A Constrained CA Model to Simulate Urban Growth of the Tokyo Metropolitan Area

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1. Introduction

The period of High Economic Growth in Japan which began in the latter half of the 1950s led to a massive migration of population from rural to urban areas. The population concentration on Tokyo and its surrounding prefectures (i.e. the Tokyo metropolitan area) was particularly noteworthy. Accompanying the population increase, urbanized area expanded rapidly. The trend would continue according to the result of population projection. Therefore, it is very essential to understand the mechanism of spatial process of urban growth of the Tokyo metropolitan area (TMA) so as to make exploration of alternative pathways into the future. Urban modelling provides an effective approach for this issue.

Urban modelling of the TMA has been experienced for several decades. In 1983, the group of Nakamura implemented the hierarchical Computer-Aided Land-Use Transport Analysis System (CALUTAS) for the TMA (Nakamura et al. 1983). The group later spread to Yokohama, where Miyamoto independently developed the Random-Utility URBAN model (RURBAN), an equilibrium land market model (Miyamoto et al. 1986; Miyamoto and Kitazume 1989). In 1993, Murayama adopted Markoff's chain model to predict aggregated changes of the land-use at micro-level scale for the TMA (Murayama 1993). In 2004, Arai and Akiyama estimated the land-use transition potential functions in a case study on the Tokyo metropolitan region (Arai and Akiyama 2004). However, they did not simulate the land-use change using the functions. Herein, an alternative constrained Cellular Automata (CA) model is proposed to simulate dynamic spatial process of urban growth of the TMA.

2. Methodology

2.1 Study area and dataset

Study area consists of Tokyo and parts of surrounding prefectures (Figure 1). The dataset used is "Detailed Digital Information (10m grid land-use) Metropolitan Area" of Tokyo (DDIMA10m), which was produced by the Geographical Survey Institute of Japan.

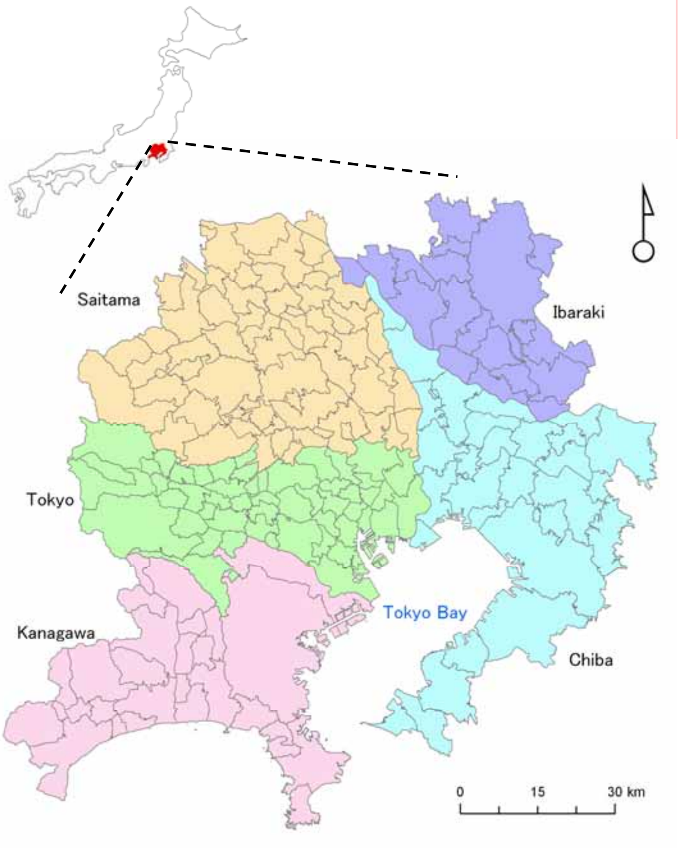


Figure 1. Study area

2.2 Constrained Cellular Automata model

In terms of basic CA framework, a city can be compared to an organism which is composed of cells with kinds of land-use. Growth or decay of the cells comes from the effect of the states and configuration of those cells in the neighbourhood. This process can be defined as an iterative probabilistic system (White et al. 1999) in which the probability *p* that a place *i* in a city is occupied by a land-use *k* in a time *t*, is a function of the neighbourhood effect *N*:

$$ {}^{t}P_{ik} = f({}^{t-1}N_{ik}) \tag{1}$$

However, the basic CA formalism is not well suited to urban applications as the framework is too simplified and constrained to represent real cities (Torrens and David 2001). It needs to be extended. One solution is to add the intrinsic suitability *S*, the zoning status *Z*, the accessibility *A*, and scalable random perturbation term *v* to the basic CA framework:

$$ {}^{t}P_{ik} = f({}^{t-1}N_{ik}, {}^{t-1}S_{ik}, {}^{t-1}Z_{ik}, {}^{t-1}A_{ik}, {}^{t-1}v) \tag{2}$$

The function can be expressed as following equation in terms of the iterative probabilistic system:

$$^{t}P_{ik} = (1+{}^{t-1}N_{ik})(1+{}^{t-1}S_{ik})(1+{}^{t-1}Z_{ik})(1+{}^{t-1}A_{ik})^{t-1}v \quad (3)$$

The system is subject to an important constraint that the growth of a city depends essentially on its position in a larger urban-economic system. This kind of model is called as constrained CA model (White et al. 1997).

However, no matter how extends the basic CA framework for urban application, neighborhood effect still is one of the important components. Herein neighbourhood configuration is defined as an area within a radius of eight cells, including 196 cells. The contribution of neighbourhood effect N on the probability of conversion to land-use k of a cell i is described as a function of a set of aggregated effect of cells in the neighbourhood:

$$Log(\frac{N_{ik}}{1-N_{ik}}) = \beta_{oi} + \sum_{k} \beta_{ihk} F_{ihk} = \beta_{oi} + \sum_{k} \beta_{ihk} G_{hk} \sum_{m} \frac{A_m}{d_{mi}^2} I_{mh} \,. \quad (4)$$

Where,

A: area of the cell,

d_{ji}: the Euclidean distance between the cell j in the neighbourhood and the developable cell i,

G_{hk}: constant of the effect of land-use h on the transition to land-use k. + stands for positive, – repulsive,

m: number of the cells in the neighborhood, and

I_{hj}: index of cells. I_{hj}=1, if the state of cell j is equal to h; I_{hj}=0, otherwise.

Where, β_{oi} and β_{ihk} are the coefficients to be calibrated.

A negative exponential function was extended to calibrate the accessibility A:

$$A^{ik} = \beta_k e^{-\lambda x} \quad (5)$$

Where, x is the radial distance from the transportation line, and λ is the density gradient. The density gradient quantifies the extent of the urban spread around the transportation line.

Evaluation of land-use intrinsic suitability S is a complicated process (Malczewski 2006). In order to simplify the process, concept of relative land-use suitability (Chen et al. 2001) was adopted in this research:

$$S_{sk} = \frac{A_{sk}}{N_k} \quad (6)$$

Where, A_{sk} is the area of land-use type k in land condition class s; N_k total area of land-use type k.

The relationship of urban growth with land zoning in the TMA was analyzed. Relative land-use zoning effect index was adopted as the zoning state Z.

The random perturbation parameter α was set following a “trial and error” approach.

3. Results

Based on the results of the calibration using the land-use map of the TMA in 1984 and 1989, simulation of spatial process of urban growth of the TMA was carried out in the period from 1989 to 1994. Result of the simulation was tested by comparing simulation with reality in 1994 to assess the model (Figure 2). Simulated new urbanized area looks similar with reality in terms of urban form.

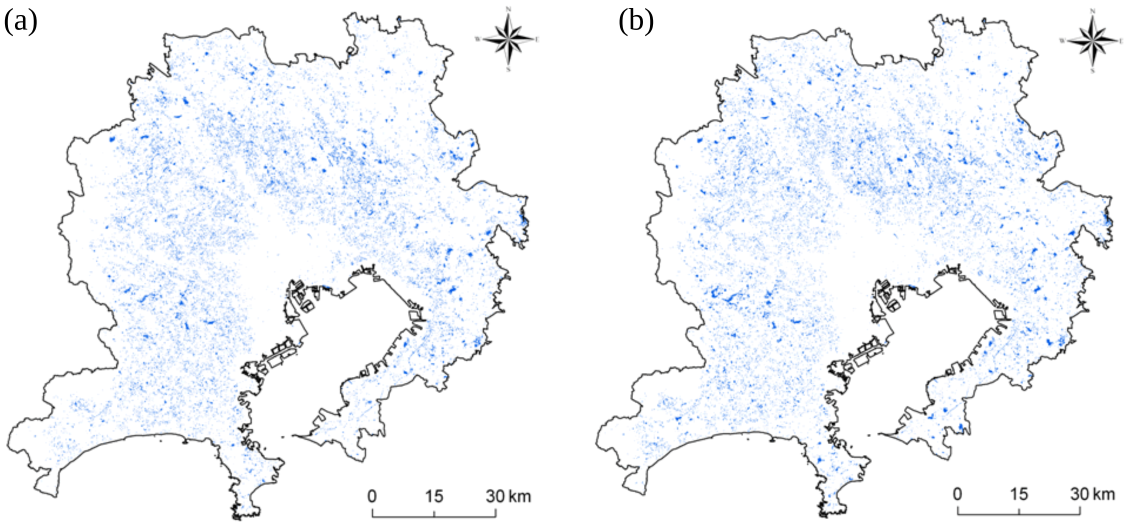


Figure 2. Comparison of new urbanized area of the TMA from 1989 to 1994 between simulation and reality. (a) simulation; (b) reality

Urbanized area was compared between simulation and reality using fractal dimension and spatial metrics (Tables 1 and 2). These two tables show that this model catches the characteristics of urban growth of the TMA in urban form and landscape.

Fractal dimension in different radius zones	**Reality in 1989**	**Reality in 1994**	**Simulation in 1994**
In 0-16km radius	1.94	1.95	1.95
In 16-50km radius	1.45	1.48	1.48

Table 1. Assessment of the simulated urbanized area in terms of fractal dimension (Note: Location of Tokyo station is treated as the centre of the TMA)

Spatial metrics	**Reality in 1989**	**Reality in 1994**	**Simulation in 1994**
NP(number of patches)	9909	9609	9594
PD(patch density)	1.20	1.16	1.16

Table 2. Assessment of the simulated urbanized area in terms of spatial metrics

Simulated industrial, residential, and commercial land also were assessed (Figures 3 and 4). These two figures indicate that this model also catches the characteristics of urban growth of the TMA at micro level of land-use classification.

Based on the assessment of simulation, this model was used to give scenario of urban land-use of the TMA in 2014. Analysis of the scenario in terms of fractal dimension and spatial metrics shows that the scenario inherits the characteristics of urban form and landscape in the TMA.

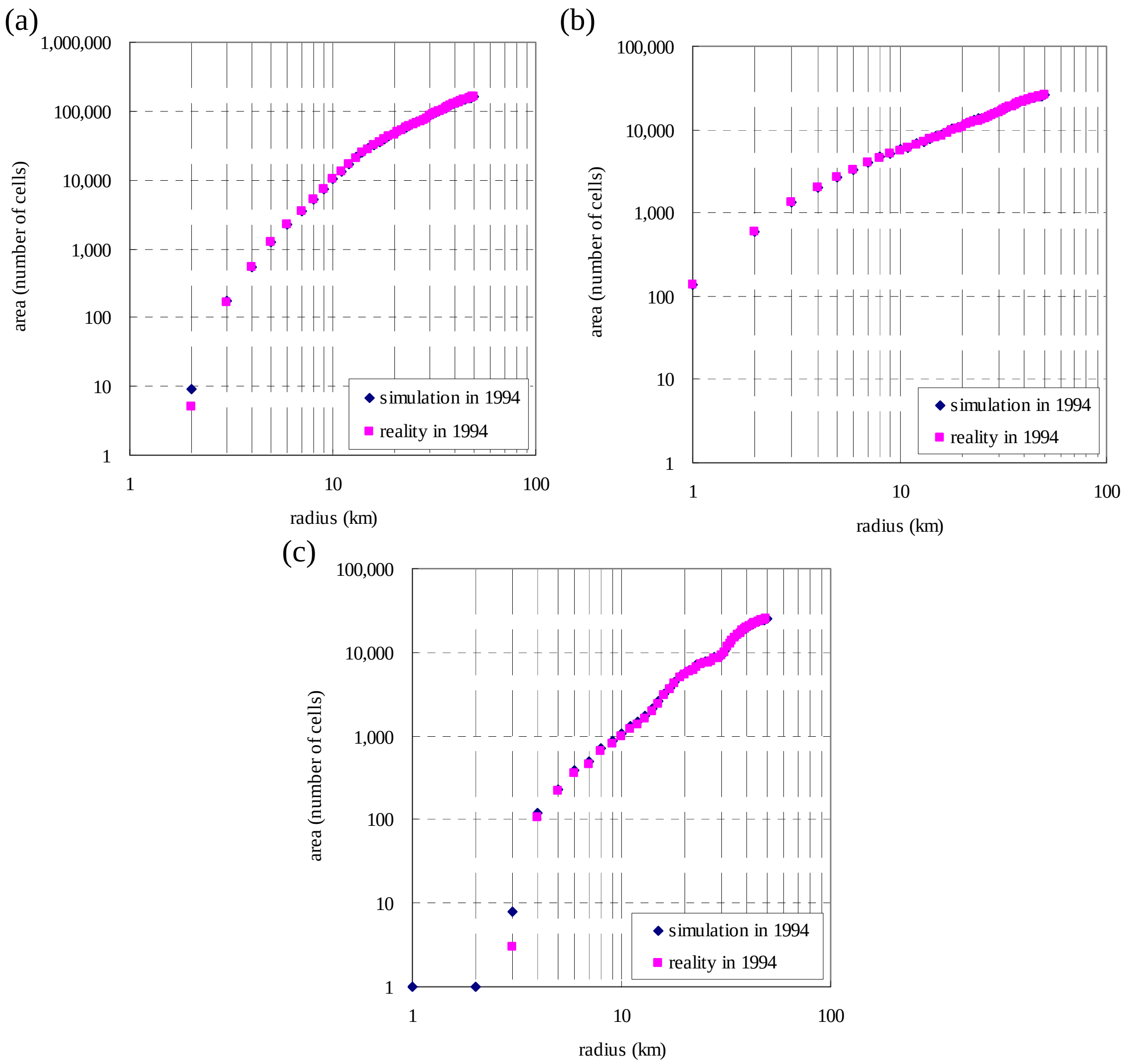
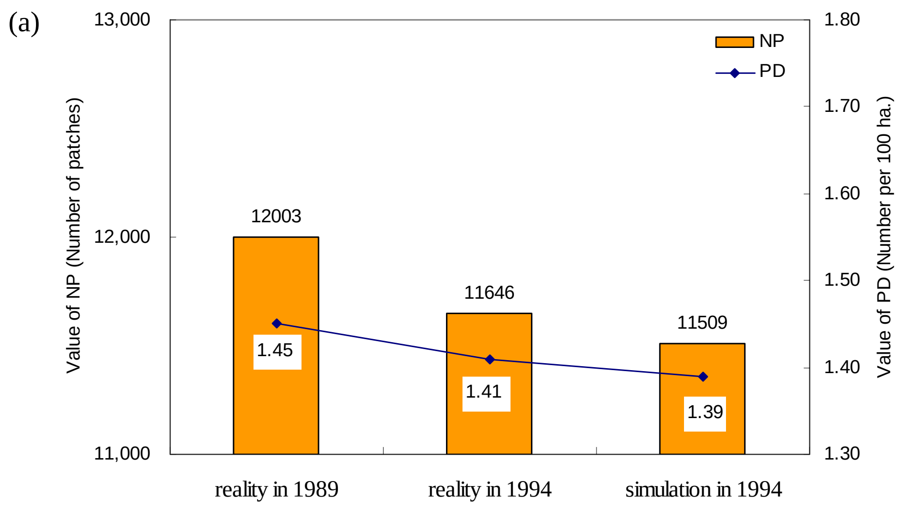


Figure 3 Area-radius plots between reality and simulation in 1994. (a) residential; (b) commercial; (c) industrial



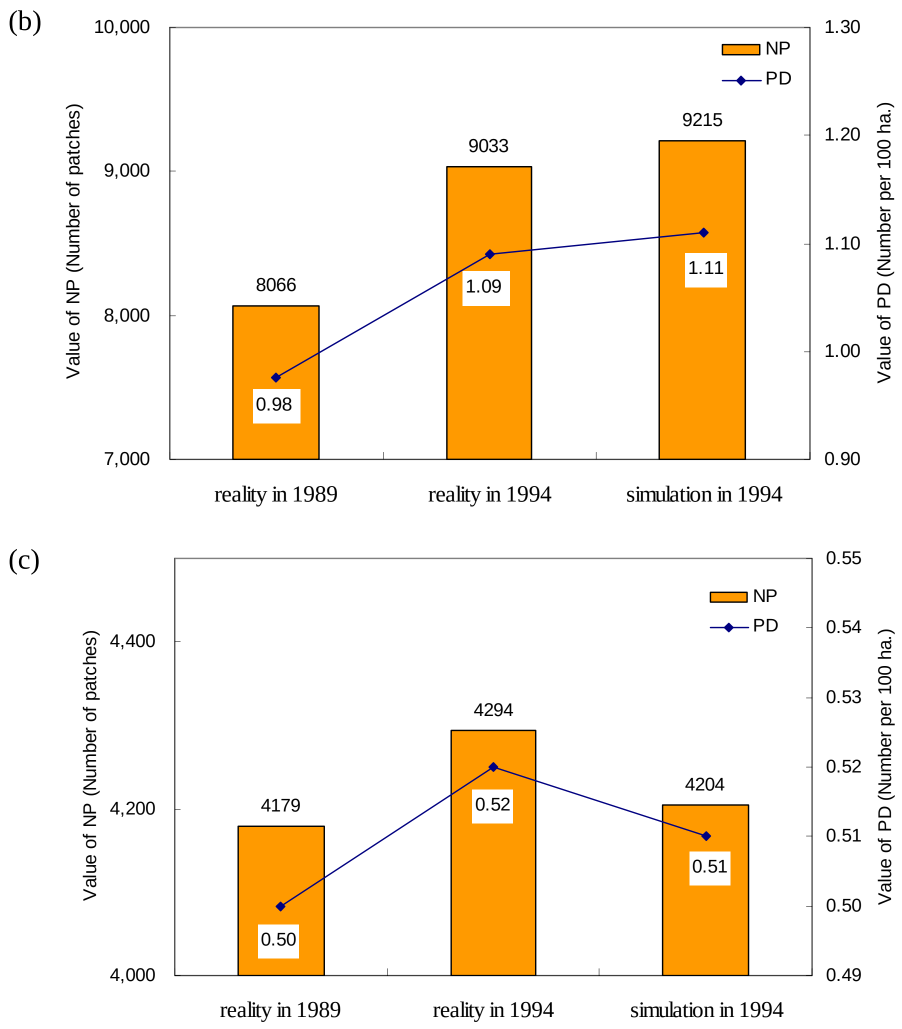


Figure 4. Comparison of urban growth significance of spatial metrics between reality and simulation. (a) residential; (b) commercial; (c) industrial

4. Concluding remarks

An alternative constrained CA model was proposed in this research to model spatial process of urban growth of the TMA. This model catches the characteristics of urban form and landscape in the spatial process of urban growth of the TMA, thus indicating the utility of this model to predict urban land-use for the future of the TMA.

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