Complex constrained CA urban model: Long-term urban form prediction for Beijing metropolitan area

1 Introduction

With the development of GIS and complex adaptive system, the urban model, based on artificial life or discrete dynamics, is dominating relevant academic researches. In recent years, it is prevailing to simulate urban growth by means of cellular automata (CA in short), which is based on self-organizing theory and different from the system dynamic type models.

Distinguished from pure CA, the CA model applied for urban growth simulation should not only consider neighborhood influence, but other factors with respect to urban developing, since urban system is definitely quite complex. Generally, the status transition rule except neighborhood is defined as the term of constraint of constrained condition (White, 1997). Some researchers are inclined to control the urban growth simulation via introducing constrained conditions to CA model. In SLEUTH model, exclusive layer is set to constrain urban growth (Clark and Gaydos, 1998); White *et al* (1997) initiated the concept of constrained CA, in which suitability (spatial constraint) is considered; Engelen *et al* (1997) takes macro socio-economic constraint into account in the urban planning support system integrating CA, GIS and other decision support toolkit; In Simland model using CA by Wu (1998), variable *con* is set to signify the constraints for land development; The urban model by Ward *et al* (1999, 2000) employs physical constraint, geographic constraints and institutional controls, in addition to macro socio-economic constraint; Li and Yeh classify the constraints into three types, local, regional and global, in their constrained CA model (Li and Yeh, 2000; Yeh and Li, 2001); David *et al* (2000) integrates macro socio-economic as global constraint in the CA urban model; White *et al* (2004) employs not only macro constraint, but also physical characteristics, accessibility and zoning as constrained conditions; Alkheder and Shan (2005) regard rivers and lakes as urban growth constraints, similar with exclusive layer in SLEUTH; In Guan *et al* (2005)'s urban model using CA and artificial neural network (ANN), macro socio-economic and institutional constraints are introduced; Zhao and Murayama (2007) develop urban growth model using CA for Tokyo metropolitan area, in which suitability, zoning status and accessibility are included as constrained conditions; Liu *et al* (2007) develop CA model basing on niche, and apply to simulate the sustainable land developing of Guangzhou considering macro constraint and spatial constraints.

Generally speaking, the constrained conditions in CA urban model could be classified into three types, macro socio-economic constrained condition, spatial constrained condition and institutional constrained condition. Regarding macro socio-economic constraint, it stands for the macro level constrained factors, such as urban economy development and population control, which is used to control the amount of urban built-up land in simulation. With respect to spatial constrained constraint, it indicates the location condition, such as the accessibility of high dense residential area or public facility; the institutional constraint represents the government policies of urban planning, zoning, natural protected area, etc. Among the constraints in current CA urban model, it is not obvious for one model simultaneously considering all the three types of constraints. Especially, less attention is paid to institutional constraint by existing CA model, and institutional constrained condition is often set over simple even if it is included in some models. Furthermore, on one hand, the role of institutional conditions in the historical urban growth is not identified, thus calibrating the model in an over subjective process without identifying the historical trends. On the other hand, various specific institutional policies can not be simulated in detail, for the reason of lacking particular in the simplified institutional constraint setting of already developed urban model using CA.

Accordingly, we bring forward the term of complex constrained CA (CC-CA in short), which integrates the constrained conditions of macro socio-economic, spatial and institutional. Particularly, constructing constrained zoning planning, as one institutional constrained condition, is considered in CC-CA model. The planning is generated by 110 constructing constrained factors (CCFs in short) relevant with natural resources protection and hazard prevention, signifying the constrained degree for urban developing (Long *et al*, 2006). Without taking above 110 CCFs into account during urban growth management, not only the natural protected area will be encroached in some degree, but environmental hazard will be confronted. Supported by CC-CA model, the role of constrained conditions in urban growth can be identified and compared between various historical phases, thus providing possibility to simulate urban form influenced by different constraints. In section 2, the conceptual model of complex constrained CA model is introduced together with the form of transition rule. In section 3, the CC-CA model for Beijing is developed, and we discuss the complex constrained conditions in Beijing. Furthermore, in section 4, we show how to set institutional constraints in planning controlled scenario to control the urban growth pattern of Beijing. Finally, the paper is summarized, followed by further research on CC-CA model in the last section.

2 Research approach

2.1 Conceptual model

Hedonic price model provides a study framework on the assumption that commodity price is determined by the total utility of its different properties, and price differs with various numbers and composition of commodity's properties (Lancaster, 1966). For example, Butler (1982) holds that residential price is affected by three types of factors, location, architecture structure and neighborhood, and its price reflects the total preferences by the consumer. With the same logic, urban development is quite familiar with real estate price, and its probability is the reflection of relevant parameters of the lot or block by developer. Hence, we choose spatial variables in CC-CA model as shown below.

(1) LOCATION type (Spatial constrained conditions): the minimum distance to urban or town centers of different hierarchic administration (main city, namely tiananmen square, *d_tam*, important new city *d_vcity*, new city *d_city,* important town *d_vto*wn, town *d_town*), to wetland *d_river*, to regional road *d_road*, to township division *d_bdtown*, and the attracting force by Greater Beijing area *f_rgn*;

(2) NEIGHBOR type (Spatial constrained condition): developing intensity in the neighborhood *neighbor* (number of urban built-up cells divided by total neighbor cells);

(3) GOVERNMENT type (Institutional constrained conditions): urban planning condition *planning*、suitability for cultivation *landresource*、constructing constrained zoning *con_f*.

Among above spatial variables in CC-CA model, LOCATION and NEIGHBOR types variables are both spatial constrained conditions, and GOVERNMENT type variables stand for institutional constrained conditions, in which *planning* indicates the land use scheme in urban master planning, signifying the land developing and urban morphology control policy of the government. *landresource* denotes the suitability for cultivation, and can be applied as the cropland protecting policy of the government. With respect to *con_f*, it stands for the constructing constrained factors counteracting urban growth, and provides possibility to simulate natural resources protecting and environmental hazard preventing policies by the government. Generally, the institutional constrained conditions, including *planning*, *landresource* and *con*_f, are and will be effective and efficient measures for the government to control urban growth.

Moreover, macro socio-economic constrained conditions are included in CC-CA conceptual model. In respect that population control, economic developing having great influence on urban growth speed, the urban growth speed can be reflected by some macro parameters, such as GDP, urban population, average urban salary, communication cost, cropland product, industrial land area, etc., and through adjusting macro level urban policies, urban growth speed and amount is possible to be altered to control the urban growth pattern.

With the above analysis, Concept model of CC-CA using CA is established (Shown in formula 1). Generally, the status of one cell is determined by itself status in the last iteration, neighbor cells, macro socio-economic, spatial and institutional constrained conditions. In CC-CA model, the transition from urban non built-up to urban built-up is simulated, while the reversed process, urban redevelopment process, is not considered.

$$
\begin{aligned}
V_{i,j}^{t+1} &= f\left\{V_{i,j}^{t}, Global, Local\right\} \\
&= \left\{V_{i,j}^{t}, LOCATION, GOVERNMENT, NEIGHBOR\right\} \\
&= f\left\{\begin{array}{l}
V_{i,j}^{t}, \\
d\_tam_{i,j}, d\_vcity_{i,j}, d\_city_{i,j}, d\_vtown_{i,j}, d\_town_{i,j}, \\
d\_river_{i,j}, r\_road_{i,j}, d\_bdtown_{i,j}, f\_rgn_{i,j}, \\
planning_{i,j}, con\_f_{i,j}, landresource_{i,j}, \\
neighbor^{t}_{i,j}
\end{array}\right\} \qquad (1)
\end{aligned}
$$

$V_{i,j}^{t}$ is the cell status at ij of time t

$V_{i,j}^{t+1}$ is of the cell status at ij of time t+1

f is the transition rule

2.2 Complex constrained conditions in status transition rule

MCE is implemented to establish the status transition rule of CC-CA model. MCE formatted transition rule has the capability to transparently include urban growth promoting and control factors within one framework. We integrate the methods of Wu (2002) and Clark and Gaydos (1998), with each advantage, to retrieve the weights in transition rule (Shown in formula 2).

$$
\begin{aligned}
& s_{ij}{}^{t} = \beta_0 \\
& +\beta_1 * d\_tam_{ij} + \beta_2 * d\_vcity_{ij} + \beta_3 * d\_city_{ij} + \beta_4 * d\_vtown_{ij} + \beta_5 * d\_town_{ij} \\
& +\beta_6 * d\_river_{ij} + \beta_7 * r\_road_{ij} + \beta_8 * d\_bdtown_{ij} + \beta_9 * f\_rgn_{ij} \\
& +\beta_{10} * planning_{ij} + \beta_{11} * con\_f_{ij} + \beta_{12} * landresource_{ij} \\
& +\beta_{13} * neighbor^{t}{}_{ij} \\
& p_g{}^{t} = \frac{1}{1+e^{-s_{ij}{}^{t}}} \\
& p_{ij}{}^{t} = \exp\left[\alpha\left(\frac{p_g{}^{t}}{p_g{}^{t}{}_{\max}} - 1\right)\right] \\
& if\ \ p_{ij}{}^{t} > p_{threshold}\ then\, V_{ij}{}^{t+1} = 1
\end{aligned}
\tag{2}
$$

In formula 2, s_{ij}^t stands for developing suitability, β, coefficients in logistic regression, p_g^t, initial transition probability, $p_g{}^t{}_{max}$, the max value of p_g^t in iteration t, p_{ij}^t, final transition probability, $p_{threshold}$, urban growth threshold, and α stands for dispersion parameter ranging from 1 to 10, indicating the rigid level for developing.

In CC-CA model, all the spatial variables, except *neighbor*, are included in the logistic regression, and the corresponding coefficients, namely weights w^{1-12} in MCE, can be obtained. After that, the weight for variable neighbor (*wN**) can be calibrated out, by using sole parameter looping method (**MonoLoop**), instead of looping all parameters' weights like Clark and Gaydos (1998). Various *wN* values are calibrated to find *wN** with the best matching index while keeping obtained w^{1-12} constant. Then, *wN** retrieved accomplishing with w^{1-12} are inputted in the transition rule to simulate urban growth form. *Goodness-of-fit* (accuracy of point to point comparing, *GOF* in short) is selected to assess the matching degree between simulated and observed urban forms, and its maximum value in theory is 100%. For one thing, our method combining logistic regression and MonoLoop can reduce model calibrating time greatly. For another thing, the method is able to identify actual historical urban growth trend, including neighbor and constraints influences. [1]

3 Model Application

3.1 Study area

Under the background of the boom of domestic macro-economy and Olympic economy, it is in great need of identifying the future urban form. Hence, we develop CC-CA model for Beijing metropolitan area, with an area of 16410 km^2, and its spatial resolution is 500m. We develop the model using ESRI ArcObjects 9.0 and Visual Basic 6.0, and the model is attempting to simulate urban growth scenarios by various complex constrained conditions.

The study area lies in north China, to the east of Shanxi altiplano and to the south of Inner Mongolia altiplano. The southeastern part of study area is plain, with a distance to Bohai sea 150 km (Fig. 1). It is covered by mountainous area with an area of 10072 km^2, 61% of the whole area. GDP in 2006 is 787 billions, total population 15.81 million, and urban built-up area 1324 km^2.

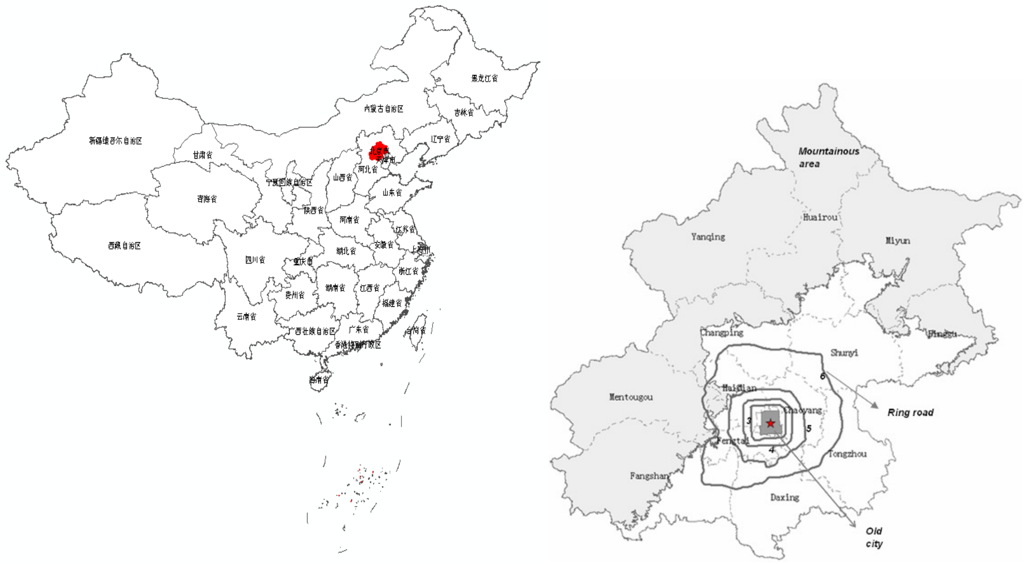

Fig. 1. Study area of CC-CA model

3.2 Complex constrained data

We classify spatial data in CC-CA model into six types, LANDUSE, CONSTRAIN, LANDRESOURCE, PLANNING, LOCATION, as well as SOCIO-ECONOMIC.

(1)LANDUSE

The time points of LANDUSE cover the years of 1986, 1991, 1996, 2001 and 2006, and the data is classified into six land use types, urban built-up area, rural built-up area, agriculture area, forest area and vacant area. In the model, all the land types except urban built-up area are merged as non urban built-up area since that competing land use simulating is not considered in the model.

(2)CONSTRAIN

110 CCFs[2] are included in CONSTRAIN data to signify urban growth control condition. CCFs can be classified into 17 types as followed, wetland, water source protection, groundwater over-exploitation prevention, flooding control, steep area, green land protection, green belt, cropland protection, historical relic protection, geological vestige protection, geological condition for engineering, seism prevention, geological disaster prevention, pollutant centralized treatment facilities prevention, environmental radiation prevention, municipal infrastructure protection, and environmental noise prevention.

According to current laws, legislations, and standards of China, CCFs can be congregated into three zones (Fig. 2): constructing forbidden area (7130.1km^2), constructing restricted area (8697.4km^2), and constructing suitable area (527.1km^2). All the urban and rural constructions are forbidden in constructing forbidden area, and in constructing restricted area, urban construction and activity are restricted in the form of constructing scale, type, height, or intensity.

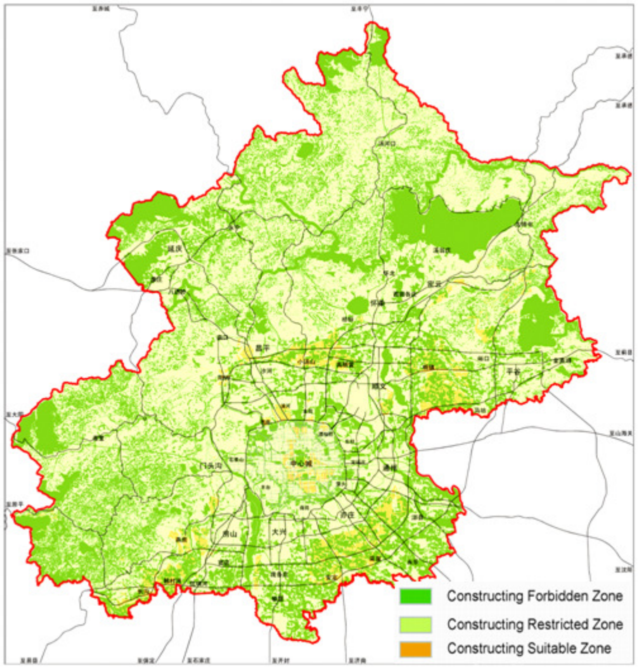

Fig. 2. Spatial distribution of CONSTRAIN

For the reason of the large amount of CCFs in CONSTRAIN, one factor always overlaps with others. We synthesis all CCFs into one UAZ (Unified analysis zone) layer as to conduct further analysis (Fig. 3). Regarding UAZ, the points within one UAZ object, have the same spatial distributing conditions of all 110 factors.

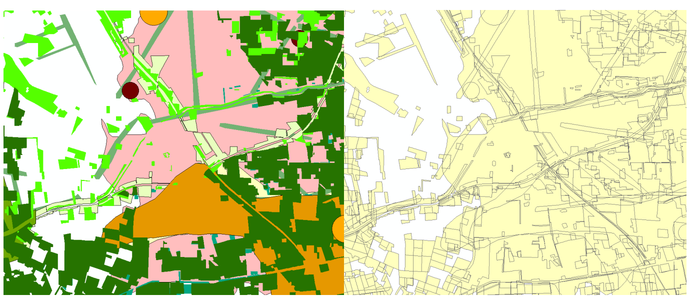

Fig. 3. CCFs (left) and corresponding UAZ (right) in some area

Constructing constrained index, showing the exactly degree for constructing restricting, is putted forward after zoning process, considering that one factor may differ from other factors although they share the same zone of constructing restricted, not to speak of the UAZs in constructing restricted area constituted by different CCFs set. For an instance, in constructing restricted area, UAZ1 contains CCF a, b, and c, while UAZ2 contains CCF a, b, c, and d. From the view of zoning condition, they are even; however, the restricted degree for UAZ2 is definitely greater than that of UAZ1 for one more CCF is in UAZ2. Constructing constrained index supplies possibility to simulate more detailed and practical constructing constrained condition.

In addition to constructing constrained zoning and index, constructing constrained zoning for each urban land use type, including residential, commercial, industrial, etc., are analyzed and specified since that the constructing constrained condition varies from different urban land use types. The zoning for various urban land uses provides fundamental support to simulate competing land use types in the further research.

In the study, we regard constructing forbidden area for urban constructions as one of institutional constrained condition into the model, namely, variable *con_f*[3]. The greater the implementing intensity of *con_f* is, the more area of constructing forbidden will be encroached during urban grow. Meanwhile, for the government, it will control urban growth by means of setting more national parks, eco-protected areas, etc. to change the spatial distribution of the constructing forbidden zone itself.

(3)LANDRESOURCE

It stands for the suitability of cultivation, which is classed into eight types ranging from 1 to 8 (Fig. 4), showing the suitability in turn (e.g. 1, most suitable; 8 least suitable). Variable *landresource* is obtained from LANDRESOURCE, representing objective evaluating for cultivation considering factors of soil, climate, terrain, etc. The most cultivating suitable area lies in the central plain area, southeastern Changping district, Yizhuang new city. It is clear that the most suitable area conflicts with existing urban built-up area, i.e. current urban growth overlaps best cropland in great degree. Accordingly, the cropland protecting policy can be reflected using this kind of institutional constrained condition, and the more attention for suitable cultivating area paid by the government, the less cropland will be encroached by urban growth.

(4)LOCATION

It stands for the location condition, and variable *d_tam, d_vcity, d_city, d_vtown, d_town, d_river, d_road, d_bdtown, f_rgn* are retrieved from LOCATION.

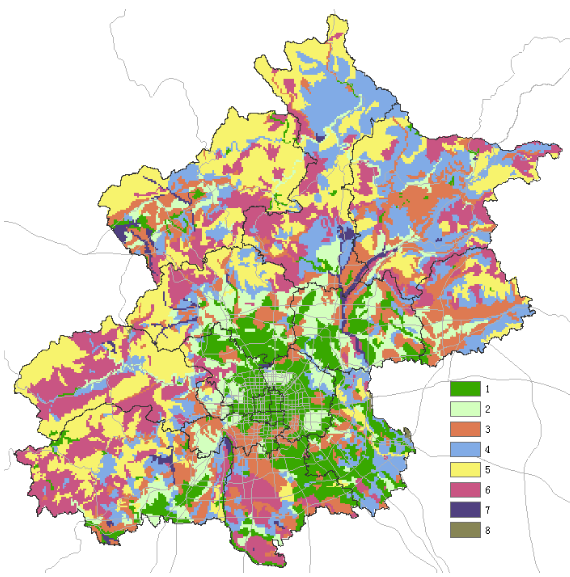

Fig. 4. Spatial distribution of LANDRESOURCE

(5)PLANNING

Five times urban master plans for Beijing metropolitan area were conducted, and it covers the years of 1958, 1973, 1982, 1992 and 2004 (Fig. 5), which is classified into urban built-up area and non urban built-up area. Variable *planning* is retrieved from PLANNING. To the government, planned urban built-up land will get more opportunities to be developed if urban planning policy, as one institutional condition, is implemented with more intensity. In addition, the government is capable to control the urban growth pattern through adjusting the urban planning scheme.

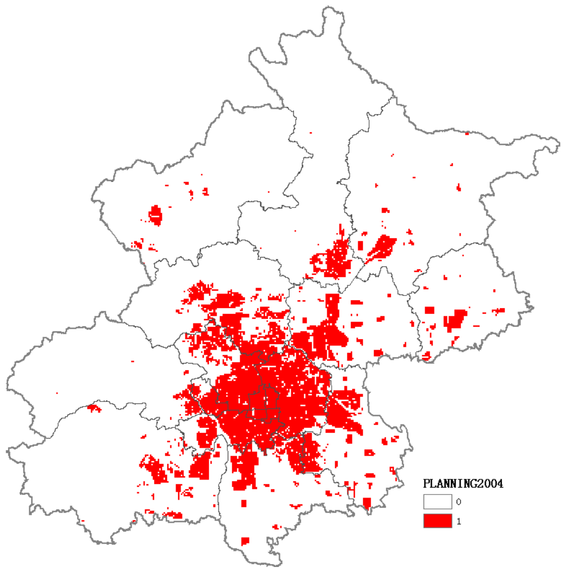

Fig. 5. Spatial distribution of PLANNING2004 [4]

(6)SOCIO-ECONOMIC

Population, resources, environment, economy and society data since 1952 are included in SOCIO-ECONOMIC, which favor identifying the relationship between the amount of urban built-up area (or annual urban growth amount) and various macro indicators as to setting macro socio-economic constrained conditions.

4 Planning controlled scenario

4.1 Complex constrained conditions in history

The weights of evident in different historical phases for spatial variables are available via logistic regression, thus providing preconditions to identify and compare the complex constrained conditions in various phases. Furthermore, the weights of evident, namely calibrated parameters can be applied in model simulation as input parameters, and is the fundamental work for model application.

Urban growth rules in various historical phases can be acquired by logistic regression, including 1986-1991, 1991-1996, 1996-2001, and 2001-2006. In logistic regression, variables *d_tam*, *d_vcity*, *d_city*, *d_vtown*, *d_town*, *d_bdtown*, *landresource*, *con_f*, and *f_rgn* do not vary from historical phases; however, variables *planning*, *d_road*, and dependent variable vary from historical phases. The coefficients of logistic regression in different historical phases are shown in Table 1.

Table 1. Coefficients of logistic regression in various historical phases

Variable	B(2001-2006)	B(1996-2001)	B(1991-1996)	B(1986-1991)
d_tam	-0.000016*	-0.000035*	-0.000041*	
d_vcity	-0.000025*	-0.000031*		-0.000031*
d_city	-0.000019*	-0.000066*	-0.000033*	
d_vtown			0.000025*	0.000058*
d_town		0.000089*	0.000066*	

Variable	B(2001-2006)	B(1996-2001)	B(1991-1996)	B(1986-1991)
d_river	-0.000138*			
d_road	-0.000256*	-0.000804*	-0.000524*	-0.001092*
d_bdtown		-0.000377*		
f_rgn	4.302458*	-13.737258*		
planning	**-0.410472***	**0.254173**	**0.575671***	**1.310654***
con_f	**-0.521103***	**-0.453115***	**-0.497453***	**-1.506241***
landresource			**-0.075543**	**-0.233262**
Constant	-0.174524	0.588961	-0.998267*	-3.610055*

*Significant at 0.001 level

Comparing the dominant factors in different phases according to Table 1, it is clear that these urban growth mechanisms differ from each other to a great degree; in addition, market and government role also vary in different phases. Generally, regional road plays an important role in urban growth of all phases. Comparing the variation of various institutional constraints in different phases, with regard to $w^{planning}$, it keeps positive except the phase 2001-2006, and reaches its maximum value in 1986-1991. In recent years, the effect of urban planning is fading, which reflects that in the first several years of social market economy, urban planning played a leading role in urban growth. However, with the introduction of market mechanism into China, its role is being partially replaced by market factors. Regarding w^{con_f}, it remains negative, and its absolute value reaches its peak in the phase 1986-1991, which shows that the protecting strength is the most great in that phase. In recent years, its role in urban growth remains steady, and has effectively influenced the urban growth process. Additionally, $w^{landresource}$ is positive in 1986-1991, while not significant after 1996, which signifying that the cultivating suitable area did not play an essential role in urban growth, and urban growth has encroached suitable cropland these years.

The coefficients in logistic regression can be availed to simulate short-term and long-term urban growth, and in the next sub-section, introduced is the urban growth scenario with current developing trend using the coefficients.

4.2 Basic scenario with current developing trend

As is known, 2020 is the ending year of this round of urban master planning drafted by Beijing municipal planning committee, while year 2049 is the hundredth anniversary of Beijing as the capital of P. R. China. To prepare for the next round of urban planning of Beijing, it is necessary to predict the urban form from 2020 to 2049, especially 2049. It will be more accurate to predict Beijing urban form of 2049 basing on the planned urban form of 2020 than basing on the observed urban form of 2006, conditioning the higher probability for BEIJING2020 to realize. In China, land developing is controlled by government by means of urban planning to a large degree, and urban planning form can explain most of urban developing activities, which are mostly located in area planned as urban built-up. Therefore, it is reliable to forecast long-term urban growth using planed urban form of some middle year, which is possible to reduce the uncertainty of long-term forecasting.

The basis scenario for 2049 urban growth is generated, by setting the annual urban growth speed 30 km^2 (3412 km^2 urban built-up area, namely, 13650 cells) and urban growth trend keeping the same with current developing trend (2001-2006) [5]. Below in Fig. 6, 1 stands for urban built-up land, is the simulating result for basic scenario with current developing trend, from which we can see that generally urban is sprawling from central city, and the main increasing urban built-up land distribute in the new cities of Shunyi, Changping and Tongzhou. Moreover, the southern part grows a little slower than that of northern part, which is also obvious in nowadays land use map.

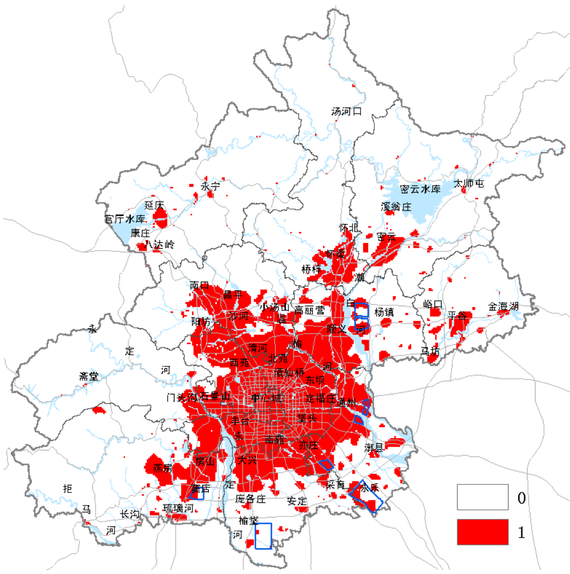

Fig. 6. Simulated urban form of 2001-2006 trend scenario

4.3 Planning controlled scenario through adjusting complex constrained conditions

Basing one basic scenario above mentioned, supported by CC-CA model, it is available to simulate urban growth scenarios constituted by various macro policies, such as population control policy, economy control policy, etc., by means of adjusting the macro socio-economic constrained conditions as to control the urban growth speed. Furthermore, we can establish or change the institutional constrained conditions, such as building 7^{th} ring road, setting new develop promoting area, etc., to simulate corresponding urban growth pattern. In addition, the intensity for implementing various institutional conditions by the government can be used to simulate different urban growth scenarios with various developing purpose.

The planning controlled scenario is generated through adjusting the intensity of implementing institutional constrained conditions. In the scenario, not only the urban growth promoting factors are considered, but kinds of urban growth constrained conditions. The scenario, including both the government control and urban trend developing, has reflected the domestic urban growth circumstance.

Planning control scenario has the same urban growth speed with that of trend scenario, and only the weights of evident for some spatial variables are adjusted to alter the corresponding policies' implementing intensity. Detailedly, the intensity for constructing constrained zoning *w_conf* is increased to -2 (-0.521103 in trend scenario), the intensity for urban planning *w_planning* is increased to -3 (-0.410472 in trend scenario), and all the other parameters maintain the same with that of trend scenario. Generally the intensity of implementing institutional constrained policies is strengthened. Fig. 7 is the simulation result of planning controlled scenario, compared with trend scenario, the urban built-up land is more scattered, less natural resource is destroyed, and environmental hazard is influenced. The scenario is regarded as one more sustainable urban growth pattern than trend scenario.

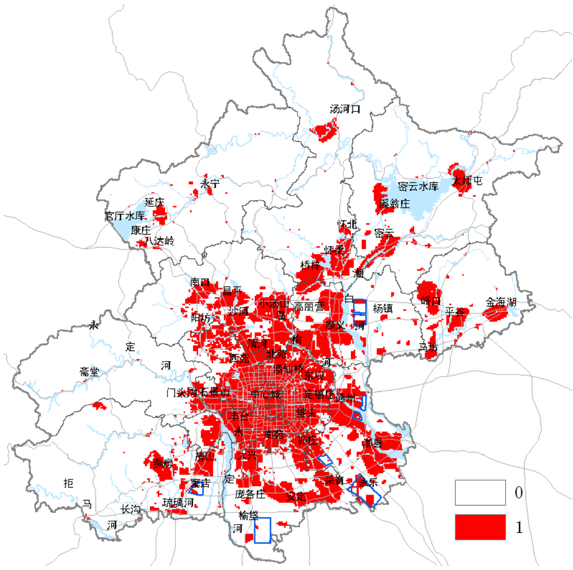

Fig. 7. Simulated urban form of planning controlled scenario

To compare the above two urban growth scenarios, selected are four indicators, including encroached constructing forbidden area “conf”, encroached green belt area “green”, encroached rural built-up land area “rural”, and the urban sprawl degree Moron I. The analysis result is listed in Table 2, showing that relative with trend scenario, planning controlled scenario encroached less ecological sensitive land, embodying the sustainable character of the scenario. Meanwhile, planning controlled scenario has lower degree of urban sprawl than trend scenario.

Table 2. Contrast of 2001-2006 trend scenario and planning controlled scenario (Unit of area: km^2)

Scenario name	conf	green	rural	Moron I
BEIJING2020[6]	538	1128	169	0.14
Trend scenario	843	1595	284	0.25
Planning controlled scenario	765	1181	248	0.13

5 Conclusion & Next steps

Complex constrained CA urban model is brought forward and introduced in detailed in the paper, which includes macro socio-economic, spatial and institutional constrained conditions. Particularly, constructing constrained zoning, as one institutional constrained condition, is introduced into the model. The zoning, combining 110 constructing constrained factors, together with urban master plan and cultivating suitable area, provide opportunities to reflect complex institutional constrained conditions for urban growth. The complex constrained urban model, integrating complex constrained conditions with classical CA urban model, is capable to simulate more practical and effective urban growth phenomenon/pattern in rapid urbanization area, and can be the urban growth policies simulation platform for the government by means of various factors’ scenarios analysis.

In the application of CC-CA model in Beijing metropolitan area, the role of complex constrained conditions in urban growth can be dynamically identified in various historical phases, by means of logistic regression. We let out the planning controlled scenario, generated by intensifying the implementation of urban planning and constructing constrained zoning basing on basic scenario with current developing trend. The planning controlled scenario shows that complex constrained conditions can be availed to affect the urban growth process, and simulate more practical urban growth pattern. However, only the constructing constrained zoning, as one institutional constrained condition, is considered in the application. In the further research, constructing constrained index is considered to be introduced into CC-CA model to simulate urban growth under more detailed constrained conditions. Meanwhile, we also plan to simulate competing land uses (e.g. residential, commercial, and industrial land type) in block scale through considering the constructing constrained zoning for various urban land uses.

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[1] Details regarding transition rule are available in (Long *et al*, 2008).
[2] Complex constrained conditions are discussed in (Long *et al*, 2008) detailedly.
[3] Constructing restricted zone is not included because the correlation coefficient between it and *con_f* is-0.936, negative correlated.
[4] Page limited, spatial distribution of other PLANNING data are not listed in the paper.
[5] Regression coefficients of other historical phases can also be regarded as the model input, thus enabling the model to simulate corresponding urban growth scenario with other historical developing trend.
[6] BEIJING2020 stands for the planning scheme of 2004.

References

1. Alkheder, S. and Shan, J. (2005) "Cellular Automata Urban Growth Simulation and Evaluation - A Case Study of Indianapolis", *Proceedings of the 8th International Conference on GeoComputation*, University of Michigan, United States of America, 31 July - 3 August 2005.
2. Butler, R.W.H. (1982) "A structural analysis of the Moine Thrust zone between Loch Eriboll and Foinaven, NW Scotland", *Journal of Structural Geology*, No.4, 19-29.
3. Clark, K.C. and Gaydos, L.J. (1998) "Loose-Coupling a Cellular Automation Model and GIS: Long-Term Urban Growth Prediction For San Francisco and Washington/Baltimore", *Geographical Information Sciences*, Vol.12 No. 7, 699-714.
4. David O'Sullivan and Torrens, P. M. (2000) "Cellular Models of Urban Systems", *CASA working paper*, No.22.
5. Engelen, G., White, R., and Uljee, I. (1997), "Integrating Constrained Cellular Automata Models, GIS and Decision Support Tools for Urban and Regional Planning and Policy Making", Timmermans, H. (ed): *Decision Support Systems in Urban Planning*. London: E&FN Spon. pp. 125-155.
6. Guan, G., Wang, L., and Clark, K.C. (2005) "An artificial-neural-network-based, constrained CA model for simulating urban growth", *Cartography and Geographic Information Science*, Vol.32 No. 4, 369-380.
7. Lancaster, K. (1966) "A new approach to consumer theory", *Journal of Political Economy*, Vol.74 No.2, 132-157.
8. Landis, L D. (1994) "The California urban future model: a new generation of metropolitan simulation models", *Environment and Planning* B: Planning and Design, Vol.21 No.4, 399-420.
9. Landis, L D. (1995) "Imaging land use futures: applying the California urban future model", *Journal of American Planning Association*, Vol.61 No.4, 438-457.
10. Landis, L D. and Zhang, M. (1998a) "The second generation of the California urban future model, Part1: Model logic and theory", *Environment and Planning B: Planning and Desig*n, Vol.25 No.5, 657-666.
11. Landis, L D. and Zhang, M. (1998b) "The second generation of the California urban future model, Part2: Specification and calibration results of the land-use change submodel". *Environment and Planning B: Planning and Design*, Vol.25 No.6, 795-824.
12. Li, X. and Yeh, A G O. (2000) "Modeling sustainable urban development by the integration of constrained cellular automata and GIS", *International Journal of Geographical Information Science*, Vol.14 No.2, 131-152.
13. Liu, X., Li, X., and Peng, X. (2007) "Niche-based cellular automata for sustainable land use planning", *ACTA Ecological Sinica (in Chinese)*, Vol.27 No.6, 2391-2402.
14. Long, Y., He, Y., Liu, X., and Du, L. (2006) "Planning of the controlled-construction area in Beijing: Establishing urban expansion boundary", *City planning review (in Chinese)*, Vol.30 No.12.
15. Long, Y., Shen, Z., Du, L., Mao, Q., and Gao, Z. (2008) "BUDEM: an urban growth simulation

model using CA for Beijing metropolitan area”. *Geoinformatics*, Guangzhou, China, 28 - 29 June.
16. Ward, D. P. and Murray, A. T. (1999) “An optimized cellular automata approach for sustainable urban development in rapidly urbanizing regions”, *International Journal of Geographical Information Science*, Vol.7 No.5: 235 - 250.
17. Ward, D. P., Murray, A. T., and Phinn, S. R. (2000) “A stochastically constrained cellular model of urban growth”, *Computers, Environment and Urban Systems*, Vol.24 No.6, 539-558.
18. White, R., Engelen, G., and Uijee, I. (1997) “The use of constrained cellular automata for high-resolution modelling of urban land-use dynamics”, *Environment and Planning B: Planning and Design*, Vol.24: 323-343.
19. White, R., Straatman, B., and Engelen, G. (2004) “Planning scenario visualization and assessment - a cellular automata based integrated spatial decision support system”. In: Goodchild, M.F., Janelle, D.G., Shrore, Z.G. (Eds.), *Spatially Integrated Social Science*, Oxford University Press. pp. 420-442.
20. Wu, F. (1998) “Simland: a prototype to simulate land conversion through the integrated GIS and CA with AHP-derived transition rules”, *International Journal of Geographical Information Science*, Vol.12 No.1, 63-82.
21. Wu, F. (2002) “Calibration of stochastic cellular automata: the application to rural-urban land conversions”, *International journal of Geographical Information Science*, Vol.16 No.8, 795-818.
22. Yeh, A G O. and Li, X. (2001) “A constrained CA model for the simulation and planning of sustainable urban forms by using GIS”, *Environment and Planning B: Planning and Design*, Vol.28, 733-753.
23. Zhao, Y. and Murayama, Y. (2007) “A Constrained CA Model to Simulate Urban Growth of the Tokyo Metropolitan Area”. *Proceedings of the 9th International Conference on GeoComputation*, National University of Ireland, Maynooth, Ireland, 3 – 5 September.