which depend on the functions of information connectivity and financial allocation respectively, influence regional development capacity, stability capacity, and innovation capacity via the factors of mobility (factor mobility), risk governance, and innovation diffusion. Through the factor mobility mechanism, the development of the Internet can boost information connectivity and digital applications, lower transaction costs and information asymmetry, and facilitate the cross-regional flow and optimal distribution of factors such as capital and technology [15]; digital finance can extend the scope of financial services and alleviate the problem of financing constraints and enhance the efficiency of capital allocation [16, 17], thus increasing the regional development capacity. Through the risk governance mechanism, the development of the Internet can boost information acquisition, resource allocation, and adaptive adjustment abilities, as well as increase the absorptive and recovery capabilities of the regional economy in the case of external shocks [18]; digital finance can enhance the accessibility to external capital for market participants and decrease the adverse effects of shocks on the operational stability of businesses [19], thus improving the regional stability capacity. Through the innovation diffusion mechanism, the digital connectivity and application capacity created by Internet development can stimulate cross-regional spread and dissemination of new knowledge, new technologies, and new models, and promote technological innovation and industrial restructuring and upgrading [20]; through fintech and digital inclusive finance, digital finance can make the financial access to innovation activities better and fund innovation and entrepreneurship and development of emerging industries [21], hence promoting regional innovation capacity. On the reverse, development capacity, stability capacity, and innovation capacity respectively offer support to Internet development and digital finance development by demand pull, risk mitigation, and innovation generation mechanisms. Improving the development capacity will expand the field of practice of digital infrastructure development, digital application promotion, and digital finance application; the improvement of stability capacity will help to minimize the uncertainty of operation of platforms and extension of digital financial services, improving the credit base and expected risks; the improvement of innovation capacity, with the help of accumulating science and technology investments, knowledge creation and achievement transformation capabilities, drives the iteration of digital technologies, digital application innovations and fintech development. Hence, the digital economy and economic resilience constitute a reciprocal coupling relationship that reads as follows: the digital empowerment leads to improved resilience, and increased resilience is fed back into the process of digital development, and within the context of developing the unified national market, this interaction becomes a coordinated evolution at the regional level. It means that the coordination level of the two does not only indicate how well digital development and

economic resilience building match, but it also gives an insight into the understanding of their regional coordinated evolution in the situation of a unified national market.

On this basis, the current study takes the nine cities of the Pearl River Delta of 2012-2022 as the research objects, establishes an index system for evaluating the digital economy and economic resilience, and applies the entropy weight method, coupling coordination degree model, obstacle degree model, and spatial visualization methods to investigate in an organized manner the development stages, coupling coordination conditions, spatiotemporal differentiation properties, and main restrictions of the two systems. Relative to current research, this paper also analyzes the relationship of the coupling between the digital economy and economic resilience by looking at it in terms of the two-way interaction mechanism and incorporating both spatiotemporal evolution analysis and identification of obstacle factors to describe the spatial differentiation and evolutionary characteristics of coordinated development of the two systems, identify their key sources of constraints, with the aim of giving an empirical perspective of regional coordinated development and resilience building under the framework of a single national market.

Figure 1: Coupling coordination mechanism between digital economy and economic resilience under the unified national market



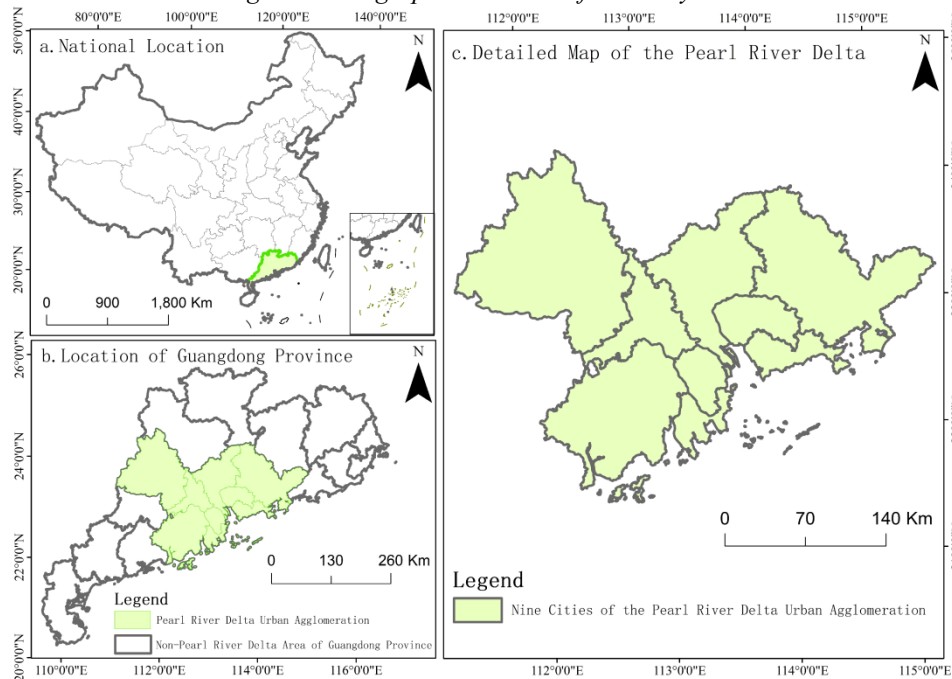
2. Study Area, Methods, and Data

2.1 Overview of the Study Area

The Pearl River Delta area lies in the central-southern part of Guangdong Province and consists of nine cities, namely Guangzhou, Shenzhen, Zhuhai, Foshan, Huizhou, Dongguan, Zhongshan, Jiangmen, and Zhaoqing. This is a significant component of the Guangdong-Hong Kong-Macao Greater Bay Area and also a border region to create a unified national market, digital transformation, and regional balanced development (see Figure 2). Having a strong background in manufacturing, a relatively large degree of openness, and well-established intercity connections, the region has a realistic basis to develop the digital economy at a relatively high pace, but also has a typical importance to watch the evolution of economic resilience and mutual interaction of the two systems. Between 2012 and 2022, the Pearl River Delta still made progress in the construction of digital infrastructure, industrial upgrading and regional coordination, but there were still significant gradients in the developmental foundations, innovative capabilities and absorptive capacities of cities. On these premises, this paper chooses the nine cities of the Pearl River Delta between the years of 2012-2022 as the research subjects because it aims to investigate the development levels of the digital economy and

economic resilience, their spatiotemporal evolutionary features, their coupling coordination relations and their obstacles.

Figure 2: Geographic Location of the Study Area



2.2 Construction of the Indicator System

This paper uses the principles of scientificity, systematicness, availability and regional adaptability to develop a dual-system evaluation indicator system of the digital economy and economic resilience in order to systematically describe the evolution of the digital economy and economic resilience in the Pearl River Delta (Table 1). The choice of indicators is based on the well-developed research models [22,23] as well as on the presence and the possibility of comparing the data across the Pearl River Delta area to ensure an appropriate depiction of the development stages of the two systems and their internal structural divergence.

The digital economy system is built on two dimensions that are the level of development of the Internet and the development of digital finance. The level of development of the Internet mostly shows the regional digital base, the ability to connect information, and the intensity of using digital applications. The four selected indicators include: the number of Internet users per 100 people, the number of employees in knowledge-intensive service industries, per capita telecom business volume, and the number of mobile phone users per 100 people, which indicate the popularization of digital infrastructure, the development of digital industries, the intensity of information and communication use, and the coverage of mobile scenarios, respectively. The Peking University Digital Inclusive Finance Index is used as a measure of the digital finance development level, which indicates the coverage width, usage depth, and accessibility of digital financial services. The above treatment is aligned with the current research findings and may be fairly stable in reflecting the state of development of the digital economy in the Pearl River Delta.

The economic resilience framework has three dimensions that include development capacity, stability capacity, and innovation capacity. Development capacity mostly indicates the basis of regional economic development, openness, and structural support. Per capita regional GDP, energy consumption (use of electricity/total area), trade openness (total imports and exports/GDP), industrial structure coordination degree (value added of the tertiary industry/value added of the secondary industry), and consumption scale per unit area (total retail sales of consumer goods/built-up area) are chosen as indicators; stability capacity measures the capability of the regional economy to resist shocks and continue operating. Average wage of employees, financial loan-to-deposit ratio (loan balance of financial institutions/deposit balance), structure of government spending (expenditures on general-purpose government services/expenditure on general-purpose government budget), registered unemployment in the cities, and per capita deposit balance are chosen as indicators;

the growth rates and rates of change in the text are computed using the full raw calculation values, some of them may not match the individual results that can be obtained directly through the displayed values; this is caused by the accuracy of the numerical rounding.

2.3.1 Entropy Weighting Method

The digital economy and economic resilience are common topics of multi-indicator comprehensive assessment, and there are big differences in the information volume of indicators. In order to reduce the impact of subjective weighting on the outcomes of measurements, the current paper uses the approach of entropy weighting to provide an objective weight to each indicator. It considers the level of dispersion of an indicator in the sample and decides on its contribution to the overall information of the other indicators; the more dispersed it is, the more it can distinguish between regions, and thus has a larger contribution to information. In the particular calculation procedure, positive and negative indicators are standardized independently. Since entropy calculations are logarithmic processes, a small constant A is introduced to the standardized values to prevent the effect of zeros, which in this case will be 0.0001. On the basis of this, the proportions, entropy values, and coefficients of variation of each indicator are then calculated, and the weights of the indicators are derived, finally producing composite scores of the digital economy and economic resilience respectively. The calculation formulas are shown below:

$$x_{ij}' = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)}; x_{ij}'' = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)}, y_{ij}' = x_{ij}' + A \quad (1)$$

$$P_{ij} = \frac{y_{ij}}{\sum_{i=1}^m y_{ij}}, e_j = K \sum_{i=1}^m P_{ij} \ln P_{ij}, w_j = \frac{1 - e_j}{\sum_{i=1}^n (1 - e_j)} \quad (2)$$

$$S_{ij} = \sum_{i=1}^n (w_j * x_{ij}) \quad (3)$$

2.3.2 Coupling Coordination Model

This paper uses the coupling coordination model to measure the level of synergistic development between the digital economy and economic resilience. Suppose the composite scores of the digital economy and economic resilience can be denoted as U1 and U2 respectively. To start with, the coupling degree C of two systems is determined, then the comprehensive development degree T, and finally, the coupling coordination degree D. Based on the fact that the digital economy and economic resilience are equally significant within the research context of the present paper, the parameters α and β are defined as 0.5. The coupling coordination index varies between 0 and 1 and a larger index implies more coordination in developing the two systems. The calculation formula is given below:

$$D = \sqrt{C \times T} = \left[U_1 \times U_2 / \left(\frac{U_1 + U_2}{2} \right)^2 \times (\alpha \times U_1 + \beta \times U_2) \right]^{1/2} \quad (4)$$

According to the classification method of coupling coordination adopted in the available research, this paper will classify the coupling coordination index D into five groups based on its value as follows: if D is in the range (0, 0.2], it means that there is a very high level of imbalance; if D is in the range (0.2, 0.4], then it means that the level of imbalance is relatively moderate; if D is in the range (0.4, 0.6], then it means that the balance is almost achieved; if D is in the range (0.6, 0.8], then there is a well-coordinated state, and if D is in the range (0.8, 1.0], it means that there is an exceptionally coordinated state [24,25] .

2.3.3 Obstacle Degree Model

In order to find out what the main limitations to the process of digital economy and economic resilience improvement are, this paper uses an obstruction degree model to measure how much every indicator impedes the total system development. This model involves the deviation of an indicator with respect to its ideal state and the weight of each indicator, where the deviation is defined as the difference between a particular indicator and its ideal state, and the factor contribution is measured in terms of the weights of the indicators evaluated through the entropy-weighted approach. On this basis, the obstruction degree of each indicator can be computed and added up to get the criterion level obstruction degree. An increased value of the obstruction degree means that the indicator or dimension under consideration imposes a greater limitation on the improvement of the system. The fundamental calculation formula is given below:

$$H_j = \frac{D_{ij} * F_j}{\sum_{j=1}^n F_j * D_{ij}} * 100\% \quad (5)$$

$$O_{ij} = \sum H_j \quad (6)$$

2.3.4 Spatiotemporal Pattern Analysis

This paper will present the digital economy, economic resilience, and coupling coordination in a stratified form to improve the understanding of spatial stratification results. Namely, coupling coordination has different types depending on fixed interval criteria; the digital economy and economic resilience are stratified by manual partitioning in accordance with the research requirements to better demonstrate the discrepancy between development levels of the cities within the Pearl River Delta. Spatial distribution maps of a typical year were produced using ArcGIS 10.8 based on the above classification outcomes to present the development levels of cities in the Pearl River Delta and their spatial evolution features.

2.4 Data Sources

The paper is based on panel data of the nine cities in the Pearl River Delta over the period 2012-2022. The raw data are mainly derived from the official website of the National Bureau of Statistics, the Guangdong Statistical Yearbook, the China Urban Statistical Yearbook, and the statistical yearbooks and government bulletins of every city under the Pearl River Delta; digital finance-related data are obtained through the Index of Digital Inclusive Finance released by the Peking University Center of Digital Finance. The number of employees working in knowledge-intensive service industries was calculated based on the industry classification standards by the National Bureau of Statistics, whereas some of the ratio-based indicators were calculated using the underlying data. In the cases where an indicator had a missing value in particular years, the arithmetic mean approach and interpolation were applied to plug the gaps so that the integrity of the sample series would be maintained and the comparability of the annual data could be sustained.

3. Analysis of Results

3.1 Analysis of the Level of Digital Economic Development

3.1.1 Time Series Evolution

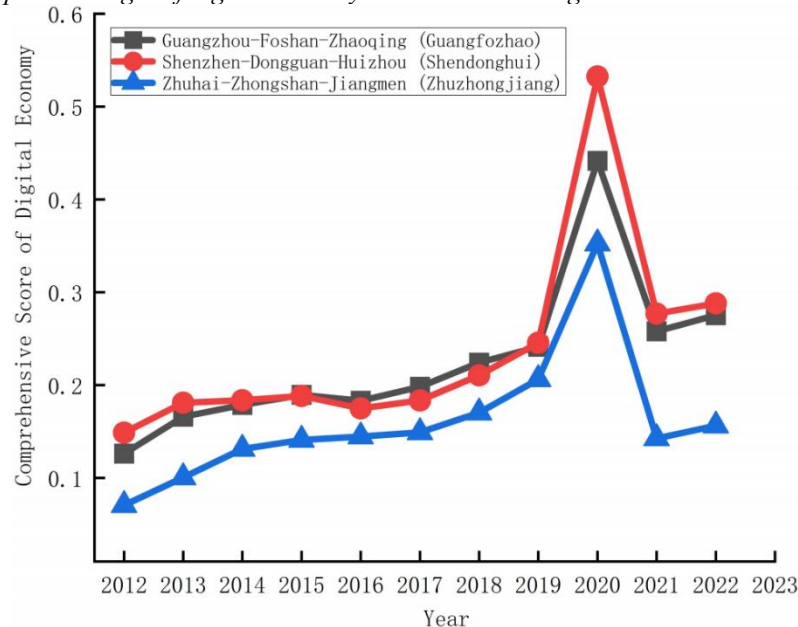
From 2012 to 2022, the average composite score of the Pearl River Delta digital economy increased by 108.23 percent, or 0.115 to 0.240, indicating an upward trend. If considered by phases, the score increased gradually over time: the score increased steadily between 2012 and 2019 (0.115 - 0.231), which indicated a smooth increase; the score rose sharply in 2020 to 0.442, or 91.44% higher than in 2019; in 2021, the score decreased to 0.226, and then recovered to 0.240 in 2022. On average, the digital economy of the Pearl River Delta has been on an upward trend throughout the observation period, although its yearly development has not been linear; the sharp increase in the year 2020 was mainly due to the intense demand and implementation of digitalization during a limited time, then a gradual correction and a slow recovery took place.

The digital economy has been characterized by a tiered distribution of the three main regional clusters as follows: Shenzhen-Dongguan-Huizhou - Guangzhou-Foshan-Zhaoqing - Zhuhai-Zhongshan-Jiangmen since a long time ago. The average levels of the three regional clusters in 2012 were 0.149, 0.126, and 0.071, respectively, and in 2022, they were 0.288, 0.275, and 0.156, respectively, which was an increase of 93.62, 118.07, and 121.43 percent, respectively. Despite the fact that the Guangzhou-Foshan-Zhaoqing and Zhuhai-Zhongshan-Jiangmen regions developed at a higher rate, the discrepancy between regions increased over time (0.078 in 2012 to 0.132 in 2022), which implies that although the lagging regions were closing the gap, the overall hierarchy was basically unaltered. On some occasions, the Guangzhou-Foshan-Zhaoqing region could be near or even exceed the Shenzhen-Dongguan-Huizhou region, but it does not imply that the ranking of these regions is absolutely unchanging; in general, throughout the period of observation, the cumulative benefits of the Eastern Coast region have remained relatively constant (Figure 3).

Viewed through the prism of the temporal development, the digital economy in the Pearl River Delta grew in a complex, non-synchronous way, and was marked by the essential features of core-led growth, gradient differentiation, and continuous stratification. Improvement in levels was not accompanied by the convergence

of regional disparities and, instead, points to the fact that digital factors, digital industries as well as digital application capabilities are still mainly clustered in high-performers. To put it differently, although the spread of the digital economy has created new opportunities to improve future economic resiliency, various regional clusters have not enjoyed the benefits of the digital dividend equally, which is also a useful foundation to the stratified nature of the coordinated development of both the dual systems.

Figure 3: Temporal changes of digital economy across the three regional blocs in the Pearl River Delta



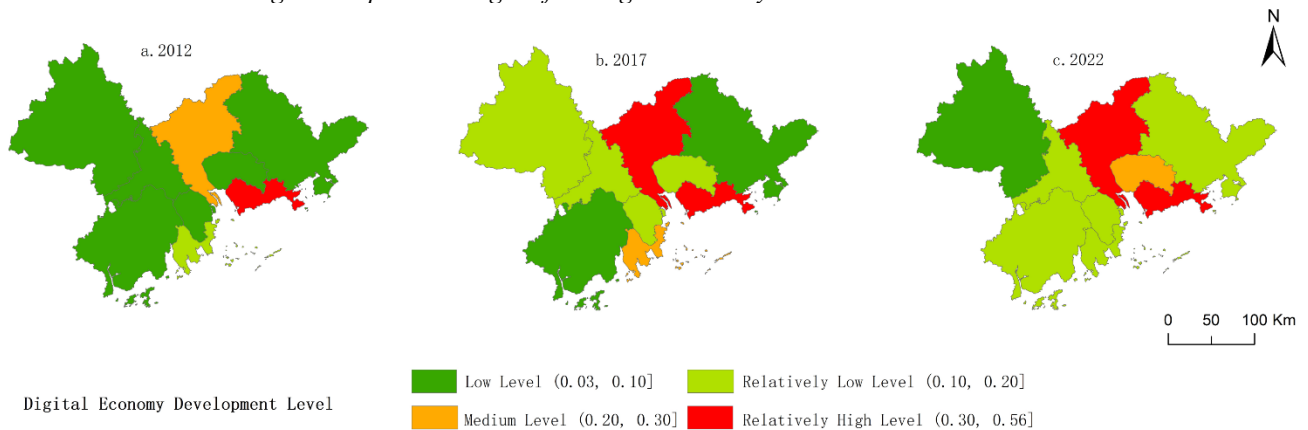
3.1.2 Characteristics of Spatial Evolution

The digital economy in the Pearl River Delta in the context of spatial distribution also tends to follow an evolutionary trend where there are core leading cities, a number of cities that follow in tiers, and some cities that are relatively behind in the periphery. As far as the start of the research, it can be stated that in 2012, Shenzhen had already reached the high level of the range, Guangzhou was in the middle level, Zhuhai was at the bottom end of the range and most other cities were at the bottom of the range, which means that the benefits of the digital economy were mainly centered in a small number of core cities. Both Guangzhou and Shenzhen, by 2017, were now in the high-level range, and Zhuhai had moved up to the medium level, whereas Foshan, Dongguan, Zhongshan, and Zhaoqing were still at the low level, which further indicates the stratification in the area. Guangzhou and Shenzhen scored 0.559 and 0.505 in 2022, respectively, and retained their lead; Dongguan fell into the medium-level range, and Zhuhai, Foshan, Zhongshan, Huizhou, and Jiangmen were in a lower level, with Zhaoqing remaining in the low-level range (Figure 4).

The given spatial pattern represents not merely the distinctions between cities in their ranking but also the disparities in their ability to aggregate digital factors, the capacity to support digital industries, as well as the complexity of the application settings. Guangzhou and Shenzhen have had high scores for a long time that are very similar to the presence of their clusters of knowledge-intensive service industries and dynamic information and communications industries; the increase in the scores of Dongguan, Foshan and Zhuhai is, however, mostly due to the strong manufacturing backgrounds and abundance of digital application conditions; and despite the simultaneous improvement of the peripheral cities, their advancement in aggregating high-end service factors and digital applications has also been relatively moderate.

To sum up the spatial development of the Pearl River Delta digital economy in general, it could be described as gradient evolution with dual cores. High value areas within the study period were concentrated around and fixed in Guangzhou and Shenzhen, and surrounding cities with differences in the region being represented through the order of hierarchy of core cities secondary core cities, and peripheral cities. The digital economy is not just some important representation of regional development disparities but also prepares the grounds for further economic resilience and spatially distinct coupling and coordination.

Figure 4: Spatial changes of the digital economy in the Pearl River Delta



3.2 Analysis of Economic Resilience Levels

3.2.1 Time-Series Evolution

The time development of economic resiliency in the Pearl River Delta has been more stable with respect to the digital economy. In the period of 2012-2022, the composite score of economic resiliency increased by an average of 76.51 percent, or by 0.213 to 0.376. Particularly, between 2012 and 2015, the score increased by 0.213 to 0.233, which means that the growth was relatively moderate; between 2016 and 2019, it rose by 0.255 to 0.329, which is a faster growth rate; in 2020, it dropped by a small margin to 0.328, which is 0.43 percent lower than in 2019; and in 2021-22, it continued to recover to 0.359 and 0.376 respectively. Taken together, the gains in economic resilience are largely manifested in the form of a gradual advancement based on long-term underpinnings, where the changes in the scores in the course of a year are much less noticeable compared to the changes in the digital economy.

Considering the three most significant regional clusters namely, Shenzhen-Dongguan-Huizhou has constantly had the greatest economic resilience with its value increasing by 90.83% due to an increase of its value from 0.237 to 0.452 in 2022; Guangzhou-Foshan-Zhaoqing increased by 83.49% as the value of economic resilience increased from 0.199 to 0.365; and Zhuhai-Zhongshan-Jiangmen increased by 53.08% as the value of economic resilience increased from 0.204 to 0.312. Initially, the difference between Zhuhai-Zhongshan-Jiangmen and Guangzhou-Foshan-Zhaoqing was insignificant, however, post-2016, the improvement of Guangzhou-Foshan-Zhaoqing grew much faster, slowly increasing the distance between the two clusters; by 2022, the distance between Shenzhen-Dongguan-Huizhou and Zhuhai-Zhongshan-Jiangmen increased by 0.140 compared to 0.033 in 2012. It is indicative of the fact that although the overall economic resilience of the Pearl River Delta has risen, the rate of change differs by various sub-regions and regional stratification has become even more evident in the final stages (Figure 5).

According to the pattern, the economic resilience of the Pearl River Delta shows a stratified development, which was described as the phenomenon of stable improvements in the core and gradual slowdown in the periphery. In contrast to the fast growth of the digital economy, economic resilience is based more on investment in innovation, coordinated industrial structure and the cumulative build-up of long term adaptive capacity; thus, its development is more sluggish and vulnerable to path dependence. In other words, the digital economy may offer new opportunities for development, but it is still unclear how these may be converted into more sustainable levels of development resilience, depending on whether every region has the appropriate innovation base and the ability to change structure.

3.2.2 Characteristics of Spatial Evolution

Spatially speaking, the economic resilience of the Pearl River Delta has different gradients, but has a more stable spatial hierarchy compared to the digital economy. In 2012, the level of Shenzhen was significantly high, and Guangzhou, Zhuhai, Foshan, Dongguan, and Zhongshan were at the middle level, whereas the others like Jiangmen, Huizhou, and Zhaoqing were mostly at the low level. The leading positions of Guangzhou and Shenzhen were further strengthened by 2017, and other cities like Zhuhai and Foshan have steadily climbed the ranks. In 2022, Shenzhen stood first with a score of 0.717, and Guangzhou came next with 0.527, and

Foshan, Dongguan, and Zhuhai scored 0.414, 0.392, and 0.385 respectively. Even though the peripheral cities improved to some extent, their overall level was still quite low (Figure 6).

Figure 5: Temporal changes of economic resilience across the three regional blocs in the Pearl River Delta

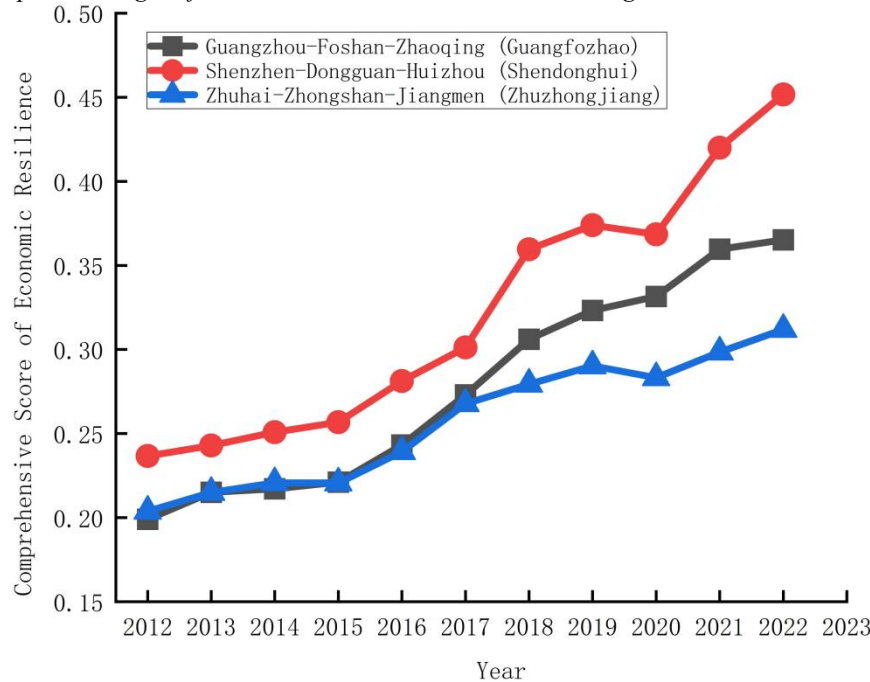
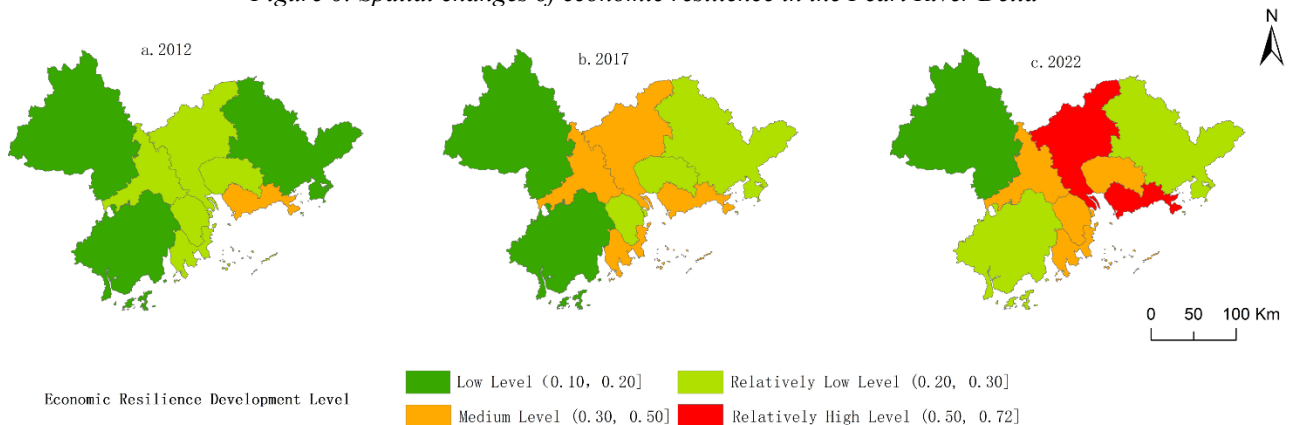


Figure 6: Spatial changes of economic resilience in the Pearl River Delta



In contrast with the spatial inequities of the digital economy, economic resilience is a more appropriate indicator of the long-term inequality in the basis of urban development. The cities of Guangzhou and Shenzhen have had a high level over a long time that not only indicates their high comprehensive performance but also indicates their high level of innovation resource aggregation, industry system diversification, and risk absorption capacity; Foshan and Dongguan were found to improve at a faster rate towards the end of the study period showing that cities with a powerful manufacturing base could be resilient to structural adjustments and changes in industries; and the peripheral cities improved a little but they took time to develop in the aspects of investment in R&D, patent production, and structural coordination, therefore keeping a considerable gap with the central cities.

The spatial development of economic resilience in the Pearl River Delta is clearly not just a simple case of high and low, but it is a hierarchy that has as its defining feature: steady improvement in core cities, gradual improvement of manufacturing powerhouses, and somewhat slow catching up of peripheral cities. The process of economic resilience is slower than that of the digital economy and the stratification is more deeply rooted. It means that the synchronized development of two systems cannot depend only on the growth of the digital

economy but should be combined with the simultaneous improvement of economic resilience in terms of innovation capability and structural optimization.

3.3 Analysis of the Coupling and Coordination Between the Digital Economy and Economic Resilience

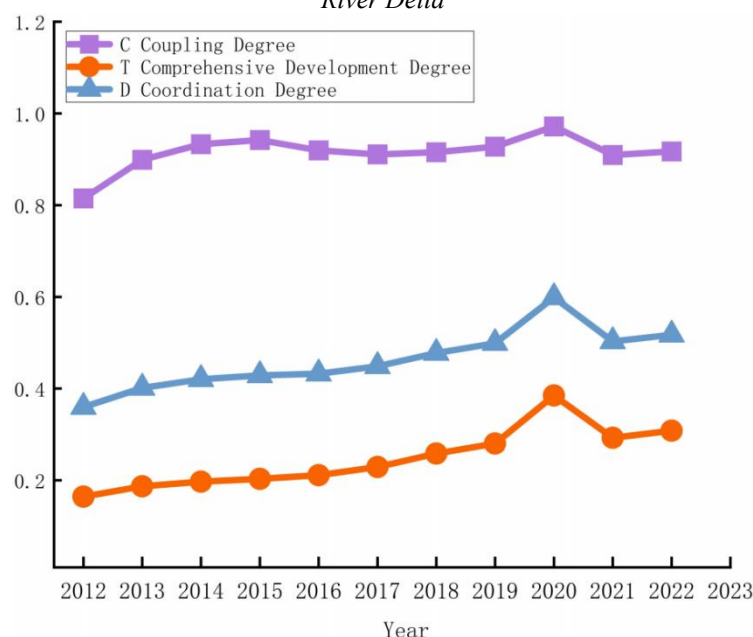
3.3.1 Time-Series Evolution

The digital economy and economic resilience in the Pearl River Delta have developed a significant correlation over time, although the degree of connection and coordination is still being optimized. Since 2012, the average degree of coupling in the region has grown from 0.815 to 0.917, which is constantly within a high range; it was in the same 2012-2022 that the index of comprehensive development grew from 0.164 to 0.308; based on this base, the index of coupling coordination increased from 0.359 to 0.517, or by 43.96 percent in total. The general tendency shows a positive change, which means that the interaction of the two systems is slowly changing its condition of imbalance to a more coordinated condition. It implies that despite the fact that the two systems have had strong links over a long period of time, the coordination level will still be improved based on the sustained growth of the comprehensive development base (Figure 7).

In terms of phase, the coupling coordination index increased between 2012 and 2016 from 0.359 to 0.432 (gradual), increased again to 0.499 in 2017-2019, followed by an ongoing increase in the level of synergy; in 2020, it reached the peak of 0.599 or 20.07 percent higher than in 2019, which was the highest in the course of the investigation; in 2021, it returned to 0.503 and then rebounded to 0.517 in 2022. The combination of results of C, T and D shows that the high increase in coordination in 2020 had a stronger relationship with the simultaneous growth of total development than the corresponding jump in the coupling degree. It means that in the near future, the progress in coordination was largely due to the simultaneous increase in development levels of both systems, and not because of the essential shift in the relationship between them.

This finding shows that the enhancement of coupling coordination through the course of the research depended more on the upgrading of the comprehensive development base, as opposed to a substantial increase in the strength of the coupling relationship. It means that the two systems are not disconnected in the Pearl River Delta but it is the disparity between the digital economy and economic resilience in terms of development, speed of change and level of correspondence that indeed limits any additional coordination improvements. Put differently, the existence of both systems in a state of growth does not automatically indicate a greater state of coordinated development; the stability of coordination and optimization is only achieved when the two systems develop at a relatively similar pace and have similar levels of development.

Figure7 Temporal changes of coupling coordination between the digital economy and economic resilience in the Pearl River Delta



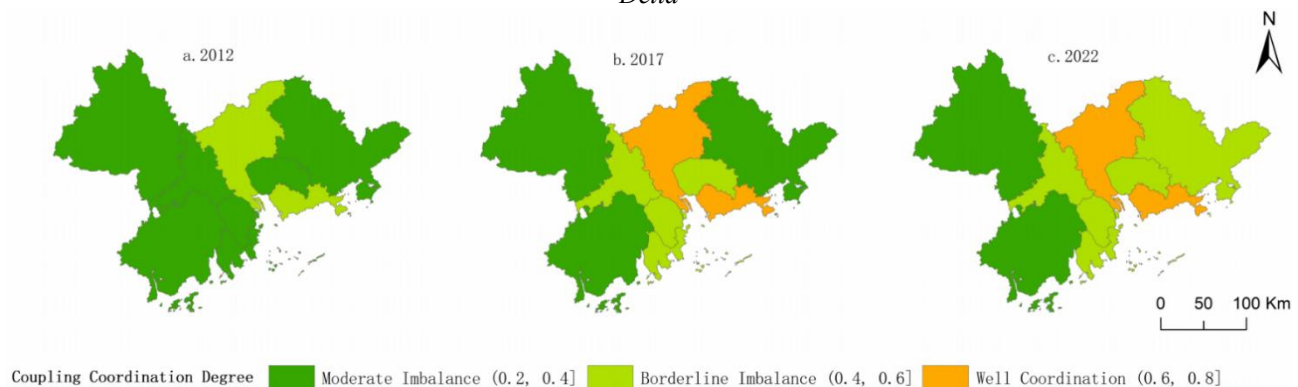
3.3.2 Spatial Evolution Characteristics

Spatially speaking, the degree of coupling coordination in the Pearl River Delta can be described as having a gradient pattern with the level of coordination decreasing gradually as one moves away from core cities to peripheral ones. In 2012, the coordination rates of Shenzhen and Guangzhou were 0.575 and 0.516 respectively, which were much higher than those of other cities where peripheral cities generally have lower coordination rates. As of 2017, Shenzhen and Guangzhou had gone up to 0.623 and 0.602 respectively, Zhuhai went up to 0.538 and Foshan, Dongguan and Zhongshan all surpassed 0.40 and it can be concluded that the overall regional level of synergy has gone up. In 2022, Shenzhen and Guangzhou still maintained high levels at 0.770 and 0.736 respectively, whereas Dongguan, Zhuhai, and Foshan remained at 0.50, which means that the region had developed a relatively clear gradient structure (Figure 8).

Comparing the three largest regional clusters, the mean degrees of coupling and coordination among Shenzhen-Dongguan-Huizhou, Guangzhou-Foshan-Zhaoqing and Zhuhai-Zhongshan-Jiangmen increased by 44.08 percent, 43.93 percent and 43.83 percent respectively, as the mean values were 0.399, 0.364 and 0.316 in 2012 and 0.574, 0.524 and 0.454 in 2022. Even though all three regional clusters advanced at the same time, the difference between them increased by 0.083-0.120, which means that the enhancement in coordination did not go hand in hand with the reduction of regional differences significantly. However, after closer investigation, it is clear that the Shenzhen-Dongguan-Huizhou region has kept its high level of coordination over the long term not only because it has a higher level of digital economy development, but also because its digital economy and economic resilience are relatively high; the relatively slow progress of coordination in the Zhuhai-Zhongshan-Jiangmen region cannot be explained by the weakness of a single system, but by the relatively weak total base and extent of congruence between the two systems.

To sum up, the spatial development of coupling and coordination of the Pearl River Delta cannot be facilitated by one system, which is functioning at a high level, but rather it relies largely on the correspondence between the rate of development and spatial scales of the two systems. It was hierarchical in nature, with high-level coordination between the two cores, and steady improvement in the secondary cores, and slow catch-up in the peripheral sectors, but the disparities among regional sectors have not lessened significantly as they all have improved. Such a statement also indicates that the emergence of the digital economy, the strengthening of economic resilience, and coordination and optimization are not some parallel processes, but one continuous process that is influenced by the basis of development, absorption and the extent to which these processes are aligned.

Figure 8: Spatial changes of coupling coordination between digital economy and economic resilience in the Pearl River Delta



3.4 Analysis of Obstacle Factors

3.4.1 Digital Economy Obstacle Factors

According to annual rates and comparisons in Tables 1 and 2, the major barrier factors of the Pearl River Delta digital economy are highly stable. Their position has traditionally corresponded with the pattern of indicator weights and has historically focused on a handful of the most important indicators. The total number of employees in knowledge-intensive service industries and per capita telecommunications service volume ranked first and second, respectively, in 2012-2019 and 2021-2022 and their aggregate obstacle level has

stayed within about 78-81% over time; The two indicators took the lead in 2021-2022 with their aggregate share reaching nearly 80%. At the same time, the number of Internet users per 100 people has always been one of the strongest factors. However, the obstacle degree of the Digital Inclusive Finance Index declined from 6.16% in 2012 to 0.72% in 2022, which shows that restrictions in the basic access level have considerably diminished.

Based on the development of barrier structures, the most significant limitations to the digital economy of the Pearl River Delta region have shifted from early-stage deficiencies in basic access to a lack of aggregation of high-end service factors and insufficient deepening of digital applications. Per capita telecommunications service volume was the top constraint factor for both Guangzhou and Shenzhen in 2022, whereas the number of employees in knowledge-intensive service industries was the top constraint factor for Zhuhai, Foshan, Dongguan, Zhongshan, Jiangmen, Huizhou, and Zhaoqing. This suggests that the major constraint of core cities is not enough improvement in the level of digital application, but other cities face the problem of not enough aggregation of high-end service elements. Therefore, the limitation to the digital economy has over time moved away from the question of whether or not there is access to the economy to more incremental limits on whether or not that access may be deepened, reinforced, and raised to a high-end form.

The findings demonstrate that the process of digital economy development in the Pearl River Delta has gone over the initial popularization, yet the level of disparities between cities with regard to high-end service agglomeration, application deepening, and functional upgrading is still significant. It is exactly this reason that can explain why the general increase in the digital economy has not necessarily resulted in the reduction of spatial disparities, but in fact has contributed to the hierarchical distinction between central and peripheral cities in their ability to coordinate digital resources.

3.4.2 Factors Hindering Economic Resilience

Considering annual averages, the main constraints to the economic resilience of the Pearl River Delta also demonstrate significant levels of stability and consist mainly of indicators of innovation investment and structural coordination. During this time frame, overall R&D spending was always the highest constraining factor, which had a stable level of constraints at 23.75-25.86; industrial structure coordination has always been the second highest, increasing by 10.77% in 2012 to 12.14% in 2022; Other indicators, including the number of patents awarded per 10,000 population, trade openness, the officially recorded rate of urban unemployment, government spending on science and technology, and the percentage of the labor force working in science and technology, were also among the leading factors in different years (Table 2). It means that the main obstacles to the economic resilience of the Pearl River Delta are not represented in short-term fluctuations, but in the possibility of further improvements in innovation investment, industrial structure optimization, and other supporting conditions.

Based on the development of constraint structures, the focal points that limit the economic resilience of the Pearl River Delta have largely been stable and have been focused on important domains like innovation investment and structural coordination for a long time. As of 2022, however, besides Shenzhen, the main constraint factor of the other eight cities was the total amount of R&D expenditures within the society, which means that the lack of investments in innovation continues to be the leading constraint of improving economic resilience in most cities; in case of Shenzhen, the main constraint factor turned out to be the official level of urban unemployment (second place: industrial structure coordination), which indicates that the most salient constraints of this city are related to the aspect of employment stability and structural optimization. On closer inspection, the level of industrial structure coordination is also one of the key constraint factors in most of the cities and trade openness is also one of the key factors in most cities. Patent numbers per 10,000 people and the share in government spending on science and technology are especially high in certain cities. It implies that despite different sources of constraints in various cities, the improvement of economic resilience can be affected by a combination of factors such as innovation investment, structural coordination, openness and connectivity, and scientific and technological support.

The findings show that the improvement of economic resilience has stronger long-term and cumulative features. In comparison with the digital economy, economic resilience changes are more dependent on the accumulation of innovation investment, the optimization of industry structure, and the steady improvement of other supporting conditions, so it is hard to make significant progress in the short term by improving one factor alone. Although the digital economy may create new market circumstances and technological facilities, the

improvement of economic resilience will remain limited unless there are simultaneous improvements to innovation investment, industrial structure optimization, and supporting conditions related to them, which will influence the further optimization of coordination level between the two systems.

An in-depth analysis of how the nature of the primary challenges in the digital economy and economic resilience changes over time shows that the greatest hindrances to the former have gradually shifted from insufficient basic access to a lack of aggregation of high-end service elements and insufficient deepening of applications, whereas the latter is being more and more defined by several factors operating together, the most dominant of which are the restrictions on investment in innovation. This difference between the rates of change of such two categories of barriers is a strong reflection of the fact that the digital economy is growing at a faster rate than economic resilience, in the integrated development of the dual system in the Pearl River Delta. It implies that the key to subsequent coordinated progress will not be based on further increasing digital coverage, but it will be based on promoting a greater degree of congruency between innovation buildup, structural optimization, and digitalization.

Table 2: Ranking of major obstacle factors in the whole study area

Year	Project	Digital Economy					Project	Economic Resilience				
		1	2	3	4	5		1	2	3	4	5
2012	Barrier Factors	X2	X3	X1	X5	X4	Barrier Factors	X18	X9	X17	X16	X14
	Obstruction Level/%	41.62	37.11	10.21	6.16	4.90	Obstruction Level/%	25.02	10.77	9.87	7.69	7.47
2013	Barrier Factors	X2	X3	X1	X5	X4	Barrier Factors	X18	X9	X17	X16	X19
	Obstruction Level/%	41.96	38.66	10.10	5.31	3.96	Obstruction Level/%	25.06	10.90	9.74	7.70	7.61
2014	Barrier Factors	X2	X3	X1	X5	X4	Barrier Factors	X18	X9	X17	X16	X14
	Obstruction Level/%	42.46	38.15	10.26	5.09	4.05	Obstruction Level/%	24.95	10.93	9.74	7.97	7.30
2015	Barrier Factors	X2	X3	X1	X5	X4	Barrier Factors	X18	X9	X17	X14	X19
	Obstruction Level/%	42.11	39.27	10.17	4.27	4.18	Obstruction Level/%	24.71	10.61	9.66	7.38	7.22
2016	Barrier Factors	X2	X3	X1	X4	X5	Barrier Factors	X18	X9	X17	X14	X19
	Obstruction Level/%	41.24	39.09	10.32	5.68	3.66	Obstruction Level/%	25.02	10.50	9.78	7.75	7.18
2017	Barrier Factors	X2	X3	X1	X4	X5	Barrier Factors	X18	X9	X17	X14	X8
	Obstruction Level/%	41.15	39.72	10.44	5.89	2.79	Obstruction Level/%	25.39	10.61	9.52	7.97	7.32
2018	Barrier Factors	X2	X3	X1	X4	X5	Barrier Factors	X18	X9	X17	X8	X14
	Obstruction Level/%	41.06	40.74	10.29	5.48	2.44	Obstruction Level/%	25.86	10.99	8.80	7.88	7.59
2019	Barrier Factors	X3	X2	X1	X4	X5	Barrier Factors	X18	X9	X17	X8	X14
	Obstruction Level/%	41.22	39.08	11.54	6.06	2.09	Obstruction Level/%	25.51	10.75	9.28	8.47	7.61
2020	Barrier Factors	X2	X1	X3	X4	X5	Barrier Factors	X18	X9	X14	X8	X17
	Obstruction Level/%	50.83	19.30	16.94	10.37	2.56	Obstruction Level/%	24.54	10.27	9.48	8.70	7.45
2021	Barrier Factors	X3	X2	X1	X4	X5	Barrier Factors	X18	X9	X8	X14	X16
	Obstruction Level/%	45.01	35.96	11.67	6.47	0.89	Obstruction Level/%	24.43	11.41	9.08	8.97	7.66
2022	Barrier Factors	X3	X2	X1	X4	X5	Barrier Factors	X18	X9	X8	X14	X16
	Obstruction Level/%	45.96	35.50	11.38	6.43	0.72	Obstruction Level/%	23.75	12.14	9.65	9.46	7.98

Note: The barrier index is the arithmetic mean of the barrier indices for the same indicator in the nine cities of the Pearl River Delta in the same year, expressed as a percentage

4. Conclusions and Recommendations

4.1 Research Conclusions

(1) From 2012 to 2022, the digital economy in the Pearl River Delta and economic resilience in the region have had a tendency to increase over time, though they do so at different rates. The digital economy increased at a higher rate with more significant variations, whereas economic resilience has been increasing at a relatively steady pace. Looking at it subregionally, both systems had a stratified structure with the most dominant core subregions and the less developed peripheral subregions. Finally, as the research period came to an end, the gradient system of the pattern of Shenzhen -Dongguan-Huizhou-Guangzhou-Foshan-Zhaoqing-Zhuhai-Zhongshan- Jiangmen became more apparent; the overall progress could not substantially change the existing hierarchical differences between the regions.

(2) The high-value areas of the digital economy have been historically and consistently focused on and around Guangzhou and Shenzhen, showing clear signs of dual-core leadership; the economic resilience hierarchy is more deeply rooted, and the core cities have preserved their superiority. The cities having robust manufacturing industries like Foshan and Dongguan show some level of gradient-based catch-up, whereas the peripheral cities are catching up rather slowly. It shows that although digital expansion has opened new opportunities in regional development, it has not automatically led to a convergence of economic resilience gaps across regions.

(3) The level of coupling and coordination between the digital economy and economic resilience in the Pearl River Delta has generally increased, but the process of improvement has experienced phased fluctuations. It is more embodied in the synchronized increase of the development base, rather than the substantial intensification of the connection. On average, over the long term, the coupling degree has been high, which means that the two systems have developed a close relationship, nonetheless, the coordination level is still influenced by the differences in the development stages and the mismatch of the rate of development. It implies that the secret to enhancing synergy between the two systems is no longer the mere reinforcement of the links between the systems but reduction of the disparity in their development bases as well as enhancement of the extent of coordination between them.

(4) The findings on constraining factors indicate that the main constraints confronting the digital economy and economic resilience are very different. The challenges to the digital economy have historically been focused on the size of the workforce in the knowledge-intensive business sectors and the volume of telecommunications services per capita, whereas the level of digital inclusive finance index restraint has further reduced, which means that the critical factors causing a limit have shifted from inadequate access to basic services to insufficient agglomeration of high-end service factors and insufficient depth of digital applications; conversely, impediments to economic resilience have long focused on measures like gross R&D spending across society, coordination of industrial structures, and patents issued per 10,000 inhabitants, implying that its enhancement is still mainly limited by the amount of investment in innovation, the volume of innovation outputs, and the ability to optimize structures.

4.2 Policy Recommendations

(1) A differentiated policy strategy is required to increase the overall ability of less developed areas to take up digital opportunities. In order to solve the age-old problem of regional stratification in the Pearl River Delta, without undermining the dominant position of such core cities as Guangzhou and Shenzhen, special attention should be paid to improving the supportive functions of such areas as Guangzhou-Foshan-Zhaoqing and Zhuhai-Zhongshan-Jiangmen in respect of innovation platforms, public services, industrial support systems, and the incorporation of high-end factors. It will help to consolidate the underlying conditions under which less-developed cities can benefit from digitalization and utilize the institutional benefits of the unified national market.

(2) Encourage the concerted development of the digital economy and building resiliency. Digital infrastructure development, platform functionality growth, and digital finance expansion must be combined with resiliency goals, including industrial chain stability, risk prevention, service delivery by the state, and employment security, so that investments in digitalization can be better converted into regional shock resistance, recovery capability, and transformational capacity.

(3) Enhance the endogenous basis of resilience by investing in innovation and optimizing structure. The focus should be set on increasing the level of R&D investments and the effectiveness of budgetary allocations to science and technology, enhancing the structures relating to the commercialization of patents, technology dissemination, and industry modernization, as well as on improving the digitalization of traditional industries and fostering new industries, building upon the existing local industrial base, in order to increase structural consistency and market responsiveness.

(4) Switch the digital economy to a quality-based perspective instead of an expansion-based one. To overcome the outstanding limitations including poor clustering of knowledge-intensive services and lack of deepening applications, priorities in policy-making should be shifted over time toward the creation of high-end service capabilities, extension of application scenarios, and improvement of ability to arrange digital resources. It will reinforce the leading position of the core cities and the potential of the peripheral cities to accommodate application scenarios.

(5) The improvement of inter-city coordination and regulatory alignment mechanisms is needed. In the context of an integrated national market, it is necessary to continue to foster the orderly movement of major factors (including data, technology, capital, and talent) in the Pearl River Delta, lessen institutional friction and duplication of construction, and through the use of network platforms and market hubs of the core cities, develop mechanisms of inter-city cooperation and interest congruence to improve the regional coherence of the joint development of the dual systems.

4.3 Discussion

The results of this paper suggest that in the context of the current establishment of the unified large market, the harmonization of regulation, market integration, and increased factor mobility offer a fairly positive external environment for the synergistic development of the digital economy and economic resiliency. Nevertheless, whether the institutional situation can be extended beyond the symbolic manifestations of coordinated development largely depends on the existing innovation base, industrial structure, as well as the overall ability to host development of each city. In this view, the united great market will enhance the outside conditions to develop both systems but will not necessarily remove the regional hierarchical differences.

Moreover, the designs of the barriers to the digital economy and economic resiliency within the Pearl River Delta do not go hand-in-hand. The digital economy is mostly at an advanced level in terms of high-end service clustering and further development of applications, whereas economic resiliency is still highly limited by innovation investment and structural optimization potential. It indicates that policy making in the future must not only focus on the growth of digitalization as such but put more emphasis on the relationships between the formation of the digital economy and innovation stockpile, industrial transformation, job stability, and government regulation.

It is important to mention that the present work mainly depends on panel data of the nine cities of the Pearl River Delta (2012–2022) to carry out a measurement and descriptive examination of the coupling and coordination of the digital economy and economic resilience, in particular, its spatiotemporal development features and major sources of barriers. Due to the limited scale of the research and methodological restrictions, the discovery of the interaction mechanisms between the two systems in the present paper remains largely based on measurement outcomes and theoretical reasoning; additional studies may be performed with more detailed data and more elaborate analytical approaches.

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