

# Modelling urban spatial impacts of land-use/transport policies

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**Abstract:** China is now experiencing rapid urbanization. Powerful tools are required to assess its urban spatial policies before implemented toward a more competitive and sustainable development paradigm. This study develops a Land Use Transport Interaction (LUTI) model to evaluate the impacts of urban land-use policies on urban spatial development. The model consists of four sub-models, i.e., transport, residential location, employment location and real estate rent sub-models. It is then applied to Beijing metropolitan area to forecast the urban activity evolution trend based on the land-use policies between 2009 and 2013. The modeling results show that more and more residents and enterprises in the city choose to agglomerate on outskirts, and new centers gradually emerge to share the services originally delivered by central Beijing. The general trend verifies the objectives of the government plan to develop more sub-centers around Beijing. The proposed activity-based model provides a distinct tool for the urban spatial policy makers in China. Further research is also discussed at the end.

**Keywords:** model/simulation; LUTI; accessibility; urban activity; policy scenarios

## 1 Introduction

With further development of new-type urbanization, a large number of migrants are pouring into cities, and there will be a series of changes in the economic activities, transportation and spatial structure of the cities. Therefore, in order to ensure healthy and orderly development of urban space, the scientific rationality of urban space policy is raised to high requirements. Decision-making in urban space usually needs to answer the following questions: what is the influence of developing a certain number of housing or commercial floorspace for urban space, what is the influence of building a new highway (or rail transit) for the distribution of population and the enterprise? Urban development cannot be rehearsed, hence, in order to

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ensure the sustainability of urban space policy, simulation of urban spatial evolution process and policy experimentation are crucial for decision-making.

Research on urban spatial evolution has experienced a long history. Since quantitative revolution in geography in the 1960s, model simulation has been adopted to study the evolution of urban space, e.g., Lowry model (Lowry, 1964). In the 1980s, Dentrinos and Mullaly introduced the Volterra-Lotka equation of the predator-prey relationship into the urban system and constructed a dynamic analysis model. In the 1990s, Wegener established the Dortmund model with integrating the models of various subsystems in the city (Li and Ye, 2007). Since the 1990s, with the great breakthroughs in microscopic simulation method based on artificial intelligence, the macroscopic evolution law of urban space has been studied by simulating the behavior of the microcosmic body. Among them, the application of cellular automata (CA) significantly improved the prediction precision (Lowry, 1964; Long *et al.*, 2009), and the multi-agent simulation (MAS) transferred the focus from grid unit to the intelligent agent (Xue and Yang, 2002; Long *et al.*, 2011; Shan and Zhu, 2011; Shen, 2011). The specific application areas include urban space growth (Lowry, 1964; Wu *et al.*, 2008; Long *et al.*, 2009; Yang and Li, 2009), residential space evolution (Liu *et al.*, 2010; Dang *et al.*, 2011; Dong *et al.*, 2011), land use change, traffic flow and urban morphological evolution etc. (Dai and Li, 2009; Chen *et al.*, 2010; Niu and Liu, 2017; Chen *et al.*, 2018). In general, the research results are enriched, and the research methods of the model are constantly innovated, which provides a good scientific support for the development of Chinese cities. However, the application field is relatively dispersed, and the integrated simulation research in various fields is weak. Meanwhile, urban space mentioned in the model refers to the physical meaning of land use (e.g., construction land), which is lack of the comprehensive integration of economic development, population and other urban indicators, and mining of the internal driving force of city evolution. Moreover, in the process of China's economic reform, urban land use plays an important role in local economic growth. With the exception of the market, the development of the city is mainly guided by the government (Zhang, 2000; Liao and Wei, 2014). Therefore, it is urgent to strengthen the comprehensive integration simulation, and dynamic forecasting the urban space development trend under the policy constraint.

Urban physical space is the spatial projection of socio-economic activities, and the change of urban physical space is the change of spatial distribution of urban socio-economic activities (Lowry, 1964; Wang and Liu, 2011; Wang *et al.*, 2013; Ryan *et al.*, 2015). The implementation of urban space policy will change the distribution pattern of urban socio-economic activities. Therefore, based on socio-economic activities, this study will carry out the research on the integration of urban spatial evolution and provide scientific support for urban space decision-making in the context of rapid urbanization. Urban land use/transport interaction (LUTI) model is supposed to be a powerful tool for urban socio-economic activity space evolution (Liao and Wei, 2014; Geurs and Wee, 2004; Pierlugi, 2013) which is often used for auxiliary decision-making of urban development in developed countries (Niu 2017; Niu and Li, 2017). However, in the domestic, this application is weak, and there is almost no successful application case. For these reasons, we believe that: 1) domestic urban studies, especially quantitative research, started late, and there are few people involved in LUTI model research. 2) Domestic studies have focused on macro issues and qualitative analysis. Although quantitative simulation research has gained more and more attention, the research

attention, the research on complex integration simulation is still weak. 3) LUTI model actually is a computer model to describe the theoretical framework (Lowry, 1964). The key is to simulate infinite city development with computer processing function of the infinite loop. In addition to the professional knowledge of urban development and economic knowledge, the development of the model also requires the technology of computer program development, which hinders the popularization application of LUTI model. 4) The operation of LUTI model requires a large amount of detailed urban land use data, traffic data, and a lot of mathematical calculation (Niu, 2017), which also limits its promotion and use. The development and application of LUTI model for simulating the core function of urban spatial evolution is still very weak, which also provides opportunities and challenges for this research.

The city model developed by Lowry (1964) is a milestone in the development of LUTI model, which is named as Lowry model. As a static model, Lowry model predicts the development trend of urban space at a certain time point based on the assumption of many variables, characterizes the traffic condition between locations with displacement distance, and evaluates the attractiveness of land based on market rules. The above aspects have become the main focus of the expansion of scholars. As far as the implementation of LUTI model is concerned, it is necessary to build a dynamic model in order to realize the annual prediction for the future, and predict the annual situation according to the annual change of variables. In addition, from the perspective of model implementation technology, research on “activity-based” LUTI model is considered as a new development trend (Pierluci *et al.*, 2013; Brand *et al.*, 2014). The “activity-based” LUTI model evaluates urban location characteristics according to the needs of various socio-economic activities, and the same location has different values for different urban activities. In this regard, common methods of evaluating location advantages using spatial distance are not adequate (e.g., distance to CBD, or traffic station).

In view of the domestic demand for the rapid development of urbanization, and the domestic research status and development trend of LUTI model, this paper constructed the “activity-based” LUTI model, which is known as Spatial Distribution of the Activity (SDA). The main urban activities considered in this study are household and employment. The SDA model is a dynamic model, which is used to simulate the urban spatial evolution process and predict the distribution pattern of socio-economic activities. Then the influence of urban land-use policy on urban space is simulated with Beijing as a case study area.

## 2 Origin of LUTI model

LUTI model is an integrated framework for theory, data and algorithm, which is used to describe the interaction process between two major components of urban space (transportation and land use system). The word “land use” of LUTI is not the physical meaning of land use (e.g., construction land and farmland, etc.), but rather refers to the user of “urban space”: socio-economic activities. “Urban space” usually refers to the floorspace, rather than land (Simmonds and Feldman, 2011). In some research, “land use” refers to physical meaning of land use, but such models do not belong to LUTI model (Landis, 2001; Niu and Li, 2017).

The LUTI model contains essentially interrelated land use model and traffic model. In the 1950s, the American scholar Hansen (1959) put forward the thought about the interaction of

urban land use and transportation: the urban land use pattern (such as residential, industrial and commercial distribution, etc.) determines the space separation about the location of the human activities (live, work, shopping, etc.). All kinds of urban activities need to interact through traffic, and the transportation convenience determines the location selection of activities, so as to lead to the changes of land use system. Conversely, the land use system changes also affect the traffic system. Then the equilibrium is reached by such interaction. This idea swept the American planning area and laid the theoretical framework of LUTI. Subsequently, in the early 1960s, quantitative simulation has received unprecedented attention in the field of urban planning. In 1964, Lowry first tried to establish a city model (Lowry model) using computer technology based on LUTI theory, which became a milestone in the development of LUTI model. Lowry model considers urban space is composed of traffic network and land use, and divides socio-economic activities into three kinds: household, basic production department and service department. Given the location of the basic department, the spatial distribution of residents and service departments shall be given. The Lowry model contains the residential location model and the service sector location model, which are nested with each other.

3 Implementation of the SDA model

3.1 Model components

The SDA model was designed to predict the changes of the spatial distribution of urban activities when urban land use or traffic system changes. The assumptions of the model are: urban activities tend to location with higher utility; location utility is influenced by factors such as the rent or traffic accessibility; the change of location utility leads to the change of socio-economic activity distribution.

The SDA model divides urban activities into two categories: household and economic activities, among which economic activities include education, medical care, research and service industries. Housing floorspace is corresponding to household, and commercial floorspace is corresponding to various sectors of the economy, including companies, hospitals, schools, research institutes etc. (which are all called enterprises in this paper). In addition to the household, all kinds of activities can provide jobs, so economic activities are also collectively known as employment activities. The scale of economic activity is calculated according to the number of jobs. For example, the number of economic activities in a zone is 5000, that is, there are 5,000 jobs in the zone.

As shown in Figure 1, the SDA model includes four sub-models: traffic sub-model, household location sub-model, economic activity location sub-model and rent forecast sub-model. The specific details of each sub-model will be further discussed below.

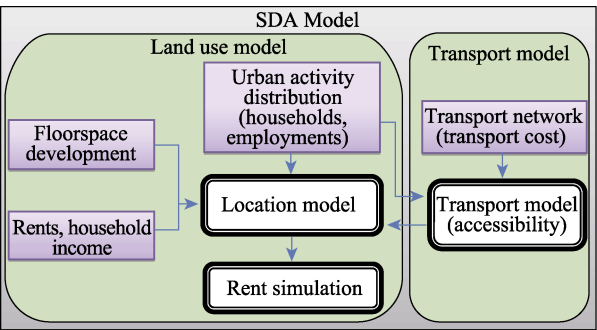


Figure 1 Components of the SDA model

### 3.2 Transport model

Based on the spatial distribution of urban road network and socio-economic activities (household and economic activities), the traffic sub-model is adopted to evaluate the accessibility of the zone, which is used to represent the convenience of travel from the zone. The definition of accessibility in this paper is that the convenience of engaging in various socio-economic activities in the zone. For family residents, the accessibility of the zone reflects the convenience of working and travelling (household accessibility). For economic activities (enterprises), the accessibility of the zones reflects the convenience (enterprise accessibility) of the zones to be reached by residents as the end point. Accessibility is determined by the spatial distribution of the conditions and opportunities. For household, the accessibility is affected by the spatial distribution of surrounding job opportunities; for enterprise, it is affected by the spatial distribution of surrounding residents. Accessibility evaluation is based on activities and zones, that is, traffic accessibility evaluation is different for different activities in the same zone. The SDA model uses formula (1) to evaluate traffic accessibility.

$$A_i = \frac{1}{\lambda} \ln \left\{ \sum_j W_j \exp(\lambda \cdot gc_{ij}) \right\} \quad (1)$$

where  $A_i$  is the traffic accessibility of zone  $i$ ;  $W_j$  is the weight of zone  $j$  (for household,  $W_j$  is the number of jobs in zone  $j$ ; for enterprise,  $W_j$  is the number of residents in zone  $j$ ),  $gc_{ij}$  is the minimum tolls between zone  $i$  and zone  $j$ , which reflects the traffic conditions between zones.  $gc_{ij}$ , which is calculated by GIS software with calculation result as a  $M \times M$  order matrix ( $M$  is the number of zones), is the shortest transit time between two zones

Formula (1) is a logarithmic sum constructed in the form of logit model. Accessibility  $A_i$  has the same dimension as transport expense  $gc_{ij}$ . Therefore, the higher the accessibility evaluation value, the higher the cost and the worse the accessibility. According to formula (1), the coefficient is set as a negative value. With the increase of traffic cost  $gc_{ij}$ , the value of the exponential function term will gradually decrease, and the weight of zone  $j$  will be further weakened. Therefore, if zone  $j$  is difficult to reach for zone  $i$  (the transportation cost of  $gc_{ij}$  is high), the opportunity distribution of  $j$  is meaningless for zone  $i$ . Formula (1) is used to calculate accessibility without setting a threshold.

### 3.3 Location cost

Location cost refers to the economic cost of households or enterprises choosing a location. When families dominate their income, the proportion of consumer spending on housing and others will be adjusted for utility maximization. Therefore, in this study, household spending is divided into two categories: housing consumption (rent) and other consumer goods or services (ogs). The Cobb–Douglas (1933) equation is adopted to calculate consumption utility ( $U$ ). The calculation of consumption utility does not take transportation cost into account because transportation cost has been included in the evaluation of location utility and appeared in traffic accessibility.

$$U_i = (a_i^H)^{\beta^H} \cdot (a_i^O)^{\beta^O} \quad (2)$$

$$\beta^H + \beta^O = 1 \quad (3)$$

where  $U_i$  is the consumption utility of households in zone  $i$ ;  $a_i^H$  is the average household area;  $a_i^O$  is the average household spending on ogs;  $\beta^H$  and  $\beta^O$  represent the tendency of households to allocate income to housing and ogs consumption, and the sum of them is 1. In this case, the two are attached to empirical values based on research experience.

For the company, the most important thing is to maximize profits. The rent is adopted to calculate its location cost.

### 3.4 Household location model

The household location (residential location) model is used to calculate the spatial distribution of urban families and determine the number of families in each zone. The factors considered in the model include traffic accessibility and rent (consumption utility). The weight of each influencing factor is a representative value, which is called location utility ( $V$ ). The utility of location reflects the value of location in a certain type of economic activity. Different applications will have different emphases on variable selection, and even consider other variables (such as environmental quality, etc.).

Choice of household location tends to zones which already have household, and it is also affected by the location utility change (incremental) and the number of homes available (household distribution). Hence, the incremental model is adopted. In addition, it is impossible for researchers to know how each individual evaluates its location, hence, we chose the probabilistic discrete selection model. The probabilistic discrete selection model considers that the error terms are distributed uniformly and independently. Thus, as a housing consumer, the household's evaluation of location can be regarded as a function of a series of influencing factors. Based on this, the household location model is constructed as follows:

$$\Delta V_{t+1,i}^H = \theta^U (U_{t+1,i} - U_{ti}) + \theta^A (A_{t+1,i}^H - A_{ti}^H) \quad (4)$$

$$H(L)_{t+1,i} = H(M)_{t+1} \cdot \frac{H_{ti} \cdot F(A)_{t+1,i}^H \cdot \exp(\Delta V_{t+1,i}^H)}{\sum_i \{H_{ti} \cdot F(A)_{t+1,i}^H \cdot \exp(\Delta V_{t+1,i}^H)\}} \quad (5)$$

where  $\Delta V_{t+1,i}^H$  is the variable of household location utility in zone  $i$  within the time period of  $t+1$ , which is the weight of the change of household accessibility and location cost, with  $\theta$  as the weight coefficient.  $H(L)_{t+1,i}$  is the number of families that move into zone  $i$  within the time period of  $t+1$ .  $H(M)_{t+1}$  is the total number of families who move in cities during the period of  $t+1$ .  $H_{ti}$  is the number of households in zone  $i$  during the period  $t$  (the previous period);  $F(A)_{t+1,i}^H$  is the number of available housing floorspace during the period of  $t+1$ .

### 3.5 Location model of economic activities

Economic activity location model is used to determine the spatial distribution of economic activities and the amount of economic activity in each zone. Economic activity distribution is affected by enterprise location. As mentioned before, this study focuses on the interaction between "living-work", with an assumption that enterprise location choice is affected by household distribution. Then the enterprise location model is similar to the household location model, as shown in formula (6).

$$E(L)_{t+1,i} = E(M)_{t+1} \cdot \frac{E_{ti} \cdot F(A)_{t+1,i}^e \cdot \exp(\Delta V_{t+1,i}^e)}{\sum_i \{E_{ti} \cdot F(A)_{t+1,i}^e \cdot \exp(\Delta V_{t+1,i}^e)\}} \quad (6)$$

where  $E(L)_{t+1,i}$  is the number of economic activities that move into zone  $i$  within the time period of  $t+1$ ;  $\Delta V_{t+1,i}^e$  is the variable in location utility of an enterprise in zone  $i$  within the time period of  $t+1$ . Similar to the utility of household location, the utility of enterprise location is calculated by enterprise accessibility and rent, that is, household accessibility and consumption utility in formula (4) are changed into enterprise accessibility and rent fees;  $E(M)_{t+1}$  is the total amount of economic activities that need to be relocated in the city during  $t+1$  period.  $F(A)_{t+1,i}^e$  is the number of commercial floorspace available in zone  $i$  during  $t+1$  period;  $E_{ti}$  is the amount of economic activity in zone  $i$  during the period of  $t$  (the previous period)

### 3.6 Rent model

Rent or housing price is the key factor that affects the location utility of urban socio-economic activities. After the urban activity distribution calculated by the location model, the rent will inevitably change as the urban activity distribution changes and the supply and demand change. The rent model is used to adjust the rent changes in real time. The new rent is used again to calculate the spatial distribution of urban activities. Based on the demand and supply of real estate, the rent model is adopted to predict the new rent by referring to the previous rent (Mumtax, 1995; Albouy, 2014). Based on the rent model, the greater the demand for real estate in a zone, the higher the rent in the zone. Formula (7) shows the housing rent prediction model, which is similar to the commercial rent model.

$$r'_{pi}^H = r_{pi}^H \left[ \frac{a_{pi}^H \cdot H(L)_{pi}}{F(A)_{pi}^H} \right] \quad (7)$$

where  $r'_{pi}^H$  is the estimated rent of zone  $i$ .  $r_{pi}^H$  is the last rent (the location model is the recursive process, as shown in Figure 2). The variable  $a$  is the current household distribution density;  $H(L)_{pi}$  is the number of families moved into zone  $i$ ;  $F(A)_{pi}^H$  is the total area of currently available residential floorspace.

Commercial rent adjustment equation can be obtained with the household variable being replaced by the corresponding economic activity variable, i.e., replacing  $H(L)$  into  $E(L)$ ,  $r^H$  into  $r^e$ ,  $a^H$  into  $a^e$  and  $F(A)^H$  into  $F(A)^e$ .

### 3.7 Algorithm of location model

As mentioned before, the urban space evolution process is an interaction process of land use and transportation system. The transportation system affects the land use system through accessibility (socio-economic activity distribution), and land use system also affects the traffic system. These two form a cycle with an equilibrium state. Any change in factors will lead to a new balance in the urban system (Torrens, 2000). The location model algorithm is based on this idea. The process of urban land use and traffic interaction corresponds to the iterative process of the algorithm (Figure 2).

As shown in Figure 2: traffic accessibility is calculated by traffic model based on the dis-

tribution of socio-economic activities and traffic costs; the location cost (household consumption utility and company location cost) of each zone is calculated according to the rent and household income; then, the location utility of each zone is calculated based on traffic accessibility and location cost; the spatial distribution of economic activities is calculated by location model based on the location of the utility and the floorspace distribution.

At this point, the density distribution of urban socio-economic activities changes, and further leads to changes in rent. The above process is repeated until the completion condition is satisfied and the program stops. At this time, the state of urban space is the predicted value. Condition for the end of a cycle refers to that the results of two cycles do not change or change very little, in this case, the model outputs the predicted value of the next period (such as the next year). The predicted value of the model, together with the policy scenario setting (policy scenario in year  $t+2$ ), can further predict the situation of year  $t+2$ . By analogy, the future urban space situation can be predicted year by year.

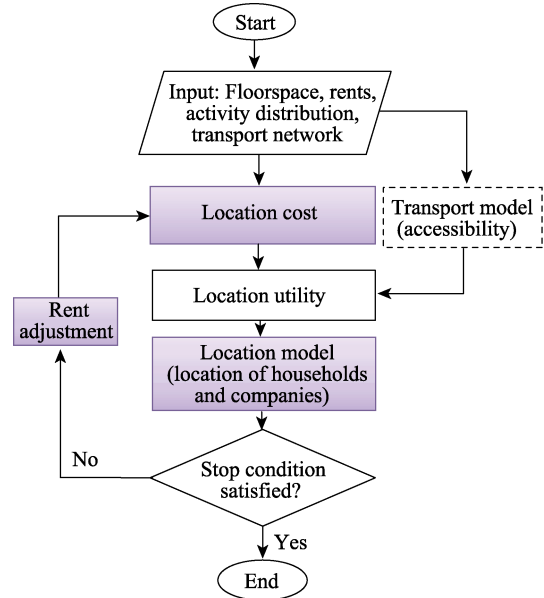


Figure 2 Algorithm of the SDA model

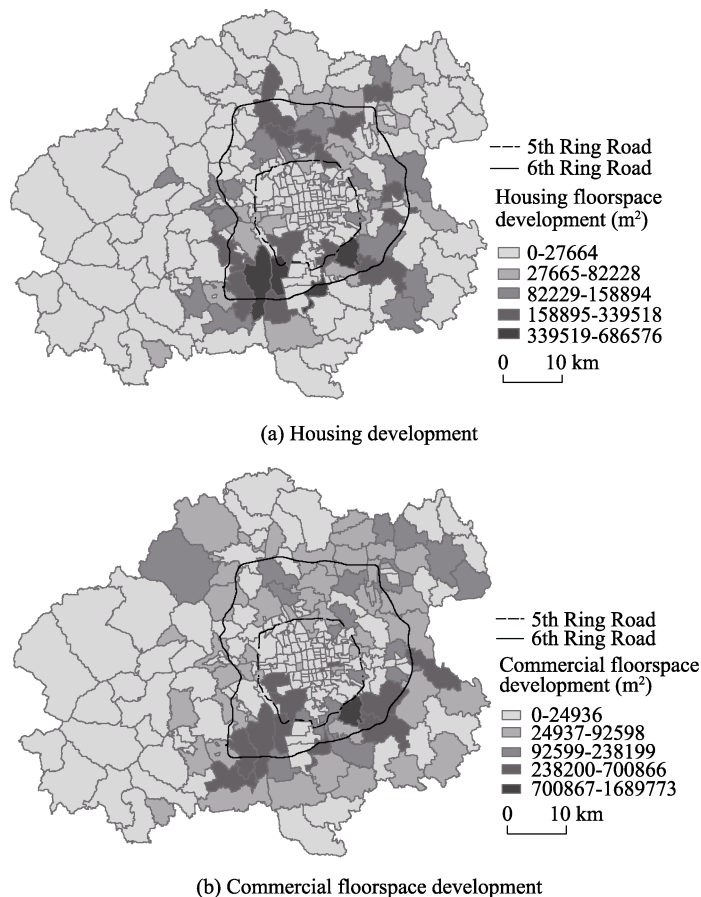
## 4 Case study: policy scenario experiments

### 4.1 Study area

Beijing was taken as a case area with a total of 18 districts (counties) and later changed to 16 in 2010. In this paper, eight urban districts and their surrounding suburban districts are taken as research areas. Using *Jiedao* (township) as scale, there are 239 *Jiedaos* (zones) as shown in Figure 3.

Spatial data of this study includes administrative division, road network data (including highways, urban expressways, national highways, provincial roads, county roads, metro lines and other traffic line at all levels) in the case study area. The minimum transportation costs ( $gc$ ) between every two zones are estimated based on the network. The result of traffic cost evaluation is a  $239 \times 239$  matrix.

In terms of socio-economic data, China's sixth population census data is still the most detailed data. As for the economic activity distribution data, POI (Point of Interest) data is obtained through remote access interface (API) provided by the electronic map suppliers, including the basic information and spatial location of the various units. Then the POI is matched with economic census data, so as to obtain the spatial information and attribute information for each unit. For the few POI data mismatch, combining with field investigation, interpolation is adopted. The data include almost all companies, schools, research institutes, hospitals and other units in Beijing. With this data, the detailed distribution of various kinds of employment in Beijing can be obtained by using GIS technology.



**Figure 3** Floorspace development of Beijing

## 4.2 Policy scenarios

Model can be used to test land-use policy, traffic policy or a combination of both. Due to the relatively slow changes in traffic system, as an application case, this paper will simulate the influence of current land-use policy on urban space.

Land-use policy: Corresponding to the classification of socio-economic activities, this study divides land use (real estate development) into two categories: housing development and commercial development. Area is used as a measurement unit, e.g., the number of housing developments is 200,000 square meters in a certain zone in a certain year. Each year, the government gives land to developers, and each land sold is generally used for its purpose (for residential or commercial purposes, etc.) and development area is specified. Land transaction data in Beijing for the past five years (2009–2013) have been collected and prepared, from which the number of various kinds of real estate developed is calculated in each zone every year. The average annual development of each zone is calculated as the future annual real estate development. According to Figure 3, land use development is mainly distributed outside the main urban areas, between the Fifth and Sixth Ring Roads, as well as counties and cities in suburban counties. This is also in line with the current macro-policy of easing the socio-economic activities, establishing multi-centers and easing traffic congestion in the main urban areas of Beijing. Another important reason is that the main urban areas are

already in a state of high development, and further development and construction is difficult and costly. Compared with housing development and commercial development, commercial development is more decentralized, which can be predicted to lead to further decentralization of employment distribution. Commercial development is widely found in the south of the city.

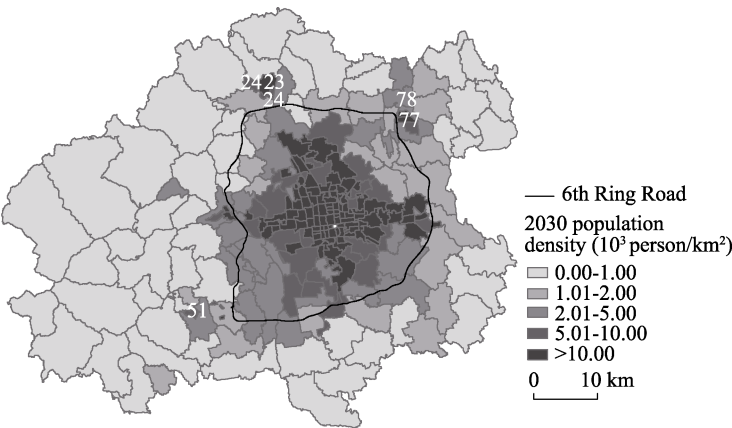
In addition to transportation and land-use policy, annual growth of urban socio-economic activity also needs to set. Taking into account the average speed of population and employment growth in recent years, this paper set the urban households and economic activities of annual growth rate is 0.023 and 0.020, respectively.

4.3 Results

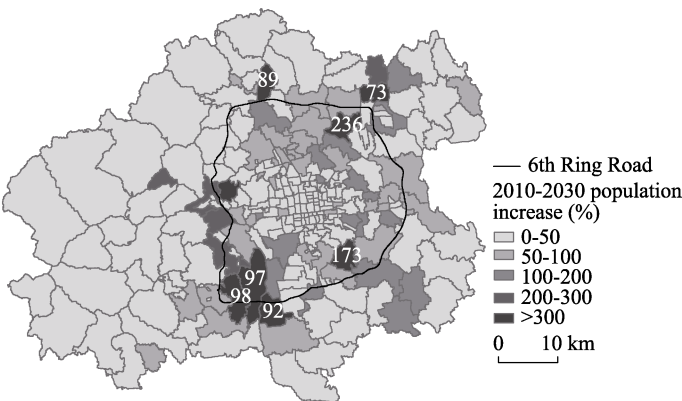
Based on the above scenario, the SDA model is adopted to forecast the distribution pattern of population and economic activity every other until 2030. At the end of the paper, the forecast results of each year are attached. The following is a brief analysis of the predicted results.

(1) Population distribution

The forecast of household population distribution in Beijing in 2030 is shown in Figure 4a. By 2030, most of the population will still be in the main urban areas within the Fifth Ring Road. This is because historically the main urban areas have been highly developed, with a



(a) 2030 population density by zone



(b) 2010–2030 population increase by zone (%)

Figure 4 2030 Population distribution forecasted

large number of population and economic activities, and high traffic accessibility. When the population increases year by year, there will also be some people settling in the region. With the original population base, the main urban area is still the most densely populated area. As can be seen from Figure 4, the traffic route has a great influence on the spatial distribution of residents, and the population tends to the location along the traffic line. A few zones away from the city center also have the high population density, which are usually suburban county towns, such as north zone (23) and south zone (24) in Changping, Guangming (77) and Shengli in Shunyi (78), and Yingfeng in Fangshan (51), etc.

Figure 4b shows the percentage change of population in each zone in 2030 compared to the population growth model in 2010. As can be seen from the figure, with the annual growth of the population, more and more people tend to move beyond the fourth ring road. With considering the factors of the rent, transportation accessibility and property distribution by the SDA model, it can be concluded that the city has been highly developed with high population density, causing further less housing construction. In addition, high rents also hindered the further population agglomeration. The suburbanization of new population is consistent with land-use policy. The development of a large number of houses in the suburbs has resulted in a decrease in rent. Moreover, a large number of commercial floorspace construction has attracted a large number of economic activities, which has further improved the accessibility of household transportation in the region

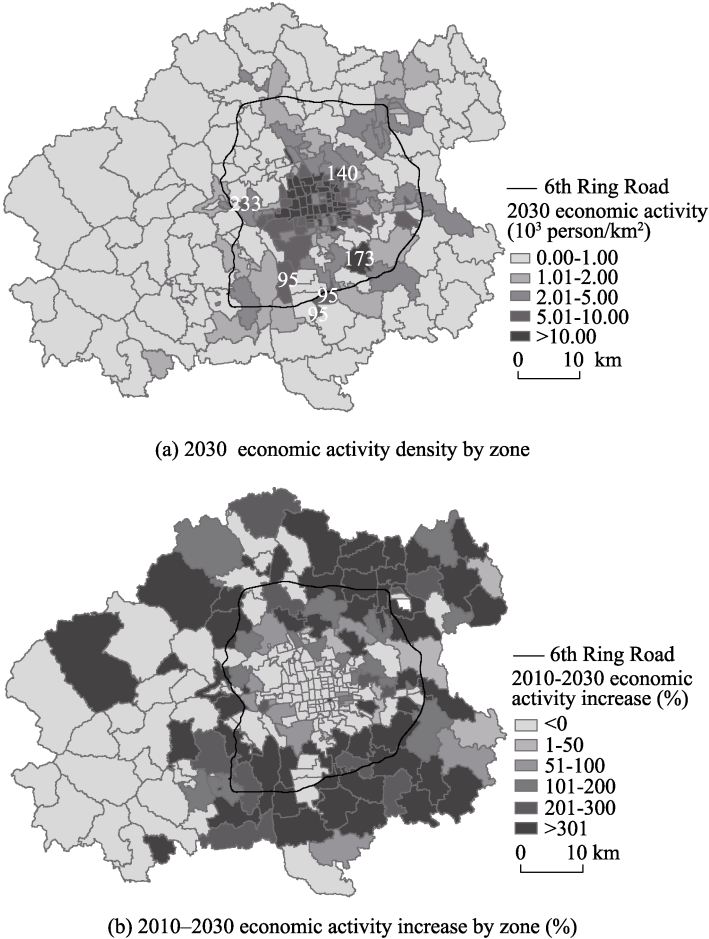
According to Figure 4b, it can be concluded that the areas with relatively rapid population growth are mostly located along the Sixth Ring Road and between the Fifth and Sixth Ring Roads. And the growth is significantly higher than the surrounding areas, e.g., Nanshao (89), Mapo (73), Houshayu (236), Beizang (92), Changyang (97), Liangxiang (98), and Yizhuang (173). According to the present land-use policy, these areas will gradually develop into sub-centers of the city. The distribution of these potential sub-centers is consistent with the current government's goal of developing a multi-center structure to ease traffic congestion. According to the simulation results, Yizhuang will gradually have more people agglomerated, and the economic activity simulation has a similar trend.

## (2) Economic activity distribution

Figure 5a shows the distribution pattern of economic activities in 2030. By 2030, most economic activities will still be in the main urban areas within the Fourth Ring Road. However, the distribution of economic activities in the periphery is mainly concentrated in areas around the main trunk traffic lines and areas with good accessibility. In addition to the main urban areas, there are relatively concentrated economic activities in the suburban areas, such as Yizhuang (173), Huangcun (95), Wangjing (140) and Jinding (233). In the context of land-use and development policy (see Figure 3), these zones have a high amount of property development, which leads to a decrease in rent and attracts more companies to move in. According to the predicted results, the density of economic activities in these areas is also significantly higher than that in the surrounding areas.

Figure 5b shows the growth model of economic activities in 2030. The figure shows that employment growth percentage of a large number of zones in central and southwestern parts is less than zero, indicating that economic activity in these areas will be lower in 2030 than in 2010. Compared with land-use policy, commercial floorspace development in these zones is less or none. And for other suburbs where there are more developments, the rent must de-

cline. The companies tend to zone with low rent so as to reduce the cost of location, which led to a rapid increase in employment activity in the suburbs. The simulation results are also consistent with the current planning objectives of evacuation economic activities in the main urban areas, which further proves the effectiveness of the model.



**Figure 5** 2030 economic activity distribution forecasted

Comparing the growth model of population (Figure 4b) with the growth model of economic activities (Figure 5b), we can find that the growth model of economic activities is more dispersed in space, and the growth rate in the suburbs is larger. It can be concluded that the location of enterprises is more sensitive to location cost (rent) driven by the market. With the development of commercial real estate in the surrounding areas, the rent will decrease, and a large number of companies will move to the suburbs to reduce their location costs. What can be predicted is that the migration of economic activities will further drive the migration of family population. In addition, in Figure 5b, it can be found that areas with high growth intensity of economic activities are mostly distributed on both sides of the Sixth Ring Road, which is similar to the commercial development model (Figure 3). It reflects that the government can guide the urban spatial distribution of economic activities through land-use policy, thereby indirectly control the spatial distribution pattern of urban economic activities.

## 5 Discussion

### 5.1 Validity and usefulness

In the calibration process, the coefficient is adjusted according to the comparison of the predicted and observed values (actual values). Apart from the year 2010, the other years do not have detailed *Jiedao* scale population data, but the rent plays a crucial role in the model, so the rent data is used to verify the simulation results of the model. In each test, the coefficient is adjusted according to the difference between the predicted rent and the observed rent. For example, if the predicted value of rent in all zones is larger than the observed value, and the  $R$  test is less than 0.50, the coefficient of positive correlation with rent will be reduced by 0.5%, and vice versa. Other coefficient adjustments are similar, until the predicted value is close to the actual observed value. In comparison of the predicted value of 2014 with the actual observed value, the correlation ( $R^2$ ) was 0.7.

This paper predicts urban space changes according to the law of the market, but the rent of the city, which is too high or too low, is not the result of market factors. Hence, all such data is excluded from the actual data in the process of pretreatment. This process enhances the correlation between the predicted value and the actual value.

We acknowledge that the SDA models are difficult to predict the future accurately, and we do not believe that there are models that can predict the future accurately. A city is a huge complex system. Its development process is affected by many factors, including unpredictable factors. Therefore, for the application of the model, the relative value of its simulation is more meaningful than the absolute value. The relative value includes two aspects. One is to compare different policy situations and find their differences. The other is to calculate the relative size of simulation values of different zones. These two points are very helpful to assist decision making. The hypothesis of the case study in this paper is that the past land-use policy will extend to the future, which is set for the application of the model and does not represent the official policy.

LUTI theory is considered to describe the law of urban space development (Simmonds and Feldman O, 2011; Brandi *et al.*, 2014; Liao and Wei, 2014). Therefore, modification and calibration to different degrees can be further applied to other cities under the framework of this model. Through more case application comparisons, the model can be improved step by step in variable selection and parameter setting. This study is helpful to further popularize and apply LUTI model in China, assist urban spatial decision-making, and enrich and develop the research contents of domestic urban sustainable development simulation and analysis discipline.

### 5.2 Limitations and development

Compared to the Lowry model, the SDA is a dynamic model. The SDA model allows the elements to change over time and to predict different years of urban space, but the SDA model is still a balance model, and iterative process of the model ultimately converge to a state of equilibrium. Some people believe that although urban space development tends to be balanced, it will never reach equilibrium due to the disconnection between supply and demand (Kryvobokov *et al.*, 2013). Therefore, the SDA model belongs to the “quasi-dynamic model”.

Location utility evaluation mainly considers traffic accessibility and location cost. However, there are many factors influencing the location selection of urban activities, such as household location selection, which is affected by family member structure, residential comfort and environment. Therefore, including a variety of factors is the future direction of development. This work will also face the problem of data acquisition, model algorithm will tend to be complex, running time will increase.

### 5.3 Optimization of transport model

Due to limited space, the case does not consider the traffic policy scenario. Traffic is the key factors influencing the urban socio-economic activity location, the change of traffic (such as the construction of roads or subway) certainly changes the accessibility of cities, especially accessibility along the way, and ultimately affects the spatial distribution of urban activities. According to the traffic sub models in the SDA model, the change of the traffic system will affect the cost of urban traffic and the traffic accessibility, and ultimately change the simulation results. Hence, the SDA model also can be used for transport policy test. Compared to the land use system, the urban traffic system changes more slowly, therefore, in the process of model operation, it does not need to run traffic model year by year, which only needs to operate in the year when the transportation system changes, such as the year when a highway opens.

The traffic model uses the speed of “car” to calculate the traffic time. On a more subtle level, city have different socio-economic groups, their travel corresponds to different traffic patterns, e.g., walking, cycling, public transport, driving etc., which led to their spatial distribution being different. Therefore, the implementation of multi-mode traffic simulation analysis is a problem faced by the SDA model. There are many researches and fierce competitions in the field of transportation, and there are a lot of mature traffic software, such as START and TRAM.

Traffic cost parameters in traffic accessibility evaluation of the SDA model ( $gc$ , see formula 1) provide interface with existing intelligent traffic models, which can use mature intelligent transportation model to evaluate the urban traffic. The integration with the intelligent traffic model will further enhance the function of this model.

### 5.4 Modeling changes in total urban activities and location

This paper uses the growth rate to calculate the total number of households. However, the change of the total number of households is affected by both the local population change and the floating population (moving in and out). In order to achieve a more accurate model, it is necessary to establish a population flow model to simulate the urban and external population flow, and a population change model to simulate the local household transit. The same problem is also in the economic activity. Influencing factors for location selection of local household relocation are different with those for migrant population, hence, the location model needs to explore the location choice of local population flow and the floating population respectively.

## 6 Conclusions

Based on the interaction theory of land use and transportation, the SDA model is constructed

to simulate the urban spatial evolution process. Taking Beijing as an example, based on the land development trend in recent years, the distribution pattern of population and economic activities in the future is predicted. The research shows that the SDA model can quantitatively predict the number of population and economic activities in each zone, which provides a good tool for the policy test of urban land use. The core work of this study is the construction and development of the SDA model. The SDA model mainly includes four sub-models: traffic sub-model, household location sub-model, economic activity location sub-model and rent forecast sub-model. The SDA model is based on the “active” LUTI model. The evaluation of location value based on “activity” model is based on various activity demands, such as a location for different households has different values, which differ from the physical location (e.g., the distance to the CBD). From the perspective of the development process of the model, the construction of active SDA model conforms to the new trend of LUTI model development (Wegener, 2004). As a preliminary exploration of the application of LUTI theory to Chinese cities, this study is conducive to promoting the development of LUTI model and its application in China, and enriching the research contents of urban space simulation analysis. The SDA model will also be improved gradually in the application.

## References

- Albouy D, Ehrlich G, 2014. Housing demand and expenditures: How rising rent levels affect behaviour and costs-of-living over space and time. NBER. Available at: <http://cba.unl.edu/academic-programs/departments/economics/about/seminar-series/documents/housingexpenditures.pdf> (accessed 14 March 2016).
- Brandi A, Gori S, Nigro M *et al.*, 2014. Development of an integrated transport-land use model for the activities relocation in urban areas. *Transportation Research Procedia*, 3: 374–383.
- Chen W, Liu W D, Ke W Q *et al.*, 2018. Understanding spatial structures and organizational patterns of city networks in China: A highway passenger flow perspective. *Journal of Geographical Sciences*, 28(4): 477–494.
- Chen Y M, Li S Y, Li X, 2010. Simulating compact urban form using cellular automata (CA) and multi-criteria evaluation: A case study in Dongguan. *Acta Scientiarum Naturalium Universitatis Sunyatseni*, 49(6): 110–114. (in Chinese)
- Cobb C W, Douglas P H, 1928. A theory of production. *American Economic Review*, 18(Suppl.): 139–165.
- Dai J C, Li X, 2009. Multi-agent systems for simulating traffic behaviors. *Chinese Science Bulletin*, 54(21): 3380–3389. (in Chinese)
- Dang Y X, Zhang W Z, Wu W J, 2010. Residents housing preferences and consuming behaviors in a transitional economy: New evidence from Beijing, China. *Progress in Geography*, 30(10): 1203–1209. (in Chinese)
- Ding C, Lichtenberg E, 2011. Land and urban economic growth in China. *Journal of Regional Science*, 51: 299–317.
- Dong G P, Zhang W Z, Wu W J *et al.*, 2011. Spatial heterogeneity in determinants of residential land price: Simulation and prediction. *Acta Geographica Sinica*, 66(6): 750–760. (in Chinese)
- Gao J, Wei Y D, Chen W *et al.*, 2014. Economic transition and urban land expansion in provincial China. *Habitat International*, 44: 461–473.
- Geurs K T, Wee B V, 2004. Land-use/transport interaction models as tools for sustainability impact assessment of transport investment: Review and research perspectives. *European Journal of Transport and Infrastructure Research*, 4(3): 333–355.
- Hansen W G, 1959. How accessibility shapes land use. *Journal of the American Institute of Planners*, 25: 73–76.
- Jing W, Jianzhong L, 2011. Study on the urban expansion and model of Lianyungang city based on the multi-temporal remote sensing images. *Procedia Environmental Sciences*, 10: 2159–2164.
- Kryvobokov M, Chesneau J B, Bonnafous A *et al.*, 2013. Comparison of static and dynamic land use-transport interaction models: Transportation research record. *Journal of the Transportation Research Board*, 2344(1):

- 49–58.
- Landis J, 2001. CUF, CUF II and CURBA: A family of spatially explicit urban growth and land-use policy simulation models. In: Brail R K, Klosterman R E eds. *Planning Support Systems: Integrating Geographic Information Systems, Models and Visualization Tools*. Redlands, CA: ESRI Press.
- Li X, Ye J A, Liu X P *et al.*, 2007. *Geographical Simulation Systems: CA and MAS*. Beijing: Science Press. (in Chinese)
- Liao F H F, Wei Y H D, 2014. Modeling determinants of urban growth in Dongguan, China: A spatial logistic approach. *Stochastic Environmental Research and Risk Assessment*, 28(4): 801–816.
- Liu X P, Li X, Chen Y M *et al.*, 2010. Agent-based model of residential location. *Acta Geographica Sinica*, 65(6): 695–707. (in Chinese)
- Long Y, Han H Y, Mao Q Z, 2009. Establishing urban growth boundaries using constrained CA. *Acta Geographica Sinica*, 64(8): 999–1008. (in Chinese)
- Long Y, Mao Q Z, Dang A R, 2009. Beijing urban development model: Urban growth analysis and simulation. *Tsinghua Science and Technology*, 14(6): 787–794. (in Chinese)
- Long Y, Mao Q Z, Yang D F, 2011. A multi-agent model for urban form: Transportation energy consumption and environmental impact integrated simulation. *Acta Geographica Sinica*, 66(8): 1033–1044. (in Chinese)
- Lowry I S. A Model of Metropolis RM-4035-RC. Santa Monica CA: Rand Corp, 1964.
- Mumtaz B, 1995. Meeting the demand for housing, a model for establishing affordability parameters. The Bartlett Development Planning Unit. Available at: [www.ucl.ac.uk/silva/bartlett/dpu/publications/dpu-paper-73](http://www.ucl.ac.uk/silva/bartlett/dpu/publications/dpu-paper-73) (accessed 14 March 2016).
- Niu F Q, 2017. Overview of urban land-use/transport interaction model: Origin, techniques and future. *Scientia Geographica Sinica*, 37(1): 46–54. (in Chinese)
- Niu F Q, Li J, 2017. An activity-based integrated land-use transport model for urban spatial distribution simulation. *Environment and Planning B: Urban Analytics and City Sciences*, 6: 1–14.
- Niu F Q, Liu W D, 2017. Modeling urban housing price: The perspective of household activity demand. *Journal of Geographical Sciences*, 27(5): 619–630.
- Niu F Q, Wang Z Q, Hu Y *et al.*, 2015. A model of urban spatial evolution process based on economic and social activities. *Progress in Geography*, 34(1): 30–37. (in Chinese)
- Pierluci C, Angel I, Luigi D *et al.*, 2013. LUTI model for the metropolitan area of Santander. *Urban Planning and Development*, 139(3): 153–165.
- Ryan P P, Txomin H, Nicholas C C *et al.*, 2015. Remote sensing and object-based techniques for mapping fine-scale industrial disturbances. *International Journal of Applied Earth Observation and Geoinformation*, 34: 51–57.
- Shan Y H, Zhu X Y, 2011. Multi-agents model for simulation of urban residential space evolution. *Progress in Geography*, 30(8): 956–966. (in Chinese)
- Shen Z J, 2011. Simulating spatial market share patterns for impacts analysis of large-scale shopping centre on downtown revitalization. *Environment and Planning B: Planning and Design*, 38(1): 142–162.
- Simmonds D, Feldman O, 2011. Alternative approaches to spatial modelling. *Research in Transportation Economics*, 31(1): 2–11.
- Torrens P M, 2000. *How land-use transportation models work*. London: Centre for Advanced Spatial Analysis.
- Wang H, He S, Xingjian L *et al.*, 2013. Simulating urban expansion using a cloud-based cellular automata model: A case study of Jiangxia, Wuhan, China. *Landscape and Urban Planning*, 110: 99–112.
- Wegener M, 2004. Overview of land-use transport models. In: Hensher D A, Button K eds. *Transport Geography and Spatial Systems*. Oxford: Elsevier, 127–146.
- Wei Y H D, 2012. Restructuring for growth in urban China: Transitional institutions, urban development, and spatial transformation. *Habitat International*, 36: 396–405.
- Wu S K, Li X, Liu X P, 2008. GeoCA based dynamic site selection model: Shenzhen city as a case study. *Scientia Geographica Sinica*, 28(3): 314–319. (in Chinese)
- Xue L, Yang K Z, 2002. Sciences of complexity and studies of evolutionary simulation of regional spatial structure. *Geographical Research*, 21(1): 79–88. (in Chinese)
- Yang Q S, Li X, 2009. Agent-based micro-simulation of urban industrial spatial evolution. *Scientia Geographica Sinica*, 29(4): 515–522. (in Chinese)
- Zhang T, 2000. Land market forces and government's role in sprawl: The case of China. *Cities*, 17: 123–135.