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Target or dream? Examining the possibility of implementing planned urban forms using a constrained cellular automata model

Abstract: Extensive urban planning implementation evaluation research has reported that actual urban growth significantly deviates from planned urban forms officially approved by planning departments. Researchers, planners and decision makers are concern whether a planned urban form can be fully implemented in future. In this paper, we propose an approach “form scenario analysis” (FSA) for examining the “possibility of implementing planned urban forms. This process is of the opposite to conventional urban growth scenario analysis, in which development policies are set as the input scenario conditions to generate various urban forms. A constrained cellular automata tool as a planning support system is developed for applying the FSA approach to evaluate planned urban forms. This model employs a planned urban form as the input scenario condition, aiming to identify whether any of the existing development policies can be used to realize the predefined urban form. If yes, the development policies required for the scenario form can be followed. To illustrate the applicability of FSA, We evaluated four planning alternatives for the Beijing Metropolitan Area Master Plan 2020 using the tool. The corresponding policy parameters are generated, together with in-depth policy implications for the study area. Our finding is that the planned urban form approved by the State Council of P. R. China (Alternative A in the paper) cannot be realized in the context of the current development policies of Beijing. The other three alternatives (Alternative B, C and D) differ from each other in terms of implementation probability and development policies required. This suggests that planners can adopt this simple tool to eliminate impossible planned urban forms in the early stage of compiling plans.

Key words: urban planning evaluation; planned urban form; constrained cellular automata; Beijing

1 Introduction

This paper proposes an alternative process to conventional urban growth scenario analysis (SA), which has been extensively studied in urban growth models. Standard urban growth models regard development policies as scenario conditions for reflecting future uncertainties of urban developments (for instance, Landis, 1994, 1995; Klosterman, 1999). Couclelis (2005) argued that the standard land use models have done little to investigate desired or unwanted outcomes in future plans. In support of Couclelis’ argument, we use the future urban form as the scenario condition to identify the spatial policies required to realize the predefined urban form. We propose an approach which we have labeled “form scenario analysis” (FSA). This analyzes the consistency between the predefined urban form and the corresponding spatial policies, together with the effects of the required spatial policies on various planning alternatives. Urban form is associated with many issues, and inappropriate urban forms (e.g. sprawling cities) may create various negative impacts such as over-consumption of land resources, increased commuting distances and traffic jams, decreased provision of affordable housing, increased urban infrastructure construction costs, reduced water supplies, poor neighborhood interactions, and poor public health (Kahn, 2000; Ewing et al., 2003). FSA can potentially be applied in identifying policies required to create sustainable urban forms.

The driving force for FSA in China is threefold. First, unlike in the West, most urban planners in China work in state-owned planning institutions. They tend to retain the approaches of the planned economy before the 1978 reform and opening-up policy. This has resulted in widespread ignorance of market factors (such as location of commercial centers and roads). Second, senior planners in China generally have a tradition of hand drawing plans, which originates from limited computer resources decades ago. Junior planners and students have partially inherited this tradition. Third, decision makers prefer a good plan based on a sound theoretical approach (such as concepts like axis and cluster), rather than considering its implementation. These three points have driven planners to create the desired planned form first, and then consider the spatial policies required to realize the desired urban planning form. Consequently, the actual urban growth often differs from the planned form. For instance, the planned form evaluation results indicate that more than 35% of urban developments in Beijing and Guangzhou exceed the original planned form (Han et al., 2009; Tian & Shen, 2011). Planning departments, lacking appropriate policy guidance, have little knowledge of the policies required to create the planned form and the differences between the policies needed and the current policies. From this point of view, the government is commonly concerned with the urban policies required to create the planned form. Therefore, FSA has great practical potential for solving this problem in China.

The term "scenario" is defined as "the assumption of a reasonable event with uncertainty happening in the next period of time" (see, Kahn & Wiener, 1967; Pearman, 1988). The term "scenario analysis", defined as "the entire process of predicting and analyzing the possible influences of the scenario" (see Ratcliffe, 1999), acknowledges that the future development is diversified and has a wide range of possible trends (Schoemaker, 1995; Ringland, 1998). Scenario analysis is widely applied in urban growth models since accurate prediction of the future urban form is often difficult. Various sets of policy parameters can be employed to generate the corresponding urban form (Landis, 1994; Landis, 1995; Klosterman, 1999). Recently, constrained cellular automata (CA) models have also been extensively applied for urban growth scenario analysis (Wu, 1998; Li & Yeh, 2000; White et al., 2004; Long & Shen, 2011).

In an alternative approach, this paper proposes using FSA with constrained CA, which analyzes the development policies required for form scenarios in order to present institutional implications for urban planning practices. This novel exploration of FSA can identify the existence of the required policies as well as the policy variations among planning alternatives (namely planned urban forms). This approach differs from traditional applications of constrained CA. This paper is organized as follows. In Section 2, we explain in detail the methodology for FSA using the constrained CA. We use four planning alternatives from the latest urban master plan of the Beijing Metropolitan Area as the case study for the FSA approach. In Section 3, the research materials including the study area, location constraints and planning alternatives are described. The form scenario analysis results are provided in Section 4. Finally, we discuss the findings and conclusions and then consider the next steps for the FSA research in the last two sections of this paper.

2 Method

2.1 Form scenario analysis

Urban growth SA, as a vision of future urban form (namely urban layout) in essence, is an allocation process for imaging future urban form based on initial urban form at the base year and the total land to be developed in future, while considering constraints and a model for combining these constraints. Constraints and the combination model are for prioritizing locations for future urban development and are the key elements in the allocation process for urban growth SA. In detail, urban growth SA can then be expressed as follows (*x* and *a* are all spatial explicit variables which should contain *ij* subscript to represent spatial location. The subscript is omitted in order to simplify the equation):

$$
\begin{aligned}
&Y = \Psi(P) \\
&P = f(X, A) \\
&X = \{x_k{}^t \mid k = 1,2,3,...,n; t = 1,2,3,..., p\} \\
&A = \{a_k{}^t \mid k = 1,2,3,...,n; t = 1,2,3,..., q\} \\
&T^p = \{T_t^p \mid t = 1,2,3,..., p; T_t^p \in [T_s, T_e]\} \\
&T^q = \{T_t^q \mid t = 1,2,3,..., q; T_t^q \in [T_s, T_e]\}
\end{aligned}
\qquad (1)
$$

where *A* as the term "policy", stands for the urban development policy, which is a temporal dynamic variable. *X* as the term "policy parameter" and a temporal dynamic variable, stands for the implementation intensity of the corresponding policy *A*. *X* can be regarded as the acceptable degree for the corresponding urban form of *A*. *P* is the development probability based on *A* and *X* using the development probability calculation function *f*. Ψ stands for the function which is used to determine which places are to be developed based on the development probability. *Y* stands for the urban form, and y_{ij} stands for the land occupation status at the location *ij*. y_{ij} =1 means the location *ij* is developed as urban built-up from non urban built-up, while y_{ij} =0 means undeveloped. *n* stands for the total number of policies. T_s stands for the starting time of the scenario analysis, and T_e the ending time. *Y* corresponds to the urban form at the ending time T_e. *q* and *p*, respectively, stand for the variation times of *A* and *X* from T_s to T_e. T^q and T^p, respectively, stand for the value changed time of *A* and *X*. The urban form of the future time *t* is the accumulative influenced result of *A* and *X* from the base time to *t*.

We draw three basic premises for the urban growth SA process, considering the limitations of the dataset available and the calculation time needed. (1) The function *f* is based on the multi-criteria evaluation (MCE), and the function Ψ is comparing the development probability with the development threshold. (2) *X* and *A* remain static from T_s to T_e (in most conditions equals to the value of the-time T_s or T_e), so both *p* and *q* are equal to 1. (3) *X* is homogenous in location.

Based on these three premises, Equation 1 is then transformed into Equation 2:

$$\begin{aligned}
&X = \{x_k \mid k = 1,2,3,\ldots,n\} \\
&A = \{A_k \mid k = 1,2,3,\ldots,n\} \\
&\quad \text{where } A_k = \{a_{k,ij} \mid k = 1,2,3,\ldots,n;\ ij \in \Omega\} \\
&p_{ij} = \sum_{k=1}^{n} x_k * a_{k,ij} \\
&y_{ij} = 1,\ \text{if } p_{ij} \geq p_{\text{threshold}} \\
&Y = \{y_{ij} \mid ij \in \Omega\} \subseteq \Omega
\end{aligned} \tag{2}$$

where *ij* is the geographical location, A_k is the spatial distribution of the policy *k*, $a_{k,ij}$ is the value of the policy *k* at *ij*, x_k is the policy parameter of the policy *k*, Ω is the entire study area, p_{ij} is the development probability at *ij*, $p_{\text{threshold}}$ is the development threshold. If p_{ij} is greater than or equal to $p_{\text{threshold}}$, then the space *ij* will be developed.

These three premises are also currently applied in the urban growth SA. For instance, Klosterman (1999) developed the planning support system "*What if?*" in which *A* is the policy of soil condition, flooding control and transportation, and *X* stands for the corresponding implementation intensity. Landis (1994, 1995) and Landis & Zhang (1998a, 1999b), respectively, developed CUF (California Urban Future Model) and CUF-2, in which *A* stands for the policy of location, environmental condition, land-use control, zoning, existing development density, accessibility for each development land unit (DLU), and *X* stands for the policy's implementation intensity. In the routine urban growth SA, *X* and *A*, the scenario analysis conditions as input, are applied to generate the corresponding urban form *Y*. We can get the corresponding urban form based on any development policy and policy parameter set. In most existing traditional urban growth scenarios, *A* is adjusted to estimate the dynamic change of *Y*, while *X* remains constant, to simplify the urban growth SA process.

The FSA approach, proposed in this paper, can be regarded as the reverse process to standard urban growth SA. Three premises are also considered in FSA, in which the urban form *Y* as the scenario condition is used to identify development policies required and their parameters (*A* and *X*). From the view of solving the equation, for any independent variable *Y*, dependent variables, including *X* and *A*, can be classified as two conditions. The first is No solution, namely there are no policies to yield *Y* and the second is Multi solutions, namely at least one policy set can be used to realize *Y*. Constrained CA are adopted to investigate the FSA issue, which regards the desired urban form *Y* and the already-known policies *A* as model inputs to solve the equation in order to validate the existing policy parameters *X*. To simplify the FSA process, we assume the development policies are already known variables, and will focus on the identification of the policy parameters.

2.2 Identification of urban policy parameters

Recent literature relevant to the constrained CA has not explored the urban form as the scenario condition. Whether the constrained CA can be adopted to solve FSA and whether the urban form can be regarded as the scenario condition also remains unexplored. First, we will investigate the status transition rule acquisition method of the constrained CA, which is the key procedure in using the traditional constrained CA to simulate urban growth (Wu, 1998; Li & Yeh, 2000, 2002, 2004;). The observed forms (*Y*) and the known constrained conditions (*A*), namely policies, in some historical stages are required to identify parameters (*X*) for the constrained conditions (*A*). FSA is aimed at acquiring *X* based on *Y* and *A*. In the standard model calibration process, the urban form is based on historical observation, while in FSA, the urban form is based on the predefined urban form. Therefore, the two processes are, in essence, identical.

The key issue for FSA using the constrained CA is the identification of policy parameters (*X*), which can enable the model calibration method mentioned above. In FSA, T_s can be regarded as the start of the historical stage, and T_e the end. Therefore, the time phase of SA, namely, from T_s – T_e , corresponds to the historical stage, and FSA can be transformed into the model calibration issue of standard constrained CA, in which approaches such as logistic regression, artificial neural network, genetic algorithm, and nested loops are widely adopted.

The evaluation indicator for the consistency of the form scenario (*Y*) and current policies (*A*) should be established in FSA. As the input of the constrained CA, *X* is applied to get the simulated urban form (Y'). The Kappa index, the evaluation indicator, is applied to compare the simulated form Y' with the form scenario *Y* cell by cell and evaluate the goodness-of-fit. Kappa less than 80% stands for none solution condition (no policy parameters to realize the predefined form), and greater than or equal to 80% stands for the multi solutions condition, denoting that the calibrated parameters can be used to simulate the designated scenario form. Generally speaking, solutions for FSA can be expressed as $\{X \mid Y' = f(X, A), Kappa(Y, Y') \geq 80\%\}$, which stands for the solution location of *X*.

2.3 Constrained cellular automata (CA)

The simulation logic of urban growth in China is influenced by the socialist market economy. First, the government determines at the macro-level the amount of land development in different time phases according to socio-economic conditions. Second, the developers acquire suitable development land from the government during the allocation process, taking account of the comprehensive constraints at micro-level. At the micro-level, a constrained CA model is used to allocate urban developments to locations.

Constraint selection is a core procedure for constrained CA, and existing constrained CA models have distinctive constraints. For instance, White et al. (1997) initiated the concept of constrained CA by taking spatial constraints into account. Engelen et al. (1997) took macro socio-economic constraints into account in a planning support system incorporating CA, GIS and other toolkits. An exclusive layer is set to constrain urban growth in SLEUTH (Clark and Gaydos, 1998). In Simland, developed by Wu (1998), constraints for land developments were also considered. Ward and Murray (1999) employed physical constraints, geographic constraints and institutional controls, in addition to the macro socio-economic constraint. Li and Yeh (2000) classified all constraints into three types, local, regional and global. Engelen et al. (2003) and White et al. (2004) employed not only macro constraints, but also physical characteristics, accessibility and zoning as constraints. In Guan et al. (2005)'s CA urban model, macro socio-economic and institutional constraints were included. Social factors, transportation infrastructure, proximity to city centers, facilities infrastructure, neighboring land uses, geographic factors, and spontaneous growth were constraints in the CA-based model LEAM (Sun et al., 2009). Long and Shen (2011) proposed a CA urban growth model for Beijing taking into account spatial and institutional constraints. For our constrained CA model, we selected three types of factors which influence urban growth based on studies in urban economics (especially those using the Hedonic approach (Rosen, 1974)) and other research we reviewed. These factors (namely spatial constraints) include the location constraints (standing for market incentives), the neighbor constraint, namely the development ratio within the neighborhood, as well as the institutional constraints.

Based on simulation logic and the selected factors, the conceptual model of the constrained CA for FSA is shown as follows:

$$V_{ij}^{t+1} = f\left(V_{ij}^{t}, A_{mac}, A_{loc}, A_{ins}, A_{nei}^{t}\right) \tag{3}$$

where V_{ij}^{t+1} and V_{ij}^{t}, respectively, are the cell status at *ij* of time *t*+1 and *t*, and *f* is the transition rule of the constrained CA.

Constrained conditions in the urban growth process, namely development policies, consist of four types, including the macro socio-economic constraint A_{mac} (non-spatial explicit variable, and thus no corresponding policy parameter *X* for it), location constraints A_{loc}, institutional constraints A_{ins}, and neighbor constraints $A_{nei}{}^{t}$. Location and institutional constraints are assumed to remain fixed during the future urban growth process, and the macro socio-economic constraint reflects the total number of built-up cells to be developed. The neighbor constraint is defined as the development intensity in the neighborhood of each cell, and equals the ratio of developed cells to all cells in the neighborhood (excluding the cell itself). The neighbor constraint keeps changing with iterations of the constrained CA since its value is recalculated based on the simulated urban form in each iteration. In addition, the configuration of the neighborhood of the constrained CA is the Moore type, with eight adjacent cells for each cell, and the discrete time of CA is one month in the real world.

The status transition rule of the constrained CA is expressed as follows:

$$\begin{aligned}
&LandDemand = \sum_{t} stepNum^{t} \\
&\text{In iteration } t+1\text{:} \\
&s^{t} = x_{0} + \sum_{k=1}^{n-1} x_{k} * a_{k} + x_{n} * a_{n}^{t} = s_{0} + x_{n} * a_{n}^{t} \\
&p_{g}^{t} = \frac{1}{1+e^{-s^{t}}} \\
&p^{t} = \exp\left[\alpha * \left(\frac{p_{g}^{t}}{p_{g\max}^{t}} - 1 \right) \right] \\
&\text{if } p_{ij}^{t} \geq p_{threshold}(p^{t}, stepNum^{t+1}) \text{ then } y_{ij}^{t+i} = 1 \\
&\qquad \text{otherwise } y_{ij}^{t+i} = 0
\end{aligned} \tag{4}$$

where *LandDemand* is the total number of cells to be developed, $stepNum^{t}$ is the number of cells developed in iteration *t* reflecting the land development demand as the macro constraint, *ij* is the cell's coordinate, s^{t}, calculated from the sum of weighted spatial constraints, is the urban development suitability of cell *ij*, $p_{g}{}^{t}$ is the initial transition potential, $p_{g}{}^{t}{}_{\max}$ is the max value of $p_{g}{}^{t}$ across the whole lattices, *α* is the dispersion parameter ranging from 1 to 10, indicating the rigid level of urban development, p^{t} is the final transition potential, $p^{t}{}_{ij}$ is the final transition potential of cell *ij*, x_{0} is the constant item, a_{n} is the neighborhood development policy, x_{n} is the weight of a_{n}, a_{k} is the spatial constraint (the neighborhood effect excluded), x_k is the weight of a_k , s_0 is the constant part (except the neighborhood effect) of $s_{ij}^{\ t}$ among all iterations, $y_{ij}^{\ t+i}$ is the cell *ij*'s status at iteration *t*+1, and $p_{threshold}(p^t, stepNum^{t+1})$ is the development threshold to control the development speed and quantity which varies from the value of p^t and $stepNum^{t+1}$ to guarantee $stepNum^{t+1}$ cells will be developed in iteration *t*+1. In general, this equation is used to allocate future development land into cells using constrained CA, which evaluates the transition potential based on the traditional land use suitability.

We will discuss how to identify model parameters for the constrained CA. The parameters needing to be calibrated include $stepNum^t$, x_k , and x_n . Various approaches can be adopted. The calibration of $stepNum^t$, reflecting the total amount of land required for economic developments which is assumed to be constant throughout the simulation period, can be calculated as follows:

$$stepNum = \frac{C_{T_e} - C_{T_s}}{(T_e - T_s)/t_0} \tag{5}$$

where C_T and C_t are the total number of developed cells, respectively, in scenario form and current form, T_e and T_s are, respectively, the future and current time, and t_0 is the time in the real world corresponding to one iteration of CA.

Regarding the calibration of x_k and x_n reflecting the intensity of policies, the logistic regression and heuristic approaches can both be applied. In our constrained CA, we integrate the methods of Wu (2002) and Clark & Gaydos (1998), combining their benefits, to identify the parameters of the MCE formatted status transition rule. The weights x_k for locational constraints can be retrieved by logistic regression, in which whether a cell is developed from non-urban to urban is the dependent variable (1 for developed and 0 for non-developed), and location constraints are the independent variables (for details see Wu, 2002). The binary logistic regression progress can be represented as $P = \frac{1}{1+e^{-z}}$

$$z = x_0 + \sum_k x_k * a_k$$

where x_0 is constant, x_k is the regression coefficient, a_k is the influencing factor, and *P* is the transformation probability (from non-urban to urban, namely developed).

Keeping the identified x_k static, x_n can be calibrated using the MonoLoop method (for details see Long et al., 2009), with x_n continually sampled from 0 to $x_{n,\max}$ with an interval of $x_{n,\max}/M$. $x_{n,\max}$, which can be set based on the user's experience. M is set as 100 in this paper. The sampled x_n and the already calibrated weights x_k are used as the input variables for the constrained CA model. x_k and x_n calibrated (X^*) represent the policy implementation intensity for the scenario form. Our proposed approach can both identify the overall historical urban growth trend and reduce the time consumed for the model calibration. The Kappa index is calculated by comparing the simulated form

(Y') and form scenario (Y). X^* stands for the maximum consistency between Y and Y'. X^*, as one solution, is not the only parameter for the realization standard of the form scenario. However, we consider only X^* in this paper, and other solutions will be investigated in future research.

Policy implications can be drawn from the calibrated policy parameters. When the policy parameter *X* is positive, the corresponding policy *A* should be encouraged, otherwise *A* should be rejected. The parameters for various policies can also be compared in parallel to show the policy tendencies. Meanwhile, we can compare the parameters with the historical ones to "visualize" the policy implications. In the following sections, the constrained CA will be empirically applied to the 2020 Beijing master plan to examine the consistency of four planning scenarios with already-known spatial policies as well as to identify the policy parameters required.

3 Study area and data

3.1 Study area

The study area for constrained CA is the Beijing Metropolitan Area (BMA) as shown in Fig. 1. With an area of 16,410 km^2, it lies in northern China, to the east of the Shanxi altiplano and south of the Inner Mongolian altiplano. The southeastern part of the BMA is a plain, extending east for 150 km to the coast of the Bohai Sea. Mountains cover an area of 10,072 km^2, 61% of the whole study area. See Yang et al. (2011) for more background information on Beijing.

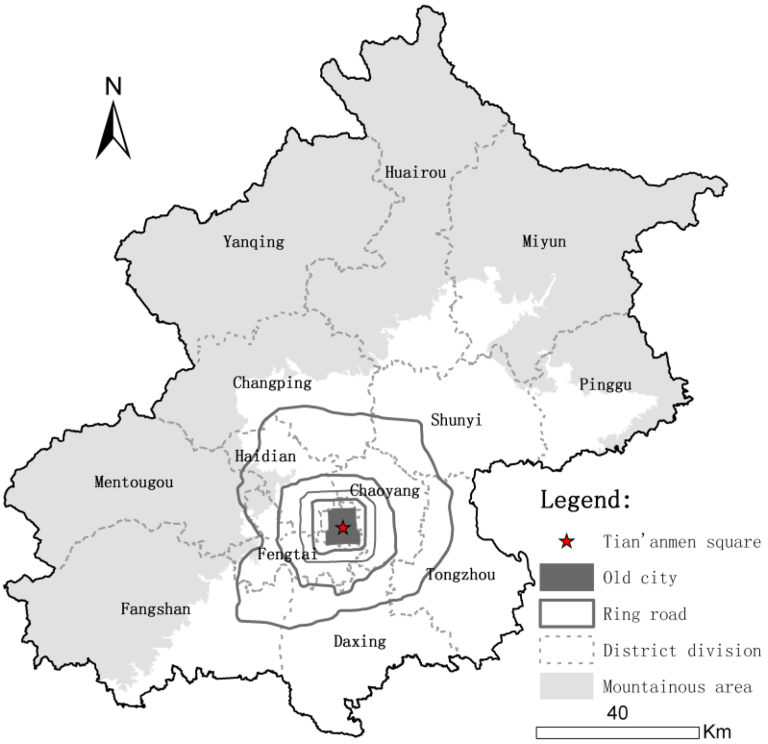

Fig. 1. The Beijing Metropolitan Area map

The BMA has experienced rapid urbanization in terms of GDP and population growth since the 1978 Reform and Opening by the central government. The GDP in 2006 was ￥787 billion, an 83.7 fold increase from 1976 when it was ￥9.4 billion. The population in 2006 was 15.81 million, 1.9 times greater than in 1976 when it was 8.29 million (Beijing Municipal Statistics Bureau & NBS Survey Office in Beijing, 1987 and 2007). Using Landsat imageries, the built-up area in 2006 was 1,324 km^2 (Fig. 2), nearly three times larger than in 1976, when it was 495 km^2. Urban growth is predicted by the BMA government to continue for another two decades. Therefore, scholars and decision makers are concerned about the urban growth pattern, especially about how to develop towards the future predefined planned urban form.

To address this concern, we tested the form scenario analysis approach in the BMA to identify policy implications for planning alternatives. The constrained CA proved suitable for simulating urban growth of the Pearl River Delta, where urban growth is also quite rapid (Li & Yeh, 2000, 2002). The driving forces for urban growth of the BMA and the Pearl River Delta are similar with the same domestic socio-economic development background as both these metropolitan areas are the dominating economic growth clusters. Therefore, we also used the constrained CA in the form scenario analysis of the BMA.

3.2 Constraints in Cellular Automata (CA)

We used a constrained CA based model BUDEM for the FSA using the Python script language based on the ESRI Geoprocessing module (for more detail see Long et al., 2009). BUDEM was established for analyzing historical urban growth and simulating future urban growth in the BMA using cellular automata. In BUDEM, the logistic regression is applied to deriving the transition rule from historical datasets, similar to those in this paper. As the cell size of BUDEM is 500 m * 500 m, there are 65,628 cells in the BMA. The precision of BUDEM is 87.5% in terms of Kappa using datasets from 2001 and 2006 (see Table 2). This indicates that the model can accurately replicate historical urban growth in Beijing and therefore can be applied for FSA in this paper.

The policies and the corresponding dataset of the constrained CA in the BMA are listed in Table 1. The spatial distribution of various policies is shown in Fig. 2. *StepNum*, the macro constraint, as a global control parameter, reflects the total amount of future land development. This constraint is related to the key objective of the socio-economic development plan. The location constraints denote the special plans or policies, e.g., the city hierarchy, flood control and transportation development. The institutional constraints denote the ecological protection, disaster prevention, and farm protection. The neighbor constraint represents the connected development control policy. The three types of spatial constraints are weighted for computing development suitability as shown in Equation (4). The weights are the policy parameters to be identified in this paper.

Table 1 Datasets of the constrained CA in the BMA

Type	***Variable***	***Description***	***Value range***	***Data source***
Macro constraint	*stepNum*	Socio-economic development	>0	Socio-economic Development plan
Location constraints	a_1	Attractiveness of Tiananmen	0-1	Derived from spatial dataset
	a_2	Attractiveness of new cities	0-1	Derived from spatial dataset
	a_3	Attractiveness of towns	0-1	Derived from spatial dataset
	a_4	Attractiveness of rivers	0-1	Derived from spatial dataset
	a_5	Attractiveness of roads in 2006	0-1	Interpreted from TM image of 2006-11-01
Institutional constraints	a_6	Construction prevention policy	0 or 1	Beijing Municipal Planning Committee 2007 *
	a_7	Suitability for agricultural development	0-1	Beijing Planning Commission et al., 1988
Neighbor constraint	a_n^t	Development intensity in neighborhood	0-1	Calculated by CA

* For details of the calculation approach, see Long *et al*., 2010.

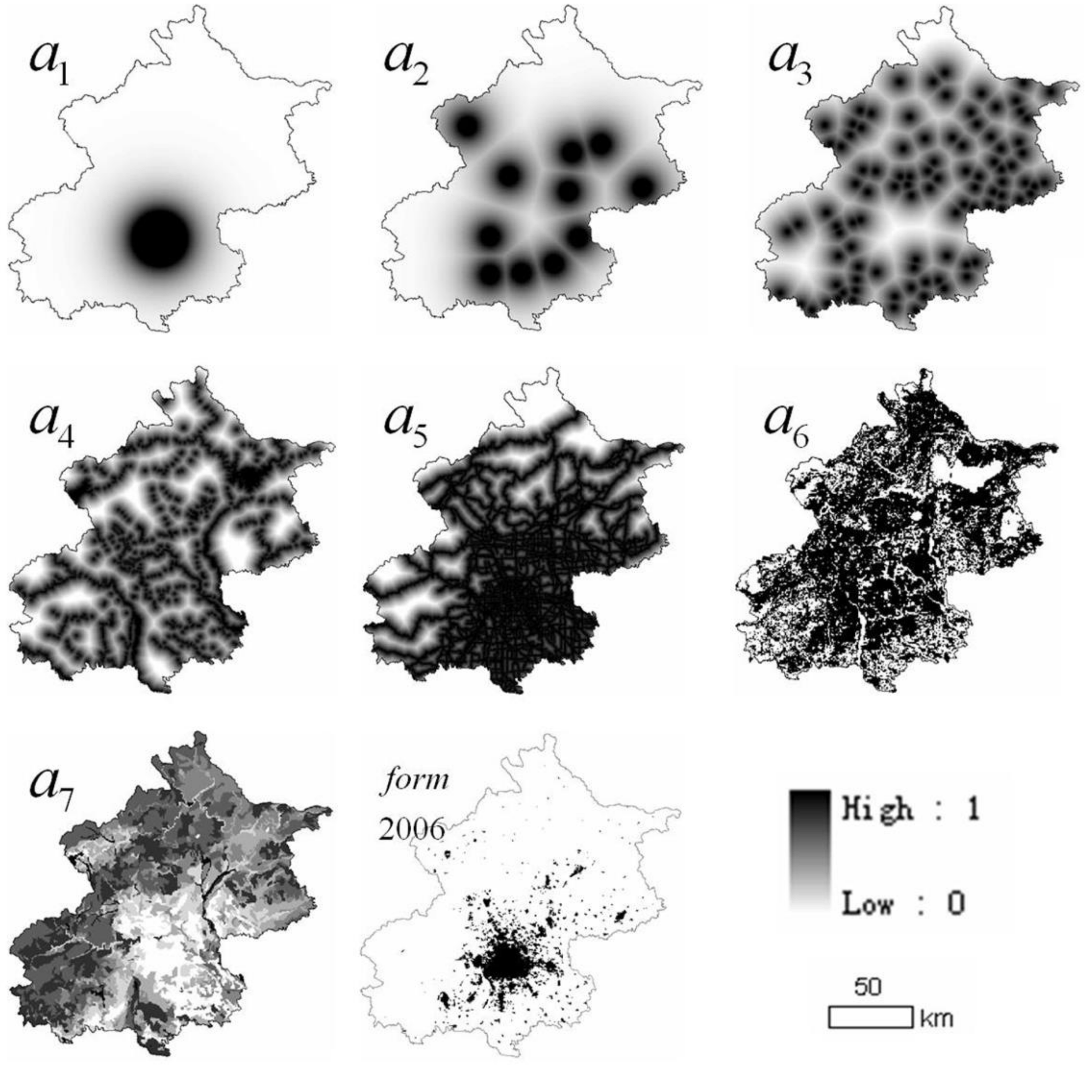

Fig. 2. Maps of spatial policies and the urban form of the BMA in 2006

For convenience in comparing parameters of various policies in parallel and vertically (namely within and across the time periods), policies (*A*) are standardized to range from 0 to 1, with 1 denoting the greatest probability of development, and 0 the least. The location constraint a_k , using the corresponding spatial feature class as the data source, is processed by the “Distance/Straight Line” toolbox of the Spatial Analyst module in the ESRI ArcGIS package to acquire $dist_k$ followed by $a_k = e^{-\beta * dist_k}$ to calculate the attractive potential, where β =0.0001 based on the BUDEM model calibration results. Regarding institutional constraints, when the construction prevention policy a_6 and the suitability for agricultural development policy a_7 are equal to 0, there will be the least probability of development, and when they are equal to 1, there will be the greatest probability of development.

The spatial distributions of various constraints in the BMA, shown in Fig. 2, influence the possible future urban growth pattern. Looking at each constraint individually, we can directly and easily recognize the corresponding urban form without considering other constraints. For instance, the construction prevention constraint a_6 stands for the dispersed urban form, with the Miyun Reservoir, partial western mountain area, farmland in the plain area, and the Great Wall protection zone undeveloped. The road constraint a_5 stands for the urban form along the traffic corridors mainly in the plain area due to the high density road networks in this area and the low density in the remote mountain areas. Considering combined constraints and the currently existing urban form featuring the central city sprawl, the future urban form in the BMA is likely to be further sprawl around the central city in the plain area, with scattered developed locations in the mountain areas. Therefore, in the following context, we will come to set form scenarios (namely planning alternatives) and identify policy parameters required for scenarios using constrained CA.

3.3 Planning alternatives

Five versions of the urban master plan for the BMA have been created since 1958, issued separately in 1958, 1973, 1982, 1992 and 2004 (Beijing Municipal Planning Committee et al., 2006). In the 1992 plan for 1991-2010, Han et al. (2009) pointed out that up to 51.8% of urban developments from 1991 to 2005, within the sixth ring road area (Fig. 1), were beyond the planned form. The actual urban developments were significantly inconsistent with the planned form in the BMA. Therefore, form scenario analysis is essential for validating the planned form.

The target of the 2004 plan is for the year 2020, and the plan has estimated a population of 18 million, the developed land to be 2,300 km^2, and specified an urban spatial structure of “Two axes, two belts and multi-sub-centers”. In the plan, four planning alternatives, shown in Fig. 3, were generated. These alternatives were different in terms of the spatial layout and reflected the preferences of planners. Each alternative reflected different development perspectives of various groups of decision makers and urban planners (details available below). During the creation and approval of the plan, the possibility of realizing each alternative was not considered in detail, and finally Alternative A was approved by the State Council of P. R. China. In this paper, we apply the FSA approach and develop a constrained CA model to identify the consistency between the planned form and existing policies, thus evaluating the possibility of implementing each alternative.

Below are the detailed descriptions for the four planning alternatives in the BMA.

- Alternative A (Y_{A}): The approved alternative by the State Council of P. R. China (see, Beijing Municipal Planning Committee *et al*., 2006), is characterized by preventing the central city from sprawling further and promoting the development of new cities.
- Alternative B (Y_{B}): The sprawl alternative, termed Tandabing in Chinese (circle-spread), is characterized by promoting developments in the central city and controlling new developments in new cities.
- Alternative C (Y_{C}): The grape-cluster alternative, which is characterized by promoting developments both along the transport corridors and around small towns.
- Alternative D (Y_{D}): The sustainable alternative, which is characterized by preventing construction in specific areas and on high-quality farm land, resulting in a more dispersed form.

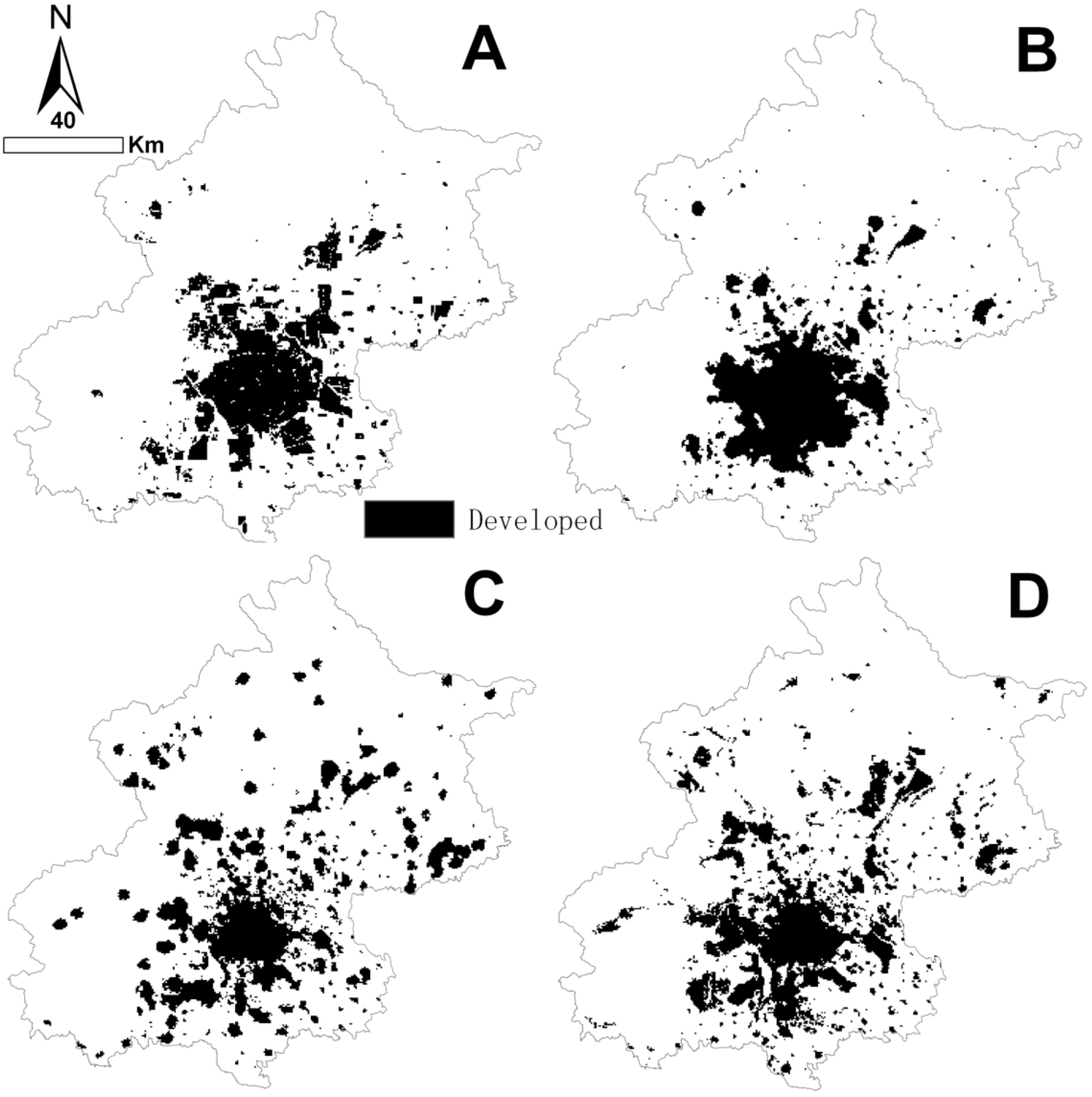

Fig. 3. Four planning alternatives in the BMA

4 Results

4.1 Identification of policy parameters

To calculate *stepNum*, the total number of iterations is (2020-2006)*12=168. C_{T_s} =5,011 according to the urban form of 2006 (baseline year), namely Y_{2006}. In Alternative A, C_{T_e} =9,254 is the total number of cells to be developed in the future (2020), and *stepNum* is equal to (9,254-5,011)/168=25. The calculation results of *stepNum* for other planning alternatives are listed in Table 2, and are slightly different from those of Alternative A. Alternative D has the greatest *stepNum* value, indicating the fastest urban growth among all the alternatives.

The calculation results for the policy parameters, together with the Kappa index, are listed in Table 2. All the independent variables are significant at the acceptable 0.001 level. The Kappa index for Alternatives B, C and D are greater than 80%, indicating that these alternatives have a high probability of implementation. For instance, to implement Alternative B, decision makers proposed a focus on developments around the central city, existing developments and new cities. Other constraints will not be key factors for Alternative B. In contrast, the development route of Alternative C would be different from that of Alternative A, and Alternative C suggested decision makers pay more attention to developments around small towns and along rivers. However, the Kappa index for Alternative A is only 67.5%, denoting this planning alternative can not be achieved within the current policy context.

Table 2 Policy parameters calculation results for four planning alternatives in the BMA

Variable	**Alternative A**	**Alternative B**	**Alternative C**	**Alternative D**	**Historical urban form (2001-2006)**
Developed cells number	9254	9270	9895	10679	5297
stepNum	25	25	29	34	11
x_0 (Intercept)	-8.700	-30.696	-63.599	-55.624	-15.874
x_1 (The city center)	15.268	54.558	15.106	20.849	10.192
x_2 (New cities)	3.575	10.294	10.046	9.701	3.347
x_3 (Towns)	-0.717	5.272	31.639	7.807	-2.839
x_4 (Rivers)	4.105	8.765	24.348	11.622	4.004
x_5 (Roads)	1.368	6.027	7.627	8.113	0.737
x_6 (Construction forbidden policy)	1.193	3.672	4.078	23.000	2.140
x_7 (Agriculture suitability)	-2.396	5.066	6.094	12.003	-3.001
x_n (Neighbor)	15	17	9	7	17
Kappa (%)	69.4	91.8	85.0	85.8	87.5
Valid	False	True	True	True	True

4.2 Validation of planning alternatives

The *MonoLoop*'s byproduct is the validation process using the Kappa index. When Kappa is greater than or equal to 80%, the planning alternative is defined as "validated" which means that the parameters identified can be used to realize the planning alternative. When Kappa is less than 80%, the planning alternative is defined as "not validated". The simulated urban form Y' can be generated using the constrained CA with input parameters listed in Table 2, including *stepNum*, x_{0-7}, and x_n. The cell-by-cell comparison results of Y' and Y (the planning alternative) are shown in Fig. 4. The confusion matrix is given in Table 3. In each planning alternative, the undeveloped cells substantially outnumber the developed ones, so the overall accuracy is generally high due to the unbalanced dataset.

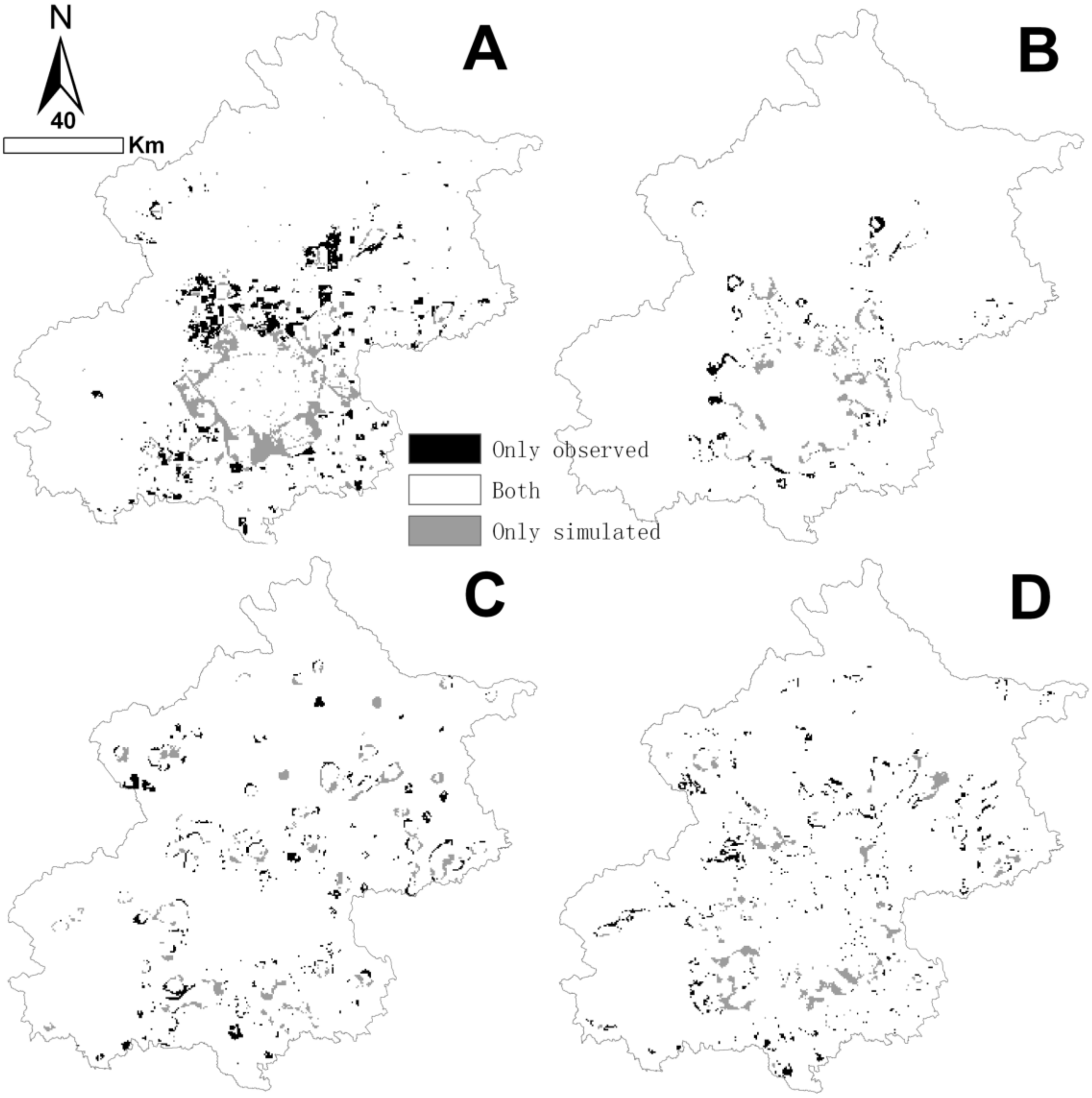

Fig. 4. The simulated urban forms compared with the planning alternatives in the BMA

Table 3 The confusion matrix of the planning alternatives and simulated urban forms

Alternative	**Planned Simulated**	**0**	**1**	**SUM**	**User accuracy (%)**
A	**0**	53919	2428	56347	95.7
	1	2440	6826	9266	73.7
	SUM	56359	9254	65613	
	Producer accuracy (%)	95.7	73.8	Overall accuracy is 92.6%	
B	**0**	55482	620	56102	98.9
	1	793	8650	9443	91.6
	SUM	56275	9270	65545	
	Producer accuracy (%)	98.6	93.31	Overall accuracy is 97.8%	
C	**0**	54391	1256	55647	97.7
	1	1259	8639	9898	87.3
	SUM	55650	9895	65545	
	Producer accuracy (%)	97.7	87.3	Overall accuracy is 96.2%	
D	**0**	53590	1273	54863	97.7
	1	1276	9406	10682	88.1
	SUM	54866	10679	65545	

Alternative	**Planned Simulated**	**0**	**1**	**SUM**	**User accuracy (%)**
	Producer accuracy (%)	97.7	88.1	Overall accuracy is 96.1%	

In addition to the cell-by-cell map comparison method *Kappa* used in this paper for comparing simulated and planned urban forms, we further applied other map comparison methods for validating our FSA results using The Map Comparison Kit 3 (MCK3) developed by Research Institute for Knowledge Systems, The Netherland (Visser and de nijs, 2006). These methods are Fuzzy-based and include Fuzzy Kappa, and Fuzzy Inference System. The objective of fuzzy-based map comparison is to propose a method trying to mimics human comparison and gives a detailed assessment of similarity. In Fuzzy Inference System, a global agreement value termed as Fuzzy global matching can be derived by the fuzzy summation of the local matching. The results shown in Table 4 indicate that Fuzzy Kappa values for Alternative A to D in percentage are 67.8, 88.1, 81.4 and 81.2, respectively. Fuzzy global matching for Alternative A to D in percentage are 67.0, 82.3, 81.2 and 80.9, respectively. Generally, Fuzzy Kappa and Fuzzy global matching are both slightly lower than Kappa. For each valid alternative in terms of Kappa is also valid in terms of Fuzzy Kappa and Fuzzy global matching in the BMA experiment. This further proves the stability of our approach for FSA.

Table 4 Comparing planning alternatives with simulated urban forms using various map comparison methods

Alternative	**A**	**B**	**C**	**D**
***Kappa* (%)**	**69.4**	**91.8**	**85.0**	**85.8**
Valid	False	True	True	True
Fuzzy Kappa (%)	*67.8*	*88.1*	*81.4*	*81.2*
Fuzzy global matching (%)	*67.0*	*82.3*	*81.2*	*80.9*
Kappa Simulation (%)	71.1	91.2	85.0	85.7

5 Discussion

The Kappa validation and cell-by-cell comparison results show that Alternatives B, C and D match the simulated forms relatively closely. Policy implications for the validated planning alternatives can be presented according to the results of calculation of the policy parameters since the value of each constraint has been standardized to 0 to 1. Three aspects of policy implications are as follows.

(1) Parallel comparison of parameters within each planning alternative. For Alternative B, the speed of development of the urban built-up land is 25*12/4=75 km^2 per year from 2006–2020 according to *stepNum*. Therefore, the annual population increase is 750,000 based on the assumption of 100 m^2 built-up land per capita. Other parameters can also be compared in parallel, and the greater the parameter is, the more intensely the policy should be implemented to realize the planning alternative. For instance, Alternative B should promote the central city, new city and river side development policies more than other policies.

(2) Parallel comparison of parameters across planning alternatives. The different requirements for policy implementation can be easily identified by comparing every parameter for each planning alternative. For instance, x_1 of Alternative B is greater than x_1 of Alternative C. This means that to realize Alternative B, the central city development policy must be implemented much more intensely than in Alternative C. In the same way, the construction protection intensity required to realize Alternative D will be much greater than for Alternative C since the parameter x_6 of Alternative D is obviously greater than that of Alternative C.

(3) Parallel comparison of parameters with the historical phase. The policy parameters of 2001–2006, listed in the last column in Table 2, can be calculated by the same calibration model approach used with the planning alternatives, using observed forms and historical policies. The speed of urban growth of the four planning alternatives is 2–3 times of that of the historical phase from 2001–2006, denoting

that, to realize the planning alternatives, urban economic and population developments will need to be promoted much more intensely than during the historical phase. The expansion of neighbor developments should also be controlled to realize the planning alternatives, especially for Alternative C and D.

The calibration result of Alternative A, however, demonstrates that no policy parameter will realize this predefined urban form. For this condition, either Y_{A} or *A* should be adjusted to reach the consistency between the predefined planning alternative and the development policies. By adjusting the predefined urban form, a more feasible planned urban from can be established based on constrained CA simulation using different urban growth scenarios. By adjusting the spatial distribution of development policies (e.g. the transportation network, the eco-space distribution), the experiments can also be conducted in constrained CA until the predefined urban form can be realized using the adjusted policies.

6 Conclusions and future perspectives

In this paper we attempt to use the urban form as the scenario condition to enable discussions with planners about establishing the possible urban forms within the framework of current development policies from the perspective of development demand, geographical conditions, and institutional controls. Constrained CA is incorporated with the form scenario analysis approach. We use four planning alternatives of the master plan in the Beijing Metropolitan Area as a case study to test successfully our proposed form scenario analysis approach.

FSA using the constrained CA is a breakthrough for CA applications as follows. First, FSA is capable of evaluating the consistency between the planned form and development policies, namely specialty plans. Nowadays in China, planning implementation evaluation is a compulsory requirement in urban planning practices to examine the consistency between the actual urban spatial developments and planned form after several years of planning implementation. The existing reports on planning implementation evaluation are not optimistic as the planned forms have occasionally been exceeded. FSA can detect this in practice. Second, in addition to planning implementation evaluation, FSA can be conducted at the very beginning of the plan creation to assess the possibility of implementing the planned form within the integrated urban development policy environment. FSA can assist planners to design a better layout based on the evaluation results. Third, for a valid plan, the required policies (identified coefficients in this paper) can be identified as development pathways to guide decision-makers in implementing the urban plan. Fourth, FSA can be used during the urban planning compilation process to evaluate in terms of spatial constraints the conformity between a spatial plan drafted by planners and corresponding specialized plans proposed by different local government departments. Examples of these specialized plans include hazard-sensitive areas proposed by the geological department and farmland conservation plans proposed by the agriculture department. In sum, FSA can be used as a tool for evaluating the spatial plan compiled by planners and adopted to solve problems faced by planning departments and planners.

Further work is still needed on some aspects of this paper. First, we drew three premises to simplify the FSA process. To simulate urban growth much more accurately, we suggest further research to focus on the current simplifications. The policy itself (*A*), beside the policy parameter (*X*), can be taken into account in FSA to identify not only the required intensity of policy implementation but also the spatial distribution policy required. The spatial heterogeneity of the policy parameter also needs to be considered as various studies indicate that forces driving urban growth in China vary between the sub-regions in the metropolitan area (Liu et al., 2005; Li et al., 2008). Second, agent based modeling can be applied in FSA to represent planners and other decision makers' preferences as the planner agents, to investigate FSA from another perspective (Ligtenberg et al., 2001; Saarloos et al., 2005). Third, we set a Kappa value of 80% as the benchmark for accepting or declining policy parameters for the predefined urban form based on our experience. How an 80% Kappa insures a good match between two urban forms needs further examination.

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