Geosimulation model using geographic automata for simulating land-use patterns in urban partitions

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Zhenjiang Shen[a,d], Mitsuhiko Kawakami [b], Ippei Kawamura [c]

[a] Kanazawa University, Kakuma Machi, Kanazawa City 920-1192, Japan
shenzhe@t.kanazawa-u.ac.jp,
[b] Kanazawa University, Kakuma Machi, Kanazawa City 920-1192, Japan
kawakami@t.kanazawa-u.ac.jp,
[c] Fukui Prefecture Government, Fukui City 910-8580, Japan
ipi_musicman@yahoo.co.jp
[d] State Innovative Institute for Public Management and Public Policy Studies, Fudan University, Handan Road, Shanghai City 200433, China,

Abstract

Cellular automata (CA) are an effective means of urban growth simulation. Moreover, the development of a planning support system associated with the theory of artificial intelligence has recently become a new global challenge. In this paper, we investigate a geo-simulation model using CA based on Geographic information system (GIS) for visualizing land use patterns in urban partitions. Most recent simulation models using CA have been developed in regular grid nets or networks, where adjacent grids or networks in urban space are easily addressed. Our project explores how to utilize an irregular polygon data set in a GIS database in order to deal with spatial micro simulation. A new concept in this project is to take into account the effects of urban planning, such as land use zoning and street networks, at the level of parcels and blocks in urban space. Adjacent irregular parcels on both sides of a street are intended targets in the simulation. In this paper, a method of simulating land use patterns in urban space after implementation of land readjustment projects is discussed.

Keywords: block, parcel, percolation model, land use formation and geographic automata

1. Introduction

Recently, numerous simulation models using CA (cellular automata) and MAS (multi-agent system) have been developed for simulating urban growth (Batty, 2004). These models provide powerful tools for exploring the uncertainty and complexity inherent in urban land-use and transport systems (Kii and Doi, 2005; Chabrol et al., 2006). However, most existing studies have focused on urban sprawl, in which research is restricted to modelling a two-dimensional regular lattice for large-scale urban spaces.

Additional reports (Erickson and Lloyd-Jones, 1997) have shown examples of emerging urban patterns accounting for buildings and road segments. This suggests that it may also be possible to employ CA for modelling small-scale urban spaces. To expand the possibility of urban modelling using CA, we propose a new approach and discuss its possible use for urban micro simulation. Our principle concern is to discover a way to use CA to simulate urban partitions, such as blocks and parcels, after urban redevelopment projects that cause parcels and street networks to be readjusted, and force property owners to reconstruct buildings.

For land readjustment projects implemented in most cities in Japan, the formation process of land use after redevelopment takes dozens of years, as former land owners have to deal with compensation affairs with developers while new owners gradually move into the project areas. One reason this process is so troublesome is the fact that it is difficult for planners and developers to imagine the state of project areas after redevelopment. Planners note that there is a significant difference between the concepts developed in the planning stages, and situation after construction. For this reason, tools that can provide insight into the future while embracing the complexity and uncertainty of urban partitions inherent in the formation process of land use are needed.

Many different CA-based simulation models have been described in past studies. Torrens (2000) described the basic concepts of cellular models for urban modelling; cell state, lattice, neighbourhoods, and transition rules. Prior to that study, Engelen et al. (1997) discussed the integration of the cellular automata model, GIS and decision support tools for urban planning and policymaking. In one of the earlier practical studies of the CA model, Batty and Xie (1994) discussed a CA model for simulating dynamic urban sprawl, in which the effects of the spread parameter, the vacancy parameter, and the redevelopment process parameter were estimated respectively as threshold values according to potential-based transition rules. Another study (Wu, 1996) integrated CA with heuristically-defined fuzzy set transition rules to simulate land use conversions in the rural-urban fringe of a fast growing metropolis. This study expanded upon CA research related to not only the urban sprawl phenomenon, but also urban patterns based on different types of land use in simulation. In another CA model developed, fuzzy-logic-controlled (Liu and Phinn, 2003) transition rules were introduced into a cellular automata model to simulate the process of urban development. Wu (2002) employed Multi-criteria evaluation (MCE) to find the status transition rule of CA with a probability process and apply it to urban expansion simulation, while Li and Yeh (2000) explored various intelligent methods to retrieve a transition rule of CA and bring forward a constrained CA model to simulate sustainable urban form. These studies have provided a number of mathematical methods to calculate the potential or probability of land use formation.

Another factor involved in the simulation of urban spaces deals with the level at which the simulation takes place. This level can range from a whole city regular grid net to census tracts and urban partitions such as parcels and blocks. Most studies have attempted to simulate the formation process of urban growth at the level of the whole city using automata-based modelling, based on a regular lattice and network or a Voronoi partition of urban space within the same layer or between different layers.

With regard to simulations of urban partitions employing irregular polygons, Erickson and Lloyd-Jones (1997), who resolved many of the inconveniences of the standard CA framework, simulated the spatial pattern of buildings and road segments of an English village. Blecic et al. (2003) defined neighbourhoods as adjacent cells in one layer that can be based on regular grids or irregular Voronoi partitions, in which the Euclidean distance between cells are comprised as special cases of neighbour definition. However, in CAGE (Cellular Automata General Environment) that is a simulation tool, land parcels and blocks are not considered geographic automata either.

Benenson (2004) provided a GAS (geographic automata system) framework in which direct and indirect geo-referencing of fixed and non-fixed GA (geographic automata) is presented in two-dimensional space. The buildings and road segments are fixed GA, while agents such as householders are non-fixed GA. However, land parcels were not considered. In our project, in the absence of land parcels, no reasonable boundaries for householders to construct their buildings exist. Thus, geographic automata such as land parcels and blocks are necessary. Moreover, building forms that are the result of householder construction are overly complicated for CA simulations.

In irregular or regular urban spaces, land use patterns, defined herein as ratios of different land use as well as their spatial distributions, which are under the control of planning regulations, are important. Planning regulations have control over the process of urban sprawl; thus, they are considered planning conditions in a simulation. For example, the research team of UrbanSim (www.urbansim.org) discussed the structures of urban simulation models that include planning regulations as control conditions in their simulation process (Waddell, 2002). Furthermore, Wu and Webster (1998) explored the influences of natural zoning and prescriptive land use zonings under free-market, government-regulated market, and self-regulated market conditions. Otherwise, a CA model can simulate urban space based on different scenarios defined by various planning condition parameter sets. By providing a series of scenarios, the model can reveal many future urban development strategies.

The purpose of our study is to explore the effectiveness of CA for simulating the potential impacts of urban planning at the level of an urban district by examining simulated land use patterns. Recently, a model prototype (Stevens and Dragićević, 2007) employing irregularly sized and shaped land parcels was developed for a common desktop GIS and applied to a rapidly developing area of a mid-sized Canadian city. Our investigation similarly allowed urban planners and other stakeholders to evaluate planning alternatives by focusing on how planning conditions influence land use patterns rather than how different subdivision designs influence development under varying population growth rates. We attempted to introduce land use zoning and street networks as planning conditions into the parameters of the CA simulation model. The simulation was conducted in an example project area where the land readjustment project is implemented. Thus, the impact of land use zoning and street networks as planning controls for projects proposed in the area can be predicted using the simulation, and planners can inquire into the impacts of urban planning if CA is verified to be available at the urban district level.

2. Research approach

2.1 Establishing the data structure of urban partitions for GA

As mentioned previously, the urban space of our simulation target is blocks and parcels. Land parcels have common boundaries within blocks, but the numbers of common boundaries differ based on the shape of the land parcels. Adjacent blocks can be defined according to the road networks that are common boundaries. Therefore, the data structure of blocks and parcels for GA can be established in two layers of blocks and parcels in our project. As mentioned above, the spatial pattern of irregular blocks and parcels can be adopted in CA simulation because they have a neighbour data structure similar to the basic characteristics of grid data. However, an indicator reflecting shape should also be considered in the simulation model.

Many CA studies regarding urban growth simulate the spatial pattern as growing from a small seed area to the whole city. However, blocks and parcels are artificial boundaries from planning drawings. In this study, the simulation cannot cross the boundary of an urban district. Moreover, the formation process of land use is simulated, but no urban sprawl phenomenon or birth and death of blocks and parcels are necessary. Thus, the data structure for simulation can be edited using GIS as irregular polygon layers that represent blocks and parcels.

2.2 Construction of a simulation model with planning condition parameters

Because planning conditions including land use zoning, front street and parcel position have significant impacts on the spatial distribution of land use (Rachi and Kawakami, 2000), these planning conditions should be taken into account in the simulation model. In the simulation, we divide land use into four types: residential, commercial, industrial and unoccupied parcels. We assume that each parcel has the potential to become any type of these land uses, which are defined as quantity variables indicating different states of a parcel that is consistent with different types of land use. The value with the max state among four types of land use in each parcel is estimated as the simulation result, and the type of land use is assigned to the parcel based on a potential-based CA model with if-then rules.

In the initial step of simulation, all parcels are unoccupied but input with the initial state of each type of land use that will develop under the influence of planning conditions, neighbours, and new land use demand in the urban district. The simulation should represent the formation process of land use in parcels, and the land use change between different types of land use.

2.3 Validation of simulation model through an analysis of land use patterns

To investigate the impact of planning conditions, we examined land use patterns that are ratios of different types of land use and their spatial distribution in urban spaces. Because the irregular shapes of land parcels are randomly planned, it is necessary to examine their probability distribution theoretically. For validation of simulation model in this stage, we try to use a virtual space with regular land parcels so that parameter behaviours can be checked without the influence of the random shape of irregular polygons.

The percolation model can be utilized to check if the simulation model satisfies CA theoretically. The percolation probability has a causal relationship with the size and number of clusters whereby validation of the simulation model can be carried out through the outputted spatial distribution of land use patterns. With much circumstance, occupied parcels percolate on an urban space based on a prescribed transition rule whereby the spatial distribution of occupied parcels generates land use patterns in simulation. By defining the ratio of occupied parcels as the percolation probability, the spatial distribution of occupied parcels can be investigated via the size and number of clusters according to percolation theory.

However, because the urban space is composed of irregular polygons, even if we erase the space between streets, the urban district will not become a space with an orderly matrix of cells. Here, we have to assume that percolation model is also available for testing CA simulation using irregular polygons.

2.4 Simulation of land use patterns in a real urban area

Even though the simulation model seems to provide a good fit with the CA in theory, this does not mean that it will work in planning practice. A study area was chosen for calibration of the model in which a land readjustment project was carried out. We investigate the land use change of each parcel respectively. After simulation, the ratio of each type of land use, and the spatial distribution pattern of clusters based on the percolation model in the real urban area is compared with those of simulation result.

3. Establishing a concept model

We establish the concept model for land use state of each parcel, in which a parcel and its neighbours are considered as geographic automata. In the simulation model that has the following expression:

$$X^m(t+1) = f(X^m(t), NX^m(t), De^m(t), Tr^m(t), p^m), \quad (1)$$

where $m \in M, M = \{R, C, I\}$,

the type *m* of land uses is classified into residential, commercial and industrial use, which are represented respectively as *R*, *C* and *I*. The parcel state $X^m(t)$ in each step *t* decides the state $X^m(t+1)$ in next step *t+1*. However, the state $X^m(t)$ is of a continuous quantity that is calculated by equation (1) but the type of land use *L(t)* is a discrete quantity that is decided by transition rules as described later.

For simulating land use change in urban partitions, not only neighbour state $NX^m(t)$ but also planning conditions P^m reflecting the influences of land use zoning, front road and parcel shape are taken into account. To reflect a bottom-up land use demand and supply process, we add $Tr^m(t)$ as the influence from the internal economic for simulating the land use conversion phenomenon between different types of land use in each parcel, and $De^m(t)$ as the influence from the external economic for simulating the increasing and decreasing demand of each type of land use.

3.1 Planning conditions

As described above, the spatial distribution of land use types is greatly affected by planning conditions (Rachi and Kawakami, 2000). Thus, we use parameters of planning conditions for controlling the state in its entirety as follows:

$$P^m = \left(\frac{1}{3}\sum_{j=1}^{3} P_j^m\right)^q = \left(\frac{P_1^{mu} + P_2^{mr} + P_3^{mc}}{3}\right)^q, \quad (2)$$

$$q = 2\frac{\sqrt{\pi a}}{p}; \quad (3)$$

The parameter *mu* represents land use zoning, *mr* represents front road, and *mc* represents parcel position, whether the parcel is positioned in the corner of a block or not. Furthermore, the parameter *q* is employed for controlling the impact from planning conditions based on the different shapes of irregular polygons, which is proposed in the research report of Maniruzzaman et al. (1994). Parameter *a* is the area of the parcel and parameter *p* is the peripheral length of the parcel. However, the shape of irregular polygons is formed randomly in different urban districts, which makes them difficult to analyse theoretically in this paper. Thus, we focused on the influence of planning conditions designated for irregular parcels.

3.2 Neighbourhood

The influence from neighbours is normally considered in the state of each parcel. Thus, for a parcel in a block, the adjacent parcels were considered neighbours according to the Moore neighbourhood. Moreover, even though some blocks are separated by streets, they still influence each other with regard to land use. As described in equation (4):

$$NX^m(t) = \Delta x_i^m(t) + \Delta x_B^m(t), \quad (4)$$

$NX^m(t)$ is the state of neighbour calculated for different type *m* of land uses. The state of the neighbours is the sum of neighbour parcels' quantity $\Delta x_i^m(t)$ and neighbour blocks' quantity $\Delta x_B^m(t)$, which are shown as follows:

$$\Delta x_i^m(t) = G^m \bullet \left\{ \frac{1}{N_k(t)} \sum_{k \subset \Omega_i; k \neq i} x_k^m(t) - x_i^m(t) \right\}, \quad (5)$$

$$\Delta x_B^m(t) = G^m \bullet \left\{ \frac{1}{N_b(t)} \sum_{b \subset \Omega_B; b \neq B} x_b^m(t) - x_B^m(t) \right\}. \quad (6)$$

Accordingly, *B* is the block in which parcel *i* is located, and $X^m_B(t)$ is average of the states of all parcels in block *B*. Parcels *k* or blocks *b* represent the neighbour parcels and blocks. To control the degree of a neighbours' potential in simulation, a parameter G^m was employed respectively according to different type *m* of land uses.

3.3 Land use demand

A city and its urban districts are economic entities. For a bottom-up allocation process for land use demand, we considered the total amount of demand allocated in the simulation area as being decided by all land owners collectively. Using the state of each parcel, the amount of external land use demand that can be allocated is simulated based on the capacity or limitations of the supply-side, depending on the total parcel number *n*. Accordingly, the average state of all parcels is employed for evaluating the potential of demand allocation in each parcel. This can be seen in the model of Takizawa et al. (2000), shown in equation (7):

$$De_i^m(t) = \frac{GT^m \cdot x_i^m(t) \cdot \frac{\sum_{j=1}^{n} x_j^m(t)}{n}}{1 + \frac{\sum_{j=1}^{n} x_j^m(t)}{n}}; \quad (7)$$

$De^m(t)$ reflects the state of external land use demand, which has an impact on demand-side quantity in the state of each parcel. We used GT^m to control the state for demand allocation. If GT^m has a negative value, demand is decreasing.

Even though land use conversion from one type to another does occur, it is considered a relatively stable phenomenon in a real urban district. The land use type with the maximum state in one parcel will decide the parcel's land use type; thus, the adjustment of states between different types of land use will contribute to the improvement of land use conversion. That is, the inflow or outflow of the states between different types will control the land use conversion phenomenon. As shown in equation (8):

$$Tr_i^m(t) = \frac{D^m \cdot x_i^m(t) \cdot x_i^{m\_in}(t)}{1 + x_i^{m\_in}(t)} - \frac{S^m \cdot x_i^m(t) \cdot x_i^{m\_out}(t)}{1 + x_i^m(t)}, \quad (8)$$

$Tr^m(t)$, as part of the total state of one parcel, flows in from *m_in* type of land use and flows out to *m_out* type of land use controlled respectively by parameters D^m and S^m. In urban areas, the parcels occupied by the industrial use in urban areas are gradually replaced by the residential use whereby more parcels of the commercial use are necessary for the increasing residents; meanwhile commodity production is necessary for the increasing commercial services. Thence, the land use conversion phenomenon is

I->R->C->I. If the type *m* is *R*, *m_in* is *I* and *m_out* is *C*. Actually, even though there are numerous patterns of land use conversion, only pattern *I->R->C->I* is employed in this project.

3.4 Transition rule

As a whole, the total state of a parcel is expressed by equations (9):

$$x_i^m(t+1) = \left(x_i^m(t) + \Delta x_i^m(t) + \Delta x_I^m(t) + De_i^m(t) + Tr_i^m(t)\right) \cdot \left(\frac{1}{3}\sum_{j=1}^{3} P_j^m\right)^q, \qquad (9)$$

which includes the impacts from planning conditions, parcel neighbourhood, and land use demand.

When simulation starts, the initial land use type is set as 0, which means unoccupied. However, the initial state is then assigned by a random value between 0-1 that can be seen as the households' trends. The transition rule employed in the simulation is shown as equation (10):

$$L_i(t+1) = \begin{cases} 0, & if \quad \sum_{m \in M} x_i^m(t+1) \le \zeta_{\min}, \\ l, & if \quad \sum_{m \in M} x_i^m(t+1) \ge \zeta_{\min}, L_i(t) = 0 \quad and \quad x_i^l(t+1) = \max(x_i^m(t+1)), \\ L_i(t), & if \quad \zeta_{\min} \le \sum_{m \in M} x_i^m(t+1) \le \zeta_{\max} \\ l, & if \quad \sum_{m \in M} x_i^m(t+1) \ge \zeta_{\max} \quad and \quad x_i^l(t+1) = \max(x_i^m(t+1)) \end{cases} \qquad (10)$$

where $l \in M, M = \{R, C, I\}$.

Variable ζ is defined as a threshold for deciding whether a parcel will be occupied or not. When the sum of states of a parcel is larger than ζ_{min},, the parcel is occupied by the type of land use with the maximum state. If the sum of states of a parcel is between ζ_{min} and ζ_{max}, the parcel will keep its current type. Finally, when the sum of states of a parcel is larger than ζ_{max}, the parcel is changed to the type of land use with the maximum state.

To analyze the influence from planning conditions configured on the simulation space, we check how the parameters of planning conditions work with other parameters in the simulation process and validate the simulation model by checking the simulated land use patterns.

4. Planning conditions and states in the simulation process for a virtual urban space

To determine how the equations listed in the last section will act in the simulation, we examined how the state of each component will change theoretically through a computer experiment. The computer experiment was conducted with the base parameters shown in Table 1; one step in the simulation is two months, and 100 steps are about 16 years, which is the average number of years that the land use formation process takes in land readjustment projects in Japan. In this experiment, we wanted to verify the influence of planning conditions on the state in the simulation process.

As described above, a virtual urban district (Figure 1) was created for model validation, with only one type of land use zoning and one street network, which consists of one main street, one collector street, and many neighbourhood streets. The parcels are homogeneous and allocated regularly in equable blocks, all of which have a shape parameter *q* of about 0.89. This is close to the parameter *q* of the most common shapes of land parcels in real urban spaces, where the average value of *q* is around 0.84 and the standard deviation is around 0.6 (Maniruzzaman et al., 1994).

Table 1. Basic parameter settings.

	Parameters	*m=R*	*m=C*	*m=I*
Land use zoning	P_1^m: land use zoning (quasi-industrial district)	1.0000	1.0000	1.0000
Front road	P_2^{m1}: main street	0.9000	1.1000	1.0000
	P_2^{m2}:collector street	0.9000	1.0000	1.1000
	P_2^{m3}:neighbourhood street	1.0400	0.9100	0.9500
Position	P_3^{m1}:corner	0.9000	1.1010	0.9990
	P_3^{m2}:nocorner	1.0210	1.0000	0.9950
Land transition	D^m:parameter of transition from other use	0.0010	0.0010	0.0010
	S^m:parameter of transition to other use	0.0010	0.0010	0.0010
Land demand	GT^m:parameter of land demand	0.0500	0.0500	0.0500
Neighbour impact	G^m:parameter of neighbour impact	0.0100	0.0100	0.0100

Note: Land use zoning is defined as a quasi-industrial district where all land use types are permitted equitably; thus, the parameters are set as 1.

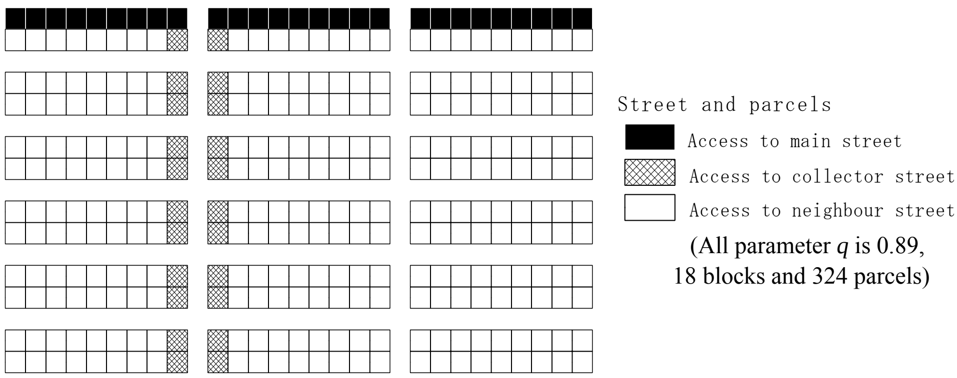


Figure 1. The simulated virtual district, configured with planning conditions.

4.1 Planning conditions and the total state

As shown in Figure 2, the average residential state of all parcels increased from step 1 to 100. Coincidentally, the standard deviation also increased, and the states of all parcels in the virtual district became more and more varied. The state is composed of the impacts from neighbouring blocks and parcels, as well as land use demand. In addition, the averages of states for commercial and industrial use have the same trend as those of the residential state. It is possible to control the speed of growth of the land use state if one of the parameters regarding land use zoning, front road or the position of the land use type is adjusted in the base parameter set. This indicates that planning condition parameters can control the state of different types of land use in the simulation model, as shown in equation (9).

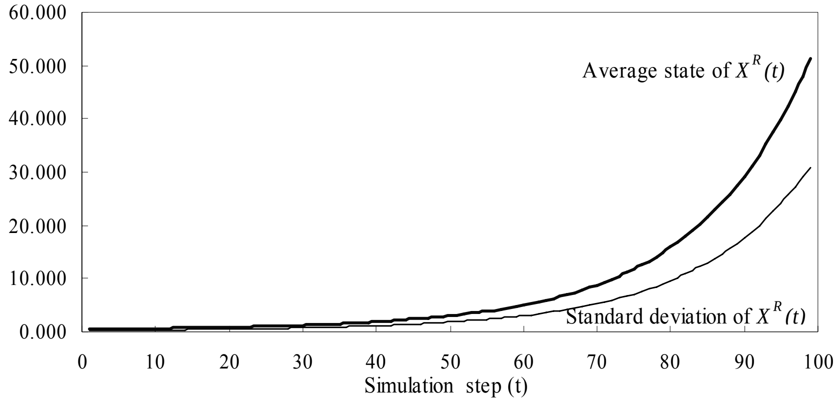


Figure 2. Average simulation residential state $X^R(t)$.

4.2 Planning conditions and neighbourhood

As shown in Figure 3, the neighbour component $NX^m(t)$ of residential, commercial and industrial states were plotted together. The positive impact of the residential state is the highest and the commercial state is the lowest among the three types of land use. This is due to the fact that the impact from neighbourhood is measured according to the subtraction of a parcel's state and the average of its neighbour state. With much circumstance, the figure shows that $NX^C(t)$ decreased gradually while $NX^R(t)$ increased because the number of neighbour streets is higher than that of the main street, and accordingly, because the commercial state has priority over the residential state. Coincidentally, the parameter of collector streets contributed to the industrial state, as shown in Table 1. However, there is only one collector street in the district, and $NX^I(t)$ also decreased. Therefore, the parameters of the front road and parcel position configured for the virtual urban space markedly influenced the neighbour state in the simulation process.

Otherwise, the graph can also display a complicated periodic wave if we respectively change the parameters of different land use types to adjust the impact from the neighbourhood.

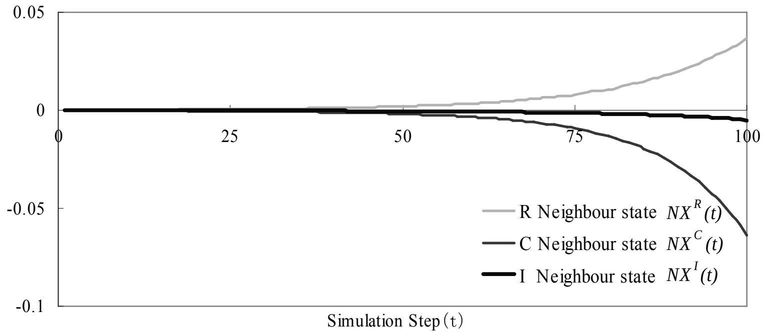


Figure 3. Average neighbour state NX^m (t), including blocks and parcels.

4.3 Planning conditions and land use demand

The influence of planning conditions on land use demand is difficult to observe because the land use demand component is calculated according to the average state of the whole simulation space, as well as the state of the parcel itself. However, because the planning condition parameters control the state by a multiplication operation, the influence of planning conditions on land use demand is part of the influence on the total state described in section 4.1.

As the state $X^R(t)$ increases, the external demand $De^R(t)$ also increases, as shown in Figure 4. Demand can be controlled by adjusting the parameter GT^R, and increases if the GT^R parameters are defined as a positive number. Conversely, if the parameter is defined as a negative number, demand will decrease.

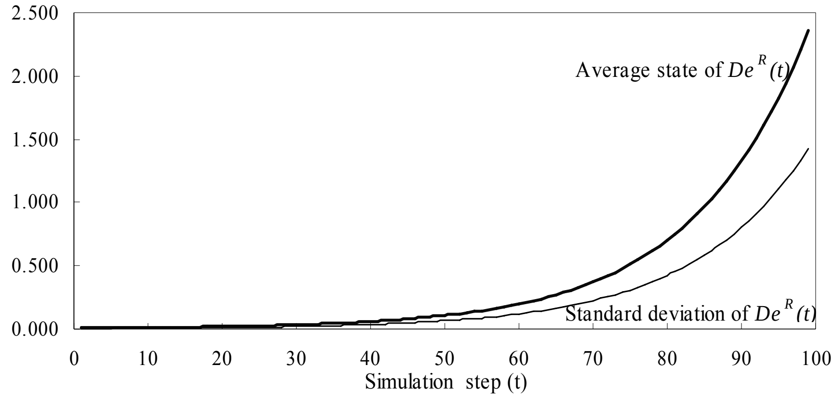


Figure 4. Average state for external land use demand $De^R(t)$.

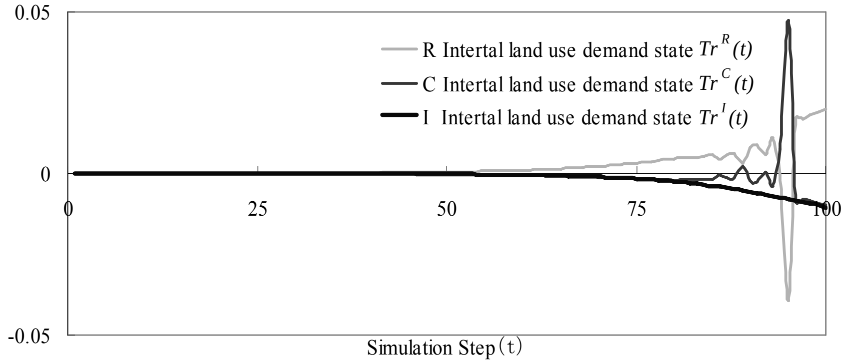


Figure 5. Average state of internal land use demand $Tr^m(t)$.

To clarify the internal demand of land use conversion, the simulation considers the transition of states between three types of land use, in which the conversion pattern is *I->R->C->I* as described in section 3.3. Based on the set of base parameters, the change of $Tr^m(t)$ is plotted in Figure 5 where $Tr^I(t)$ gradually decreases, while $Tr^R(t)$ and $Tr^C(t)$ change in complicated periodic waves, as state quantities for the residential state and the commercial state are exchanged within the parcel.

Based on the base parameter set, the state of land use demand is limited to such an extent that it has no notable impact on the total state; therefore, there is no significant land use conversion phenomenon in the simulation.

As a result, planning conditions influence the state in two ways: direct control over the total state in the simulation model and indirect control through the neighbourhood state configured for the urban space in the simulation process. However, the state is not the final output of simulation; the model should be validated through analysis of the spatial distribution of land use patterns output, as described in the next section.

5. Model validation based on land use patterns in a virtual urban space

For validation of the simulation model, we examined land use patterns that are ratios of different types of land use and their spatial distribution. In this project, the shape indicator of irregular land parcels shows the characteristics of each parcel, and is employed to control the influence of planning conditions configured on the parcel itself. However, it is difficult to analyse the probability distribution of q without enough samples, which differs randomly in different real urban districts. We employed the same virtual space simulated in section 4.

5.1 Ratios of different types of land use as aggregated simulation output

Land use type is outputted through the transition rule, employing an if-then process which is aggregated as ratios of each type of land use shown as Figure 6, based on the basic parameters set.

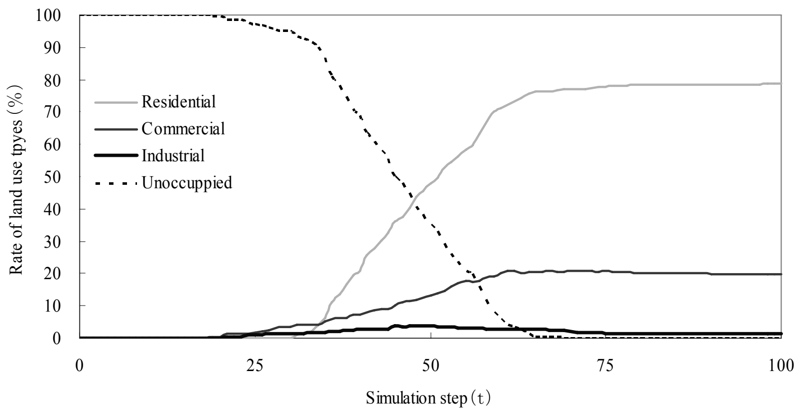


Figure 6. Simulation output with basic parameters.

5.1.1 Parameter behaviours of planning conditions

The parameters of planning conditions include land use zoning, front road and parcel position for each type of land use. As shown in Figure 7, the parameter of residential use defined for land use zoning is adjusted to 1.08, which is larger than 1 in the base parameter set. Correspondingly, the ratio of residential use became larger than that plotted in Figure 6. Increasing the residential parameter produced more parcels in which the residential state became the maximum state among the three types of land use state.

Thus, the parameters of land use zoning had a significant influence on the ratios of different types of land use in the simulation.

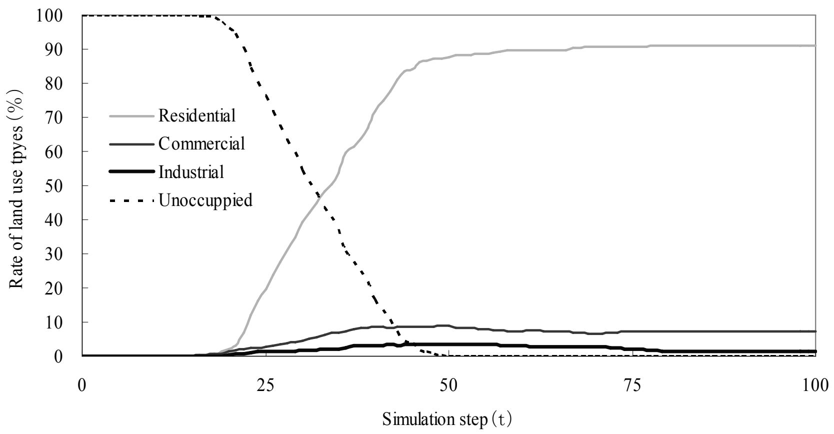


Figure 7. P_1^R=1.08 (compared to base parameter set P_1^R =1).

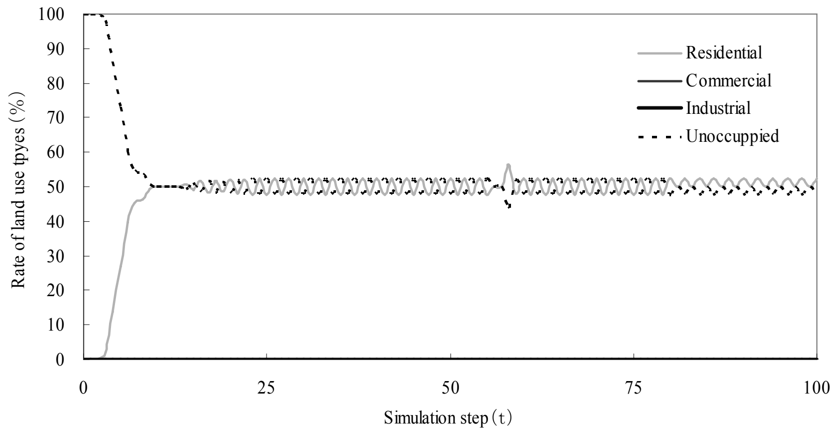


Figure 8. G^R=150 (compared to base parameters set G^R =0.01).

5.1.2 Parameter behaviours of neighbourhood

As shown as Figure 8, if we set the neighbour parameter G^R for residential use as 150 larger than the number of the base parameter, the simulation will produce two periodic waves of residential and unoccupied use. These waves emerge because the neighbour residential states are subtracted quantities from the average residential state of the neighbourhood, which will decrease if the residential state of the centre parcel itself becomes larger than the average residential state in the neighbourhood. Therefore, the neighbour residential state enhances or diminishes the residential state of the centre parcel; thus, there is a balance between the centre parcel and its neighbours. These values thus reach a stable periodic change in the ratio of residential use in this simulation. However, we should note that this complicated periodic change is indirectly influenced by neighbour states, which are in turn based on planning conditions.

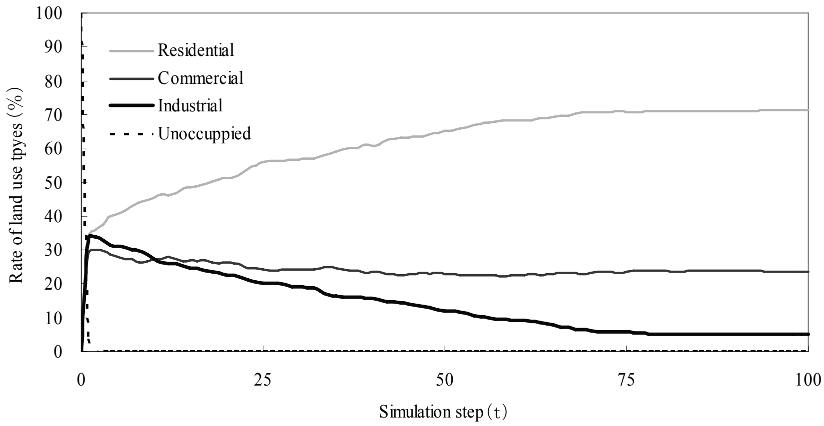


Figure 9. GT^m=20 (compared with the base parameters set GT^m=0.05).

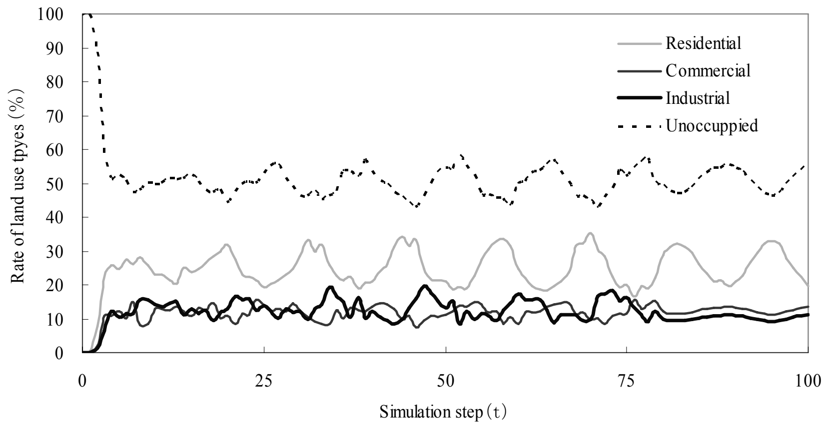


Figure 10. D^m=S^m=10 (compared with the base parameters set D^m=S^m =0.01).

5.1.3 Parameter behaviours of land use demand

As shown in Figure 9, the external demand parameter GT^m is increased from 0.05, used in the base parameter set, to 20. Thus, the three states of land use were larger than the thresholds in the earlier stage, and land use types were outputted earlier in the simulation. However, while the simulation was processing, states increased, becoming larger than the external demand states. Therefore, the parameters of planning conditions and neighbourhood were felt, and the ratios of different types of land use differed, as plotted in Figure 9.

The internal demand parameter controls the transition of a parcel's internal states in the simulation, which can be recognized as a competitive response to external economic growth in land on the supply side. When the parameter D^m and S^m were set as 10 as shown Figure10, the land use conversion was well reproduced. Thus, the parameters of land use demand were very important to control the formation process in the simulation, reflecting the ratio of change in different land uses for various time steps.

5.2 Land use pattern and percolation model

Our simulation is an approach for visualising the spatial distribution of land use patterns. To confirm spatial distribution using the percolation model, we divided the parcels into occupied and unoccupied parcels and verified the spatial patterns for different simulations steps separately through clusters and percolation probability. Concretely, the ratio of occupied parcels can be used as percolation probability, the occupied parcels that connected with each other can be aggregated as clusters, and the number of parcels in one cluster can be seen as cluster size. The street network is removed when calculating cluster sizes.

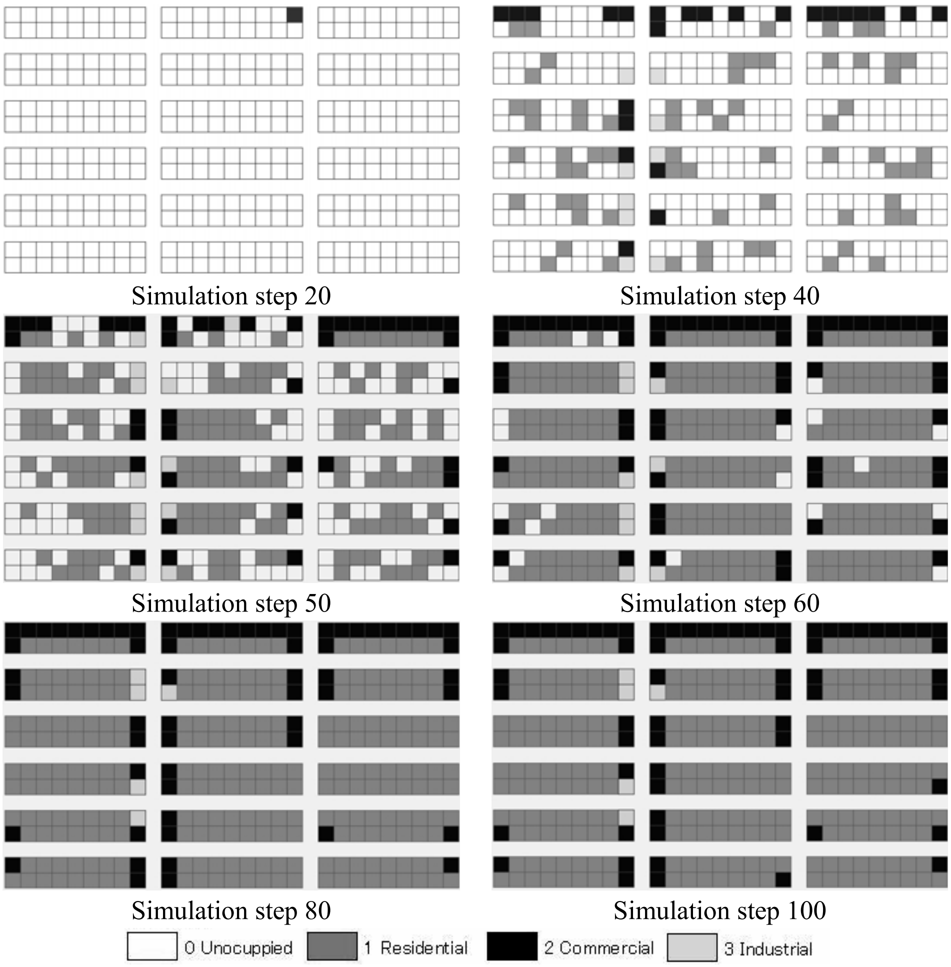


Figure 11. Simulation spatial patterns.

5.2.1 Percolation of occupied parcels and planning conditions

In the simulation, the occupied parcels percolate on the virtual district gradually within 20-60 steps (Figure 6). The spatial distribution of the occupied parcels for several different steps were visualised using GIS, and are shown in Figure 11. The transition rule based on the states of each parcel has significant impact on the ratio of occupied parcels, namely percolation probability. Particularly, it is apparent that the spatial distribution of residential and commercial use parcels has been significantly affected by both the direct and indirect influences of planning conditions. Regarding the direct influence, only one type of land use zoning, which controls the ratios of different types of land use in the front road and parcel positions with the parameters of planning conditions, was configured. The indirect influence factor was the change in spatial distribution of states of neighbour blocks and parcels.

Table 2. Clusters and percolation phenomenon.

	Occupied parcels					
Cluster size	Sim20	Sim40	Sim50	Sim60	Sim80	Sim100
1	1	17	7			
2		5				
3		1				
4		2				
5		1				
6		2				
7		1				
8						
9						
10						
11		1				
12						
22-		1	2	1	1	1
Cluster number without road	1	31	9	1	1	1
Percolation probability (Ratios of occupied parcels)	0.3	31.2	64.8	94.1	100.0	100.0

5.2.2 Model validation through percolation probability and cluster

As usual, the bond percolation model has a general characteristic with percolation probabilities of 0, 0.25, 0.5, 0.75 and 1, which are always accompanied with the number of clusters of 0, 25, 8, 2, and 1. In this simulation, the probability is decided by a transition rule, which is an if-then process defined in equation (10). As shown in Table 2, we presented the cluster number, cluster size, and probability. If we check the cluster numbers and probabilities in Table 2, the simulation result can be seen as being very similar to the bond percolation model.

However, if we check the different types of land use, the parameter set utilized in simulation improves the residential use within the neighbourhood street, and improves the commercial use along the main street and collector street. As shown in Figure 11 and Table 3, the probabilities of residential use are higher than those of commercial use. Consequently, the probabilities of industrial use are limited to 1.5-3.7%, and those of commercial use are within 7.4-20.1%. They are separated by the residential use, and certainly generated more clusters in simulation in comparison to the characteristic of the bond percolation model. However, when the probability of residential use is low in steps 40 and 50, the number of clusters increases compared to the bond percolation model, as shown in Table 3. For validation of the simulation model, a more sophisticated percolation model that can be applied for different types of land use remains a possibility for further research in the future.

Table 3. Spatial distribution of land use pattern.

	R				C				I			
Number of adjacent lots	Sim40	Sim50	Sim60	Sim100	Sim40	Sim50	Sim60	Sim100	Sim40	Sim50	Sim60	Sim100
0	28	19	1		8	15	14	8	7	8	5	3
1	7	4			4	5	9	11	1	2	2	1
2	6	4	1		1	1		1				
3	2	2	1			1						
4		3			1			1				
5		1										
6		3	2	2								
7		3										
8		1	1	1								
9		1										
10		1				1	3	2				
11		1										
12			3									
13			6	4								
14			3	1								
15			2	7								
16				1								
17				2								
Total number	43	43	20	18	14	23	26	23	8	10	7	4
Ratios of land use types	21.0	47.8	71.3	78.7	7.4	13.3	20.1	19.8	2.8	3.7	2.8	1.5

As a result of our simulation, we can conclude that the planning conditions configured on the urban space play an important role on the ratios and spatial distribution of different land use types. Land use demand parameters have significant influences on the formation process of land use in simulation. Otherwise, cluster sizes and their probabilities closely match the percolation model if only clusters of occupied parcels are considered.

6. Simulation of land use patterns on a real urban space

In this section, we wanted to calibrate the model with a real urban district. We chose a study area in Kanazawa City, Japan. The grey area in Figure 12(a), planned as a quasi-industrial zone, was used for the simulation.

6.1 Parameter settings and simulated ratios of land use types in a real urban space

As shown in Figure 12(a), there is a main street and a collector street in the study area, where a land readjustment project was carried out in 1969, and the formation process of land use from 1969 to 1992 is shown in Figure 13. With regard to the irregular parcels in the real urban space, a histogram of the shape indicator q of the irregular polygons in Figure 12(b) indicates that the pink number is 0.8-0.9. This signifies that most of the polygons have a shape similar to that of a rectangle. In addition, the parameter values of planning conditions vary subtly with the shape indicator q in the real urban space as shown in Table 4.

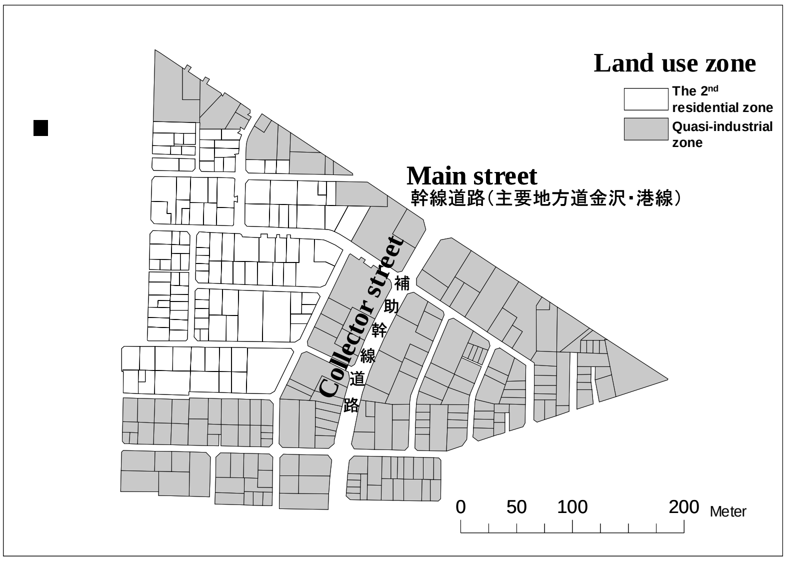


Figure 12(a). Study area (grey area = simulation area; 188 parcels, 14 blocks).

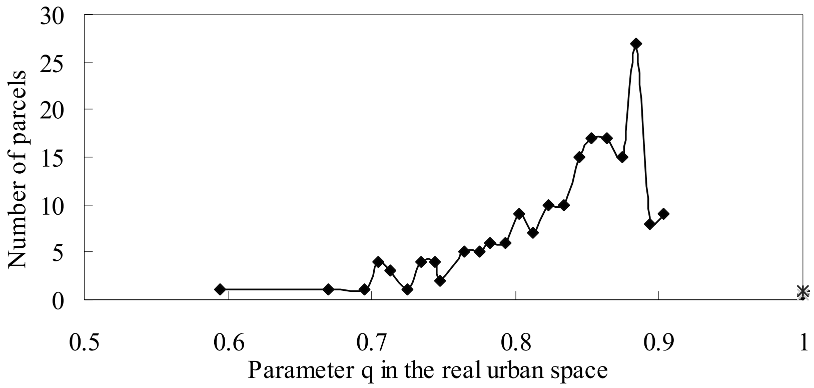


Figure 12(b). Histogram distribution of parameter *q*.

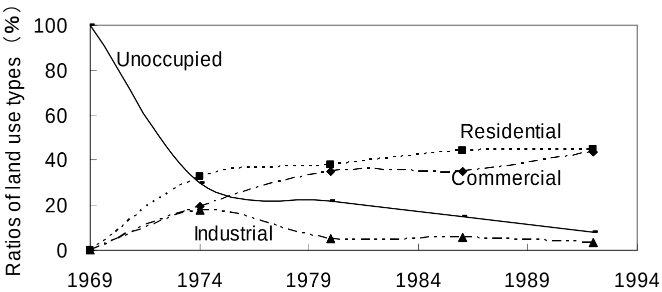


Figure 13. Formation process of land use in the real district.

Table 4. Parameters of planning conditions and shape indicator q.

P_1^m: Quasi-industrial district							
P_2^{m1}: Main street; P_3^{m1}: corner				P_2^{m2}: neighbourhood street; P_3^{m2}: nocorner			
q	0.590	0.800	0.910	q	0.590	0.800	0.910
P^R	0.960	0.946	0.939	P^R	1.012	1.016	1.018
P^C	1.039	1.053	1.061	P^C	0.982	0.976	0.973
P^I	1.000	1.000	1.000	P^I	0.989	0.985	0.983

Table 5. Simulation parameter set.

	Parameters	$m=R$	$m=C$	$m=I$
Land use zoning	P_1^m: land use zoning (quasi-industrial district)	1.0000	1.0000	1.0000
Front road	P_2^{m1}: main street	0.9000	1.1000	1.0000
	P_2^{m2}:collector street	0.9000	1.0000	1.1000
	P_2^{m3}:neighbourhood street	1.0400	0.9100	0.9500
Position	P_3^{m1}:corner	0.9000	1.1010	0.9990
	P_3^{m2}:nocorner	1.0210	1.0000	0.9950
Land transition	D^m:parameter of transition from other use	0.0451	0.0451	0.05010
	S^m:parameter of transition to other use	0.0451	0.0451	0.0500
Land demand	GT^m:parameter of land demand	0.0301	0.0301	0.0301
Neighbour impact	G^m:parameter of neighbour impact	0.0500	4.0000	3.0000

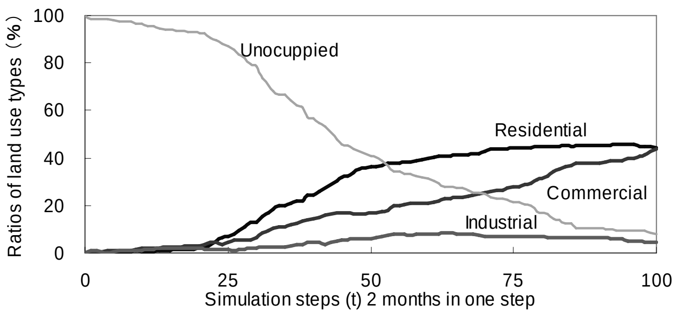


Figure 14. Simulated land use formation process.

The parameters of planning conditions employed in the simulation are listed in Table 5. The parameters of land use zoning were all set as 1.0000 because a quasi-industrial district in Japan is allowed the greatest number of land use types. With respect to the parameters of the front road and parcel position, we use the same parameters as those in the base parameter set. In the simulation, one step was calculated as two months, and 100 steps approximated the period 1969-1992. The simulation process (Figure 14) is not exactly the same as the real process, but is relatively similar. The ratio of different types land use is very well controlled by planning conditions, such as land use zoning parameters in the simulation process. The parameters of land use demand were adjusted so that the formation process of land use change could be reproduced as a stable line similar to that in real situations. However, the problem here is that the parameters of land use demand were the same for all simulation steps, which were not adjusted according to real situations of the land use demand during 1969-1992. Careful adjustment of demand parameters for different periods may thus improve simulation results, and remains a topic for further research.

6.2 Spatial distribution of land use patterns in the real urban space

Next, we verified whether the simulation output was similar to that of the real urban space. As shown in Table 6, the simulated ratios of different land use types based on the parameters set are well reproduced and comparable to the ratios in the real district. We compared the spatial pattern between the simulation result and the real district. The size and number of adjacent parcels, measured as cluster size and number, are almost the same as those in the real city. As such, it can be said that the simulation output and the real spatial pattern are very similar to each other.

We consider that the *R*, *C*, *I* and unoccupied land use types have their own percolation probabilities, as shown in Table 6. However, the number of land use types per cluster does not display a stable relationship with the percolation probabilities shown in Table 6.

Table 6. Comparison of spatial land use patterns.

	R		*C*		*I*		Unoccupied	
Size of adjacent parcels	Real	Simulated	Real	Simulated	Real	Simulated	Real	Simulated
0	6	5	11	9	3	0	6	8
1	3	5	3	6	0	2	0	2
2	1	3	4	2	0	0	0	1
3～5	4	2	3	4	1	1	2	0
6～8	2	2	2	2	0	0	0	0
9～11	2	1	1	0	0	0	0	0
12-	1	1	1	1	0	0	0	0
Total number	19	19	25	24	4	3	8	11
Parcel number	84	83	82	82	7	8	15	15
Ratios of land use types	44.7	44.1	43.6	43.6	3.7	4.3	8	8

The spatial pattern of the simulated space and the real urban space are compared in Figure. 15; results indicate that the patterns have a high degree of congruence. The figure also indicates that the parameters of road network and parcel positions have a large impact on the spatial distribution of land use types. We can conclude that the real city has the same characteristics as the simulated result based on the parameter set of planning conditions designated for the urban space. Otherwise, the number of simulated parcels of different land use types along the main and collector streets excessively reflects the influence of planning conditions, which are a slight different with the situation in the real urban district as shown in Figure 15.

	Total	Front road	
		Main street	Collector street
Block	14	4	5
Parcel			
Residential	84	5	4
Commercial	82	19	21
Industrial	7	0	1
Unoccupied	15	1	1
All parcels	188	25	27

Residential use Commercial use
Industrial use Unoccupied

(a) Real spatial pattern (quasi-industrial district)

	Total	Front road	
		Main street	Collector street
Block	14	4	5
Parcel			
Residential	83	0	0
Commercial	82	25	19
Industrial	8	0	8
Unoccupied	15	0	0
All parcels	188	25	27

Residential use Commercial use
Industrial use Unoccupied

(b) Simulated spatial pattern (quasi-industrial district)

Figure 15. Comparison of spatial patterns between real space and simulation.

7. Alternatives -- scenario analyses based on different planning conditions

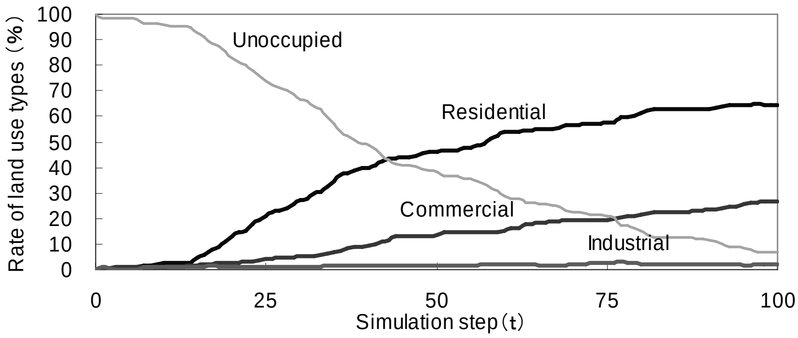
To address the land readjustment redevelopment project in the real study area, we proposed alternative methods address land use zoning and its street network. To use this simulation model in planning practice, the possibilities of scenario analysis are shown here for simulating different land use zoning alternatives. Certainly, if we replan the street network, the simulation will reproduce different results based on different infrastructures and different land parcels in the study area. Moreover, if we reset the parameters for the front road and position of land parcels, the simulation will produce a different result. Here, for the purpose of presenting the possibilities of scenario analysis, we conducted a computer experiment for alternative land use zonings. The scenario analysis can be conducted by changing the parameters only.

As shown in Table 7, the alternatives are planned as types of land use zonings that differ from the real plan of the study area, in which alternative 1 is the first exclusive residential district and alternative 2 is the neighbouring commercial district. The parameters of the alternatives are set as different values within the quasi-industrial district.

Table 7. Parameters for alternatives

		Parameters	$m=R$	$m=C$	$m=I$
Land use zoning	Alternative 1	P_1^m: The 1st residential district	1.0600	0.9800	0.9600
	Alternative 2	P_1^m: Neighbourhood commercial district	1.0000	1.0500	1.0000

As shown in figures 16-17, significant differences were observed between the alternatives in the formation process of different land use types and their spatial distribution along the street network. Compared to the quasi-industrial district, alternative 1 has more residential use and alternative 2 has more commercial use. This reflects the impacts of changing the parameters for different types of land use zoning. Consequently, scenario analysis can be conducted by changing parameter sets for different planning conditions according to planners' proposals.

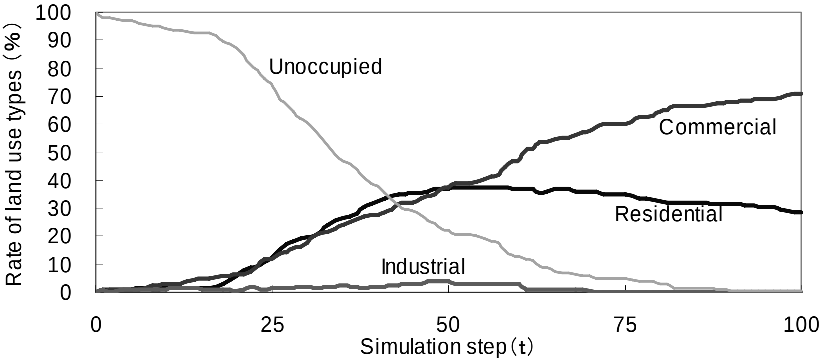


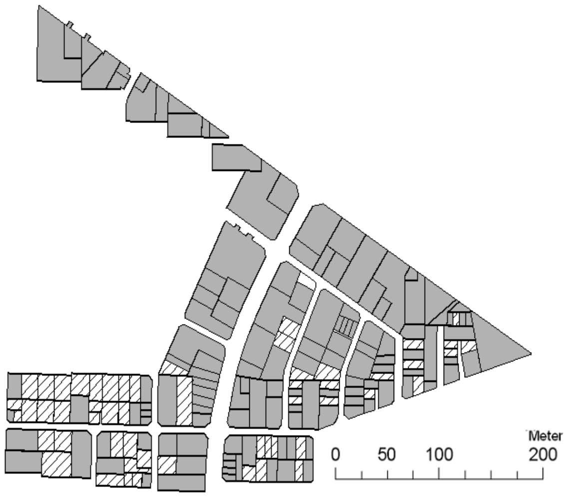
	Total	Front road	
		Main street	Collector street
Block	14	4	5
Parcel			
Residential	121	0	6
Commercial	50	25	16
Industrial	4	0	4
Unoccupied	13	0	1
All parcels	188	25	27

Residential use Commercial use
Industrial use Unoccupied

The 1st residential district

Figure 16. Simulation result of alternative 1





	Total	Front road	
		Main street	Collector street
Block	14	4	5
Parcel			
Residential	54	0	0
Commercial	133	25	27
Industrial	0	0	0
Unoccupied	1	0	0
All parcels	188	25	27

Residential use
Commercial use
Industrial use
Unoccupied

Neighbourhood commercial district

Figure 17. Simulation result of alternative 2

8. Conclusions

In this paper, we examined methods of applying CA theory to simulate land use patterns while considering the potential impacts of planning conditions, parcel neighbourhood and land use demand in an urban district. As a novel attempt at using CA for the modelling of an irregular data structure, we developed a data structure that can be easily edited in a GIS as two irregular polygon layers of blocks and parcels.

A simulation model which takes into consideration the impacts of planning conditions, parcel neighbourhood and land use demand was constructed, and the behaviours of the parameters were examined. The planning conditions were configured on each parcel of urban space, which is a spatial configuration involving a road network, land use zoning, and parcel position. Results indicated that the planning conditions were well correlated with the simulation model, indicating that they had an influence on the spatial distribution of different land use types, including a direct influence on the total state in the simulation model and an indirect influence on the neighbour state in the simulation process. Land use demand parameters also have a marked influence on the formation process of land use types in the simulation.

To validate the simulation model, the percolation model was employed to validate the spatial distribution of land use patterns simulated in the virtual urban space by analyzing cluster sizes and percolation probability. For calibration in a real urban space, a case study was conducted in a real urban district where a land readjustment project was implemented from 1969-1992. The simulation result matched the spatial pattern of the real urban district very well. The different shapes of irregular geographic automata are recognized as a random factor in our research. This is considered a factor that influences the role of planning conditions. In the simulating process, parameter values of planning conditions varied slightly with the shape indicator in the real urban space. How to definite a more sensitive shape indicator and analyse its probability distribution in real urban spaces remain as further research topics.

As described above, we simulated the land use formation process using CA, and investigated the impacts of planning conditions in particular. Our results verified the applicability of CA for this type of micro geo-simulation. However, even though the percolation model is applicable for model validation at the level of occupied or unoccupied parcels through clusters and percolation probability, a more sophisticated percolation model is required to fully verify the spatial patterns of the various land use types utilized in simulation space.

In future studies, a multi-agent system should be introduced to this simulation in order to consider households' behaviours, decisions regarding land and building use, and number of stories.

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