

Simulation of urban affordable housing land-use evolution based on CA-MAS model

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Abstract: In order to simulate the evolution of affordable housing land use, a dynamic model that combines cellular automata (CA) and a multi-agent system (MAS) is established. This paper aims to utilize the approach of decision factors on site selection of affordable housing through a literature review to construct a hierarchy model of those factors, identifying the weight of each factor by an analytic hierarchy process (AHP). Based on those weight factors, the CA-MAS model is designed. Nanjing city is taken as an example to verify the feasibility of the model. The results show that the CA-MAS model is pragmatic and effective in simulating evolution of affordable housing land use, which also promotes the fundamental understanding and perception of the development of affordable housing and urbanization.

Key words: affordable housing; land use; CA-MAS model; simulation

doi: 10. 3969/j. issn. 1003 – 7985. 2014. 04. 022

The housing issue is a grave concern because it is directly related to the livelihoods of the citizens^[1]. In order to meet basic needs of low-income families and adapt to the urgent social demand, many districts in China have been built with affordable housing on a large scale. The reasonable evolution of urban land is an adaptive adjustment of urban system functions, which promotes the healthy development of the city and enhances its competitiveness. Therefore, the establishment of the dynamic model simulating affordable housing land use is of theoretical and practical significance to understand urbanization, especially the basic rules of land-use changes.

The evolution of affordable housing land is influenced not only by natural and social factors, but also by the underlying driving stimulus of the government and low-income residents' demand. This paper analyzes the social and natural factors that influence the CA model, followed

by a dynamic model with the characteristics of the decision-maker and low-income residents' demand developed in the MAS model. The CA-MAS model plays a critical role in understanding the development of affordable housing and urbanization.

As representatives of simulating land-use evolution, the CA and MAS models have been widely used in the research domestically and abroad^[2]. Since the CA model is of discrete dynamical systems^[3], which are particularly suitable for the research of the geographic system with complex spatial and temporal characteristics.

However, as the CA model is incapable of simulating the effect of different participators and decision makers, the MAS has been introduced. Liu et al.^[4-6] treated agents that influenced urban expansion as the research objects, so as to simulate the process of land-use evolution.

1 Construction Methods of CA-MAS Model

1.1 Construction methods

This paper integrates the CA and MAS models to simulate the evolution of affordable housing land. As shown in Fig. 1, the CA-MAS model contains an environment-related factors layer, several mobile MAS layers and an immovable CA layer.

The environment-related factors layer refers to the natural environment, which dominates macro control; the MAS layers include the government and residents; the CA layer restrains the model from the angle of individual cells and their neighborhoods, thus to gain a comprehensive effect.

Besides, the environment-related factors layer is defined as the constraints of the entire CA-MAS model. The CA layer defines the social factors that influence land conversion, and the MAS layers define the government and residents' driving effect. Along with some random interference factors, a total conversion rate P_{ij} can be obtained ultimately. This rate determines the probability that a grid transforms from other land types to the affordable housing land. P_{ij} consists of five parts: p_{ca} , $p_{resident}$, p_{plan} , $p_{constraint}$, p_{random} , as shown in Fig. 1. Compared with a preset threshold $P_{threshold}$, if $P_{ij} > P_{threshold}$, the land cellular can be converted into affordable housing land; otherwise, the land cellular will maintain its original state.

Received 2014-05-13.

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Foundation items: The National Social Science Foundation of China (No. 14AJY013), the Scientific Innovation Research of College Graduates in Jiangsu Province (No. CXLX13_126).

Citation: Zhang Jiankun, Wang Yuanyuan, Wang Xiaorong, et al. Simulation of urban affordable housing land-use evolution based on CA-MAS model[J]. Journal of Southeast University (English Edition), 2014, 30(4): 531 – 536. [doi: 10. 3969/j. issn. 1003 – 7985. 2014. 04. 022]

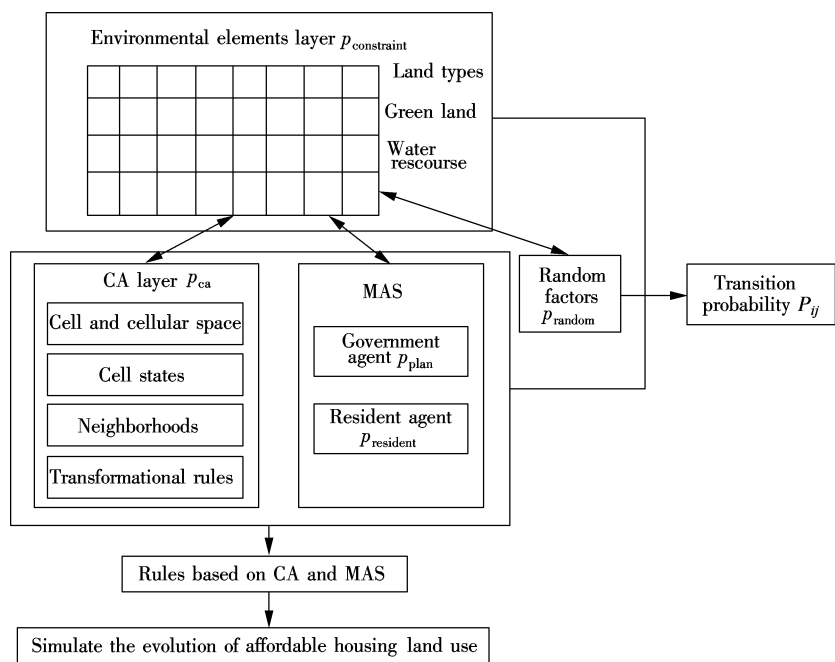


Fig. 1 Construction methods of CA-MAS model

1.2 Analysis of affordable housing land driving factors

The driving factors of affordable housing land’s evolution are broadly in line with common residential land. The difference is the particularity of the guaranteed people and the land acquisition. In current studies, the factors affecting the evolution of affordable housing land mainly include: land types, land prices, transportation, infrastructure, environment, education, as shown in Tab. 1.

Tab. 1 Factors of affordable housing land evolution

Reference	Type	Transportation	Price	Infrastructure	Environment	Education
Ref. [7]	✓	✓				
Ref. [8]	✓	✓	✓	✓	✓	
Ref. [9]	✓	✓	✓	✓	✓	✓
Ref. [10]	✓	✓				
Ref. [11]	✓	✓	✓	✓	✓	
Ref. [12]	✓	✓				
Ref. [13]		✓		✓	✓	✓
Ref. [14]	✓	✓	✓	✓	✓	✓
Ref. [6]	✓	✓	✓	✓	✓	✓

1.3 CA layer based on binary logistic regression

The CA consists of five fundamental elements: cell, cellular space, neighbors, transformational rules, and time, as shown in Fig. 2. The core of the CA is that the transformational rules determine the state of the cell; i. e., the state of cell in time $t + 1$ is determined by the state of cell in time t and its neighborhoods’ state^[15].

1) Cell and cellular space

Cellular space, as the discrete grid of the research area and a single cell, which represents a plot of the research

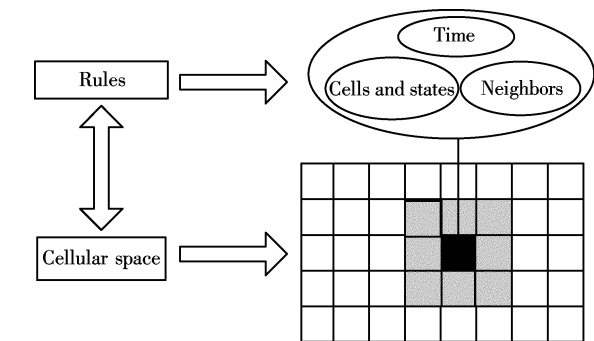


Fig. 2 Constitution of CA

area, is an individual unit of the discrete grid. This paper divides the research area into several squares of side length 30 m. In other words, it means that each cell represents a piece of $30 \times 30 = 900 \text{ m}^2$ land within the research area.

2) Cell states

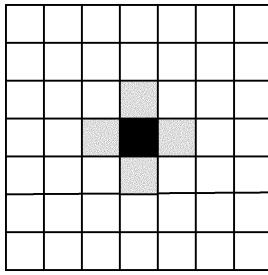
All the cells of the cellular space have merely two states, namely “can be converted into affordable housing land” and “ cannot be converted into affordable housing land” two states. Thus, the state set is defined as $S = \{\text{affordable housing land; other types}\}$, expressed as $S = \{1, 0\}$.

3) Neighbourhoods

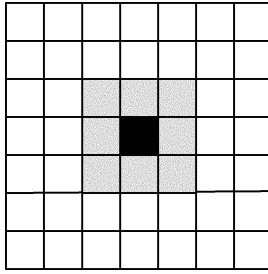
In the CA model, the next moment state of a cell is determined by the state of itself and its neighboring cell state. So the neighbors of the cells must be defined before determining the transformation rules. In fact, the cellular space is the network of $m \times n$, as shown in Fig. 3.

This model uses the extended Moore type, and the neighborhood radius $r=2$. That is to say, a cell’s neighboring space is a 5×5 grid which centers on itself. The

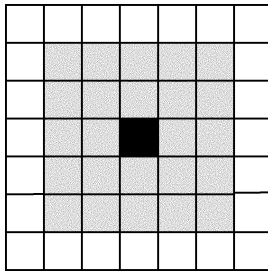
number of neighboring cells is $5 \times 5 - 1 = 24$.



(a)



(b)



(c)

Fig. 3 Types of cellular automata neighborhoods. (a) Four neighborhoods; (b) Eight neighborhoods; (c) Extended Moore type

4) Transformational rule

The core part of the CA is to define the transformational rules, which control the whole simulation process in the CA model. In this model, all the cells of the cellular space have only two states, namely “can be converted into affordable housing land” and “cannot be converted into affordable housing land”. Therefore, the transformational rule is defined as a binary logistic regression method, which will be used to analyze the social factors that influence affordable housing land evolution (see Tab. 2), and the coefficients of variables can be obtained.

Tab. 2 Social influencing factors and their corresponding variables

Influencing factors	Types	Variables
Distance to city centers	Social factor	Discenter x_1
Distance to highways	Social factor	Disroad x_2
Distance to railways	Social factor	Disrail x_3
Distance to airports	Social factor	Disairport x_4
Distance to resident	Social factor	Disresident x_5

Cellular samples are selected randomly from two periods (T_1 and T_2) of historical data, and the variation of

their state are recorded. If a land cell changes, it means that the cell has been converted into affordable housing land, and then the transition probability is 1; otherwise, the cell keeps its original state, and then the transition probability is 0. The research data regression is

$$p_{ca} = \frac{1}{1 + \exp[-(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5)]}$$

Through the regression of empirical data in order to obtain the weights of factors and establish reliable transformational rules, the conversion probability p_{ca} of each grid in the CA model can be obtained^[15].

1.4 MAS layer

1) The government agent

The implementation of a government agent’s willingness is achieved through urban planning. In the course of affordable housing land conversion, the function of government planning is stronger than that of residents’ demand. It is assumed that the planning of N (generally for 3 to 5) years later is developed according to the present data, and then the changes of each cell are influenced by planning are as follows:

$$S_{\text{change}} = P_{ij}^{T_2} - S_{ij}^{T_1}$$

where i and j are the abscissa and ordinate value; $P_{ij}^{T_2}$ is the planning state of the cell and $S_{ij}^{T_1}$ is the present state of the cell. The conversion probability caused by government planning is as follows:

$$\text{If } S_{\text{change}} = 1, P_{\text{plan}}^{i,j} = 1.$$

$$\text{If } S_{\text{change}} = 0, P_{\text{plan}}^{i,j} = 0.$$

2) The resident agent

The resident agents are individuals who have the ability to think and behave independently while seeking better residential conditions. Transportation accessibility, public facilities and good environment quality are the conditions aimed for the selection of an urban residential location.

Transportation accessibility reflects the extent of traffic convenience, which can be evaluated by the distance to subways, bus stops, etc. In the model, the index of the distance decay function is adopted to express their spatial appeal to the location^[11]:

$$E_{\text{traffic}} = a_1 A_1 e^{-B_1 D_{\text{subway}}} + a_2 A_2 e^{-B_2 D_{\text{bus}}}$$

where E_{traffic} is the index of transportation accessibility; a_1 and a_2 are the weights of the corresponding distance; A_1 and A_2 are the strength coefficients of the corresponding distance; B_1 and B_2 are the attenuation coefficients of the corresponding distance; D_{subway} and D_{bus} are the distances to the subway and bus stops, respectively.

The public facilities’ evaluation factors include distance to hospitals, schools, libraries, recreational facilities, parks, commercial centers (i. e. infrastructure and education resources in Tab. 2), and the spatial attraction of all

above is expressed by the index distance decay function.

Environmental quality is evaluated by the per capita green area and the distance from water. The per capita green area is expressed by the ratio of the number of green spaces grid within a 5×5 neighboring window to the number of the residential land's grid:

$$E_{\text{green}} = \frac{N(G(L_{ij}))}{N(H(L_{ij}))}$$

where E_{green} is the evaluation of green land; L_{ij} is a grid of the two-dimensional space; $N(G(L_{ij}))$ is the number of the green land's grid centered with L_{ij} ; $N(H(L_{ij}))$ is the number of the residential land's grid centered with L_{ij} . The influence of water on the environmental quality can also be expressed by the distance decay function as below:

$$E_{\text{environment}} = C_1 E_{\text{green}} + C_2 A_3 e^{-B_3 D_{\text{water}}}$$

where $E_{\text{environment}}$ is the index of the environmental quality; C_1 and C_2 are the weights of green land and water; A_3 is the strength coefficient of the water; B_3 is the attenuation coefficient of the water; D_{water} is the distance to water.

Based on the assumption that residents pursue maximal utility, this paper studies the resident agent behavior on the choice of residential location with the random utility model and the discrete choice model.

First, according to the random utility model, the utility of the optional location I to the resident agent n is expressed as

$$U_{in} = \partial E_{\text{traffic}} + \beta E_{\text{convenience}} + \gamma E_{\text{environment}} + \varepsilon_{in}$$

where $\partial + \beta + \gamma = 1$, and ∂, β, γ represent, respectively, the resident agent n preference coefficient for each influencing factor; E_{traffic} , $E_{\text{convenience}}$ and $E_{\text{environment}}$ represent the transportation accessibility, convenience of facilities and environmental quality, respectively. Then the values of ∂, β, γ are obtained by the Delphi method and AHP.

Finally, based on the discrete choice model, the probability of the resident agent n randomly choosing his housing location at i is equal to the probability that the utility (attraction) of i for the resident agent n is not less than the utility of any other alternative i' ; namely,

$$P_{i,n} = P_r(U_{i,n} \geq U_{i',n}) = \frac{\exp(U_{i,n})}{\sum \exp(U_{i,n})}$$

$$i = 1, 2, \dots, I; i \neq i'; n = 1, 2, \dots, N$$

The summation of resident selection probability for some certain location is

$$P_{\text{resident}} = \sum P_{i,n}$$

1.5 Random factors

The conversion of land is also affected by the random factors and accidental events. To make the calculation re-

sult conform to reality and reflect the uncertainty existing in the city system, the influence of the random factor is added to the model. The item can be expressed as

$$P_{\text{random}} = 1 + (-\lg \gamma)^\partial$$

In the formula, γ is a random number in $(0, 1)$; ∂ is a parameter that controls the influence of the random variable, and its value ranging from 1 to 10 is the number of the integer. The greater the value of ∂ , the greater the influence of the random variable in the model, the smaller the vice. Conversely, it becomes less important.

1.6 Probability expression

Synthesizing the CA model and the MAS model, the conversion probability of cell(i, j) at the time of t is expressed as

$$P_{ij} = (ap_{\text{resident}} + bp_{\text{plan}})p_{\text{ca}}p_{\text{random}}$$

where a and b are the weights of p_{resident} and p_{plan} , respectively, and they are obtained by AHP.

2 Empirical Analysis

2.1 General situation of the study area

The urban district of Nanjing is divided into eight areas, which are the Qixia district, Xuanwu district, Xiaguan district, Gulou district, Baixia district, Qinhuai district, Jianye district and Yuhuatai district, respectively.

In 1990, Nanjing started to construct anti-poverty housing as planned. Until 1995, 1×10^6 m² of anti-poverty housing has been built. From 1995 to 1998, the comfortable housing was brought under construction with the purpose to aid the settling down of families in poverty, relocate households and be part of the teaching faculty. Economical affordable housing was built from 1998 thereafter. The centralization security housing has been massively increased since 2011. Until now, the total construction area of security housing was approximately 28.64×10^6 m² covering the whole of Nanjing.

2.2 Regression results in cellular automata

In the CA model, after the logistic regression analysis on the factors in Tab.3 by the SPSS, it can be seen that the confidence level of each regression coefficient is greater than 95% (i.e., $\alpha \leq 0.05$), and all of them, except for Discenter can be incorporated into the regression equation. The historical data of affordable housing land in 2008 and 2012 have been selected.

According to the regression results in Tab.3, it can be seen that the regression coefficients of Disroad and Disairport are positive, indicating that the land is far away from the road and the airport. It can be more easily converted into affordable housing, which is in line with reality. In

general, the location of affordable housing is remote. Although there are some positive elements being close to the airport, noise pollution is still a cause of possible disturbance. Therefore, to a certain extent, the expansion of affordable housing land has a positive correlation with the distance from the airport. The regression coefficients of Disrail is negative, indicating that the land closer to railways is converted into affordable housing land with more difficulty and that they are quite consistent with the fact.

Tab. 3 Binary logistic regression of influencing factors of CA

Variables	Explanation	Regression coefficient
Disroad	Distance to highways	4.414
Disrail	Distance to railways	-0.638
Disairport	Distance to airports	0.175
Neighbor		0.150
Constant		-11.053

2.3 MAS

1) Resident agent

Based on experts' evaluations, the influencing factors when choosing residential location are determined by the Delphi method, then the obtaining factors' weights by AHP. The results are shown in Tab. 4.

Tab. 4 Resident agent's preference weights for location

Influencing factors	Traffic convenience	Public facilities	Environmental quality
Weight	0.43	0.41	0.16

2) Government agent

The function of the government agent mainly concerns decision-making; thus, the government in housing location planning decides directly affordable housing land supply and location. So the implementation of the model is mainly as follows: comparing current land-use data and planning data in 2012, if a cell's state changes, p_{plan} is 1; otherwise, p_{plan} is 0.

2.4 Analysis of simulation results

The simulation results show that affordable housing land use in Nanjing is mainly distributed in the Qixia, Xiaguan and Yuhua districts, which is basically in line with the actual situation (see Fig. 4). In addition, two basic features can be found in the spatial layout: remote location and relatively concentrated distribution. The location remoteness contributes to the lack of infrastructure in the surroundings and expensive transportation costs, while concentrated distribution may lead to residential space differentiation, which risks the building of large scale centralized affordable housing settlements. These all indicate that it is necessary to fully consider the construc-

tion and feasibility of surrounding facilities when planning affordable housing project addresses, thus ensuring that low-income groups live and work in harmonious environments.

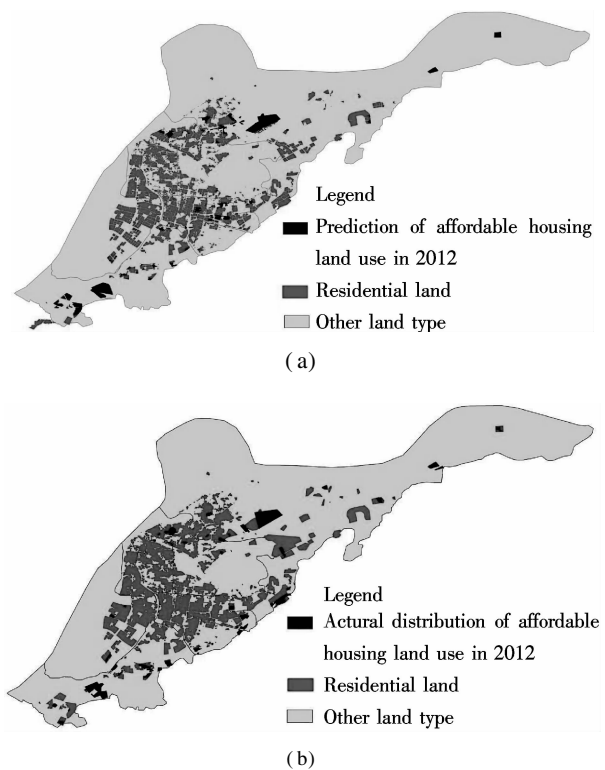


Fig. 4 Affordable housing land-use of Nanjing's urban district in 2012. (a) Simulation; (b) Actual situation

3 Conclusion

Based on the combination of CA and MAS, a dynamic model of urban land utilization is constructed. By reviewing former research, factors influencing the conversion of affordable housing land utilization are obtained. In the MAS layer, the government and the residents are chosen as two of the most crucial decision-makers influencing the conversion of affordable housing land utilization. Finally, the integration of the CA and MAS models is established, not only taking advantage of the characteristics of holistic transformation generated by self-organized developed regulation law, but also critical decisions are made based on the choices of the resident agent and macro control of the government agent. However, final choices will be made according to the synthesized consideration of the probability of two models. Empirical studies suggest that this dynamic model accurately simulates the evolution status of affordable housing land utilization, providing a decision-making basis for the location of affordable housing and a scientific development of cities.

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基于 CA-MAS 模型的城市保障房用地演变模拟

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摘要: 为了模拟保障房用地的演变过程, 建立了元胞自动机(CA)和多智能体(MAS)相结合模型。通过文献综述法, 对保障房选址的决策因素进行梳理, 构建关于保障房选址决策因素的层次结构模型, 运用层次分析法(AHP)得出各层次因素的权重; 基于各因素及其权重, 建立 CA 和 MAS 相结合的模型; 最后, 以南京市主城区为例, 验证模型的可行性。结果表明: CA-MAS 模型能够对保障房建设用地进行有效的演化模拟, 对于认识、理解保障房的发展和城市化进程具有重要的理论和实践意义。

关键词: 保障性住房; 土地利用; CA-MAS 模型; 模拟

中图分类号: P208