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Research Article

Revealing the Pattern of Causality in Processes of Urbanization and Economic Growth: An Evidence from China

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This paper introduces a method of combining phase space reconstruction and symbolic dynamics to study the causality between urbanization and economic growth at different regional levels in Shandong Province and finds that there is a strong positive relationship between urbanization and economic growth from China, indicating that the development of urbanization can drive the economic growth. Then, according to the results of correlation analysis between respective subvariables belonging to urbanization and economic growth and the principle of "deleting strong and reserving weak," the paper selects the independent variable and dependent variable to explore the hidden causal mechanisms that drive the developing of urbanization and economic growth from China. The results show that (1) the pattern causality between the independent variable and the dependent variable is dominated by dark causality at the provincial level; (2) the pattern causality between the independent variable and the dependent variable is dominated by dark causality at the Jinan economic circles and the Lunan economic circles, but the positive causality is dominated at the Jiaodong economic circles; (3) the types of causality between the same evaluation index and PU in different regions are different, and furthermore the degrees of positive, negative, and dark causality are different at two levels and three regions. The conclusion shows that although there is an obvious positive interaction between urbanization and economic growth, the influences of many factors are neither positive nor negative causality, but dark causality, which plays an important role in developing urbanization and economic growth. This work is useful for studying the law of causality between urbanization and economic growth, and this interesting result can be extended to other economic events.

1. Introduction

The study of social systems is hard-wired with the understanding of time series interdependencies of indicators. The research on the relationship between urbanization and economic growth and its driving factors has always been the focus of academic circles. Knowing the evolution of this relationship is vital to planning effective urbanization and economic growth strategies. It is even more important to identify hidden causality in the processes of urbanization and economic growth if the shift in driving forces is considered.

A straightforward tool to study the interaction between urbanization and economic growth is correlation, but it is known to be misleading in nonlinear relationships of social systems [1, 2], when causality is more appropriate. Causality in social system has been approached via methods such as Granger causality [3–7], cointegration [8–10], transfer entropy [11], Mann–Kendall [12], regression model [13–15], differential equation [16], structural equation [17], spatial Durbin model [18–20], and convergent cross mapping [21]. Nevertheless, none of the aforementioned methods provide insight regarding more complex interactions, namely, dark causality [22], which cannot be classified as purely positive or negative. Such causality also exists in the processes of urbanization development and economic growth.

Positive causality (and positive correlation) is anticipated in the relationship between urbanization and

economic growth. Urbanization can promote population agglomeration [16], agglomeration of production factors [13], and scale of urban infrastructure and institutional settings [23] and is also conducive to promoting innovation and social division of labor [12], thereby promoting industrial structure upgrading and economic growth. At the same time, economic growth will bring more employment opportunities and attract more labor force to gather in cities and towns, so as to promote the further improvement of urbanization level [24]. On the other hand, negative causality is proved to be between urbanization and economic growth in recent literature. When urbanization reaches a certain degree, it will impede economic growth [7, 25], which is consistent with the inverted U-shaped relationship between the old and the new urbanization and economic growth obtained by Chinese scholars [26]. Such shift in the above relationship between urbanization and economic growth suggests that a weak influence in one period may become a dominant influence in the next period, which reflects the effect from environment to social system [27]. The hidden nature of interdependencies between urbanization and economic growth may be the missing link leading to a deeper understanding of relationship between urbanization and economic growth. These hidden causalities have neither been focused on by scientists, nor been discovered. Therefore, it is important to uncover dark causality between urbanization and economic growth, which is an important innovation.

To analyze the types of causal interactions, both transparent (positive, negative) and opaque (dark) in the processes of urbanization development and economic growth, we introduce a method of combining phase space reconstruction and symbolic dynamics proposed by Stavros et al. [28] to explore the hidden causality in the processes of urbanization and economic growth at different regional levels in Shandong Province from China. The rest of the paper is arranged as follows. Section 2 provides the evaluation indicator system, data, and methodology used in this paper. In Section 3, we use Pearson correlation analysis of the indicators of urbanization and economic growth to recognize the weak factors defined as independent variables and dependent variables. In Section 4, we introduce the discrete algorithm of entropy for the continuous data, analyze the empirical results, and discover the complex causalities between subvariables belonging to urbanization and economic growth, which consist of positive causality, negative causality, and hidden causality. Finally, the discussion of conclusion and the future research possibility are provided in the last section.

2. Data and Methodology

2.1. Construction of Indicator System. According to [5, 29], urbanization and economic growth go hand in hand, and urbanization both reflects and contributes to economic growth and economic development patterns. Therefore, in this paper, the percent of urban population in total population (PU) reflecting urbanization level is used as dependent variable, the factors of which are used as independent variables. Based on the literature [30–37], we establish an indicator system consisting of 17 evaluation indexes calculated from 26 statistical indicators, as shown in Table 1. These indicators reflect the development level of regional politics (LGBR, LGBE), economy (PGDP, RTS, RRUHCE, IN), society (RRUE, RRUEP), culture (PLCPT), education (EE, RST), healthcare (BPT, MEPPT), and infrastructure (communication and transportation) (PT, VFT, BVPTS). Further, in order to better reflect the urban-rural gap, we simply calculate some statistical indicators to obtain the evaluation indexes such as RRUHCE [38, 39], RRUE, and RRUEP [40, 41].

2.2. Data Resource. The statistic indicator data are derived from the 2001–2018 Shandong Statistical Year book. Due to the consistency of the research unit and given the availability of data, this study selected 17 cities in Shandong Province from 2000 to 2017 as samples to measure the hidden causality among the processes of urbanization and economic growth.

2.3. Method. We simplify the method proposed in [28] to explore the types of causality that exist in the process of urbanization and economic growth. In this method, arbitrary variable can be projected at multidimension space, which increases the observability of the data and could simply the complexity of the data, and then, by analyzing the corresponding relationship between variables, the causality could be clearer. Details are as follows.

2.3.1. Reconstructing the Shadow Attractors $M_{\mathbf{X}}$ and $M_{\mathbf{y}}$. Firstly, we reconstruct the shadow attractor $M_{\mathbf{X}}$ of the independent variable $\mathbf{x}_t$, and the formula is as follows:

$$M_x = \begin{pmatrix} X_1 = < x_{1+(E-1)\tau}, \ldots, x_{1+\tau}, x_1 > \\ X_2 = < x_{2+(E-1)\tau}, \ldots, x_{2+\tau}, x_2 > \\ \vdots \\ X_{L-(E-1)\tau} = < x_{L-(E-1)\tau}, \ldots, x_{L+\tau}, x_L > \end{pmatrix}. \quad (1)$$

Similarly, the reconstruction formula of the shadow attractor $M_{\mathbf{y}}$ of the dependent variable y_t is as follows:

$$M_y = \begin{pmatrix} Y_1 = < y_{1+(E-1)\tau}, \ldots, y_{1+\tau}, y_1 > \\ Y_2 = < y_{2+(E-1)\tau}, \ldots, y_{2+\tau}, y_2 > \\ \vdots \\ Y_{L-(E-1)\tau} = < y_{L-(E-1)\tau}, \ldots, y_{L+\tau}, y_L > \end{pmatrix}. \quad (2)$$

In order to reduce the difficulty of causal mode judgment, refer to the Takens theorem to select the appropriate embedding dimension E and time lag τ to construct the shadow attractors and phase space. In this paper, we use $E = 3$ and $\tau = 1$. Then, the formulas of $M_{\mathbf{X}}$ and $M_{\mathbf{y}}$, respectively, become

Table 1: Indicator system.

Number	Evaluation indexes	Name and calculation	Statistic indicators
1	PGDP (yuan)	Per capita GDP	Per capita GDP
2	PU (%)	Population urbanization rate (urban population/total registered population) × 100%	Total registered population; urban population
3	RTS	Ratio of tertiary-secondary industry (tertiary industry/secondary industry)	Secondary industry and tertiary industry in GDP
4	RRUHCE	Ratio of rural-urban household consumption expenditure (value of rural household consumption expenditure/value of urban household consumption expenditure)	Value of urban household consumption expenditure; value of rural household consumption expenditure
5	RRUE	Ratio of rural/urban employment (number of employed persons in rural area/number of employed persons in urban area)	Number of employed persons in urban area; number of employed persons in rural area
6	RRUEP	Ratio of the proportion of rural employees to agricultural population divided by the proportion of urban employees to nonagricultural population (number of employed persons in rural area/agricultural population/number of employed persons in urban area/nonagricultural population)	Number of employed persons in urban area; number of employed persons in rural area; agricultural population; nonagricultural population
7	LGBR (10000 yuan)	Local government budgetary revenue	Local government budgetary revenue
8	LGBE (10000 yuan)	Local government budgetary expenditure	Local government budgetary expenditure
9	EE (10000 yuan)	Education expenditure	Education in local government budgetary expenditure
10	PLCPT (volumes per thousand)	Total collections per thousand	Total collections in public libraries

Table 1: Continued.

Number	Evaluation indexes	Name and calculation	Statistic indicators
11	BPT (beds per thousand)	Beds per thousand	Number of beds in medical institutions
12	MEPPT (person per thousand)	Number of medical personnel per thousand	Number of medical personnel
13	IN (10000 yuan)	Investment in fixed assets	Investment in fixed assets (excluding investment in fixed assets of rural households)
14	RST	Ratio of student-teacher (total enrollment in primary, senior, and junior secondary schools/full – time teachers in primary, senior, and junior secondary schools)	Total enrollment and full-time teachers in senior and junior secondary schools, total enrollment and full-time teachers in primary schools
15	PT (10000 persons)	Passenger traffic	Passenger traffic
16	VFT (10000 tons)	Volume of freight traffic	Volume of freight traffic
17	BVPTS (100 million yuan)	Business volume of post and telecommunication services	Business volume of post and telecommunication services

$$M_x = (X_T) = (X_T, X_{T+1}, X_{T+2}), \quad (3)$$

$$M_y = (Y_T) = (Y_T, Y_{T+1}, Y_{T+2}). \quad (4)$$

2.3.2. Calculating the Distance Matrices $D_{\mathbf{x}}$ and $D_{\mathbf{y}}$. The first-order difference between variables at two adjacent time points is used as the element to calculate distance matrices $D_{\mathbf{x}}$ and $D_{\mathbf{y}}$ of the shadow attractors $M_{\mathbf{X}}$ and $M_{\mathbf{y}}$; then, the distance matrix $D_{\mathbf{x}}$ of $M_{\mathbf{X}}$ can be expressed as

$$D_X = \begin{pmatrix} d(X_1, X_1), d(X_1, X_2), \ldots d\left(X_1, X_{L-(E-1)\tau}\right) \\ d(X_2, X_1), d(X_2, X_2), \ldots, d\left(X_2, X_{L-(E-1)\tau}\right) \\ \vdots \\ d\left(X_{L-(E-1)\tau}, X_1\right), d\left(X_{L-(E-1)\tau}, X_2\right), \ldots, d\left(X_{L-(E-1)\tau}, X_{L-(E-1)\tau}\right) \end{pmatrix}, \quad (5)$$

where $d(X_m, X_n) = \Delta X_{mn} = X_n - X_m$. Similarly, the distance matrix $D_{\mathbf{y}}$ of $M_{\mathbf{y}}$ can be expressed as

$$D_y = \begin{pmatrix} d(Y_1, Y_1), d(Y_1, Y_2), \ldots, d\left(Y_1, Y_{L-(E-1)\tau}\right) \\ d(Y_2, Y_1), d(Y_2, Y_2), \ldots, d\left(Y_2, Y_{L-(E-1)\tau}\right) \\ \vdots \\ d\left(Y_{L-(E-1)\tau}, Y_1\right), d\left(Y_{L-(E-1)\tau}, Y_2\right), \ldots, d\left(Y_{L-(E-1)\tau}, Y_{L-(E-1)\tau}\right) \end{pmatrix}, \quad (6)$$

where $d(Y_m, Y_n) = \Delta Y_{mn} = Y_n - Y_m$.

2.3.3. Identifying the Change Pattern of x_t and y_t and Signature Calculation. In order to eliminate the influence of the value level and measurement unit of the variable on the judgment of the causality pattern, we define the change pattern of x_t and y_t as $s_n^{\mathbf{x}}$ and $s_n^{\mathbf{y}}$, and the formulas of $s_n^{\mathbf{x}}$ and $s_n^{\mathbf{y}}$ are as follows:

$$s_n^x = \left(\frac{x_n - x_m}{x_m}\right), \quad (7)$$

$$s_n^y = \left(\frac{y_n - y_m}{y_m}\right). \quad (8)$$

Since $E = 3$ is used as an embedding parameter, the change of variables and corresponding pattern signatures follow the symbolic rules, as follows:

(i) $\nearrow\nearrow$: $X_T < X_{T+1} < X_{T+2}$.
(ii) $\longrightarrow\nearrow$: $X_T = X_{T+1} < X_{T+2}$.
(iii) $\searrow\nearrow$: $X_T > X_{T+1} < X_{T+2}$.
(iv) $\nearrow\longrightarrow$: $X_T < X_{T+1} = X_{T+2}$.
(v) $\longrightarrow\longrightarrow$: $X_T = X_{T+1} = X_{T+2}$.
(vi) $\searrow\longrightarrow$: $X_T > X_{T+1} = X_{T+2}$.
(vii) $\nearrow\searrow$: $X_T < X_{T+1} > X_{T+2}$.
(viii) $\longrightarrow\searrow$: $X_T = X_{T+1} > X_{T+2}$.
(ix) $\searrow\searrow$: $X_T > X_{T+1} > X_{T+2}$.

Furthermore, according to the pattern signatures, we calculate the pattern probability $P_{\mathbf{X}_T}$ and $P_{\mathbf{Y}_T}$, and the formulas of $P_{\mathbf{X}_T}$ and $P_{\mathbf{Y}_T}$ are as follows:

$$P_{X_T} = \text{Signature}\left(s_n^x\right), \quad P_{Y_T} = \text{Signature}\left(s_m^y\right). \quad (9)$$

2.3.4. Pattern Causality Matrix and Separating PC Pattern. We fill $P_{\mathbf{X}_T}$ and $P_{\mathbf{Y}_T}$ into pattern matrix for $E = 3$ and then divide the pattern matrix to calculate the cumulative probability (denoted as PC) of the positive, negative, and dark causality patterns, and the functions are as follows [22]:

$$\begin{aligned}
\mathrm{PC}(\mathrm{Positive}) &= \frac{1}{L}\sum \mathrm{diag}_{\mathrm{main}}(\mathrm{PC}),\ \mathrm{PC}(\mathrm{Positive}) \in [0,1],\\
\mathrm{PC}(\mathrm{Negative}) &= \frac{1}{L}\sum \mathrm{diag}_{\mathrm{counter}}(\mathrm{PC}),\ \mathrm{PC}(\mathrm{Negative}) \in [0,1],\\
\mathrm{PC}(\mathrm{Dark}) &= \frac{1}{L}\sum\left(PC \notin \left(\mathrm{diag}_{\mathrm{main}}(\mathrm{PC})\right) \cup \left(\mathrm{diag}_{\mathrm{counter}}(\mathrm{PC})\right)\right),\ \mathrm{PC}(\mathrm{Dark}) \in [0,1],
\end{aligned} \tag{10}$$

where PC(positive) + PC(negative) + PC(dark) = 1.

2.3.5. Theorems and Proofs. According to [22], the reason that this method enables identification of the nature of influence is that it satisfies two important definitions.

Definition 1

(1) If X causes same-direction changes to Y, then we say that X has a positive influence on Y.

(2) If X causes opposite-direction changes to Y, then we say that X has a negative influence on Y.

(3) If X causes changes to Y which are of neither the same nor the opposite direction, then we say that X has a "dark" influence on Y.

(4) $\rightarrowtail\!\!\!\!\rightarrow$ symbolizes diffeomorphism.

In terms of Definition 1, four lemmas are introduced to analyze all kinds of causalities in the processes of urbanization and economic growth.

Lemma 1. *Let M be an m-dimensional compact manifold and $X: M \longrightarrow \mathbb{R}$, $Y: M \longrightarrow \mathbb{R}$ be smooth observation functions. Let φ: MM be a smooth diffeomorphism. If there exists ψ: $M_X M_Y$ such that ψ is bijective, then M_X causes M_Y.*

Lemma 2. *Let M be an m-dimensional compact manifold and $X: M \longrightarrow \mathbb{R}$, $Y: M \longrightarrow \mathbb{R}$ be smooth observation functions. If M_X causes M_Y (through a bijective map ψ) and there exist h: $M_X X$ and gM_Y Y, with h, g being bijective, then X causes Y as well.*

Lemma 3. *Let M be an m-dimensional compact manifold and $X: M \longrightarrow \mathbb{R}$, $Y: M \longrightarrow \mathbb{R}$ be smooth observation functions. Let φ: MM be a smooth diffeomorphism. If there exists ψ: $M_X \rightarrowtail M_Y$ such that ψ is injective, then M_X weakly causes M_Y.*

Lemma 4. *Let M be an m-dimensional compact manifold and $X: M \longrightarrow \mathbb{R}$, $Y: M \longrightarrow \mathbb{R}$ be smooth observation functions. If M_X weakly causes M_Y (through an injective map ψ) and there exist h: $M_X \rightarrowtail X$ and g: $M_Y \rightarrowtail Y$ with h, g being injective, then X weakly causes Y as well.*

Definition 2

(1) P: $M_X \longrightarrow^{+} M_Y$, $\longrightarrow^{+}$: $\{\underline{x} \longrightarrow \underline{y} \mid p\,\underline{x} \overset{+}{\leftrightarrow} +p\,\underline{x}\}$P corresponds to the same patterns (i.e., positive mapping).

(2) N: $M_X \overset{-}{\rightarrow} M_Y$, $\overset{-}{\rightarrow}$: $\{\underline{x} \longrightarrow \underline{y} \mid p\,\underline{x} \overset{-}{\leftrightarrow} -p\,\underline{x}\}$N corresponds to opposite patterns (i.e., negative mapping).

(3) D: $M_X \longrightarrow * \ M_Y$, $\longrightarrow *$: $\{\underline{x} \longrightarrow \underline{y} \mid p\,\underline{x} \overset{*}{\leftrightarrow} p\,\underline{x}\}$. D corresponds to patterns that are neither the same nor opposite (i.e., dark mapping).

Definition 2 is used extensively in the formulation and proof of the following three important theorems.

Theorem 1. *Let M be an m-dimensional compact manifold and $X: M \longrightarrow \mathbb{R}$, $Y: M \longrightarrow \mathbb{R}$ be smooth observation functions. Let φ: MM be a smooth diffeomorphism. Let M_X and M_Y be the shadow attractors of X and Y, respectively. If* P: $M_X \longrightarrow^{+} M_Y$ *such that* P *is bijective (or injective) and there exist h: $M_X \longrightarrow X$ and g: $M_Y \longrightarrow Y$, with h, g being bijective (or injective), then X exerts a positive influence on Y.*

Theorem 2. *Let M be an m-dimensional compact manifold and $X: M \longrightarrow \mathbb{R}$, $Y: M \longrightarrow \mathbb{R}$ be smooth observation functions. Let φ: MM be a smooth diffeomorphism. Let M_X and M_Y be the shadow attractors of X and Y, respectively. If* N: $M_X \overset{-}{\rightarrow} M_Y$ *is bijective (or injective) and there exist h: $M_X \longrightarrow X$ and g: $M_Y \longrightarrow Y$ that are bijective (or injective), then X exerts a negative influence on Y.*

Theorem 3. *Let M be an m-dimensional compact manifold and $X: M \longrightarrow \mathbb{R}$, $Y: M \longrightarrow \mathbb{R}$ be smooth observation functions. Let φ: MM be a smooth diffeomorphism. Let M_X and M_Y be the shadow attractors of X and Y, respectively. If* D: $M_X \longrightarrow * \ M_Y$ *such that* D *is bijective (or injective) and there exist h: $M_X \longrightarrow X$ and g: $M_Y \longrightarrow Y$ that are bijective (or injective), then X exerts a dark influence on Y.*

Proofs of the above theorems are given in the supplementary information in [22].

3. Correlation Analysis

3.1. Population Urbanization Rate and Per Capita GDP of Shandong Province. As shown in Figure 1, since 1952, the processes of economic growth and urbanization in Shandong Province have experienced two periods of slow and rapid development: the relatively slow period from 1952 to 1987 and the rapid development period from 1987 to 2019. From 1952 to 1987, per capita GDP increased from y91 to y1,131, an increase of 11.4 times, and the urbanization rate rose from 5.99% to 13.25%. From 1987 to 2019, per capita GDP increased from y1,131 to y70,653, an increase of 61 times, and the urbanization rate increased from 13.25% to 49.94% (the highest value in 2018 was 50.94%).

Figure 1: The relationship between per capital GDP and PU from 1952 to 2019.

Figure 1 shows that from 1952 to 2019, per capital GDP increased in the way of logistic, and PU increased linearly. The linear growth of PU promoted the growth of per capital GDP in logistic pattern, and the causality between per capital GDP and PU was significant.

3.2. Correlation Analysis of Per Capita GDP and Population Urbanization Rate. The correlation between per capita GDP and PU of 17 cities from 2000 to 2017 is analyzed year by year, and the results are shown in Figure 2. It can be observed that the correlation between per capita GDP and PU shows three stages: (1) from 2000 to 2004, there was a strong positive correlation between per capita GDP and PU, indicating a strong interaction between economic growth and urbanization development; (2) from 2004 to 2012, the positive correlation between per capita GDP and PU gradually decreased, and the correlation coefficient decreased from 0.861 to 0.503, indicating that the interaction between the two is weakening; (3) from 2012 to 2013, the correlation between per capita GDP and PU returned to the highly positive correlation, which remained consistent until 2017, indicating that the relation between economic growth and urbanization became strongly interactive. The main reason for the above changes is the shift of urbanization strategy, which was proposed at the Central Economic Work Conference in December 2012: from "traditional urbanization" to "new urbanization." New urbanization has become an important engine of economic growth, which is proved by the high positive correlation between per capita GDP and PU from 2013 to 2017.

3.3. Correlation Analysis of Evaluation Indexes. The correlation analysis of the sequences of 17 evaluation indicators in 17 cities from 2000 to 2017 is carried out, and the results are shown in Figure 3. The correlation coefficients of arbitrary two indexes of LGBR, LGBE, EE, IN, and the correlation coefficient between BPT and MEPPT, are all larger than 0.9. The correlation coefficients between PU, BPT, MEPPT, and PGDP and between RRUE, BPT, MEPPT, and PU were greater than 0.8 and less than 0.9. The correlation coefficients between PGDP and RRUE, LGBR, and IN, between RTS and LGBR and LGBE, between PU and LGBR, LGBE, EE, and IN, between RRUE and RRUEP, BPT, and MEPPT, and between LGBR/LGBE/EE and BPT, MEPPT, VFT, and BVPTS are greater than 0.6 and less than 0.8. It shows that there is strong interaction among these evaluation indexes. However, except the correlation coefficients between RRUEP and RRUE, PT and VFT, the correlation coefficients of arbitrary two indexes of RRUHCE, RRUEP, PLCPT, RST, PT, and the correlation coefficients between the above five indexes and the other indexes are all less than 0.5. The correlation coefficients of arbitrary two indexes of LGBR, LGBE, EE, IN, and the correlation coefficient between BPT and MEPPT, are all larger than 0.9, indicating weak interaction among them, which is exactly the problem to be studied in this paper.

Figure 3 shows the following. (1) In the matrix, the diagonal represents the probability density distribution function of variables, from which it can be seen that the vast majority of variables follow normal distribution or biased normal distribution; the distribution of some variables, such as PLCPT, LGBR, LGBE, EE and IN, is far from the standard normal distribution. (2) The data in the upper triangle of the matrix represent the correlation coefficient of two variables, which expresses the strength of correlation between two variables, where $*$, $**$, and $***$ denote significance at 10, 5, and 1% levels, respectively. (3) The lower triangle of the matrix represents the scatter diagram between two variables, from which we can intuitively observe the relationships, such as positive correlation, negative correlation, or no correlation. (4) In summary, our research object meets certain causality conditions, and among the above correlations, the correlations of two variables including PU, RST, RRUHCE, RRUEP, PLCPT, RST, and PT are not obvious. We suspect that there is some dark causality in the progress of urbanization and economic growth, which will be further analyzed in the following sections.

3.4. Selection of Independent Variable and Dependent Variable. Our purpose is mainly to judge the causality

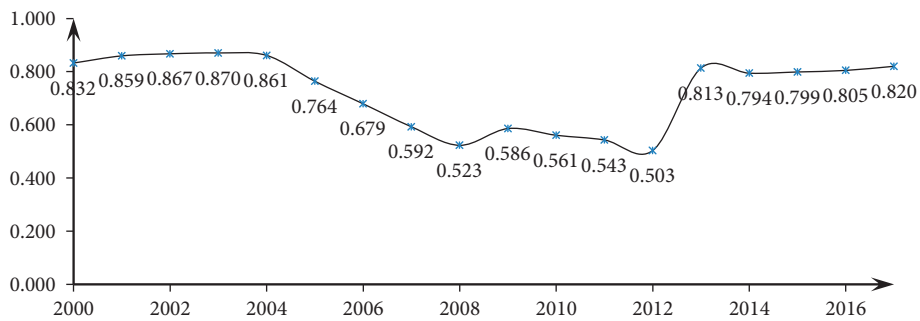

Figure 2: The correlation coefficients between per capital GDP and PU of 17 cities from 2000 to 2017.

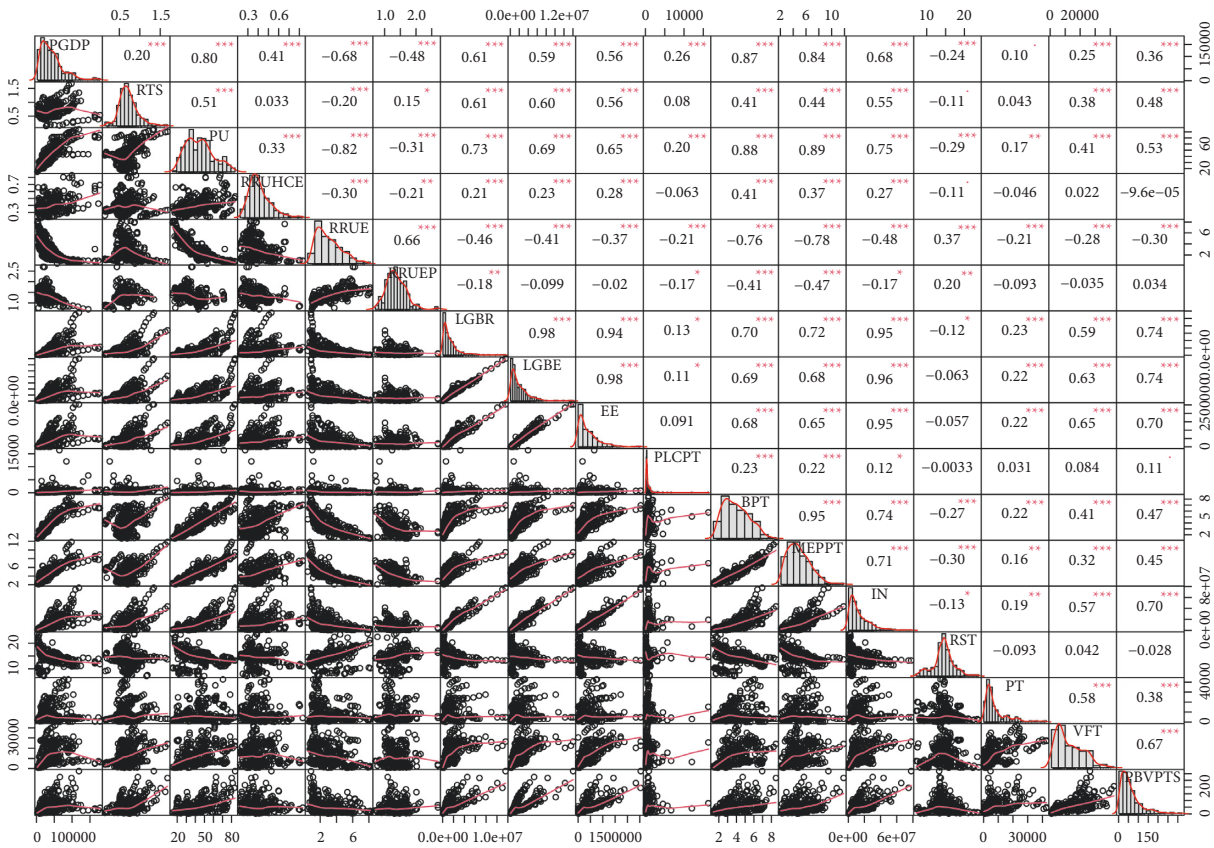

Figure 3: Pairwise correlation coefficient between 17 evaluation indexes.

between weakly correlated variables. Therefore, we omit the evaluation indexes with large correlation coefficients and retain those with small correlation coefficients, including PU, RTS, RRUHCE, RRUEP, PLCPT, RST, and PT, as shown in Figure 4, to study the hidden causality by multiobjective artificial bee colony algorithm [32] among the processes of urbanization development and economic growth. Among them, PU, which has the strongest correlation with per capita GDP, is used as the dependent variable to reflect the level of urbanization and economic development, denoted as $\mathbf{y}_t = (\mathrm{PU}_{\mathrm{it}})$. Let $y = \mathrm{PU}$; then, $\mathbf{y}_t = (y_{\mathrm{it}})$. The other six evaluation indexes are used as independent variables, denoted as $\mathbf{x}_t = (\mathrm{RST}_{\mathrm{it}}, \mathrm{RRUHCE}_{\mathrm{it}}, \mathrm{RRUEP}_{\mathrm{it}}, \mathrm{PLCPT}_{\mathrm{it}}, \mathrm{RST}_{\mathrm{it}}, \mathrm{PT}_{\mathrm{it}})$. Let $\mathrm{RST} = x^1, \mathrm{RRUHCE} = x^2, \mathrm{RRUEP} = x^3, \mathrm{PLCPT} = x^4, \mathrm{RST} = x^5, \mathrm{PT} = x^6$; then, $x_t = (x_{it}^1, x_{it}^2, x_{it}^3, x_{it}^4, x_{it}^5, x_{it}^6)$, where $i = 1, 2, \ldots, 17$, respectively, indicate 17 cities, and $t = 1, 2, \ldots, 18$ indicate the year from 2000 to 2017.

4. Empirical Results of Pattern Causality Matrix in Shandong Province

4.1. Discrete Algorithm of Entropy for the Continuous Data. We adopted the discrete algorithm of entropy [42] to treat the time series data of continuous variables, and the details are as follows.

X is a continuous variable, its time series value is $(x_1, x_2, \cdots, x_n)$, $P(x_i)$ represents the probability of occurrence of x_i, and $\sum P(x_i) = 1$. Then, the information entropy of X is

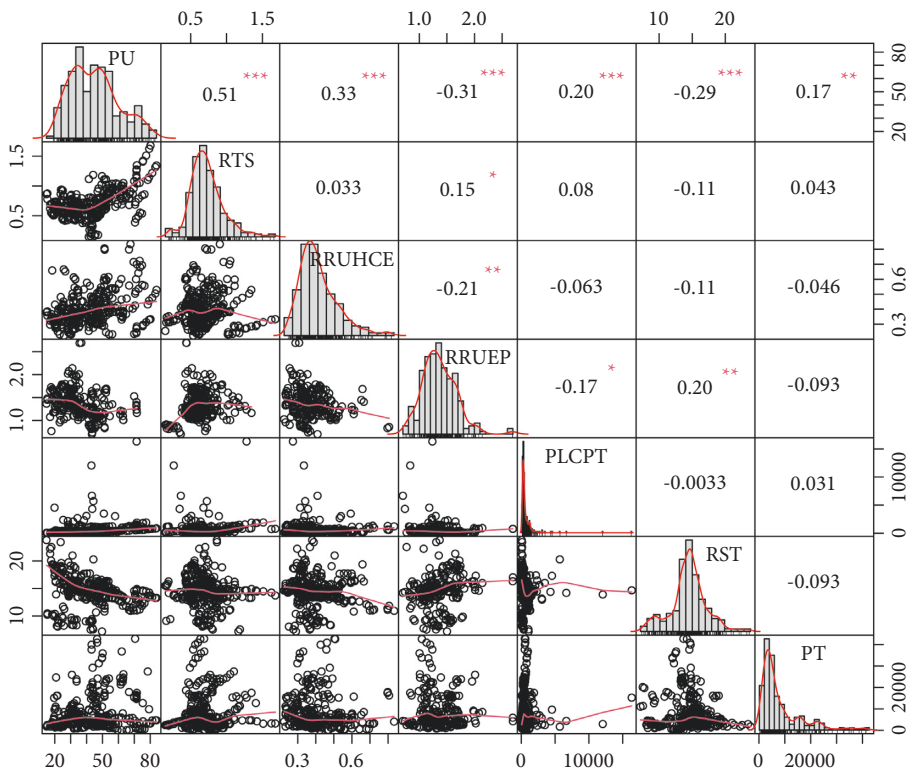

Figure 4: Pairwise correlation coefficient between 7 evaluation indexes.

$$H(X) = E[-\log P(x_i)] = -\sum_{i=1}^{N} P(x_i)\log P(x_i). \quad (11)$$

In 1993, Fayyad and Irani proposed the minimum information entropy discretization method [43]. The discrete threshold boundary value is selected by the class information entropy of the candidate interval. The information entropy of the subsets S_1 and S_2 is $\mathrm{Ent}(S_1)$ and $\mathrm{Ent}(S_2)$; then, the class information entropy of the breakpoint T on attribute A can be expressed as

$$E(A,T;S) = \left(\frac{|S_1|}{|S|}\right)\cdot \mathrm{Ent}(S_1) + \left(\frac{|S_2|}{|S|}\right)\cdot \mathrm{Ent}(S_2), \quad (12)$$

where $|S|$ represents the number of elements in the set S.

For a given attribute A, the point with the smallest value of $E(A,T;S)$ is taken as the partition point of discretization, denoted as $T\min$. The partition point $T\min$ divides the interval into two parts, and the sample set is also divided into two sets S_1 and S_2. In the calculation of all partition points of S_1 and S_2, it is assumed that T_1 and T_2 are the best partition points of S_1 and S_2, respectively, and their corresponding class information entropy is $E(A,T_1,S_1)$ and $E(A,T_2,S_2)$, respectively. If $E(A,T_1,S_1) > E(A,T_2,S_2)$, continue to divide S_1; otherwise, divide S_2. In other words, whichever is bigger is divided. Then, they are recursively invoked until the recursive stop condition is met. The stopping condition is to use the minimum discriminant length criterion to judge whether the recursive discretization stops, that is, the partition interval of recursion in the set S stops when the following conditions are met:

$$\mathrm{Gain}(A,T;S) < \left(\frac{\log_2(N-1)}{N}\right) + \left(\frac{(\Delta A,T;S)}{N}\right), \quad (13)$$

where N is the number of samples in the set $S\mathrm{Gain}(A,T;S) = \mathrm{Ent}(s) - \mathrm{Ent}(A,T,S)$.

$$\Delta(A,T;S) = \log_2\left(3^k - 2\right) - \left[k\cdot \mathrm{Ent}(S) - k_1\cdot \mathrm{Ent}(S_2) - k_2\cdot \mathrm{Ent}(S_2)\right], \quad (14)$$

where k_1 and k_2 represent the number of categories in the sets S_1 and S_2, namely, $k = |S|$, $k_1 = |S_1|$, $k_2 = |S_2|$.

According to this process, all continuous variables involved in this paper are discretized.

After the discretization of variable data, we invoke the corresponding algorithms and theorems mentioned in Section 2.3, i.e., equations (1)–(10), to analyze the hidden causalities in the progress of urbanization and economic growth in Shandong Province.

4.2. Empirical Results at the Provincial Level. PC (from x to y) pattern to pattern matrix at the provincial level is shown in Table 2. Cumulative probability of the positive, negative, and dark PC from RST to PU is 0.393382, 0.209559, and 0.397059, respectively, calculated according to Table 2(a). Cumulative probability of the positive, negative, and dark PC from RRUHCE to PU is 0.316176, 0.183824, and 0.5, respectively, calculated according to Table 2(b). Cumulative probability of the positive, negative, and dark PC from RRUEP to PU is 0.26738, 0.31016, and 0.42246, respectively,

Table 2: PC (from x to y) pattern to pattern matrix at the provincial level.

(a) PC (from RTS to PU) pattern to pattern matrix

	y:↗↗	y:→↗	y:↘↗	y:↗→	y:→→	y:↘→	↗↘	y:→↘	y:↘↘
x1:↗↗	0.371324	0	0.102941	0	0	0	□.095588	0	0.022□59
x1:→↗	0.007353	0	0	0	0	0	0	0	0
x1:↘↗	0.069853	0	0.018382	0	0	0	0.007353	0	0
x1:↗→	0.007353	0	0	0	0	0	0	0	0
x1:→→	0	0	0	0	0	0	0	0	0
x1:↘→	0	0	0	0	0	0	0	0	0
x1:↗↘	0.091912	0	0.007353	0	0	0	0.003676	0	0.003676
x1:→↘	0	0	0	0	0	0	0	0	
x1:↘↘	0.172794	0	0.011029	0	0	0	0.007353	0	0

(b) PC (from RRUHCE to PU) pattern to pattern matrix

	y:↗↗	y:→↗	y:↘↗	y:↗→	y:→→	y:↘→	y:↗↘	y:→↘	y:↘↘
x2:↗↗	0.279412	0	0.073529	0	0	0	0.066176	0	0.018382
x2:→↗	0	0	0	0	0	0	0	0	0
x2:↘↗	0.158088	0	0.029412	0		0	0.011029	0	0.0□3676
x2:↗→	0	0	0	0	0	0	0	0	0
x2:→→	0	0	0	0	0	0	0	0	0
x2:↘→	0	0	0	0	0	0	0	0	0
x2:↗↘	0.161765	0	0.022059	0	0	0	0.007353	0	0
x2:→↘	0	0	0	0	0	0	0	0	0
x2:↘↘	0.132353	0	0.029412	0	0	0	0.007353	0	0

(c) PC (from RRUEP to PU) pattern to pattern matrix

	y:↗↗	y:→↗	y:↘↗	y:↗→	y:→→	y:↘→	y:↗↘	y:→↘	y:↘↘
x3:↗↗	0.240642	0	0.02139	0	0	0	0.005348	0	0.005348
x3:→↗	0	0	0	0	0	0	0	0	0
x3:↘↗	0.15508	0	0.016043	0	0	0	0.0106□5	0	0
x3:↗→	0	0	0	0	0	0	0	0	0
x3:→→	0	0	0	0	0	0	0	0	0
x3:↘→	0	0	0	0	0	0	0	0	0
x3:↗↘	0.176471	0	0.053476	0	0	0	0.010695	0	0
x3:→↘	0	0	0	0	0	0	0	0	0
x3:↘↘	0.240642	0	0.037433	0	0	0	0.010695	0	0.016043

(d) PC (from PLCPT to PU) pattern to pattern matrix

	y:↗↗	y:→↗	y:↘↗	y:↗→	y:→→	y:↘→	y:↗↘	y:→↘	y:↘↘
x4:↗↗	0.397059	0	0.066176	0	0		0.077206	0	0.0330□8
x4:→↗	0	0	0	0	0	0	0	0	0
x4:↘↗	0.180147	0	0.007353	0	0	0	0.007353	0	0
x4:↗→	0	0	0	0	0	0	0	0	0
x4:→→	0	0	0	0	0	0	0	0	0
x4:↘→	0	0	0	0	0	0	0	0	0
x4:↗↘	0.1□6029	0	0.040441	0	0	0	0.007353	0	0
x4:→↘	0	0	0	0	0	0	0	0	0
x4:↘↘	0.040441	0	0.003676	0	0	0	0.0□3676	0	0

(e) PC (from RST to PU) pattern to pattern matrix

	y:↗↗	y:→↗	y:↘↗	y:↗→	y:→→	y:↘→	y:↗↘	y:→↘	y:↘↘
x5:↗↗	0.080882	0	0.014706	0	0	0	0.007353	0	0
x5:→↗	0	0	0	0	0	0	0	0	0
x5:↘↗	0.161765	0	0.033088	0	0	0	0.018382	0	0
x5:↗→	0	0	0	0	0	0	0	0	0
x5:→→	0	0	0	0	0	0	0	0	0
x5:↘→	0	0	0	0	0	0	0	0	0
x5:↗↘	0.172794	0	0.014706	0	0	0	0.00735	0	0.003676
x5:→↘	0	0	0	0	0	0	0	0	0
x5:↘↘	0.319853	0	0.0625	0	0	0	0.0698	0	0.033088

(f) PC (from PT to PU) pattern to pattern matrix

	y:↗↗	y:→↗	y:↘↗	y:↗→	y:→→	y:↘→	y:↗↘	y:→↘	y:↘↘
x6:↗↗	0.352941	0	0.069853	0	0	0	0.077206	0	0.033088
x6:→↗	0	0	0	0	0	0		0	0
x6:↘↗	0.158088	0	0	0	0	0		0	0
x6:↗→	0.003676	0	0.007353	0	0	0	0.0□3□76	0	0.003676
x6:→→	0	0	0	0	0	0	0	0	0
x6:↘→	0	0	0	0	0	0	0	0	0
x6:↗↘	0.15□412	0	0.033088	0	0	0	0.011029	0	0.003676
x6:→↘	0.003676	0	0	0	0	0	0	0	0
x6:↘↘	0.077206	0		0	0	0	0.0□7353	0	0

Note. (1) Each cell takes values from 0 to 1. Blue cells denote positive influence. Red cells denote negative. Purple cells denote dark influence. (2) The first column represents the change pattern of cause (x), the first line represents the change pattern of effect (y), the numbers represent the probability of effect (y) caused by cause (x), "0" represents impossible event, and "1" represents certain event. (3) From the table, we can find that the dominant causalities between RTS, RRUHCE, RRUEP, PLCPT, RST, PT, and PU are dark.

calculated according to Table 2(c). Cumulative probability of the positive, negative, and dark PC from PLCPT to PU is 0.411765, 0.121324, and 0.466912, respectively, calculated according to Table 2(d). Cumulative probability of the positive, negative, and dark PC from RST to PU is 0.121324, 0.352941, and 0.525735, respectively, calculated according to Table 2(e). Cumulative probability of the positive, negative, and dark PC from PT to PU is 0.363971, 0.143382, and 0.492647, respectively, calculated according to Table 2(f). To sum up, the dark PC dominates in PC (from **x** to **y**) pattern at the provincial level, as shown in Table 3.

4.3. Empirical Results at the Regional Level. According to the current administrative division and development strategy of Shandong Province, it is generally divided into the Jinan economic circle, the Jiaodong economic circle, and the Lunan economic circle (as shown in Figure 5). From the spatial structure, the Jinan economic circle includes Jinan (including Laiwu), Zibo, Tai'an, Liaocheng, Dezhou, Binzhou, and Dongying; the Jiaodong economic circle includes Qingdao, Yantai, Weihai, Weifang, and Rizhao; the Lunan economic circle includes Linyi, Zaozhuang, Jining, and Heze.

In Figure 5, green denotes the range of Jinan economic circle, blue denotes the range of Jiaodong economic circle, and pink denotes the range of Lunan economic circle.

4.3.1. Analysis of Pattern Causality Matrix in the Jinan Economic Circle. PC (from x to y) pattern to pattern matrix in the Jinan economic circle is shown in Table 4. Cumulative probability of the positive, negative, and dark PC from RST to PU is 0.515625, 0.21875, and 0.265625, respectively, calculated according to Table 4(a). Cumulative probability of the positive, negative, and dark PC from RRUHCE to PU is 0.3671875, 0.171875, and 0.4609375, respectively, calculated according to Table 4(b). Cumulative probability of the positive, negative, and dark PC from RRUEP to PU is 0.3984375, 0.1953125, and 0.40625, respectively, calculated according to Table 4(c). Cumulative probability of the positive, negative, and dark PC from PLCPT to PU is 0.4453125, 0.0703125, and 0.484375, respectively, calculated according to Table 4(d). Cumulative probability of the positive, negative, and dark PC from RST to PU is 0.1015625, 0.421875, and 0.4765625, respectively, calculated according to Table 4(e). Cumulative probability of the positive, negative, and dark PC from PT to PU is 0.421875, 0.1171875, and 0.4609375, respectively, calculated according to Table 4(f). To sum up, in addition to that the positive influence dominates in PC (from RTS to PU) pattern, and the dark PC dominates in PC (from the other independent variable in **x** to **y**) pattern in the Jinan economic circle, as shown in Table 3.

4.3.2. Analysis of Pattern Causality Matrix in the Jiaodong Economic Circle. PC (from **x** to **y**) pattern to pattern matrix in the Jiaodong economic circle is shown in Table 5. Cumulative probability of the positive, negative, and dark PC from RST to PU is 0.5, 0.2, and 0.3, respectively, calculated according to Table 5(a). Cumulative probability of the positive, negative, and dark PC from RRUHCE to PU is 0.4875, 0.15, and 0.3625, respectively, calculated according to Table 5(b). Cumulative probability of the positive,

Table 3: Comparison of PC pattern at different regional levels in Shandong Province.

Regional level	PC pattern with PU					
	RTS	RRUHCE	RRUEP	PLCPT	RST	PT
Provincial level	Dark > positive > negative (0.397059,0.393382,0.209559)	Dark > positive > negative (0.5,0.316176,0.183824)	Dark > negative > positive (0.42246,0.310160.26738)	Dark > positive > negative (0.466912,0.411765,0.121324)	Dark > negative > positive (0.525735,0.352941,0.121324)	Dark > positive > negative (0.492647,0.363971,0.143382)
The Jinan economic circle	Positive > dark > negative (0.515625,0.265625,0.21875)	Dark > positive > negative (0.4609375,0.3671875,0.171875)	Dark > positive > negative (0.40625,0.3984375,0.1953125)	Dark > positive > negative (0.484375,0.4453125,0.0703125)	Dark > negative > positive (0.4765625,0.421875,0.1015625)	Dark > positive > negative (0.4609375,0.421875,0.1171875)
The Jiaodong economic circle	Positive > dark > negative (0.5,0.3,0.2)	Positive > dark > negative (0.4875,0.3625,0.15)	Positive > dark > negative (0.45,0.3375,0.2125)	Positive > dark > negative (0.7125,0.2875,0)	Negative > dark > Positive (0.475,0.45,0.075)	Positive > dark > negative (0.55,0.375,0.075)
The Lunan economic circle	Dark > positive > negative (0.421875,0.390625,0.1875)	Dark > positive > negative (0.5,0.296875,0.203125)	Dark > positive > negative (0.515625,0.28125,0.203125)	Dark > positive > negative (0.546875,0.3125,0.140625)	Dark > negative > positive (0.5625,0.296875,0.140625)	Dark > positive > negative (0.515625,0.359375,0.125)

Note. Positive, negative, and dark causalities are ranked according to their importance, from which it is easy to find the dominant causality.

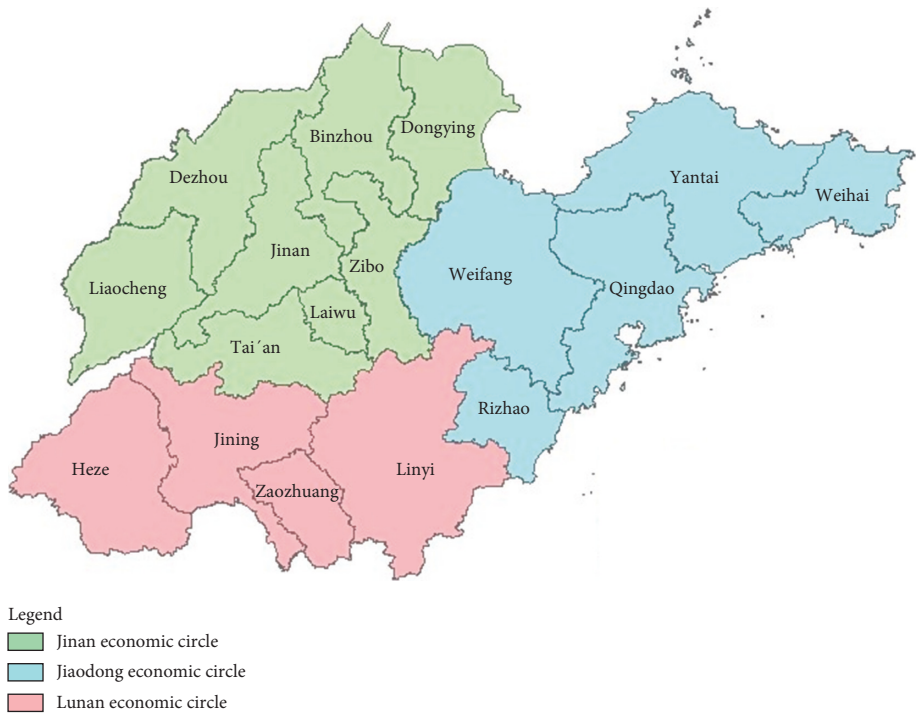

Figure 5: Three economic circles' range in Shandong Province.

Table 4: PC (from **x** to **y**) matrix in the Jinan economic circle.

(a) PC (from RTS to PU) pattern to pattern matrix

	y:↗↗	y:→↗	y:↘↗	y:↗→	y:→→	y:↘→	y:↗↘	y:→↘	y:↘↘
x1:↗↗	0.5	0	0.0625	0	0	0	0.054688	0	0.023438
x1:→↗	0	0	0	0	0	0	0	0	0
x1:↘↗	0.0625	0	0	0	0	0	0.015625	0	0
x1:↗→	0	0	0	0	0	0	0	0	0
x1:→→	0	0	0	0	0	0	0	0	0
x1:↘→	0	0	0	0	0		0	0	0
x1:↗↘	0.070313	0	0.007813		0	0	0.015625	0	0
x1:→↘	0	0	0	0	0	0	0	0	0
x1:↘↘	0.171875	0	0	0	0	0	0	0	0.015625

(b) PC (from RRUHCE to PU) pattern to pattern matrix

	y:↗↗	y:→↗	y:↘↗	y:↗→	y:→→	y:↘→	y:↗↘	y:→↘	y:↘↘
x2:↗↗	0.320313	0	0.054688	0	0	0	0.05488	0	0.007813
x2:→↗	0	0	0	0	0	0		0	0
x2:↘↗	0.148438	0	0.03125	0	0	0	0.007813	0	0.007813
x2:↗→	0	0	0	0	0	0	0	0	0
x2:→→	0	0	0	0	0	0	0	0	0
x2:↘→	0	0	0	0	0	0	0	0	0
x2:↗↘	0.164063	0	0.015625	0	0	0	0.015625	0	0
x2:→↘	0	0	0	0	0	0	0	0	0
x2:↘↘	0.140625	0	.015625	0	0	0	0.015625	0	0

(c) PC (from RRUEP to PU) pattern to pattern matrix

	y:↗↗	y:→↗	y:↘↗	y:↗→	y:→→	y:↘→	y:↗↘	y:→↘	y:↘↘
x3:↗↗	0.351563	0	0.046875	0	0	0	0.0625	0	0
x3:→↗	0	0	0	0	0	0	0	0	0
x3:↘↗	0.132813	0	0.03125	0	0	0	0.015625	0	0
x3:↗→	0	0	0	0	0	0	0	0	0
x3:→→	0	0	0	0	0	0	0	0	
x3:↘→	0	0	0	0	0	0	0	0	0
x3:↗↘	0.132813	0	0.03125	0	0	0	0.015625	0	0
x3:→↘	0	0	0	0	0	0	0	0	0
x3:↘↘	0.148438	0	0.015625	0	0	0	0.007813	0	0.007813

(d) PC (from PLCPT to PU) pattern to pattern matrix

	y:↗↗	y:→↗	y:↘↗	y:↗→	y:→→	y:↘→	y:↗↘	y:→↘	y:↘↘
x4:↗↗	029688	0	0.070313	0	0	0	0.0625	0	0.015625
x4:→↗	0	0	0	0	0	0	0	0	0
x4:↘↗	0.171875	0	0	0	0	0	0.05625	0	0
x4:↗→	0	0	0	0	0	0	0	0	0
x4:→→	0	0	0	0	0	0	0	0	0
x4:↘→	0	0	0	0	0	0	0	0	0
x4:↗↘	0.148438	0	0.007813	0	0	0	0.01562	0	0
x4:→↘	0	0	0	0	0	0	0	0	0
x4:↘↘	0.03125	0	0.015625	0	0	0	0.015625	0	0

(e) PC (from RST to PU) pattern to pattern matrix

	y:↗↗	y:→↗	y:↘↗	y:↗→	y:→→	y:↘→	y:↗↘	y:→↘	y:↘↘
x5:↗↗	0.078125	0	0.007813	0	0	0	0.015625	0	0
x5:→↗	0	0	0	0	0	0	0	0	0
x5:↘↗	0.1565	0	0.015625	0	0	0	0.015625	0	0
x5:↗→	0	0	0	0	0	0	0	0	0
x5:→→	0	0	0	0	0	0	0	0	0
x5:↘→	0	0	0	0	0	0	0	0	0
x5:↗↘	0.164063	0	0.00783	0	0	0	0.007813	0	0.007813
x5:→↘	0	0	0	0	0	0	0	0	0
x5:↘↘	0.398438	0	0.0625	0	0	0	0.046875	0	0.015625

(f) PC (from PT to PU) pattern to pattern matrix

	y:↗↗	y:→↗	y:↘↗	y:↗→	y:→→	y:↘→	y:↗↘	y:→↘	y:↘↘
x6:↗↗	0.40625	0	0.046875	0	0	0	0.046875	0	0.015625
x6:→↗	0	0	0	0	0	0	0	0	0
x6:↘↗	0.164063	0	0	0	0	0	0.007813	0	0.007813
x6:↗→	0.007813	0	0	0	0	0	0	0	0
x6:→→	0	0	0	0	0	0	0	0	0
x6:↘→	0	0	0	0	0	0	0	0	0
x6:↗↘	0.125	0	0.03125	0	0	0	0.015625	0	0
x6:→↘	0.007813	0	0	0	0	0	0	0	0
x6:↘↘	0.0625	0	0.007813	0	0	0	.015625	0	0

Note. The meaning is the same as Table 2. From the table, we can find that the dominant causalities between RRUHCE, RRUEP, PLCPT, RST, PT, and PU are dark, and the dominant causality between RTS and PU is positive.

negative, and dark PC from RRUEP to PU is 0.45, 0.2125, and 0.3375, respectively, calculated according to Table 5(c). Cumulative probability of the positive, negative, and dark PC from PLCPT to PU is 0.7125, 0, and 0.2875, respectively, calculated according to Table 5(d). Cumulative probability of the positive, negative, and dark PC from RST to PU is 0.075, 0.475, and 0.45, respectively, calculated according to Table 5(e). Cumulative probability of the positive, negative, and dark PC from PT to PU is 0.55, 0.075, and 0.375, respectively, calculated according to Table 5(f). To sum up, in addition to that the negative influence dominates in PC (from RST to PU) pattern, and the positive PC dominates in PC (from the other independent variable in **x** to **y**) pattern in the Jiaodong economic circle, as shown in Table 3.

Table 5: PC (from x to y) pattern to pattern matrix in the Jiaodong economic circle.

(a) PC (from RTS to PU) pattern to pattern matrix

	y:↗↗	y:→↗	y:↘↗	y:↗→	y:→→	y:↘→	y:↗↘	y:→↘	y:↘↘
x1:↗↗	0.4875	0	0.0125	0	0	0	0.0125	0	0
x1:→↗	0.025	0	0	0	0	0	0	0	0
x1:↘↗	0.1	0	0.0125	0	0		0	0	0
x1:↗→	0.025	0	0	0	0	0	0	0	0
x1:→→	0	0	0	0		0	0	0	0
x1:↘→	0	0	0	0	0	0	0	0	0
x1:↗↘	0.125	0	0	0	0	0	0	0	0
x1:→↘	0	0	0	0	0	0	0	0	0
x1:↘↘	0.2	0	0	0	0	0	0	0	0

(b) PC (from RRUHCE to PU) pattern to pattern matrix

	y:↗↗	y:→↗	y:↘↗	y:↗→	y:→→	y:↘→	y:↗↘	y:→↘	y:↘↘
x2:↗↗	0.475	0	0	0	0	0	0.012	0	0
x2:→↗	0	0	0	0	0	0	0	0	0
x2:↘↗	0.1875	0	0.0125	0	0	0	0	0	0
x2:↗→	0	0	0	0	0	0	0	0	0
x2:→→	0	0	0	0	0	0	0	0	0
x2:↘→	0	0	0	0	0	0	0	0	0
x2:↗↘	0.1625	0	0.0125	0	0	0	0	0	0
x2:→↘	0	0	0	0	0	0	0	0	0
x2:↘↘	0.1375	0		0	0	0		0	0

(c) PC(from RRUEP to PU) pattern to pattern matrix

	y:↗↗	y:→↗	y:↘↗	y:↗→	y:→→	y:↘→	y:↗↘	y:→↘	y:↘↘
x3:↗↗	.45	0	0.0125	0	0	0	0.0125	0	0
x3:→↗	0	0	0	0	0	0	0	0	0
x3:↘↗	0.1625	0	0	0	0	0	0	0	0
x3:↗→	0	0	0	0	0	0	0	0	0
x3:→→	0	0	0	0	0	0	0	0	0
x3:↘→	0	0	0	0	0	0	0	0	0
x3:↗↘	0.1375	0	0	0	0	0	0	0	0
x3:→↘	0	0	0	0	0	0	0	0	0
x3:↘↘	0.2125	0	0.0125	0	0	0	0	0	0

(d) PC (from PLCPT to PU) pattern to pattern matrix

	y:↗↗	y:→↗	y:↘↗	y:↗→	y:→→	y:↘→	y:↗↘	y:→↘	y:↘↘
x4:↗↗	0.7125	0	0.0125	0	0	0	0.0125	0	0
x4:→↗	0	0	0	0	0	0	0	0	0
x4:↘↗	0.1375	0	0	0	0	0	0	0	0
x4:↗→	0	0	0	0	0	0	0	0	0
x4:→→	0	0	0	0	0	0	0	0	0
x4:↘→	0	0	0	0	0	0		0	0
x4:↗↘	0.125	0	0	0	0	0	0	0	0
x4:→↘	0	0	0	0	0	0	0	0	0
x4:↘↘	0	0	0	0	0	0	0	0	0

(e) PC (from RST to PU) pattern to pattern matrix

	y:↗↗	y:→↗	y:↘↗	y:↗→	y:→→	y:↘→	y:↗↘	y:→↘	y:↘↘
x5:↗↗	.075	0	0	0	0	0	0	0	0
x5:→↗	0	0	0	0	0	0	0	0	0
x5:↘↗	0.225	0	0	0	0		0	0	0
x5:↗→	0	0	0	0	0	0	0	0	0
x5:→→	0	0	0	0	0	0	0	0	0
x5:↘→	0	0	0	0	0	0	0	0	0
x5:↗↘	0.2	0	0	0	0	0	0	0	0
x5:→↘	0	0	0	0	0	0	0	0	0
x5:↘↘	0. 75	0	0.0125	0	0	0	0.0125	0	0

(f) PC (from PT to PU) pattern to pattern matrix

	y:↗↗	y:→↗	y:↘↗	y:↗→	y:→→	y:↘→	y:↗↘	y:→↘	y:↘↘
x6:↗↗	0.55	0	0.0125	0	0	0	0.0125	0	0
x6:→↗	0	0	0	0	0	0	0	0	0
x6:↘↗	0.1625	0	0	0	0	0	0	0	0
x6:↗→	0	0	0	0	0	0	0	0	0
x6:→→		0	0	0	0	0	0	0	0
x6:↘→	0	0	0	0	0	0	0		0
x6:↗↘	0 1875	0	0	0	0	0	0	0	0
x6:→↘	0	0	0	0	0	0	0	0	0
x6:↘↘	0.075	0	0	0	0		0	0	0

Note. The meaning is the same as Table 2. From the table, we can find that the dominant causalities between RTS,RRUHCE, RRUEP, PLCPT, PT, and PU are positive, and the dominant causality between RST and PU is negative.

Table 6: PC (from **x** to **y**) pattern to pattern matrix in the Lunan economic circle.

(a) PC (from RTS to PU) pattern to pattern matrix

	y:↗↗	y:→↗	y:↘↗	y:↗→	y:→→	y:↘→	y:↗↘	y:→↘	y:↘↘
x1:↗↗	0.□75		0.09375	0	0	0	0.109375	0	0.015625
x1:→↗	0	0	0	0	0	0	0	0	0
x1:↘↗	0.09375	0	0	0	0	0	0.015625	0	0
x1:↗→	0	0	0	0	0	0	0	0	0
x1:→→	0	0	0	0	0	0	0	0	0
x1:↘→	0	0	0	0	0	0	0	0	0
x1:↗↘	0.0625	0	0.03125	0	0	0	0.015625	0	0
x1:→↘	0	0	0	0	0	0	0	0	0
x1:↘↘	0.1□5	0	0.03125	0	0	0	0.03125	0	0

(b) PC (from RRUHCE to PU) pattern to pattern matrix

	y:↗↗	y:→↗	y:↘↗	y:↗→	y:→→	y:↘→	y:↗↘	y:→↘	y:↘↘
x2:↗↗	0.21875	0	0.0625	0	0	0	0.078125	0	0.015625
x2:→↗	0	0	0	0	0	0	0	0	0
x2:↘↗	0.140625	0	0.046875	0	0	0	0.015625	0	0.0156□5
x2:↗→	0	0	0	0	0	0	0	0	0
x2:→→	0	0	0	0		0	0	0	0
x2:↘→		0	0	0	0	0	0	0	0
x2:↗↘	0.140625	0	0.03125	0	0	0	0.03125	0	0
x2:→↘	0	0	0	0	0	0	0	0	0
x2:↘↘	0.140625	0	0.03125	0	0	0	0.03125	0	0

(c) PC (from RRUEP to PU) pattern to pattern matrix

	y:↗↗	y:→↗	y:↘↗	y:↗→	y:→→	y:↘→	y:↗↘	y:→↘	y:↘↘
x3:↗↗	0.2	0	0□046875	0	0	0	0.09375	0	0
x3:→↗	0	0	0	0	0	0	0	0	0
x3:↘↗	0.140625	0	0.015625	0	0	0	0.03125	0	0
x3:↗→	0	0	0	0	0	0	0	0	0
x3:→→	0	0	0	0	0	0	0	0	0
x3:↘→	0	0	0	0	0	0	0	0	0
x3:↗↘	0.109375	0	0.03125	0	0	0	0.01□625		0.015625
x3:→↘	0	0	0	0	0	0	0	0	0
x3:↘↘	0□140625	0	0□078125	0	0	0	0.03125	0	0

(d) PC (from PLCPT to PU) pattern to pattern matrix

	y:↗↗	y:→↗	y:↘↗	y:↗→	y:→→	y:↘→	y:↗↘	y:→↘	y:↘↘
x4:↗↗	0.21875	0	0.0625	0	0	0	0.0625	0	0.015625
x4:→↗	0	0	0	0	0	0	0	0	0
x4:↘↗	0.1875	0	0.0625	0	0	0	0.015625	0	0.01□625
x4:↗→	0	0		0	0	0	0	0	0
x4:→→	0	0	0	0	0	0	0	0	0
x4:↘→	0	0	0	0	0	0	0	0	0
x4:↗↘	0.203125	0	0.046875	0	0	0	0.03125	0	0
x4:→↘	0	0	0	0	0	0	0	0	0
x4:↘↘	0.0625	0	0	0	0	0	0.015625	0	0

(e) PC (from RST to PU) pattern to pattern matrix

	y:↗↗	y:→↗	y:↘↗	y:↗→	y:→→	y:↘→	y:↗↘	y:→↘	y:↘↘
x5:↗↗	0.078125	0	0.03125	0	0	0	0.015625	0	0.015625
x5:→↗	0	0	0	0	0	0	0	0	0
x5:↘↗	0.1875	0	0.03125	0	0	0	0.015625	0	0.015625
x5:↗→	0	0	0	0	0	0	0	0	0
x5:→→	0	0	0	0	0	0	0	0	0
x5:↘→	0	0	0	0	0	0	0	0	0
x5:↗↘	0.15625	0	0.03125	0	0	0	0.□3125	0	0
x5:→↘	0	0	0	0	0	0	0	0	0
x5:↘↘	0.234375	0	0.0625	0	0	0	0.078125	0	0.015625

(f) PC (from PT to PU) pattern to pattern matrix

	y:↗↗	y:→↗	y:↘↗	y:↗→	y:→→	y:↘→	y:↗↘	y:→↘	y:↘↘
x6:↗↗	0.3125	0	0.109375	0	0	0	0□09375	0	0
x6:→↗	0	0	0	0	0	0	0	0	0
x6:↘↗	0□125	0	0.0□5625	0	0	0	0.03125	0	0
x6:↗→	0	0	0	0	0	0	0	0	0
x6:→→	0	0	0	0	0	0	0	0	0
x6:↘→	0	0	0	0	0	0	0	0	0
x6:↗↘	0.15625	0	0.03125	0	0	0	0.03125	0	0
x6:→↘	0	0	0	0	0	0	0	0	0
x6:↘↘	0.0625	0	0.015625	0	0		0.015□25	0	0

Note. The meaning is the same as Table 2. From the table, we can find that the dominant causalities between RST, RRUHCE, RRUEP, PLCPT, RST, PT, and PU are dark.

4.3.3. Analysis of Pattern Causality Matrix in the Lunan Economic Circle. PC (from **x** to **y**) pattern to pattern matrix in the Lunan economic circle is shown in Table 6. Cumulative probability of the positive, negative, and dark PC from RST to PU is 0.390625, 0.1875, and 0.421875, respectively, calculated according to Table 6(a). Cumulative probability of the positive, negative, and dark PC from RRUHCE to PU is 0.296875, 0.203125, and 0.5, respectively, calculated according to Table 6(b). Cumulative probability of the positive, negative, and dark PC from RRUEP to PU is 0.28125, 0.203125, and 0.515625, respectively, calculated according to Table 6(c). Cumulative probability of the positive, negative, and dark PC from PLCPT to PU is 0.3125, 0.140625, and 0.546875, respectively, calculated according to Table 6(d). Cumulative probability of the positive, negative, and dark PC from RST to PU is 0.140625, 0.296875, and 0.5625, respectively, calculated according to Table 6(e). Cumulative probability of the positive, negative, and dark PC from PT to PU is 0.359375, 0.125, and 0.515625, respectively, calculated according to Table 6(f). To sum up, the

dark PC dominates in PC (from **x** to **y**) pattern in the Lunan economic circle, as shown in Table 3.

4.4. Comparisons at Different Regional Levels. Table 3 summarizes the above-mentioned PC patterns at different regional levels. In general, except for the Jiaodong economic circle, the dark influence dominates in the PC patterns from **x** to **y**, which proves that there is a nonpositive/negative causality in the processes of urbanization and economic growth. However, in the Jiaodong economic circle, the dominant causality between **x** and **y** is still a positive influence, which indicates that the increase in the relevant economic indicators can obviously drive the development of urbanization and economic growth. In addition to the dominant causality, the relationship between RTS and PU is dominated by positive causality in the Jinan economic circle, indicating that promoting the developing of tertiary industry can obviously drive the development of urbanization and economic growth. The cases that the negative influence is stronger than the positive influence are observed in the causality between RST and PU and in the causality between RRUEP and PU at the provincial level. The former indicates that the decline in RST can promote urbanization and economic growth, which means that it needs to increase number of full-time teachers and optimize educational resources at the provincial level. The emergence of the latter is mainly due to the large differences between dark and positive causality in different regions, indicating that there is a large spatial difference in employment participation rates between urban and rural population, and its policy implication is to promote the employment of rural population in regions dominated by dark causality.

There is a clear interaction between urbanization, economic growth, and industrial structure in the region [44], and such interaction shows temporal and spatial differences. The processes of urbanization and economic growth start with early industrialization when people migrate from rural to urban areas [45]. However, as time goes by, industrialization has limited attractiveness to the rural population and brings about the problems such as waste of resources, increase of labor cost, and environmental damage which hinder the process of urbanization and economic growth [46]. At this period, upgrading the industrial structure and promoting the development of tertiary industry, which is strongly attractive to rural labor force, become the driving forces for urbanization and economic growth [47]. In the Jinan and Jiaodong economic circles, the development of tertiary industry plays a stronger role in promoting urbanization and economic growth, resulting in the fact that the positive causality dominates in the relationship between RST and PU. However, the industrial structure level of the Lunan economic circle is lower than that of the above two regions, which means that the secondary industry development attracts less rural population, and the tertiary industry development is relatively weak, leading to dark causality as the dominant relationship between RST and PU. The above results lead to the fact that the dark and positive causalities dominate at the provincial level.

According to the traditional view, urbanization led to widening urban-rural gap and prompting population migration from rural to urban areas [48], so as to result in the problems, such as the loss of rural labor force and hollow villages. The above problems are not conducive to agricultural and rural development, which forces the proposal of new urbanization. The research proves that there is a significant correlation between new urbanization and narrowing of the urban-rural gap [49]. In this paper, the causality between RRUHCE (gap between urban and rural residents' consumption), RRUEP (employment gap between urban and rural residents), and PU reflects the above correlation. (1) In the Jinan and Lunan economic circles, the gaps of urban-rural residents' consumption and employment are large, and the increase of the rural residents' consumption and employment positively causes the urbanization development and economic growth, but the positive causality is not continuous in time, finally resulting in the fact that dark causality is dominant among RRUHCE, RRUEP, and PU, followed by positive causality. (2) However, in Jiaodong economic circle, the consumption gap and employment gap between urban and rural residents are narrowing, and there is an obvious positive causality between the increases of rural residents' consumption and employment and urbanization and economic growth. As a result, the relationships between RRUHCE, RRUEP, and PU are dominated by positive causality. (1) and (2) result in the fact that the dark causality becomes the dominant relationship between RRUHCE, RRUEP, and PU at the provincial level.

With the deepening of urbanization and economic growth, the role of "people" becomes increasingly prominent, so education plays an increasingly important role in urbanization and economic growth [50]. But in different stages of economic development, the role of education is not the same. Generally speaking, when the level of economic development is low, the role of basic education is greater, while the role of higher education is relatively small, but when the level of economic development is high, the role of basic education is relatively small, while the role of higher education is greater [51]. In our paper, this relationship is proved by the causality between RST and PU. (1) In Jiaodong economic circle with a relatively high level of economic development, basic education is developed well and the allocation of basic education resources is relatively reasonable. As a result, the negative causality is dominant relationship between RST and PU. However, due to the differences between cities within the region, there is also an obvious dark causality between RST and PU. (2) In Jinan economic circle, the economic development levels of cities are quite different. There is a big gap between the basic education development of Dongying, Jinan, Zibo, and Tai 'an, which are relatively developed, and that of Laiwu, Binzhou, Liaocheng, and Dezhou, which are relatively backward. As a result, dark causality and negative causality are dominant relationships between RST and PU. (3) The overall economic level of Lunan economic circle is relatively low, the development of basic education is relatively backward, and there are large gaps between cities. As a result,

in Lunan economic circle, the dark causality is a dominant relationship between RST and PU, and negative causality is obviously weaker than that of Jinan economic circle. (1), (2), and (3) result in the fact that dark causality dominates in the relationship between RST and PU, followed by negative causality at the provincial level.

PLCPT, as an auxiliary indicator for improving population quality, is often used as a basic indicator in the index system to measure the level of urbanization together with education indicators in research [31]. The impact of PLCPT on urbanization and economic growth is similar to that of higher education, which makes the conclusions of the causality between PLCPT and PU similar to the causality between RST and PU in this paper, as follows:

(1) In Jiaodong economic circle with high level of economic development, there is a strong positive causality between PLCPT and PU.

(2) In Jinan economic circle, due to the large gap in the economic development level of internal cities, dark causality and positive causality are dominant.

(3) In Lunan economic circle with low level and small gap of economic development, the dark causality is the dominant relationship between PLCPT and PU. (1), (2), and (3) result in the fact that at the provincial level, the relationship between PLCPT and PU is dominated by dark causality, followed by positive causality.

As shown in existing works, population mobility and urbanization have made important contributions to the rapid economic growth [52, 53]. Generally speaking, the population usually flows from the areas with low economic development level to the areas with high economic development level [54], which makes the population flow in the areas with high economic development level larger and that in the areas with low economic development level relatively small. As a result, there is an obvious positive causality between population mobility and urbanization and economic growth. In this paper, such relationship is shown as follows:

(1) In the Jiaodong economic circle with high economic development level, the relationship between PT and PU is dominated by positive causality based on PT: ↗↗⟶PU:↗↗causal pattern.

(2) In the two economic circles of Jinan and Lunan, the positive causality between PT and PU was weakened due to the large differences among cities within them, showing that the dark causality is dominant. (1) and (2) result in the fact that the dark causality becomes the dominant relationship between PT and PU at the provincial level.

5. Conclusion

This paper introduces a method of nearest neighbor phase space reconstruction based on symbolic dynamics to study the causality between urbanization and economic growth at different regional levels in Shandong Province, and the conclusions are as follows:

(1) The analysis of the correlation between per capita GDP and population urbanization rate shows that there is a strong positive relationship between urbanization and economic growth both on the whole (Figure 1) and at the municipal level (Figure 2), indicating that the urbanization process in Shandong Province plays a significant role in driving economic growth both. In other words, it is feasible to drive economic growth by promoting urbanization development.

(2) The correlation analysis of evaluation indexes (Figures 3 and 4) shows that urbanization has a strong positive correlation with public finance, medical and health, education expenditure, and fixed asset investment and has a strong negative relationship with RRUE but has no obvious correlation with RTS, RRUHCE, RRUEP, PLCPT, RST, and PT, indicating that increasing the positive relationship variables and reducing the negative relationship variables can promote the development of urbanization and economic growth. The specific policy suggestions are as follows:

    (1) The government should appropriately expand budgetary expenditures (including the expenditures in education, medical, and health) and optimize the structure of fiscal expenditures to strengthen government functions.

    (2) Increasing investment in fixed assets to promote the upgrading of industrial structure.

    (3) Employment opportunities or preferential policies for rural residents are provided to increase their income and consumption level, so as to narrow the urban-rural gap and promote high-quality development of urbanization.

(3) The analysis of pattern causality matrix indicates that there is a dark causality in the processes of urbanization and economic growth, and except for Jiaodong economic circle, the dark influence dominates in the PC patterns from **x** to **y**. The positive influence dominates in the Jiaodong economic circle. In addition, the types of causality between the same evaluation index and PU in different regions are different. The relationship between RTS and PU is dominated by positive causality in the Jinan economic circle and the Jiaodong economic circle, while in the other two regions, dominant influence is dark causality. The relationship between RST and PU is dominated by negative causality in the Jiaodong economic circle, while in the other regions, dominant influence is dark causality. Based on the findings, policy implications about the driving factors of urbanization developing and economic growth have been proposed not only at the provincial scale but also on the three economic circles.

Although we discover the complex causalities in the processes of urbanization and economic growth and put forward some policy recommendations based on the results, other problems, such as "how these policies are implemented" and "which one is the most scientific and feasible," have not been estimated yet, and these problems would be studied in forthcoming papers.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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