OBJECT-ORIENTED 3D-GIS MODEL FOR MICROSIMULATION
OF MICROSIMULATION OF URBAN POLICIES

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ABSTRACT

Urban landscape is largely affected by landuse patterns, the design of individual buildings, and the spatial harmony among these buildings. In this paper, a micro landuse forecasting model is developed and a prototype simulation system is implemented on a PC using object-oriented GIS concepts. In the forecasting model, the probability of changes in the landuse within the area of interest is calculated based on the attributes of the lots and considering the possibility of merging adjacent lots. Several measures for improving the urban landscape are suggested and tested in a case study.

1. INTRODUCTION

Urban landscape is largely affected by landuse patterns, the design of individual buildings, and the spatial harmony among these buildings. In Japan, landuse regulations of the City Planning Law and the Building Standard Law control to some extent the former two factors. However, harmonizing the spatial distribution of buildings in terms of their heights and their volumetric distribution within a block is not clearly defined.

In addition to its effects on landscape, the spatial distribution of buildings and the relationship with the open space around them is important for the following reasons: (1) preserving adequate light and air circulation for the interior and exterior of the buildings; (2) preserving space for sidewalks and parks around the buildings that can improve the amenity of the area; (3) reducing the effect of the heat island phenomena in large cities; and (4) providing buffer zones that mitigate the danger of fire propagation. In order to control this spatial distribution, several regulations are imposed on the landuse in Japan such as floor-area ratio, building-coverage ratio, setback regulations, etc. These regulations are enforced by the Urban Planning Law and the Architectural Standard Law, and are coupled with the zoning system that defines the permissible landuse in each zone. However, these regulations only specify the possible usage and upper limits of the above mentioned ratios on the level of individual buildings. Therefore, the developer is left with great freedom in choosing the usage, shape and height of the building without being concerned with the harmony with the surrounding environment. This results in poor urban landscape including disorderly distributed buildings of different shapes and heights, some of them with pencil-like shape and very small facades.

Another problem related to the floor-area ratio in Japanese cities is the under usage of land because buildings are generally too low and the actual floor-area ratio is much less than the maximum allowed ratio. This results in cities that are highly congested with small buildings and the lack of green areas and open space. In addition, this low and inefficient landuse aggravates the urban sprawl problem.

Several new regulations have been introduced to encourage the efficient usage of land by giving a bonus floor-area ratio in special cases (e.g. Comprehensive Building Design System and Specified Block System), and to encourage the development of a better landscape by adding more restrictions on the shape and height of buildings (e.g. District Plan System). However, these regulations are optional in many aspects compared with landuse regulations in other countries such as the German Legally Binding Landuse Plan (Bebauungsplan or B-plan). The B-plan of an area includes the planning of all the infrastructure facilities such as roads and sewers, in addition to the detailed landscape design of all the buildings in the area. The plan may even dictate the height and color of the buildings or the shape of the roofs in order to assure landscape harmony. The development process of such plans is based on the cooperation and negotiation among the municipal planning office, the land owners, the representatives of residents, and other public and private service institutions.

In order to simulate changes in urban landscape and to forecast the influences of new measures regarding landscape on the block level, there is a need to develop a micro landuse model that can represent the changes of individual buildings including usage, area, height, floor-area ratio, etc. In this paper, a landuse forecasting model is developed and implemented on a PC using
floor-area ratio, etc. In this paper, a landuse forecasting model is developed and implemented on a PC using object-oriented GIS concepts. It is assumed that a zone-level model can be used for the allocation of urban activities in zones that cover the entire urban area. Then, the total quantities of activities in the zone of interest are allocated to lots according to the probability of change of the landuse and based on the attributes of these lots. The possibility of merging adjacent lots is considered. Several measures for controlling and improving the urban landscape are suggested and tested in a case study.

2. REVIEW OF RELATED RESEARCH

Traditional macro landuse models use aggregate approaches, such as the gravity theory or the entropy theory, for representing the spatial interaction among zones. Microsimulation models, usually based on discrete choice theory, require large volume of data and long computation time. The data needed to establish such models are usually not available or not accessible because of the high cost needed to collect the data or the private nature of these data (Wegener and Speckerman, 1996). Recently, because of the rapid progress in GIS and the availability of digital detailed urban maps, simulation is becoming more feasible. One possible compromise to overcome the difficulties in microsimulation is to apply the micro disaggregate model only to the specific area(s) of interest, and to combine it with a macro model that cover the whole urban area under consideration. This method ensures that the spatial interaction between the area of interest and the urban area as a whole is taken into account. In addition, it is possible to control the level of detail of the input data at each zone as necessary. The area of interest in this research is the area where the landscape is to be evaluated.

Previous research related to micro landuse forecasting and landscape assessment includes the development of a simulation model based on landuse transition probability matrix for hierarchical landscape assessment in an urban area (Ikeya, 1997). The transition probability matrix in this model is estimated directly from GIS landuse mesh data, accessibility data, and other landuse regulations' data without considering the demand and supply interactions in the land market. The California Urban Futures (CUF) model is the first urban simulation model that uses the analytical power of GIS to manipulate the detailed information needed in land development (Landis, 1995). However, it does not use lot data, and does not consider the behavior of the demand side in response to land prices. More recently, UrbanSim has been developed using lot-level GIS data (Waddell, 1998). However, the location units of UrbanSim are traffic demand forecasting zones. Miyamoto et al. (1998) developed a model of detailed physical landuse patterns to represent the changes in building types and use by block units for the purpose of evaluating environmental impacts caused by transport projects and landuse regulations. This model does not consider the possibility of lots merging and the effect on the landscape. Another system has been suggested to simulate space use in downtown planning (Kaneda, 1998). Although this system has a graphical interface that shows the simulation result, the urban patterns that it can handle are limited to chess-board-like patterns.

3. MICRO LANDUSE FORECASTING MODEL

A micro landuse forecasting model for building type selection is developed in this research. The urban activities located at the zone-level can be used as control total for the lot-level allocation. For instance, an existing micro-analytical residential mobility model is available for the forecasting of housing locations according to traffic analysis zones (Hayashi and Tomita, 1989). Also, a business location model is being developed using input-output tables to establish the relationships among the economic activities and population in the urban area.

After forecasting the total quantities of activities in the zone of interest, these activities are mapped to floor-area and allocated probabilistically according to lots' attributes within the zone. The type of the landuse in the lot depends on the profitability potential of development (Landis, 1994; Waddell 1998). The developer profit is the expected revenue minus the costs of the building. This utility can be formulated as in Eq.(1)

$$U_{il} = a_i X_i - C_i$$

where $U_{il}$ is the utility of building type $i$ at a lot $l$, $X_i$ is the array representing land conditions of the lot, and $C_i$ is the total costs of the building. The land conditions of a lot include its area, the relationship with its surrounding lots and roads, landuse regulations, land price, etc. If the age of buildings is considered, then the demolition of an old building can be an opportunity for a change in the landuse or an increase in the number of floors.

Using the logit model, the probability that a lot $l$ will be used for building type $i$ is given by Eq.(2)

$$P_{il} = \frac{\exp U_{il}}{\sum_j \exp U_{ij}}$$
Start

(1) Input lots and buildings' GIS data, and total floor areas to be allocated for each landuse activity

(2) Create lot's neighborhood information

(3) Perform lot merging and update lots' data

(4) Calculate the utility and the probability of each landuse for all lots

(5) Sort lots according to each landuse probability

Select first lot

Select next lot

(6) Change lot's landuse?

Yes

(7) Create a Building object and update floor areas to be allocated

No

Yes

(8) More floor areas to allocate?

Yes

More lots?

Feed back to the macro

No

(9) Output lots and buildings' GIS data

(10) Display simulation results in 2D and 3D

Stop

Fig. 1 Flowchart of the Simulation System
4. Micro LandUse Simulation System (MILUSS)

4.1 Simulation flow

The flow of the allocation simulation process is adopted from (Landis, 1994) as shown in Fig. 1: (1) Input lots and buildings' GIS data, and total floor areas to be allocated for each landuse. (2) Create lot's neighborhood information. (3) Perform lot merging based on the probability of merging and using Monte Carlo simulation, then update lots' data. (4) Calculate the utility and the probability of each landuse for all lots. (5) Sort lots according to each landuse probability. (6) Allocate the total demand for floor area of each activity (building type) to the lots in order using Monte Carlo simulation. (7) In case that a change in a lot's landuse occurred that involves a change in the structure on the lot, a new Building object is created (the object-oriented implementation is discussed in the following section), and the floor areas to be allocated are updated. (8) The allocation process is complete when all the demands for all activities are allocated, or when all the available lots in the zone are allocated. In the later case, the information about the remaining demand that could not be allocated is fed-back to the macro model. (9) After the end of the allocation process, GIS data of lots and buildings are saved. (10) The simulation results are displayed in 2D and 3D.

4.2 Object-oriented GIS implementation

Common approaches in GIS-based urban modeling can be classified into three methods (Sui 1998): (1) embedding GIS in the urban modeling software, (2) embedding the urban modeling software in GIS, and (3) loose or tight coupling of GIS and the urban modeling software. The Micro LandUse Simulation System (MILUSS) developed in this research follows the first method. The software is developed using Visual Basic, and the GIS functions are implemented using MapObjects (Environmental, 1997b). MapObjects is a set of GIS software components that allow to represent, display, and manipulate geographical entities using standard programming languages such as Visual Basic and Visual C++ through ActiveX controls and Windows Application Programming Interface (API). The object-oriented model of MapObjects allows the state and behavior of an object to be modeled as attributes and methods, respectively. This greatly facilitates the reuse and extension of objects because object-oriented programming supports inheritance and polymorphism of the properties of available objects (Environmental, 1997b).

Fig. 2 shows the diagrams of the basic Polygon object available in MapObjects, and the new Lot object that is a special type of the Polygon object developed in this research. The attributes and methods related to an object are shown on the right-hand side and left-hand side of each object, respectively. The Lot object has all the attributes and methods of the Polygon object such as the Area attribute and the method DistanceTo for calculating the distance from the polygon centroid to another shape. It has also all the additional attributes and methods necessary for the simulation developed in this study. For example, the method MergeWith is a function that creates a new lot by merging the lot in question with one of its neighboring lots that is found by the SearchNeighbors method according to some criteria (e.g. the neighboring lot with maximum area).

The spatial analysis functions of MapObjects are used, and several new specialized functions are developed to perform the simulation. An example of the spatial analysis functions of MapObjects is the ability to use a shape for selecting other shapes that satisfy some spatial conditions. For instance, in the process of checking the possibility of merging two adjacent lots, it is necessary to check the topology of each polygon representing a lot to find all adjacent polygons. This is done by searching for shapes that share a common line segment with the polygon of the specific lot. An example of the new specialized functions developed for the purpose of this study is a function that calculates the length of the façade of a building on the road (the attribute RoadEdge of the Lot object). This function is realized by calculating the length of the common line segment between the polygon representing the lot and the adjacent polygon representing the road (a Road object). Some of the other developed objects are: the Road object, the Building object, and the Block object.

4.3 3D visualization of simulation results

In order to evaluate the landscape resulting from MILUSS, it is desirable to visualize this landscape in 3D. Although it is possible to produce photo-realistic computer graphics simulation, the level of detail needed for evaluating the volumetric landscape does not have to be very high. Especially because this evaluation is usually done by expert urban planners and designer. This visualization can be realized using the 3D extensions of GIS software such as ArcView 3D Analyst for interactive perspective viewing and 3D navigation (Environmental 1997a). However, these extensions can only extrude the polygons by the value of some attribute (in this case, extruding the sections of buildings by the height of each building) and they lack the flexibility of adding more.
details that are necessary for landscape volumetric simulation. Therefore, a special function has been developed in the GIS simulation software that creates the basic shapes of buildings by extrusion, and uses other attributes, such as the type of the roof, to add more details to the 3D buildings' model parametrically using VRML (Virtual Reality Modeling Language).

Fig. 2 Diagrams of the Polygon Object and the New Lot Object

(a) Zoning Regulations  (b) Lots' Distribution  (c) Buildings' Distribution

Fig. 3 Area of the Case Study

Fig. 4 Land Areas Percentage of Each Landuse Type
Table 1. Results of Parameters Estimation of the Lot Merging Model

<table>
<thead>
<tr>
<th>Variable</th>
<th>Parameter value</th>
<th>t value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area (m²)</td>
<td>-0.0016</td>
<td>-6.87</td>
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<tr>
<td>On-main-road dummy</td>
<td>0.79</td>
<td>2.90</td>
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</table>

Number of observations = 320
Likelihood ratio ($\rho^2$) = 0.21
Hit ratio = 65.63

Table 2. Results of Parameters Estimation of the Landuse Model

<table>
<thead>
<tr>
<th>Variable</th>
<th>Parameter value</th>
<th>t value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Parameter value</td>
<td></td>
</tr>
<tr>
<td>Area (m²)</td>
<td>Low rise</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High rise</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Commercial</td>
<td></td>
</tr>
<tr>
<td>Floor-area ratio regulation (%)</td>
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<td>On-main-road dummy</td>
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<td>On-corner dummy</td>
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<td>Land price (10,000 Yen)</td>
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<tr>
<td>Commercial constant</td>
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<tr>
<td>High-rise housing constant</td>
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<tr>
<td>Commercial constant</td>
<td>-2.27</td>
<td>-6.99</td>
</tr>
</tbody>
</table>

Number of observations = 867
Likelihood ratio ($\rho^2$) = 0.33
Hit ratio = 66.44

(a) Present Landscape
(d) Landscape in the Case of Scenario C
Fig.7 3D Representation of the Present Landuse and Simulation Result
5. CASE STUDY

5.1 Study area

The study area is at a sub-center about 10 min. from the CBD of Nagoya City. It is a commercial and mixed-use area of about 50 ha including 1173 lots. Although this area has several main roads and a subway station connecting it to the CBD, and has undergone several land readjustment projects, it still contains a large number of small old detached houses and shops side-by-side with new high-rise buildings.

Data of lots and buildings in the study area and the changes in the landuse are usually available at the city hall for official use only and are difficult to obtain. Fortunately, 1:2500 scale maps including the shape of lots and buildings are available for major Japanese cities (Zenrin 1997). These maps are updated annually in a book form, and recently in digital form, with tables of the number of floors and names of households, shops, and companies occupying most buildings. Attributes of lots and buildings were attached to these maps for the years of 1991 and 1997. Digital data are available for 1997 only. The attributes include the areas of the lots and the buildings, the number of floors of buildings, whether the building faces a main road or is on a corner or not, and the usage of a building classified as housing, commercial, office, parking, vacant land, and other uses. Landuse regulations were also added to each lot including the allowable usage, maximum height, and maximum floor-area and building-coverage ratios. In addition, land prices of 1991 at several points in the area were added. The lots where changes in the landuse occurred, including merging of lots, between 1991 and 1997 were also extracted for comparison.

Fig.3 shows the zoning regulations, the lots' distribution, and the present buildings' distribution of the study area. The two numbers on each zone in Fig. 3(a) are the percentages of the floor-area ratio and the building-coverage ratio. Fig. 4 shows the land areas percentage of each landuse type. Fig. 5 shows the floor areas distribution with respect to the number of floors. Fig. 6 shows the land areas with respect to the used percentage of the maximum floor-area ratio. It is clear from Figs. 5 and 6 that a large part of the floor areas of the housing use is in low-rise buildings, and that the used percentage of the maximum floor-area ratio is generally small.

5.2 Parameters estimation

Tables 1 and 2 show the estimated parameters of the binary lot merging and multinomial landuse logit models, respectively, based on land conditions of lots. The results are generally acceptable.

5.3 Evaluating measures for landuse control

Several scenarios are suggested for controlling and improving the urban landscape by imposing physical constraints on building heights and building-coverage ratio or by introducing a tax reduction on property ownership. The aims and conditions of each scenario are as follows:

(1) Scenario A: Imposing a minimum and maximum heights on the buildings

(2) Scenario B: Imposing a new regulation for encouraging the merging of small lots into bigger ones with a large façade on the road by a property tax reduction. The aim of this regulation is to accelerate the replacement of old small detached houses and pencil-like buildings by larger buildings with a large façade on the road.

(3) Scenario C: Imposing a new regulation that aims to decrease the building-coverage ratio. The aim of this regulation is to increase the open space between buildings.

The present and resulting landscapes in the case of scenario C are assessed visually as shown in Fig.7.

6. SUMMARY AND FUTURE WORK

A microsimulation model for forecasting the changes in landuse on the lot level is developed and implemented using a programmable GIS library on a PC. This model assumes that the choice of a specific landuse, for example high-rise commercial use, is based on the expected improve in the utility value of a lot. The utility is assumed as a function of the area of the lot, its location with respect to a main road, the floor-area ratio, and land price. The prototype simulation system is innovative in that it allows for the dynamic manipulation of the topology of the polygons representing lots and buildings. The system is implemented using an object-oriented GIS approach and used to simulate the changes in the landscape under several scenarios. Future work includes considering the effect of the age of buildings on the redevelopment process, and the effects of setback regulations on the landscape.

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