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Policy spillover and regional linkage characteristics of the real estate market in China's urban agglomerations

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A B S T R A C T

The main purpose of this study is to determine the spillover effect of real estate regulatory policies released by core cities on the surrounding cities in major urban agglomerations based on regional linkage characteristics of China's real estate market. In this study, real estate transaction data of 157 cities were selected from 11 major urban agglomerations. Agglomeration's housing transaction volatility and spillover effect caused by the core city's regulatory policies were simulated by integrating spatial and temporal analysis model, event analysis, and symbolic time series analysis. The findings showed that (1) the regional linkage of the real estate market in the Harbin–Changchun and Middle–South Liaoning, Middle Reaches of the Yangtze River, Yangtze River Delta, Pearl River Delta, and West Side of the Straits agglomerations were remarkably tight and the core cities' policy spillover effect was significant, of which the house purchase limitation and credit limitation policies had the widest influence; (2) the regional linkage of the real estate market in the Beijing–Tianjin–Hebei agglomeration, Shandong Peninsula, Guanzhong Plain, and Chengdu–Chongqing agglomerations was relatively weaker, but the core cities' policies of market regulation and taxation had certain spillover effect; (3) there were significant differences in the spillover effects of different types of policies in different urban agglomerations; (4) generally, the core cities' policy spillover often reduced the changing characteristics of the real estate market and made it more ordered with more certainty in the whole agglomeration, with the exception of the Beijing–Tianjin–Hebei, West Side of the Straits, and Chengdu–Chongqing agglomerations.

1. Introduction

Along with China's economic power structure transformation, the demand and supply of the real estate market have dramatically changed. The significant feature now is that first-tier cities are in short supply, second-tier cities polarize in-house transaction, and third- and fourth-tier cities are facing huge pressure in reducing unsold house inventories. Since 2015, the Central government has gradually abandoned the regulatory scheme of “one policy fits all,” and established the “policies with distinction to different city”, and has encouraged the local governments to adopt accurate control strategies according to the characteristics of their local market (Ding & Ni, 2017). Although problems have remained since the

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implementation, as the real estate market has strong regional correlation characteristics, third- and fourth-tier cities have taken geographically adjacent core cities' market movements as their indicator, thereby invalidating their own real estate policies. Over the last decades, the overheated development of the real estate market and frequent regulation of policies have made the real estate markets in China closely related. The linkage between housing markets in different regions became extensive and pervasive. Thus, the regulation process and policy effect of real estate in different regions will rely not only on their own market characteristics but also on the spatial linkage with other regions. In China, a large country with an inhomogeneous economy, the real estate market between different regions is usually spatially correlated, and the mutual influence of adjacent regional markets is significantly higher than that of non-neighboring areas. The unobservable economic, cultural, and geographic behavior make a region interrelated, but with unique regional features, which creates strong space inertia with respect to segmentation of the real estate market (Yu, Wang, & Huang, 2017). This spatial stickiness[1] may result in the real estate market regulation function of some politically and economically important cities to not only take place locally but also “spill” to adjacent areas. Therefore, it is necessary to understand the regional market response of China's real estate to the regulatory policies of core cities' regulatory policies in order to achieve precise control.

The prominent representative of typical regional spatial stickiness in China is the urban agglomeration. In 2014, strategies for constructing the hierarchy of the spatial structure of urban agglomerations were put forward; so far, the urban agglomeration in the process of urbanization in China has shown strong economic aggregation effect, while also evolving as the major frame of China's future economic development. The basic form of urban agglomeration in China is in the area of higher urbanization level, in which several different classes of cities are associated through regional grids, with one or two core cities in high development having strong political and economic effects radiating to the surrounding cities (Zhao, Wang, & Liu, 2017). Therefore, the fluctuation of the real estate market owing to regulation policies in the core cities is likely to spill and spread to surrounding cities through the regional economic linkage among urban agglomerations. In view of this, a sample of 157 Chinese cities' real estate transaction data and 152 regulations policies issued by 10 core cities in 11 major urban agglomerations were selected for the regional spillover experiments for urban real estate policy impact. Spatiotemporal modeling, event analysis, and symbolic time series analysis were integrated as experiment methodology. This study aimed to answer the following: (1) What kind of regional heterogeneity response does China's real estate market have to do with core cities' policy stimulus in different agglomerations? (2) What are the regional linkage characteristics between the cities in agglomerations before and after the core cities introduced relevant policy? (3) How can different policy tools be used to regulate the real estate market in different regions? The answers to these questions would be of great practical significance for grasping the characteristics of China's real estate market and putting forward precise regulatory policies.

The remainder of this work is organized as follows. The second section discusses the spillover effects and the fundamental principles of this study. The third section is the model setting, mainly including the spatiotemporal analysis model, policy quantification construction method, and symbolic time series analysis. The fourth section gives the empirical analysis, including urban agglomeration identification, parameter estimation of spatiotemporal analysis models in different regions, 3D wave simulation, policy analysis, and extraction of the regional linkage characteristics before and after the policy variable was introduced. The last section presents the conclusions and implications.

2. Spillover effects of real estate markets

Existing research on the spillover effect of real estate markets has two basic directions. The first is the spillover effect of regional housing prices. The basic idea is that the regional housing price fluctuations in one key area can quickly spread to other areas and cause drastic market changes. The diffusion on the dimensions of time and geography demonstrates the so-called real estate diffusion effect or real estate ripple effect, supported by a large number of empirical studies at the transnational and national levels. For example, Holly, Hashem Pesaran, and Yamagata (2011) and Abbott and Vita (2013) found that British house prices have obvious regional spillover effect by respectively using the spatio-temporal model and pairwise approach. Brady (2014) and Gupta, Stephen, and Miller (2012) analyzed the impact of changes in the U.S. real estate market and reported that the impact of changes in the real estate market have significant impacts on neighboring areas. Shi, Young, Hargreaves (2009) studied the long-term diffusion relationship of the house markets in three major regions of New Zealand at the spatial level. In addition, Oikarinen (2004) and Luo, Liu, and Picken (2007) respectively studied the real estate market in Finland and Australia and confirmed the existence of the spatial transmission effect of housing prices to varying degrees. In terms of the Chinese local market, Domestic scholars Wang He (2012), Liu and Chen (2013), and Lin, Li, and Dong (2016) used spatial analysis of a geographic distance weighting matrix for the spatial spillover effects of house prices and reported that China has an obvious diffusion effect with respect to regional house prices.

The second direction is the transmission effect of monetary policy in the real estate market. This area mostly refers to the effect of interest rate, money supply, and other policy tools on the real estate market. Such research has always been a hot issue in policy and real estate industry market. For example, Fratantoni and Schuh (2003) used regional agent Vector Auto Regression (VAR) method to study the regional spillover effect of monetary policies in the real estate market. Negro, Macro, and Christopher (2007) used the VAR method to investigate the short-term impulse response of the real estate market to

[1] ‘Spatial stickiness’ is here used refers to the time connectivity, correlation and attractiveness between industries within a specific space.

monetary policy. Zhang and Liu (2015) established the STVAR model to investigate the influence mechanism of monetary policy on China's real estate market.

The existing research has provided a lot of empirical support for exploring the correlation of the real estate market and the impact of policies. However, there were several limitations. First, of the research based on the regional diffusion effect of housing prices, very few scholars have focused on the specific scope of time and space ripple effect caused by real estate regulatory policies. Second, the regional spillover effect of specific policies is basically limited to the transmission mechanism of monetary policy, and there is a lack of consideration on the interaction effect of other types of macro policies. Third, the research method on policy simulation mainly based on the VAR model and its improved versions tends to be less able to introduce space variables and explore the space inertia factors of regulation policy on the interaction between different economic regions.

Thus, the present study aimed to explore the diffusion effects of China's real estate policies in the most representative economic cluster region: urban agglomerations from the perspective of time and space. The basic idea of this study was as follows: a particular agglomeration would have a core city. When the real estate market of this core city is impacted by external regulatory policies, and the market transaction volatility will spill and spread to the surrounding neighborhoods, then this effect can be synchronized or occur in waves. Meanwhile, the adjacent cities will send “feedback” and give a reverse reaction to the core city, albeit weak and insufficient to drive the core city fluctuations of the market; therefore, the predominantly unidirectional reaction diffusion will spread in the form of ripples (Holly et al., 2011; Gupta et al., 2012; Lin et al., 2016). The schematic spillover effect of a core city's regulatory policy is shown in Fig. 1.

The key points of this study are as follows: (1) Construct spatiotemporal association models between cities in different urban agglomerations. The space dimension is usually based on the correlation between a core city and the surrounding cities (geographic or economic adjacent). The time dimension could be calculated according to the influence of time delay. The policy impact could form a graphic wavy spillover effect by our simulation. (2) Quantify and simulate the policy impact. Usually, the regulation policy will cause volatilities in the real estate market, especially changes in house prices. However, the overheating of the real estate market in the last decades has made house prices rise at a rapid rate, detailed information on which has remained limited. Meanwhile, the transaction volume has been sensitive to regulatory policies (Wiley, Zumpano, & Wang, 2009; Guo, Cui, Wang, Wang, & Cheng, 2012). Thus, policy shock was quantized by the abnormal fluctuation of real estate transactions in our study. (3) Extract the regional linkage characteristics of different agglomerations. The policy shock will spread through the regional linkage between cities in different agglomerations. Therefore, identifying the linkage characteristics of real estate markets is of great significance to forecasting market trends. In view of the strong non-linearity and non-stationarity of the real estate market fluctuation, symbolic time series was introduced to extract the changing characteristics.

3. Methodology

In this study, we integrated three models to study the market fluctuation and spillover caused by core cities’ regulation policies, as shown in Fig. 2.

Suppose the real estate market agglomeration A has N cities marked with i ($i = 0, 1, 2, \cdots, N$), of which the core city is marked $i = 0$. There exist radiation effects from core city 0 to other cities as an agglomeration's construction. A shock in house trading in the core city or region may spread out over other cities or regions with a temporal delay that is recognized as a ripple or spillover effect. In our study, a spatiotemporal model was used to capture the real estate market linkage between cities; policy shock was quantized by event analysis; and ripple characteristics were extracted by symbolic time series analysis. We start with outlining the spatiotemporal model, followed by event analysis and then the symbolic time series analysis.

3.1. Spatiotemporal model

The conventional methods to study linkage between cities are based on time series econometric methods, among which the Vector Auto Regression (VAR) has been widely employed to investigate the ripple effects between house movements across regions. However, the effects generated from spatial information could not be captured by these conventional models. Therefore, spatiotemporal techniques as a complementary tool began to be used on the interconnections between house

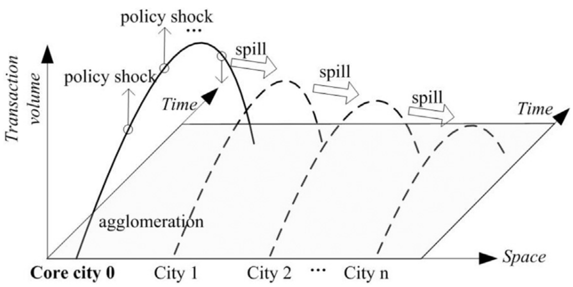

Fig. 1. Spillover effect of a core city's regulatory policies.

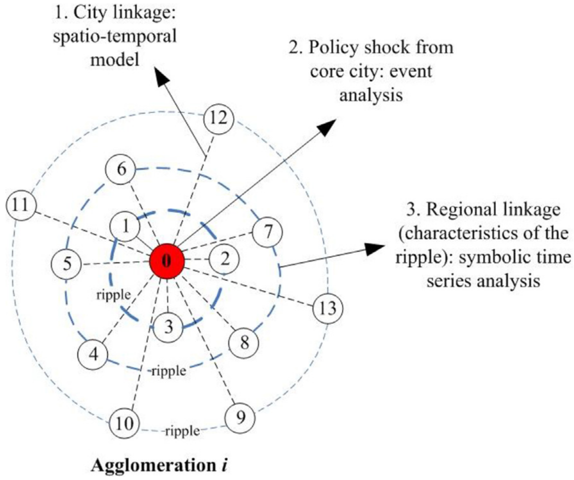

Fig. 2. Integration of the three methods.

movements across cities over time as well as space (Anselin, 1988). The spatial and time VAR, highlighted by researchers, thus became widely used to illustrate the correlation of house prices in cities across regions. An increasing number of studies confirm that the spatiotemporal model has advantages in illustrating the spatial dynamics existing in the urban real estate system, compared with the conventional non-spatial models (Holly et al., 2011; Abbott & Vita, 2013; Brady, 2014; Gupta et al., 2012; Lin et al., 2016). The basic ideas of our model, with reference to Holly's (2010, 2011) spatiotemporal settings, are as follows[2]:

① **Model setting.** In agglomeration A, $p(i)_t$ is the housing trading level of city i at time t, affected by the changes itself and other related cities in A. Especially when the core city 0 disturbed by an impact variable (policy shock), its current marginal trading $p(0)'_t$ and related cities' marginal trading $p(i)'_t$ can be expressed as follows:

$$p(0)'_t = a_0 p(0)'_{t-1} + b_0 \overline{p}^s(0)'_{t-1} + \phi\left(0\right)_s \left(p\left(0\right)_{t-1} - \overline{p}^s\left(0\right)_{t-1}\right) + c_0 + \varphi\left(0\right)_t \tag{1}$$

$$\begin{aligned} p(i)'_t = {} & \phi(i)_s \left(p(i)_{t-1} - \overline{p}^s\left(i\right)_{t-1}\right) + \phi\left(i\right)_0 \left(p\left(i\right)_{t-1} - p\left(0\right)_{t-1}\right) + a_i p(i)'_{t-1} \\ & + b_i \overline{p}^s(i)'_{t-1} + u_i p(0)'_t t + c_i + \varphi\left(i\right)_t \end{aligned} \tag{2}$$

Where $\phi(0)_s$ is the coefficient of deviation between core city 0 and radiation surrounding cities; $\varphi(0)_t$ is the core city's policy shock at time t; $\overline{p}^s(i)_t$ is the spatial variable of the city; and i represents the geo-weighted average variable (Holly et al., 2011).

② **Spatial variable.** This study used the linear distance $D(i)_j$ between city i and j divided by the sum of all the cities' distance as the weight coefficients, which could be written in matrix form. We standardized each row of the matrix and let $S\tau_{N+1} = \tau_{N+1}$. The basic conditions are as follows:

$$\overline{p}^s(i)_t = \sum_{j=0}^{N} s(i)_j p(j)_t, s(i)_j = D(i)_j \Big/ \sum_{n}^{N-1} D(i)_n, \sum_{j=0}^{N} s(i)_j = 1, i = 0, 1, \cdots, N \tag{3}$$

Then, the linkage model between the core city 0 and other cities is established.

③ **Spatiotemporal linkage function.** The change caused by policy $\varphi(0)_t$ will be passed on to other cities in A and cause the policy spillover effect. To ensure that the impact does come from city 0, let other cities' policy $\varphi(i)_t = 0$. Based on equations (1) and (2), the marginal trading of city i caused by core city 0 will be

$$p(i)'_t = A \cdot p(i)_{t-1} + B \cdot \overline{p}^s(i)_{t-1} + C \cdot p(i)'_{t-1} + D \cdot \overline{p}^s(i)'_{t-1} + u_i \varphi(0)_t + c_i \tag{4}$$

According to equation (3), equation (4) could be adjusted to

[2] Holly presented a more detailed model and formula derivation in "The spatial and temporal diffusion of house prices in the UK" and "A spatio-temporal model of house prices in the US."

$$p(i)'_t = (I_{N-1} - K)^{-1} \cdot \left(Hp\left(i\right)_{t-1} + Gp(i)'_{t-1} + u_i\varphi\left(0\right)_t + C_i\right) \tag{5}$$

$$H = \begin{pmatrix} \phi(0)_s & 0 & \cdots & 0 & 0 \\ -\phi(1)_0 & \phi(1)_s + \phi(1)_0 & 0 & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ -\phi(N-1)_0 & 0 & \cdots & \phi(N-1)_s + \phi(N-1)_0 & 0 \\ -\phi(N)_0 & 0 & \cdots & 0 & \phi(N)_s + \phi(N)_0 \end{pmatrix} - \begin{pmatrix} \phi(0)_s s'_0 \\ \phi(1)_s s'_1 \\ \vdots \\ \phi(N-1)_s s'_{N-1} \\ \phi(N)_s s'_N \end{pmatrix}$$

$$G = \begin{pmatrix} a_0 & b_0 s(0)_0 & \cdots & b_0 s(0)_{N-1} & b_0 s(0)_N \\ b_1 s(1)_0 & a_1 & \cdots & b_1 s(1)_{N-1} & b_1 s(1)_N \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ b_{N-1} s(N-1)_0 & b_{N-1} s(N-1)_1 & \cdots & a_{N-1} & b_{N-1} s(N-1)_N \\ b_N s(N)_0 & b_N s(N)_1 & \cdots & b_N s(N)_{N-1} & a_N \end{pmatrix}, K = \begin{pmatrix} 0 & 0 & \cdots & 0 & 0 \\ u_1 & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ u_{N-1} & 0 & \cdots & 0 & 0 \\ u_N & 0 & \cdots & 0 & 0 \end{pmatrix}$$

The change $p(0)'_t$ caused by policy shock $\varphi(0)_t$ is an exogenous variable to the $p(i)'_t$, which could be verified by Wu's program (Wu, 1973) and Hausman's category test (Hausman, 1978).

④**Impulse function.** As $s'\tau_{N+1} = \tau_{N+1}$ is a standardized matrix, and $H\tau_{N+1} = 0$ is rank-deficient, the marginal trading could be written as follows:

$$\begin{aligned} p(i)'_t &= (I_{N+1} - K)^{-1} a + (I_{N+1} - K)^{-1} \Pi p(i)_{t-1} + (I_{N+1} - K)^{-1} G p(i)'_{t-1} + (I_{N+1} - K)^{-1} \varphi_t \\ &= \mu + \Pi p(i)_{t-1} + \Gamma p(i)'_{t-1} + R\varphi_t \end{aligned} \tag{6}$$

Where $\mu = Ra$, $\Pi = RH$, $R = (I_{N+1}\text{-}K)^{-1}$, and $\Gamma = RG$. R is a nonsingular matrix; Π and H have the same deficit rank. Let $\Pi = \alpha\beta'$, in which α and β are $(N+1) \times r$ matrix. Equation (6) could be written in autoregressive form as follows:

$$p(i)'_t = \mu + \Phi_1 p(i)_{t-1} + \Phi_2 p(i)_{t-2} + R\varphi_t \tag{7}$$

Where $\Phi_1 = I_{N+1} + \alpha\beta' + \Gamma$, $\Phi_2 = -\Gamma$. Based on this, the time-dependent relationship of each city can be described by matrix Φ_1 and Φ_2. The impulse response function of a unit under the h level is

$$\delta(h) = E(p_{t+h} | \varphi_t = \sqrt{\sigma_{00}}, \upsilon_{t-1}) - E(p_{t+h} | \upsilon_{t-1}) = \sqrt{\sigma_{00}} \Psi_h R e_0 \tag{8}$$

Where υ_{t-1} is the information at $t-1$, σ_{00} is one unit pulse of the policy, $e_0 = (1, 0, 0, \cdots, 0)'$, $\Psi_h = \Phi_1 \Psi_{h-1} + \Phi_2 \Psi_{h-2}$, $h = 0, 1, \cdots$, and the initial setting is $\Psi_0 = I_{N+1}$.

3.2. Event analysis

Among the spatiotemporal models expressed in equations (1) and (2), the shock variables $\varphi(0)_t$ and $\varphi(i)_t$ are usually stochastic. In our model, $\varphi(0)_t$ is an impact variable caused by the core city's policy. To build and test this variable, event analysis is introduced in our study. Event analysis (Wichern, Miler, & Hsu, 1976), a method widely used in the analysis of economic time series, takes the occurrence of important events as a time node and then uses the data before and after the point to make statistical analysis so as to obtain the intervention impact of policy events. It has a wide range of applications in studying the influence of policy events on prices or trading in the securities market. The basic idea of this method is to infer the specific impact of an event by judging the accumulated abnormal fluctuation profit value before and after the policy event.

The basic steps of event analysis are as follows:

① **Logarithmic transformation.** $p(0)_t$ is the trading level of core city 0 at time t. To obtain the policy impact $\varphi(0)_t$, the logarithmic first-order difference sequence of the transaction is constructed:

$$\zeta(0)_t = \ln(p(0)_{t+1}) - \ln(p(0)_t) \tag{9}$$

② **Set event test window.** For preprocessing, each policy issued as independent "event," set i as the code of the policy, with time T being the policy issue time. For each policy i, an "estimate window" and a "test window" are constructed, as shown in Fig. 3.

The policy shock at T is

$$\varphi(0)_T = \frac{1}{m}\left(\sum_{t=T+1}^{T+m} \zeta(0)_t - \sum_{t=T-m}^{T-1} \zeta(0)_t\right) \tag{10}$$

For each policy time, the test window is divided into two independent normal parts: pre- and post-test. It is assumed that the variance caused by the policy is constant: the policy does not cause any fluctuation abnormalities.

$$S_{i1} = \sum_{t=1}^{n} R_{m+t}^2, \quad S_{i2} = \sum_{t=n}^{2n} R_{m+t}^2, \quad S_i = \sum_{t=1}^{2n} R_{m+t}^2 = S_{i1} + S_{i2} \tag{11}$$

③ **Probability function estimation.** Then, the joint density probability function of the test window could be constructed as follows:

$$f(c_{i1}+c_{i2}) = \frac{1}{(2\pi\sigma_i^2)^n e^{S_{i1}/2\sigma_i^2} e^{S_{i2}/2\sigma_i^2}} = \frac{1}{(2\pi\sigma_i^2)^n e^{S_i/2\sigma_i^2}} \tag{12}$$

Where $S_{i1}/\sigma_i{}^2$ and $S_{i2}/\sigma_i{}^2$ are independent from each other and follow the $\chi^2(n)$ distribution. Let $Y_i = S_{i2}/S_{i1}$ follow $F(n,n)$ distribution, when $Y_i > Y_{\alpha/2}(n,n)$ or $Y_i < Y_{\alpha/2}(n,n)^{-1}$ in the original hypothesis is rejected at significance level α. Subsequently, the way of policy action can be determined.

④ **Duration determination.** For the duration, remove the $\zeta(i)_t$ in $E_i = \{\zeta(i)_1, \zeta(i)_2, \cdots, \zeta(i)_m\}$, set the regression equation, and obtain the average fixed income return μ_i. Let each time point subtract μ_i and obtain the abnormal point of the post-test window. The abnormal point of the return is accumulated as $CAR(i)$:

$$\begin{cases} CAR_{T,T_{m+2n}}(\mathrm{i}) = \sum_{T}^{T_{m+2n}} AR_t(\mathrm{i}) \\ T = CAR_{T,T_{m+2n}}(\mathrm{i}) / \sqrt{\sigma^2(T, T_{m+2n})} \sim N(0,1) \end{cases} \tag{13}$$

Analyze the $CAR \sim N(0, \sigma^2)$ by T test, extending the size of the event window m until the original hypothesis stands. Based on this, the function $\varphi(0)_T$ is established and introduced into the spatial and temporal response function. If there are many policies, the continuous response function will be

$$\sum_{i=1}^{T}\sum_{j=1}^{n} \delta_j(h) = \frac{\varphi(0)_i}{\max\{|\varphi(0)_1|, \cdots, |\varphi(0)_T|\}} \frac{\Psi_h R \sum e_i}{\sqrt{\sigma_{00}}}, h = 0, 1, \cdots, H \tag{14}$$

Therefore, the function relationship between the marginal trading volume $p(i)'_t$ of city i and the core city's policy impact $\varphi(0)_t$ is established, and the policy spillover effect could be tested.

3.3. Symbolic time series analysis

According to the model in sections 3.1 and 3.2, the non-linear linkage function of cities in area A is established. Then, the ripple effect could be simulated by 3D impulse. Our study sought the regional real estate market's linkage characteristics,

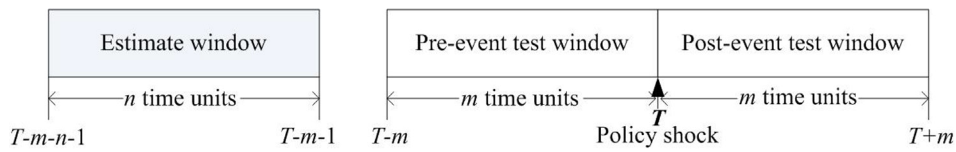

Fig. 3. Event test window.

which consist of nonlinear spatiotemporal ripples with a large amount of “noise”. Therefore, feature analysis tools were needed. Symbolic time series analysis (STSA) based on symbolic dynamics and chaotic time series theory (Tang, Tracy, & Brown, 1995; Daw, Finney, & Tracy, 2003) is suitable to be introduced to extract the changing characteristics of the model.

The basic idea of STSA method divide continuous data into a number of “discrete cell elements” represented by symbols and each cell represents a variation pattern of the original sequence, by recoding process we can make coarse-grained analysis of time series and capture the large-scale characteristics of nonlinear signals and achieve the purpose of noise suppression.

The basic operation of STSA is as follows:

① **Symbolize processing.** Divide continuous data into a number of “discrete cell elements” represented by symbols, with each cell representing a variation pattern of the original sequence. For time series $\{x_0, x_1, x_2, \cdots, x_{N-1}\}$, division criteria $P = \{P_0, P_1, P_2, \cdots, P_{n-1}\}$ is introduced:

$$s_t = \begin{cases} s(1), & x \le P_1 \\ s(2), & P_1 < x \le P_2 \\ \cdots & \\ s(i), & P_{i-1} < x \le P_i,\ i = 2, \cdots, n-1 \\ \cdots & \\ s(n), & x > P_{n-1} \end{cases} \tag{15}$$

The original sequence is then divided into several independent intervals, each of which is assigned a symbol $S_i \in \{s(1), s(2), \cdots, s(n)\}$ so that the original sequence is transformed into a new symbol sequence $\{ s_0(i), s_1(i), \cdots, s_{N-1}(i), i \in \{1, 2, \cdots, n\}\}$. Each symbol reflects the dynamic change characteristics of the original sequence. The symbol set n determines the information content of $\{x_0, x_1, x_2, \ldots, x_{N-1}\}$, in which the larger the value of n, the more information content it contains, but also more “noise.”

② **Calculate character length.** A code spacing L is needed to determine the partition of the symbol series; that is, consecutive L symbols constitute a cell (called one “character” in this study). For example, take the symbol data from 0 to L-1 as the character “0,” the symbol data from 1 to L as the character “1” …, the symbol data from N-L to N-1 as the character “N-L.”

$$\{\underbrace{s_0 s_1 \cdots s_{L-1}}_{character''0''}, \underbrace{s_1 s_2 \cdots s_L}_{character''1''}, \underbrace{s_2 s_3 \cdots s_{L+1}}_{character''2''}, \cdots, \underbrace{s_{N-L} s_{N-L+1} \cdots s_{N-1}}_{character''N-L''}\} \tag{16}$$

The L determines the degree of information granulation and directly affects the accuracy of the result as well. The usual method to determine L is the improved Shannon entropy expressed as

$$H(L) = -\frac{1}{\log_2 N_{obs}} \sum_c P_{c,L} \log_2 P_{c,L} P_{i,L} = 1 \tag{17}$$

Where N_{obs} is the number of different words in the symbol sequence and $N_{obs} \le K$; c is the decimal sequence code; and $P_{c,L}$ is the probability of the character c with length L. When $H(L) = 1$, the sequence is completely random, and the probability of all characters is equal. When $H(\mathrm{L}) = 0$, the sequence is determined, and all the probabilities are concentrated on a single character.

③ **Recoding the character.** To obtain statistics, the decimal coding rule is used to encode each character as follows:

$$Code_i = s_{i+\mathrm{L}-1}(j) \times n^0 + s_{i+\mathrm{L}-2}(j) \times n^1 + \cdots + s_i(j) \times n^{L-1}, i = 0, 1, \cdots, N-L; j = 0, 1, \cdots, \mathrm{n} \tag{18}$$

Then, the decimal time series set with length of N-L+1 and n^L types of characters are obtained. Each of these words is not only a symbol but also a subtle pattern of change in the original sequence. The computation used $n = 3$, $L = 4$ as example; that is, we used the three symbols of low (l), medium (m), and high (h) to recode the original series. Let $h = 2$, $m = 1$, and $l = 0$. Then, according to equation (18), we obtained decimal coding: the character “0” equals the symbol set {*llll*}, which means low variation in four consecutive time units; the character “6” represents {*lhll*}, which means mode changes of low, high, low, and low in four consecutive time units. Thus we recoded function (14) using applicable symbol sets and character length L to extract the linkage change characteristics between cities in urban agglomeration A.

④ **Information entropy.** To measure the real estate market's overall degree of order in each urban agglomeration, information entropy is introduced. For city i, the entropy is

$$U_{city_i}(P(code_1), P(code_2), \cdots, P(code_{n^L})) = -k\sum_{i=1}^{n^L} P(code_i)\ln P(code_i) \tag{19}$$

Where $P(code_i)$ is the probability of character i, and the overall information entropy of the real estate market in agglomeration A is

$$\underset{(city_1\cdots city_N)}{U_A} = -k\sum_{j=1}^{N}\sum_{i=1}^{n^L} P_j(code_i)\ln P_j(code_i) \Big/ N \tag{20}$$

The larger the U_A, the more disorderly the real estate market is in agglomeration A.

3.4. Contributions of this study

As the spatiotemporal model, event analysis, and STSA are common methods in the study of regional house prices and the estimation and quantization important events on market fluctuation, as well as capture the basic characteristics of non-linear time series, respectively, our contribution is a cross-research perspective in studying the spillover effects caused by policy shock. We captured regional linkage characteristics by the integrated use of these three models.

Compared with the traditional economic quantitative methods (especially VAR), the advantage of our study is that we avoided the limitation of time and space variables, which tend to be unusable at the same time, and then intuitively showed the spillover effect of policy shocks in the space and time range from a three-dimensional perspective. Meanwhile, we used a large-scale analysis perspective to shed light on the changing characteristics of three-dimensional ripples, providing a reference for intuitively understanding the characteristics of a core city's policy spillover effect in different urban agglomerations in China.

4. Empirical process

4.1. Sample selection

As there is no authorized division standard of urban agglomerations in China,[3] we used the maximum correlation method and centrality analysis based on the database of China Real Estate Index System (CREIS), to construct the network connectivity of cities. These cities were divided into five basic levels, according to the principle that there is at least one core city in a network. Thus, we identified the following 11 major urban agglomerations and their containing cities, as shown in Table 1.

According to the principles of data availability and quantifiability, the commodity residential housing transaction data[4] between January 2007 and June 2017 were selected as sample, of which missing data were supplemented by Newton interpolation method.[5] To simulate the policy spillover effect, before entering the analysis model, the seasonal factors were removed, the original data transformed as year-on-year data, and the natural logarithms of all kinds of data taken into the model.

(1) Core cities. Generally, an urban agglomeration contains a number of different properties and cities of different types and rating scales, which constitute a relatively complete city “assembly” relying on the natural environment and traffic conditions. An urban agglomeration may contain one or two especially big cities as the core. The core cities will have a certain radiation effect on the surrounding cities in the real estate market. Therefore, we identified the core cities by mean and

[3] So far, eight agglomerations have been officially approved by the state council: Middle reaches of the Yangtze River, Harbin–Changchun, Chengdu–Chongqing, Yangtze River Delta, Central Plains, Beibu Gulf, Guanzhong Plain, and Hu–Bao–Er. According to China's “13th Five-year Plan,” 19 agglomerations are being planned to be set up. However, local governments and research institutions have also released their agglomeration plans, respectively, making the form of division varied.

[4] Data source: CREIS database (http://www.creis.fang.com). Commercial housing generally includes commercial residential, office, and commercial buildings. In China, regulatory policies are mainly directed at commercial residential housing and do not affect the transaction of office and commercial buildings, so the sample transaction data refer to commercial housing. The samples include the data of primary and second-hand houses.

[5] The Gregory-Newton formula is often used to fit the missing discrete points when a set of data can only be measured by discrete data points or a corresponding relation can only be represented by a numerical solution. The characteristic of this method is that each additional point will not result in previous recalculation and only those related to the new points can be calculated. Newton interpolation is simple to calculate, convenient for calculating a large number of difference points, and logical; as it allows easy program calculation, it is widely used in experimental analyses.

Table 1
Sample cities in the urban agglomerations.

Agglomerations	Sample Cities
Harbin-Changchun & Middle-South Liaoning Agglomeration	Changchun, Harbin, Jilin, Daqing, Qiqihar, Mudanjiang, Siping, Liaoyuan, Songyuan, Yanbian, Suihua
Middle-South Liaoning Agglomeration	Shenyang, Fushun, Liaoyang, Benxi, Panjin, Yingkou, Anshan, Dandong, Dalian,
Beijing-Tianjin-Hebei Agglomeration	Beijing, Tianjin, Shijiazhuang, Tangshan, Baoding, Qinhuangdao, Langfang, Cangzhou, Chengde, Zhangjiakou
Shandong Peninsula Agglomeration	Qingdao, Jinan, Yantai, Zibo, Weifang, Dongying, Weihai, Rizhao
Central Plains Agglomeration	Zhengzhou, Luoyang, Kaifeng, Nanyang, An'yang, Shangqiu, Xinxiang, Pingdingshan, Xuchang, Jiaozuo, Zhoukou, Xinyang, Zhumadian, Hebi, Puyang, Luohe, Sanmenxia, Jiyuan, Changzhi, Jincheng, Yuncheng, Liaocheng, Heze, Suzhou, Huaibei, Fuyang, Bengbu, Bozhou, XinTai, Handan
Guanzhong Plain Agglomeration	Xi'an, Baoji, Xianyang, Tongchuan, Weinan, Shangluo, Yuncheng, Linfen, Tianshui, Pingliang, Qingyang
Middle Reaches of the Yangtze River Agglomeration	Wuhan, Huangshi, Ezhou, Huanggang, Xiaogan, Xiantao, Tianmen, Xinyang, Yichang, Jingzhou, Jinmen, Changsha, Zhuzhou, Xiangtan, Yueyang, Changde, Hengyang, Nanchang, Jiujiang, Jingdezhen, Yingtan, Shangrao
Yangtze River Delta Agglomeration	Shanghai, Nanjing, Suzhou, Wuxi, Changzhou, Nantong, Yangzhou, Zhenjiang, Taizhou, Hangzhou, Ningbo, Jiaxing, Huzhou, Shaoxing, Jinhua, Zhoushan, Hefei, Wuhan, Maanshan, An'qing,
Pearl River Delta Agglomeration	Shenzhen, Guangzhou, Foshan, Dongguan, Zhongshan, Zhuhai, Jiangmen, Zhaoqing, Huizhou, Qingyuan
The West Side of the Straits Agglomeration	Xiamen, Fuzhou, Quanzhou, Putian, Zhangzhou, Nanning, Ningde, Longyan, Wenzhou, Quzhou, Meizhou, Ganzhou, Shantou, Chaozhou
Chengdu-Chongqing Agglomeration	Chongqing, Chengdu, Zigong, Luzhou, Deyang, Mianyang, Suining, Neijiang, Leshan, Nanchong, Meishan, Yibin

variance method, as shown in Fig. 4. The real estate transaction data of the sample cities were typical nonlinear time series that revealed one city with significantly larger mean and standard deviation in the 11 urban agglomerations, indicating that city had the largest fluctuation range and frequency. Generally, cities with large real estate fluctuations within a region will have certain radiation and driving effects on the surrounding areas (Abbott & Vita, 2013; Brady, 2014; Gupta et al., 2012; Lin et al., 2016; Shi et al., 2009). These 11 core cities played a leading and pivotal role in the local region: they were constructed as national cities officially approved by the National Development and Reform Commission. Therefore, we selected these 11 cities as the core cities of their respective urban agglomerations to study the real estate regulation policy spillover effects. As the central government policies affecting the core city also directly impact the non-dominant cities, the local real estate policies of the core cities were selected to eliminate the interference of the national policies.

(2) Local real estate policies. The local real estate policies, available as public data, from January 2010 to June 2017 issued by the 11 core cities' governments were used as samples. As the local real estate policies tended to be text-heavy, for the accuracy and representation of the sample, the below principles were followed when sorting and filtering policy texts: ① issued by the department directly under the local government; ② directly and closely related to the real estate industry and bearing great influence on real estate transactions (for the specific verification method, see section 3.2); ③ the policy types include laws, regulations, planning, suggestions, and announcements that reflect the government's directives. After filtering, we finally identified 152 effective policies[6]: Shenyang (14 items), Wuhan (12 items), Shanghai (15 items), Beijing (13 items), Shenzhen (18 items), Xi'an (10 items), Chongqing (16 items), Qingdao (18 items), Zhengzhou (20 items), and Xiamen (16 items).

4.2. Parameter estimation

A unit root test was carried out on the 157 cities' data. Except for Harbin City in the Harbin–Changchun agglomeration, all the other 10 core cities had unit roots and met the requirements of the model. In view of the geographically close distance between Harbin–Changchun agglomeration and Middle–South Liaoning agglomeration, we combined the two and explored Shenyang's city policy influence on the cities of these two agglomerations. Based on the above model proposed in section 3.1, the spatiotemporal linkage models of 10 agglomerations were established according to the data of 157 cities. The spatial variable $\overline{p}^s(i)_t$ was weighted by the linear distance between city 0 and city *i*, and the regional linkage equation used the least squares estimator for regression analysis. The parameter estimation results are as shown in Table 2.

From the perspective of parameter estimation results, the core cities had strong regional linkage association with surrounding cities in the following agglomerations: Harbin–Changchun and Middle–South Liaoning, Middle Reaches of the Yangtze River, Yangtze River Delta, Pearl River Delta, and West Side of the Straits. The real estate transaction change in Shenyang showed strong relevance with Harbin, Jilin, Changchun, and other cities in the north. Shenyang and Jilin revealed a significantly negative relationship because $\widehat{\phi}(i)$ was negative, reflecting the competition between these two cities in real estate market. In the Middle Reach of the Yangtze River agglomeration, 12 in 20 cities were affected by the core city Wuhan; Changsha and Changde were negatively correlated, and the other 10 cities were positively correlated. The linkage between core city Shanghai and other cities in the Yangtze River Delta agglomeration demonstrated very obvious regional characteristics. In particular, Shanghai's real estate

[6] Owing to the length limitation of the article, the specific terms of the policies are not listed. Readers who are interested in them can ask us for them.

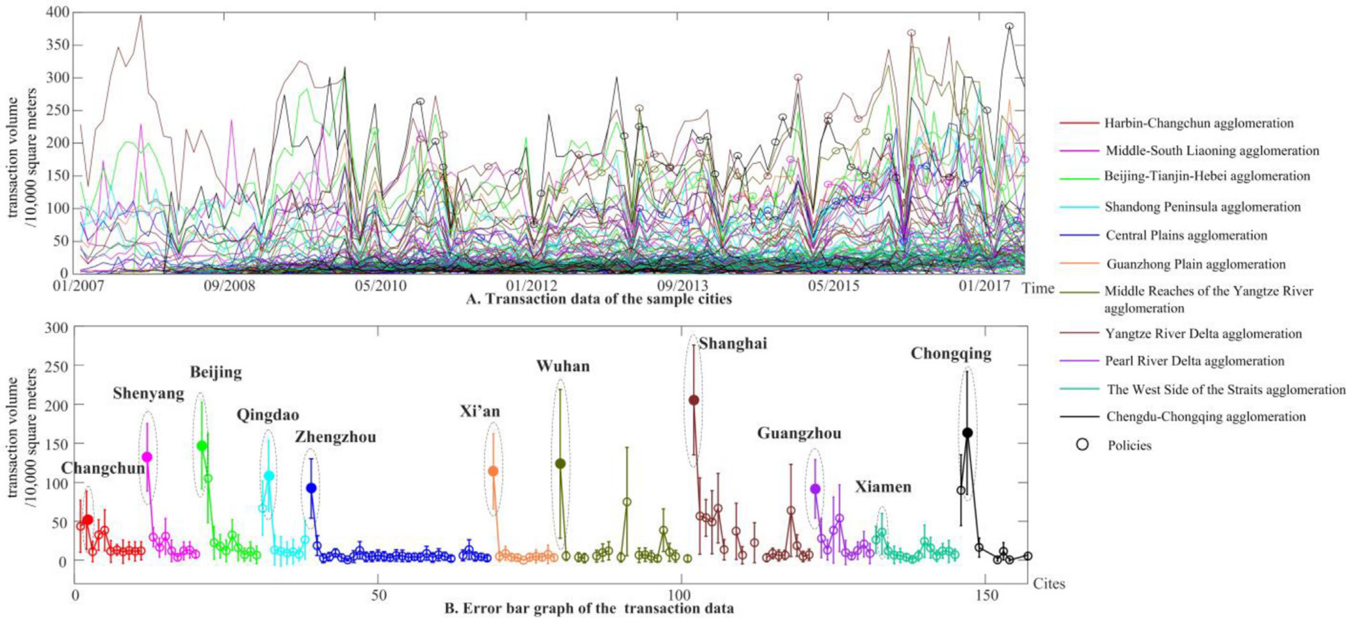

Fig. 4. Selection of core cities from the commercial residential transaction data.

Table 2
Spatiotemporal linkage estimation of the agglomerations.

Agglomerations	City	$\widehat{\phi}(0)$	$\widehat{\phi}(i)$	O-Lag	W-H T	City	$\widehat{\phi}(0)$	$\widehat{\phi}(i)$	O-Lag	W-H T
Harbin−Changchun and Middle−South Liaoning	***SY***	–	−0.088	–	–	SYU	0.072	0.012	0.044	1.783**
	JL	−0.285***	0.109***	0.035***	0.024	YB	0.023	0.007	0.012	0.566
	CC	0.443***	0.033**	0.013***	0.046	DL	−0.210**	0.010	0.003	2.011**
	HEB	0.416***	0.009	0.056***	−0.034	AS	0.432***	0.232***	0.088***	0.002
	DQ	0.122**	0.020*	0.022**	0.001	FS	−0.065	0.122**	0.075***	−0.055
	QQH	0.223**	−0.003	0.003***	0.054	BX	0.184***	0.092	0.112***	0.134
	SH	−0.044	−0.020	0.030	3.001**	DD	0.347***	0.110**	0.057**	0.909**
	MDJ	−0.237***	−0.107**	0.187***	0.080	LYA	0.452***	0.009	0.044**	0.027
	SP	0.109**	0.033*	0.045***	0.032	YK	−0.033	0.023	0.020**	0.025
	LYU	0.087*	0.003	0.002	0.009	PJ	0.004	0.100*	0.006	0.355
Beijing−Tianjin −Hebei	***BJ***	–	−0.002	–	–	QHD	0.087	−0.178**	0.087	2.093***
	TJ	0.565***	−0.090	0.201***	0.451	LF	−0.006	−0.002	0.102***	1.792***
	SJZ	−0.131***	−0.033	0.129***	0.022	CZ	−0.034	−0.039	0.088	0.002
	TS	0.022	−0.151**	0.098**	0.798	CD	0.055*	−0.004	0.005	−1.443***
	BD	0.007	0.022	0.101***	0.076	ZJK	−0.012	0.033	0.003	0.968**
Shandong Peninsula	***QD***	–	−0.021	–	–	WF	0.004	0.220***	0.189***	0.457
	JN	0.177**	0.100**	0.350***	0.194	DY	0.088	0.145**	0.114***	1.098
	YT	0.078	0.045	0.113**	1.220**	WH	−0.026	−0.201***	−0.077**	−0.222
	ZB	−0.013	0.126**	0.087*	0.400	RZ	−0.060	0.119**	0.123**	−0.107
Central Plains	***ZZ***	–	0.223	–	–	LH	0.023	0.029	0.004	1.230
	LY	0.099	0.107**	0.002	1.458**	SMX	−0.013	−0.005	0.020	1.190
	KF	0.106**	0.078	0.034**	1.890***	JY	0.089*	0.322***	0.432***	2.345***
	NY	0.007	0.019	0.001	2.557***	CZ	−0.153**	−0.297***	0.398***	−0.300
	AY	0.113**	0.008	0.000	0.230	JC	−0.003	0.023*	0.532***	0.087
	SQ	0.004	0.003	0.020**	2.345***	YC	0.030**	0.100**	0.341***	0.675
	XX	−0.071	−0.101**	0.266**	0.353	LC	−0.007	−0.092*	0.022**	0.340
	PDS	0.212***	0.175**	0.045***	0.245	HZ	0.099**	0.233***	0.342***	0.098
	XC	0.004	0.112**	0.024***	0.600***	SZ	−0.127***	−0.432***	0.553***	0.122
	JZ	0.011	0.230***	0.102***	0.330***	HB	0.068**	0.058***	0.086***	0.657***
	ZK	−0.045*	0.069	0.217***	0.109**	BY	0.002	0.077**	0.333***	0.260***
	XY	−0.038*	−0.128**	0.055**	0.030	BB	0.021*	0.109**	0.231***	0.552***
	ZMD	−0.001	−0.004	0.001	−3.768***	HZ	0.087**	0.229**	0.227***	0.562
	HB	0.084**	0.107**	0.325***	0.460	XT	0.007	0.229**	0.227***	0.562
	PY	0.033	0.099	0.065**	0.002	HD	−0.027	0.055	0.044	3.878***
Guanzhong Plains	***XA***	–	0.102**	–	–	YC	0.020*	0.233**	0.027	3.090***
	BJ	0.222***	0.076*	0.120***	0.003	LF	0.002	−0.101**	0.125***	0.072
	XY	0.004*	0.033	0.018	0.044	TS	0.004	0.004	0.022	0.223
	TC	0.055*	−0.075	0.098**	0.542	PL	0.009	0.044	0.088	1.202**
	WN	0.007	0.008	0.002	2.388**	QY	0.012	0.021	0.035	0.009
	SL	0.019	0.012	0.001	0.145	–	–	–	–	–
Middle Reaches of the Yangtze River	***WH***	–	0.003	–	–	CS	−0.110***	−0.105**	−0.223**	0.334
	HS	0.744***	0.122	0.222***	0.808	ZZ	−0.070	−0.005**	0.117*	1.878***
	EZ	0.096	0.002	0.087	1.744**	XT	0.025	0.011**	0.034	1.563***
	HG	0.179***	0.013**	0.073**	0.443	YY	0.052	0.003	0.132	1.908***
	XG	0.123***	0.026**	0.145**	0.221	CD	−0.142***	0.042	0.222**	0.563
	XT	0.175***	0.007**	0.345**	0.099	HY	0.007	0.010	0.490***	2.456***
	TM	0.150***	0.067**	0.562***	0.563	NC	0.446***	0.216**	0.330***	0.119
	XY	0.087	0.022	0.003	3.320***	JJ	0.040	0.008	0.020	4.509***
	YC	−0.042	−0.087	0.044*	−1.506	JDX	0.404***	0.187**	0.319**	0.225
	JZ	0.124***	0.202**	0.235**	0.044	YT	−0.024	−0.034	0.004	1.221**
	JM	0.230***	0.324**	0.109*	0.110	SR	−0.118***	0.156**	0.112**	0.456
Yangtze River Delta	***SH***	–	0.200**	–	–	NB	−0.073	0.005	0.023	−3.000***
	NJ	−0.133**	0.123**	0.011	−1.209**	JX	0.052	0.008	−0.001	2.878***
	SZ	0.042	0.010	0.334***	2.659***	HZ	0.132***	0.223**	0.542***	0.070
	WX	−0.185**	0.165**	0.212**	0.654	SX	0.238***	0.176**	0.348***	0.184
	CZ	0.336***	0.233***	0.087**	0.498	JH	0.304***	0.334	0.110	0.455
	NT	0.232***	0.002	0.005	4.322***	ZS	0.012	0.009	0.043	1.100**
	YZ	0.307***	0.047**	0.127***	0.003	HF	−0.113**	0.119**	0.107**	−2.072***
	ZJ	0.453***	0.012	0.111***	0.124	WH	−0.010	−0.096	0.054	−1.879***
	TZ	0.665***	0.033	0.076***	0.321	MAS	0.130**	0.073	0.076	3.230***
	HZ	−0.212***	−0.220**	0.198**	0.767	AQ	0.310***	0.215**	0.342***	0.356
Pearl River Delta	***SZ***	–	0.177**	–	–	ZH	−0.433***	−0.275**	0.194**	−0.222
	GZ	0.221***	0.201**	0.056**	0.100	JM	0.234***	0.152**	0.503***	0.450
	FS	0.102**	0.100**	0.187***	0.209	ZQ	0.600***	0.442***	0.022*	0.870
	DG	0.540***	0.120**	0.208***	0.505	HZ	0.144**	0.022	0.300***	0.290
	ZS	0.032	0.002	0.003	2.498***	QY	0.363***	0.173**	0.097*	0.621
West Side of the Straits	***XM***	0.251***	0.222**	0.133**	0.013	LY	0.170***	0.049	0.102**	0.092
	FZ	−0.207***	−0.033	0.255***	−0.098**	WZ	0.235***	0.074	0.206***	0.013
	QZ	0.099	0.107**	0.002	1.458**	QZ	−0.013	−0.005	0.020	1.190

(*continued on next page*)

Table 2 (*continued*)

Agglomerations	City	$\widehat{\phi}(0)$	$\widehat{\phi}(i)$	O-Lag	W-H T	City	$\widehat{\phi}(0)$	$\widehat{\phi}(i)$	O-Lag	W-H T
Chengdu–Chongqing	PT	0.006	0.078	0.034	1.890**	MZ	0.089	0.322***	0.432***	2.345
	ZZ	0.337***	0.019	0.001	2.557**	GZ	−0.153**	−0.297***	0.398***	−0.300
	NP	0.010	0.003	0.202**	−0.332	ST	0.430***	0.100**	0.341***	0.675***
	ND	−0.871***	−0.101**	0.266**	0.353***	CZ	−0.607***	−0.092***	0.022**	0.340***
	CQ	–	0.175**	–	–	SN	0.019*	0.033**	0.342***	0.098
	CD	−0.034**	0.112**	0.024***	0.600***	NJ	−0.007	−0.002	0.553***	0.122***
	ZG	−0.022**	0.322***	0.176***	0.400	LS	0.100**	0.103**	0.209***	0.768
	LZ	0.001	0.230***	0.102***	0.330***	NC	0.006	0.058***	0.086***	0.657***
	DY	0.011	0.169***	0.217***	0.109**	MS	0.000	0.077**	0.333***	0.260***
	MY	−0.238**	−0.128**	0.055*	0.030	YB	0.048	0.109**	0.231***	0.552***

Note: *p ≤ 0.1, **p ≤ 0.05, ***p ≤ 0.01. $\widehat{\phi}(0)$ and $\widehat{\phi}(i)$ are respectively the estimated value of the quantity coefficient $\phi(0)_s$ and $\phi(i)_s$, where $\widehat{\phi}(0)$ is the deviation coefficient between city *i* and core city 0; $\widehat{\phi}(i)$ is the deviation coefficient between city *i* and the adjacent cities around the same agglomeration; O-Lag represents the estimated lag coefficient between city *i* and core city 0; W-H T indicates the Wu–Hausman statistical test, the original hypothesis of which is that the influence of a core city on surrounding cities in real estate transaction change is as an exogenous variable.

transaction changes were closely linked to the cities, especially in the south. The influence of Shenzhen in the Pearl River Delta agglomeration was very obvious and had a significantly positive relationship with Guangzhou. Xiamen also showed a strong diffusion effect in the West Side of the Straits agglomeration, but it had a clear competitive relationship with Fuzhou.

The core cities in the Beijing–Tianjin–Hebei, Shandong Peninsula, Central Plains, Guanzhong Plain, and Chengdu–Chongqing agglomerations had a relatively small influence on other cities. A special case was seen in the Beijing–Tianjin–Hebei agglomeration: in addition to Tianjin and Shijiazhuang, the remaining seven cities were only weakly affected by Beijing, indicating that the cities in this agglomeration were not sensitive to Beijing's real estate market. Although geographically adjacent, the coordinated development strategy of Beijing–Tianjin–Hebei may have helped calm the market. Qingdao had no obvious influence on the seven cities in the Shandong Peninsula agglomeration, which may be because Qingdao is not the capital city of Shandong Province. We used Jinan, the capital city, as the core city; the linkage association was not obvious either. Zhengzhou influenced the 13 cities in the Central Plains agglomeration, but the correlation coefficients were very small. Xi'an and Chongqing only influenced four cities in their agglomeration, indicating that linkages with the surrounding cities were not wide.

4.3. Spatiotemporal simulation

The parameter estimation results provided the related changing properties of real estate transactions between a core city and its surrounding cities in urban agglomerations. To visualize the regional correlation characteristics from the angles of time and space, we used MATLAB R 2015b to obtain 3D simulation diagrams. The spatiotemporal model was introduced to simulate the situation excluding core cities' regulation policies, as shown in Fig. 5.

Fig. 6 illustrates the real estate market regional linkage between cities in the spatial and temporal dimensions of the sample agglomerations. Different urban agglomerations showed specific linkage characteristics in a morphological pattern. However, the characteristics in the situation without the policy impact $\varphi(0)_t$ showed very strong nonlinear connection with each other.

According to section 3.2, regulation policies issued in an agglomeration core city may have spillover effects to the surrounding cities. We tested and quantified the 152 sample policies of the core cities and then introduced them into the model. The simulation results illustrated the regulation policies spillover from core cities, as shown in Fig. 6.

The real estate policies of the core cities showed spillover effect and spread in the space and time dimensions. Moreover, the policy variables made the spatial and temporal correlation of the real estate market between cities more smooth and deterministic compared with the without-policies case. Graphically, the spillover effect was more noticeable in the Harbin–Changchun and Middle–South Liaoning, West Side of the Straits, Pearl River Delta, Middle Reaches of the Yangtze River, and Yangtze River Delta agglomerations, in which the spillover effect was embodied in the core city's regulation policies, thereby causing large volatility in its own real estate transaction and larger wave hits on the surrounding cities. Conversely, the policy spillover effect in the following agglomerations was relatively weak: Beijing–Tianjin–Hebei, Central Plains, Shandong Peninsula, Guanzhong Plain, and Chengdu–Chongqing. The real estate transaction was less affected by the core city's policies and caused smaller wave hits to the surrounding cities.

Combined with the parameter estimation in section 4.2 and the simulation results, the real estate policy shock of Shenyang would spread to Harbin, Jilin, Changchun, and other cities in the north. Shenyang had an obvious negative phase relationship with Jilin; the two cities showed a certain substitution effect in housing transactions. However, no obvious spillover effect was seen between Shenyang and Dalian, indicating the policy spillover effects of Shenyang to the Harbin–Changchun agglomeration was more significant compared with the nearby Middle–South Liaoning agglomeration. In the Middle Reach of the Yangtze River agglomeration, the spillover effect of Wuhan's policy was significant, affecting 14 cities, except for Changsha and Changde, which showed a certain competitive relationship. The rest of the cities had a positive relationship with Wuhan. Meanwhile, Shanghai's policy spillover effect had a very obvious regional characteristic. Policy shock would spread to the surrounding areas, especially to the southern cities; apart from geographical proximity, close economic ties may an important reason. Shenzhen's policy impact on the Pearl River Delta agglomeration was very obvious; we observed a basically positive

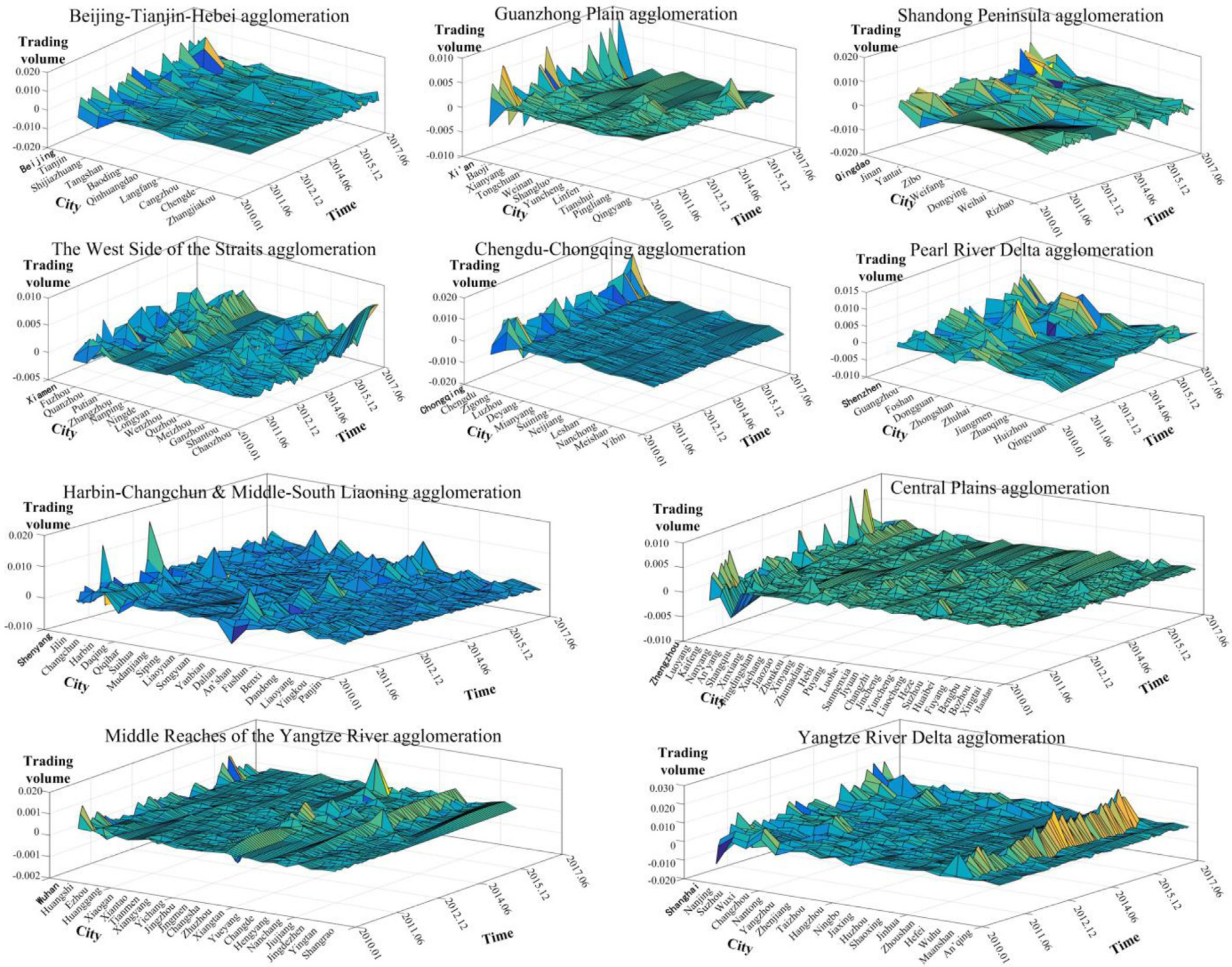

Fig. 5. Real estate market linkage between cities in the spatial and temporal dimensions.

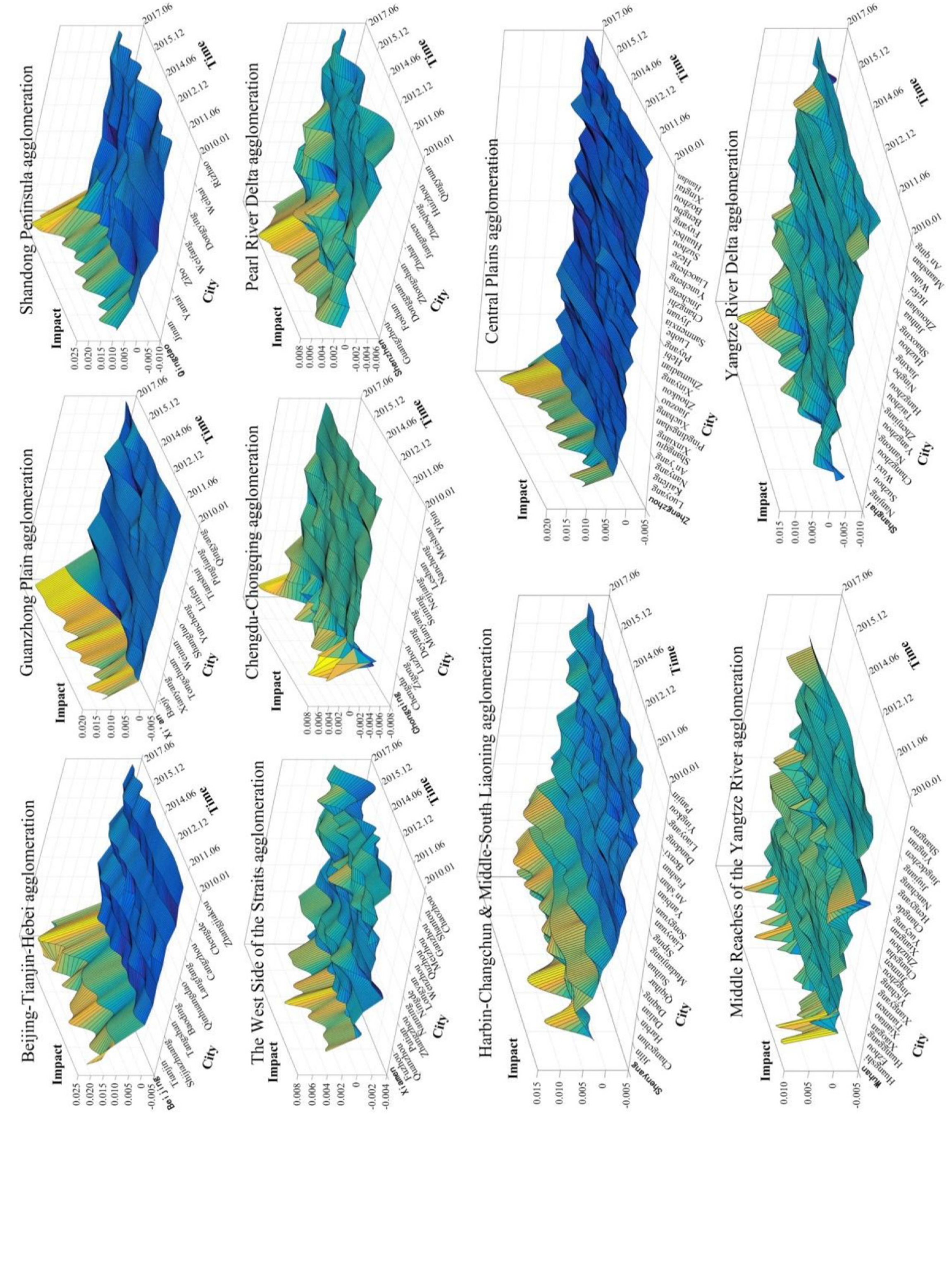

Fig. 6. Spatial and temporal wave of the real estate market with $\varphi(0)_t$.

influence. It also had a significant positive impact on Guangzhou but did not show obvious substitution effect between the two. Xiamen also showed a strong spillover effect, but it had obvious substitution effect with Fuzhou, Ningde, Ganzhou, and Chaozhou. Beijing's policy spillover effect was unexpected; except for Tianjin and Tangshan, the rest of the seven cities affected by Beijing's policy were not obvious, reflecting that the cities in the Beijing–Tianjin–Hebei agglomeration were not sensitive to Beijing's real estate policies. Despite the geographic adjacency, the coordinated development of the Beijing–Tianjin–Hebei agglomeration made the market resilient and not drastically changing not affected by Beijing's real estate market. Qingdao's policy spillover effect in the Shandong Peninsula urban agglomeration, except for Jiaodong Peninsula, was not obvious. This outcome may me because Qingdao is not the provincial capital. However, the spillover effect was not obvious in the capital city Jinan as well. Zhengzhou had an impact on 11 cities, but from the perspective of the wave shape, the impact range was very small. The policies of Xi'an and Chongqing had a significant impact on their urban agglomeration in only three cities, respectively, with a very small impact range.

4.4. Policy analyses

The above three-dimensional figures directly reflect the regional real estate policy spillover effect in the geographical and time dimension. However, each agglomeration core city had various kinds of local regulatory policies. To clarify the effect of different policy types, according to the model of section 3, we used the quantized sample policies in our model; cumulative anomaly fluctuation identification was carried out for the two dimensions of impact amplitudes and impact time. Then, the spillover of each policy was identified by calculating the O-Lag time units backward.[7] The most obvious policies were selected and shown in Table 3. The core city's policies with strong spillover effect showed that the effect lasted for a relatively long time and spread to many cities.

Agglomerations with very strong spillover effect policies were Harbin–Changchun and Middle–South Liaoning, West Side of the Straits, Middle Reaches of the Yangtze River, Yangtze River Delta, and Pearl River Delta. It can be found that the purchase limitation relaxation policies have strongest spillover effect among Shenyang's 14 policies, reflecting that the real estate market in the northeast was thus sensitive to Shenyang's housing policies stimulating consumption. The purchase and credit limitation policies, mortgage regulations among Xiamen's 16 policies spilled a wide range but with long time lag. Accumulation fund policies and purchase limitation policies of Wuhan have strongest spillover effects but the purchase limitation repressions on the market were very short and rebounded quickly. The cities in Yangtze River Delta agglomeration and Pearl River Delta agglomeration were very sensitive to the Purchase limitation policies in Shanghai and Shenzhen respectively, however the purchase restriction did not significantly suppress the real estate market for a long time, only about 0.5 months later, the market rebounded rapidly.

Among the agglomerations with weak policy spillover effects, the core city Qingdao in the Shandong Peninsula agglomeration had no real estate policies with strong spillover effect. Beijing's policy spillover effect unexpectedly was not obvious in the Beijing–Tianjin–Hebei agglomeration, with limited influence only affected 2 cities and lasted no more than 2 months. Xi'an's house market regulation policies had certain spillover effect across the Guanzhong Plains agglomeration but the impact was very short, the market always showed a fast rebound 1 month after. Business tax and accumulation fund loan policies issued by Zhengzhou had wide spillover effect in the Central Plains agglomeration but with short time of no exceed 1 month. The policies in Chongqing had strong spillover effect were involved housing property tax with impact time no more than 2 months.

4.5. Extraction of regional linkage characteristics

Policy spillover effects vary according to the heterogeneous regional characteristics of the real estate market. Therefore, it is of great significance to understand the market rules, to grasp the characteristics of the real estate market before and after the core city's policy intervention. However, the irregular wave of disorder is insufficient for measuring the regional variation traits of the real estate market. Thus, on the basis of the symbolic time series analysis model in section 3.3, the changing modes of the spatial and temporal waves were extracted. According to the measurement of Shannon entropy, the best character length $L = 4$ (i.e., four months) was selected as a unit, and the symbol $n = 3$ (i.e., using three symbols as low (l), medium (m), and high (h)) represented the trisection transaction level of the original series. Let $h = 2$, $m = 1$, and $l = 0$, and then according to equation (18), 81 characters could be obtained, each of which represents a changing mode (see Fig A1 in the Appendix). Fig. 7 shows the changing mode information of the spatial and temporal waves before the policy variable $\varphi(0)_t$ was introduced.

The spatial and temporal association waves in Fig. 6 were transformed into the representation of a series of symbolic time series reflecting the characteristics of different changing patterns in space and time. The Z axis value corresponding to each histogram represented a previous changing mode at this point for four consecutive months. The X and Y axes represented cities and time. The changing mode of each urban agglomeration tended to be numerous and chaotic. According to the statistical results of character histogram (see Fig A2 in the Appendix), each agglomeration had 81 characters representing 81 changing modes.

We then compared the situation with the intervening policy impact $\varphi(0)_t$. In the same way, let the character length $L = 4$ and symbol $n = 3$, set $h = 2$, $m = 1$, and $l = 0$. The changing mode information of the spatial and temporal waves is shown in Fig. 8.

A comparison of Figs. 7 and 8 shows reduced changing modes and characteristics becoming much more regular in the model with policy variables $\varphi(0)_t$. According to the statistics histogram (see Fig A2 in the Appendix), for the situation with policy $\varphi(0)_t$,

[7] Owing to length restrictions, the parameter test and each policy's effect were not listed. Readers who are interested in these can ask us for them.

Table 3
Policies with strong spillover effects.

Core City	Issued time	Major policy items	O-Lag /month	Effect time /month	Effect range /cities
Shenyang	Aug. 2014	Purchase limitation relaxation	0.2	3	9
	Nov.2014	House purchase subsidies	0.3	4	8
	Oct.2015	Tax preference for house purchase	0.3	3	11
Xiamen	Nov. 2014	Strengthen house purchase and credit limitation	3.1	5	11
	Jul. 2016	New mortgage regulations	3.0	2	5
	Nov. 2016	New regulations for real estate registration	2.6	2	4
Wuhan	Jan. 2011	Limited purchasing order	2.8	4	14
	Dec. 2013	New policies on public accumulation funds	0.2	3	12
	Sep. 2015	New provident fund loan details	0.1	4	12
	Nov. 2015	Cut the personal housing accumulation fund loan rate	0.1	3	10
	Oct. 2016	Restriction on purchase and loans	0.3	2	9
Shanghai	Jan. 2011	Details of limited purchasing order	0.2	12	15
	Nov. 2016	Diversified housing credit policies	0.2	4	16
Shenzhen	Sep. 2010	Curb excessive house price rises	0.2	11	7
	Oct. 2013	Stabilize housing prices	0.2	10	7
	Mar. 2016	Improve the housing security system	0.2	12	4
Beijing	Apr. 2010	12 items to curb excessive house price rises	0.1	2	2
	Feb. 2011	Consolidate and upgrade purchase limitation policies	0.2	2	2
	Oct. 2013	Set up purchase limitation supervision committee	0.1	1	3
	Mar. 2017	Diversified housing credit policies	0.3	2	2
Xi'an	Jan. 2011	Curb real estate speculation	0.4	1	5
	Feb. 2011	Limited to buy two and forbidden to buy more than three apartments	0.3	1	4
Zhengzhou	Feb. 2016	Preferential adjustment of deed and business taxes in transactions	0.3	1	12
	Oct. 2016	Restart the limited purchasing order	0.2	1	9
Chongqing	Jan. 2012	Raise the threshold for paying taxes on high-end residential property	0.4	1	7
	Sep. 2014	Implementation rules of personal housing property tax collection	0.3	2	5
	Jan. 2017	Interim measures on personal housing property tax collection	0.1	2	3

each agglomeration had no more than 35 characters: most of the characters representing changing modes disappeared, thereby greatly increasing the predictability of the real estate market in each agglomeration. This interesting result directly reflects the fact that in China, the core cities' local regulatory policies can regulate and control the regional real estate market to a certain extent.

Generally, the fewer characters there are, the more deterministic the real estate market is. The characters appearing most frequently can best represent the essential feature of linkage change between cities in each urban agglomeration. The information entropies calculated by equation (20) measured the real estate market's overall degree of order in each urban agglomeration. The main characters and information entropies were counted and shown in Table 4.

Comparing with the model without policy variables, $\varphi(0)_t$ reduced the changing modes and made the real estate market characteristic much more regular. In terms of the main characters, the Shandong Peninsula and Middle Reaches of the Yangtze River agglomerations were basically the same with the situation without $\varphi(0)_t$, which means that the core city's policy impact reduced the uncertainty but did not change the essential changing feature of the market. The main characters of the Harbin–Changchun and Middle–South Liaoning, Central Plains, Guanzhong Plain, Yangtze River Delta, and Pearl River Delta agglomerations with $\varphi(0)_t$ introduced were basically the same with the situation without $\varphi(0)_t$, albeit with minor reductions; the market changing feature became more focused. As for the Beijing–Tianjin–Hebei, West Side of the Straits, and Chengdu–Chongqing agglomerations, the main characters increased and the value changed, indicating that the core city's policies had limited impact on reducing the uncertainty but changed the major changing trends of the real estate market.

To estimate and forecast the market trend, we used the frequency of the main characters. The relative frequency of each character can be equal to the probability of each character appearing in the whole sequence (Tang et al., 1995; Daw et al., 2003). Thus, it is accurate to extrapolate the probability trading level on the fourth trading day based on the previous three continuous trading days. The formula is

$$P(t_4|t_1t_2t_3) = P(t_1t_2t_3t_4)/P(t_1t_2t_3) = P(t_1t_2t_3t_4)/[P(t_1t_2t_3H) + P(t_1t_2t_3M) + P(t_1t_2t_3L)] \tag{21}$$

Taking the Chengdu–Chongqing agglomeration as example, the frequency of characters “2,” “29,” and “56” were, respectively, 0.0005, 0.0003, and 0.0010 without the policy variable $\varphi(0)_t$ introduced. Thus, the first three continuous trading days would be *HML*, and the probability of the fourth day's trading level would be

$P(H) = P(56)/[P(2)+P(29)+P(56)] = 0.556$;
$P(M) = P(29)/[P(2)+P(29)+P(56)] = 0.167$;
$P(L) = P(2)/[P(2)+ P(29)+P(56)] = 0.278$

After $\varphi(0)_t$ was introduced, the frequency of “2,” “29,” and “56” became, respectively, 0.0001, 0.0001, and 0.0011, and the probability of the fourth day's trading level became

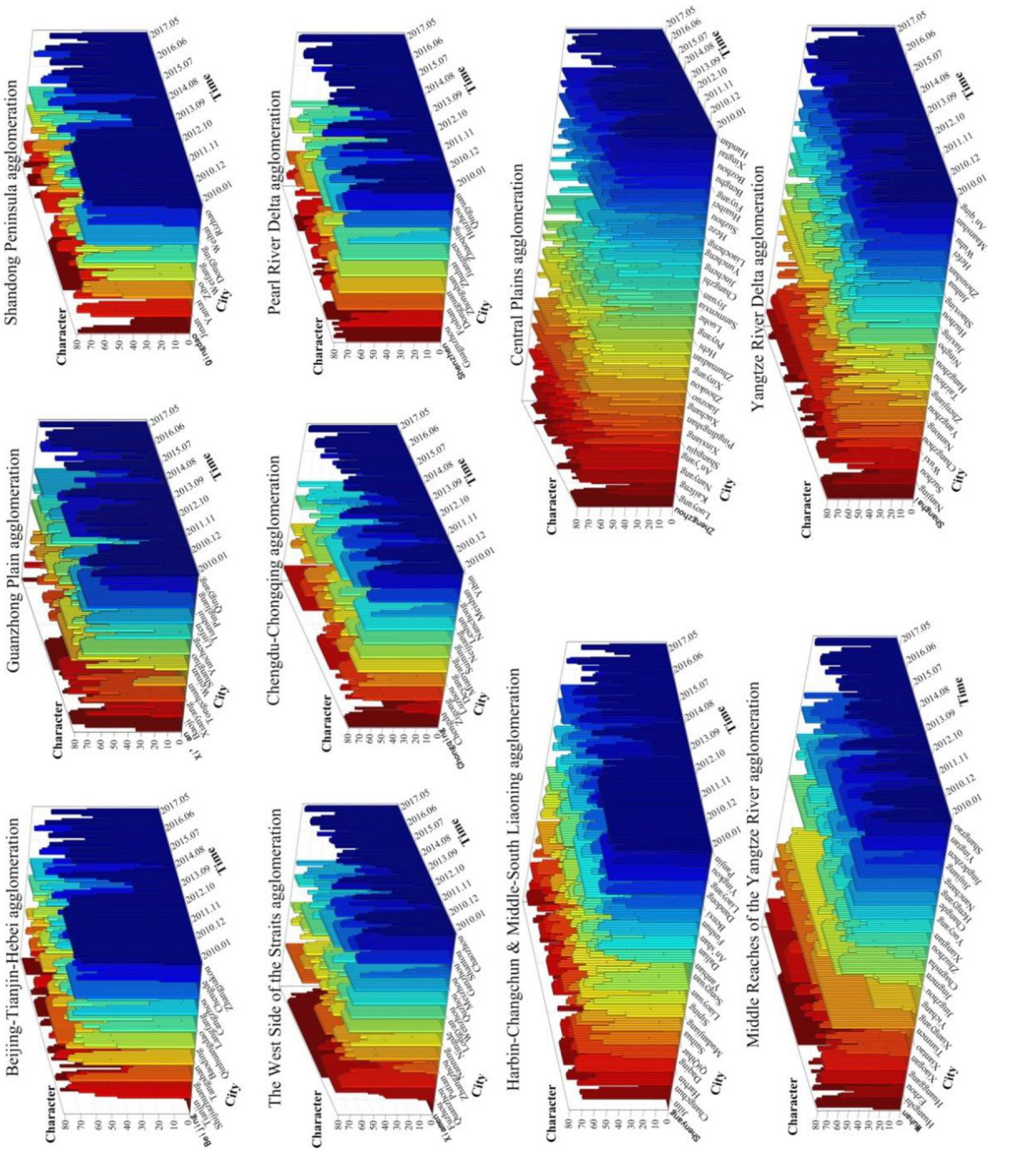

Fig. 7. Symbolic characteristic of real estate markets without $\varphi(0)_t$.

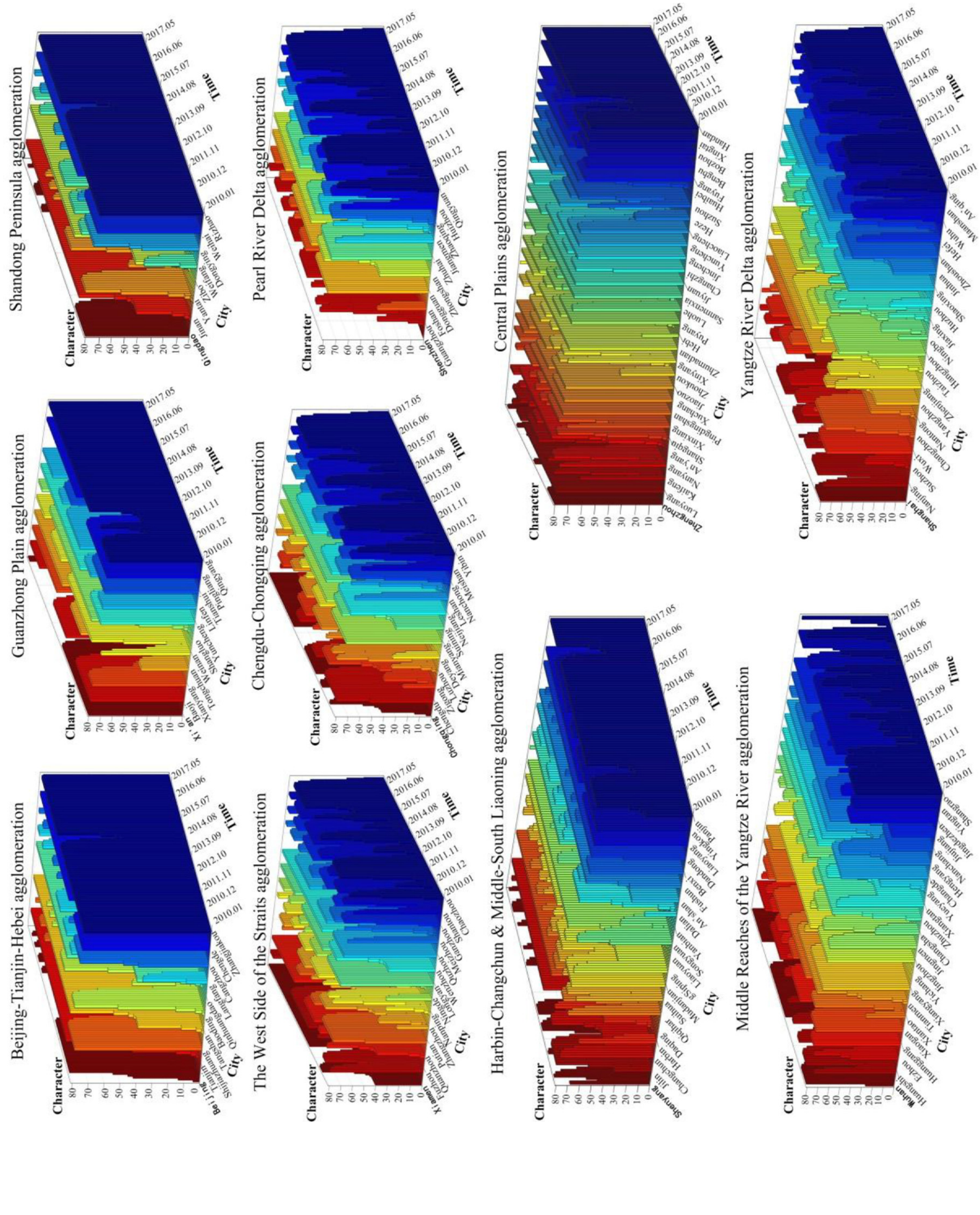

Fig. 8. The regional symbolic characteristic of real estate markets with $\varphi(0)_r$.

Table 4
Main characters and information entropy of the real estate market.

Agglomeration	Core City	Main characters (without $\varphi(0)_t$)	Information entropy (without $\varphi(0)_t$)	Main characters (with $\varphi(0)_t$)	Information entropy (with $\varphi(0)_t$)
Harbin–Changchun and Middle –South Liaoning	Shenyang	0, 26, 40, 53, 71, 78, 79, 80	0.5883	0, 40, 53, 80	0.3010
Beijing–Tianjin–Hebei	Beijing	0, 26, 40, 53, 78, 79, 80	0.5820	0, 1, 4, 27, 36, 40, 53, 76, 77, 80	0.4644
Shandong Peninsula	Qingdao	0, 80	0.3651	0, 80	0.2904
Central Plains	Zhengzhou	0, 40, 53, 80	0.4554	0, 40, 80	0.1787
Guanzhong Plain	Xi'an	0, 40, 53, 80	0.4300	0, 40, 80	0.1831
Middle Reaches of the Yangtze River	Wuhan	0, 40, 80	0.3022	0, 40, 80	0.2136
Yangtze River Delta	Shanghai	0, 26, 53, 78, 79, 80	0.4140	0, 40, 53, 80	0.2501
Pearl River Delta	Shenzhen	0, 26, 40, 53, 62, 78, 79, 80	0.4233	0, 53, 80	0.2530
West Side of the Straits	Xiamen	0, 40, 53, 79, 80	0.3882	0, 1, 4, 27, 40, 53, 79, 80	0.3392
Chengdu–Chongqing	Chongqing	0, 8, 26, 27, 40, 76, 77, 78, 79, 80	0.4206	0, 1, 4, 17, 27, 36, 40, 53, 79, 80	0.3976

$P(H) = P(56)/[P(2)+P(29)+P(56)] = 0.846;$
$P(M) = P(29)/[P(2)+P(29)+P(56)] = 0.077;$
$P(L) = P(2)/[P(2)+ P(29)+P(56)] = 0.077$

Clearly, the market trend became more certain and predictable. In terms of information entropy, the core city's policy spillover effect more or less increased the order degree of the real estate market. In general, the fewer the main characters, the smaller the information entropy and the more certain that the market will change. The real estate market of urban agglomerations in Northern China tended to be more disorderly than that in the South.

5. Conclusions and implications

The spatiotemporal and event analysis models were integrated and used to simulate the local spatiotemporal spillover effect of important real estate policies proposed by the core cities in 11 urban agglomerations. Symbolic time series analysis was used to extract the linkage characteristics of the regional real estate market. The results indicated that the spillover effect of a core city's regulation policies in an agglomeration existed extensively, with different urban agglomerations presenting specific linkage characteristics of the real estate market and varied sensitivity to different types of policies issued by its core city that could change the characteristics of real estate transactions. The results shed light on China's real estate policy effect on the fluctuation of the real estate market and offer references for precise real estate control strategies. The implications and policy regulatory suggestions are as follows:

(1) The real estate market of cities in the Harbin–Changchun and Middle–South Liaoning agglomeration was significantly affected by Shenyang's policies, especially those aimed at stimulating consumption. Shenyang's policy shock mainly spread to the northern cities. Further, the spillover effect in the Harbin–Changchun agglomeration was more than that in geographically adjacent Middle–South Liaoning agglomeration. Therefore, the control regulations of this region could make full use of Shenyang's consumption stimulus policy intervention.
(2) Regulation in the West Side of the Straits agglomeration should pay attention to Xiamen's purchase limitation, housing mortgage, and real estate registration policies, whose spillover effects were notable in both time and space ranges but with long regulating lags. Regulation in the Middle Reaches of the Yangtze River agglomeration should pay attention to the influence of Wuhan's accumulation fund policies, which had broad influence on its surrounding cities. Purchasing limitation policies could easily stimulate market rebound, which should be used cautiously.
(3) The policy spillover effect in the Yangtze River Delta agglomeration was very similar to that in the Pearl River Delta agglomeration. The most effective policies in the short term were the house purchase limitation policies issued by Shanghai and Shenzhen. However, the rapid market rebound should be monitored when using these kinds of policies.
(4) Regulation in the Guanzhong Plain agglomeration should strengthen the role of Xi'an's market supervision policies. However, the influence of regulation did not last long, so these kinds of policy should be frequently executed.
(5) The policy spillover effect in the Central Plains, Beijing–Tianjin–Hebei, and Shandong Peninsula agglomerations were basically similar. Except for the fact that there were no obvious spilled policies in Qingdao, the tax policies in Zhengzhou and administrative policies in Beijing had negligible spillover effects in their local region. Thus, the core city's policy interventions could relatively be ignored when formulating regulation and control policies.
(6) Chongqing's housing property tax in the Chengdu–Chongqing agglomeration had the most obvious spillover effect. Regulation work can thus give full play to the advantages of this type of policy tool, and this region is more suitable to carry out the pilot work for the property tax levy.

Given the model setting, the main limitation of this study is that the spillover direction is unidirectional from the core city to surrounding cities. The evolution of multiple forces from different cities was not considered in our model. Future research will help improve the model and verify the policy spillover effect, as well as extract the regional market characteristics in more complex situations.

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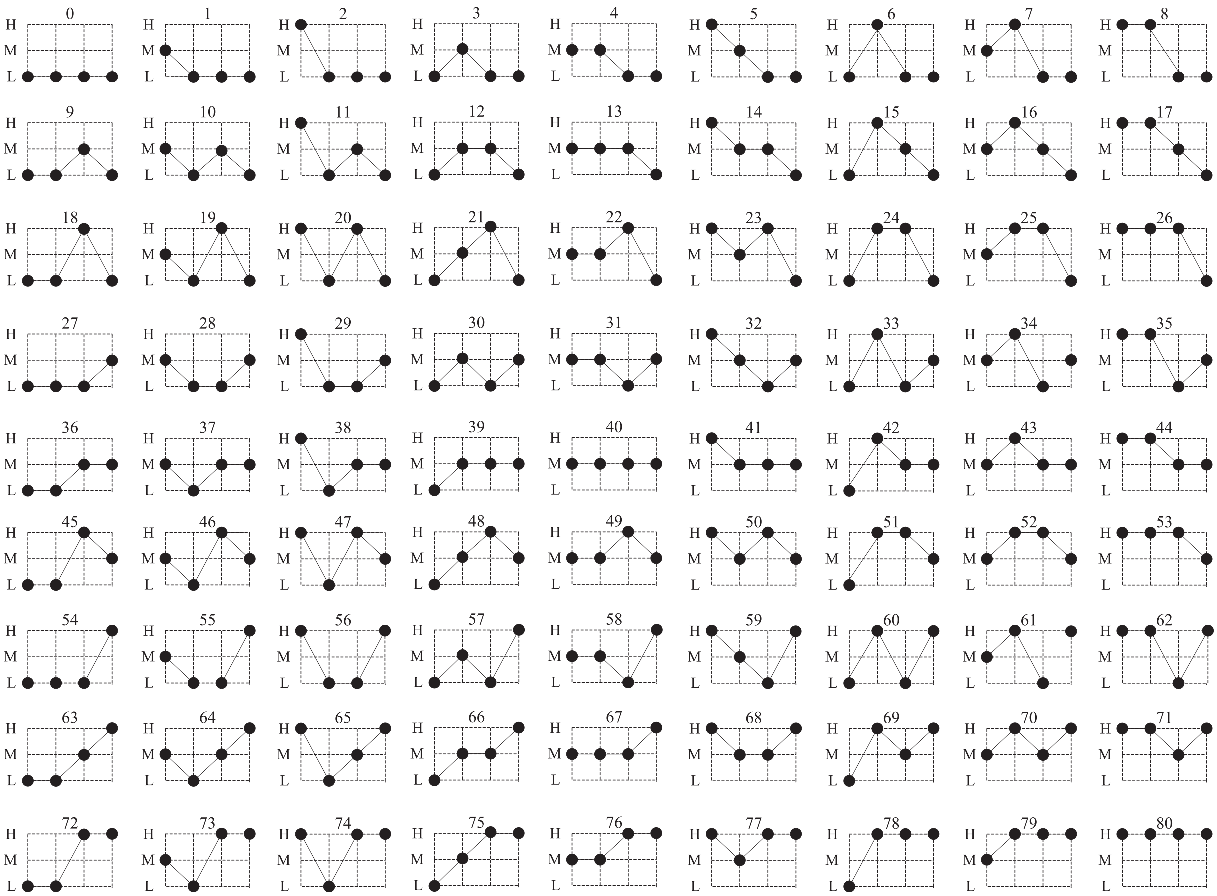
Conflicts of interest

The authors declare no conflict of interest.

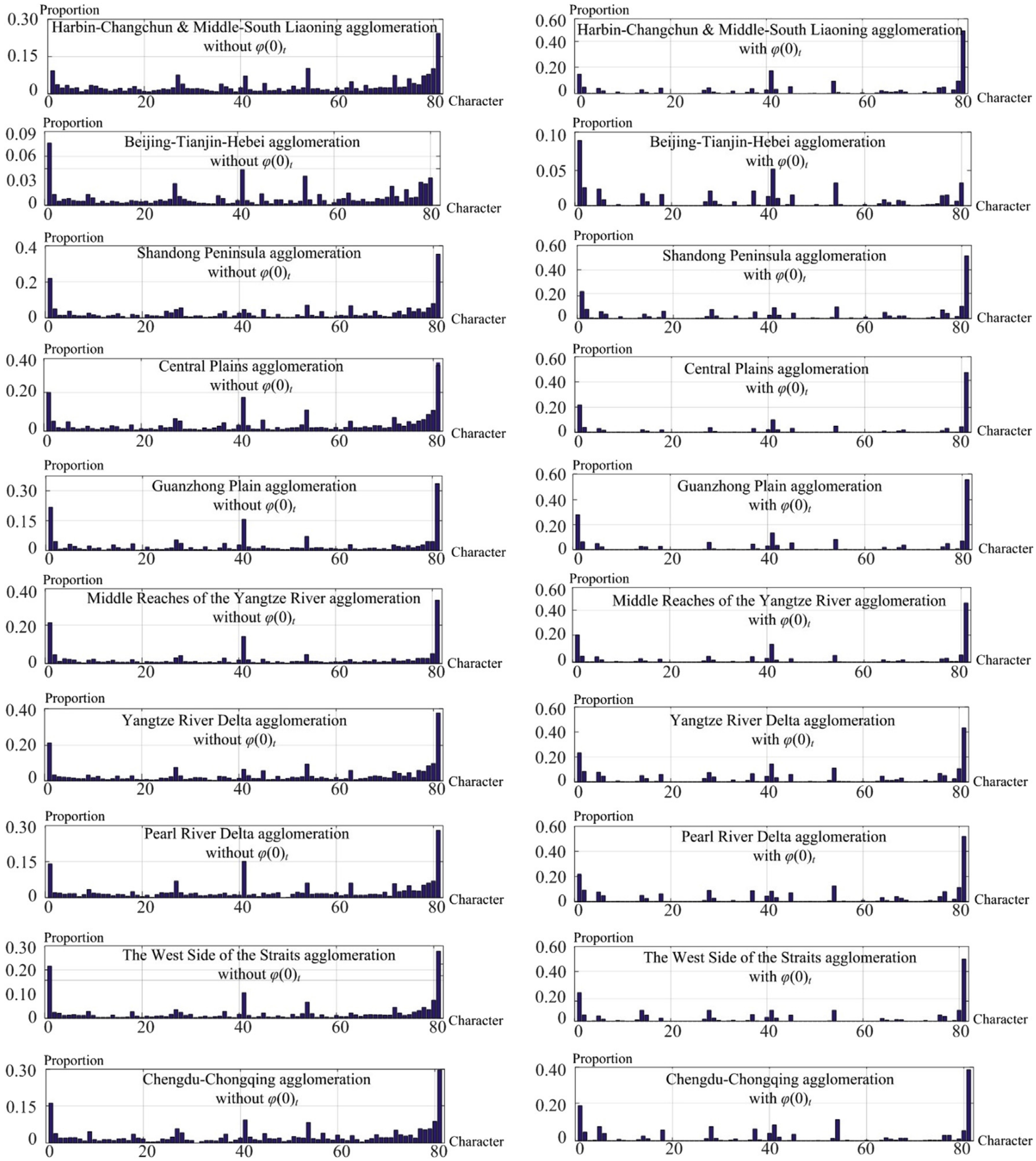
Appendix

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jmse.2019.05.004.



FigA1. The changing patterns of 81 characters.



FigA2. Histogram of characters before and after policy shock.

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