MODELLING THE DRIVING FORCES OF SYDNEY'S URBAN DEVELOPMENT (1971–1996) IN A CELLULAR ENVIRONMENT

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This paper demonstrates a flexible implementation of rules to control the simulation of urban development of Sydney from 1971 to 1996 using a cellular automata model. Five key factors, including the self-propensity for development and neighbourhood support, slope constraint, transportation support, terrain and coastal proximity attractions and urban planning support are introduced into the model in a spatially explicit format, which generated a realistic estimation of the extent and timing of Sydney's urban development. With the flexibility of rule implementation within the model, more rules can be added as new 'If-Then' statements to fine-tune the model, provided that a good understanding of the rule is maintained and accurate data are collected.

INTRODUCTION

Urban development is a significant global phenomenon and is one of the main drivers of global environmental change, which has attracted research attention. A diverse array of urban spatial models has been developed to simulate the processes and patterns of urban development. Among them, cellular automata and their application in urban modelling have been rapidly gaining favour among urban researchers.

Based on the cellular automata model of urban development developed in Liu et al. (2003), and the application of the model in the metropolitan area of Sydney, Australia (Liu et al. 2004), this paper demonstrates a flexible implementation of urban-state transition rules in the cellular automata model to control the simulation of the urban development of Sydney from 1971 to 1996. Five key factors, including the self-propensity for development and neighbourhood support, slope constraint, transportation support, terrain and coastal proximity attractions and urban planning support are implemented in the model to simulate Sydney’s urban development from 1971 to 1996.

The following section presents the model developed in Liu et al. (2003). To assess the impact of different factors on the urban development of Sydney, several transition rules are introduced into the model, resulting in five different scenarios of urban development of Sydney for the years 1971–1996. Results from the simulations enable conclusions to be established on the factors affecting Sydney’s urban development and the ability of the model to act as a planning tool for implementing ‘what-if’ urban growth scenarios.

MODEL DEVELOPMENT

Liu et al. (2003) described the development of a cellular automata model of urban development incorporating fuzzy set and fuzzy logic approaches. The model was developed based on the understanding that urban development is a fuzzy process, that is, there is no sharp boundary between
the non-urban and fully urban built-up areas (Pryor 1968; Bryant et al. 1982), and the process of urban development follows a logistic curve (Jakobson et al. 1971; Herbert et al. 1997).

Let $t_{x_{ij}}$ denote the $t^{th}$ year of development of a cell $x_{ij}$. The extent of urban development of the cell in year $t$ can be represented by a membership grade, which can be denoted by $\mu_{\text{urban}}(x_{ij}^t)$. With the understanding of the logistic curve of the process of urban development, the relationship between $t_{x_{ij}}$ and $\mu_{\text{urban}}(x_{ij}^t)$ can be represented by Eq. 1.

$$
\mu_{\text{urban}}(x_{ij}^t) = \begin{cases} 
0 & t_{x_{ij}} < 0 \\
\frac{1}{a_0 + b_0 \exp(-c_0 \cdot t_{x_{ij}})} & 0 \leq t_{x_{ij}} < n \\
1 & t_{x_{ij}} \geq n 
\end{cases}
$$

Here, $a_0$, $b_0$ and $c_0$ are parameters of the logistic function, where $a_0$ and $b_0$ are the location and scale parameters respectively, and $c_0$ adjusts how quickly $\mu_{\text{urban}}$ changes with a single unit change of the time $t$, that is, it controls the shape of the logistic curve; $n$ is the duration of the whole process of urban development in an area. The speed of urban development varies from one city to another and even from one cell to another within a city. Therefore, $a_0$, $b_0$, $c_0$ and $n$ can be defined and calibrated according to the speed of urban development of individual cities.

According to the principles of the cellular automata, the state of a cell and the states of its neighbouring cells at a previous time step determine the state of the cell in the urban fuzzy set. If a cell has a strong propensity for development and it can get support for such development from its neighbourhood, then development will occur in that cell following a logistic curve.

To determine what state a cell will be in after a certain time period, Eq. 1 can be rewritten as follows:

$$
t_{x_{ij}} = \begin{cases} 
0 & \mu_{\text{urban}}(x_{ij}^t) < 0 \\
\left(\ln(b_0) - \ln(\frac{1}{\mu_{\text{urban}}(x_{ij})} - a_0)\right) / c_0 & 0 \leq \mu_{\text{urban}}(x_{ij}^t) < 1 \\
n & \mu_{\text{urban}}(x_{ij}^t) \geq 1 
\end{cases}
$$

For each cell $x_{ij}$ in the urban fuzzy set, its membership grade $\mu_{\text{urban}}(x_{ij}^t)$ has been defined through its population density value. Therefore, the stage (or year as denoted by $t_{x_{ij}}$) of development of the cell in the urban development process can be calculated in Eq. 2. With the awareness of the current stage of development of cells in the urban development process, the grade of membership of this cell in the urban fuzzy set at another time can be computed through Eq. 1.
The cellular automata model of urban development was implemented in a GIS using ARC/INFO's Arc Macro Language. The input data illustrating actual urban development were processed using the census data from 1971 to 1996 published by the Australian Bureau of Statistics which were documented in Liu (1998). The simulated output of the model were processed and stored in GIS as grid files. Using a modified goodness-of-fit analysis approach (Liu et al. 2004), the simulation accuracies of the model were also assessed and presented.

UNDERSTANDING THE DRIVING FORCES THROUGH INDIVIDUAL RULE SETTING

Urban development is affected by numerous forces, including physical constraints, socio-economic status as well as institutional controls (Malm et al. 1966; Allen et al. 1978; Wu et al. 1998; Bell et al. 2000; Li et al. 2000; Liu et al. 2004). This section introduces a flexible approach where various factors can be introduced into the model to evaluate the impact each of the forces may have on Sydney’s urban growth, and how the urban landscape has been changing under such forces. The factors include land availability, land released or planned to be released for urban development, land contiguity as well as land accessibility represented by slope, terrain and transport networks.

URBAN NATURAL GROWTH

The cellular automata model of the urban development in Sydney first implemented the simplest rules representing the contiguity effect, that is, it concerns only the propensity of the cell itself for urban development and the support for such development it receives from its neighbourhood. This scenario of urban development was termed an urban natural growth. This development applies only to partly developed urban cells and non-urban cells that are not located in areas excluded from urban development, such as water bodies (sea, lakes and rivers), and areas reserved for various purposes under the following conditions:

For partly-urban cells,
if: a cell has a strong propensity for development and it can also get sufficient support for such development from its neighbourhood (Condition A),
then: apply the basic pattern of continued development;
else if: a cell has a strong propensity for development but it cannot get sufficient support for such development from its neighbourhood (Condition B) or if a cell does not have a strong propensity for development but it can get support for development from its neighbourhood (Condition C),
then: apply the slow pattern of continued development;
else if: a cell has a weak propensity for development and it cannot get sufficient support for such development from its neighbourhood (Condition D),
then: apply the very slow pattern of continued development.

For non-urban cells,
if: there is strong support for development from the neighbourhood (Condition E),
then: apply the slow pattern of new development.

Comparing the simulation extent of urban and non-urban areas with the actual urban extent of Sydney as defined in Liu (1998) for each of the modelled time period, it was evident that the partly developed cells had been further developed over the simulation period, many becoming

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fully urban cells. However, developments from non-urban to partly-urban or fully urban cells were extremely slow. As a result, most urban developments that occurred in the west and the southwest part of Sydney over the simulation period were not represented in the model’s results (Figure 1).

Assessing the spatial accuracy of the urban growth simulation results from 1971 to 1996, based on comparison with the actual urban development of Sydney at the same year was completed using the modified error matrix approach and Kappa analysis (Table 1). Although the overall...
agreement between the simulated urban growth and the actual extent of urban development of Sydney in 1996 was 87.1 per cent, a significant discrepancy between the two data sets exists in each category of the cell states. For instance, 3602 partly-urban cells out of a total of 47109 cells in the reference data were omitted (excluded) from the partly-urban category in the simulation results and 1072 cells committed (included) to this category incorrectly. Therefore, the omission and commission errors of the partly-urban category were as high as 77.3 per cent and 48.9 per cent respectively. A total of 3465 urban cells in the reference data were not developed as urban in the simulation results. Of these pixels, 2534 remained as non-urban and 931 developed to partly-urban, resulting in an omission error of 18.6 per cent in the fully urban category. Comparing the omission and commission errors of each category individually, it was the omission errors that were dominant in both the urban and partly-urban categories and the commission error that was dominant in the non-urban category, indicating that the model did not generate sufficient development to match the actual urban development of Sydney. Therefore, some cells were omitted from the urban or partly-urban category and committed to the non-urban category incorrectly. As such, the $K_{nat}$ coefficient was only 73.1 per cent. Even by changing the initial setting of the parameters and the balance between the transition rules, the model was not able to launch sufficient development from the non-urban cells. The discrepancy between the simulation results and the actual urban development indicated that there existed other conditions that may affect existing development and generate new development.

<table>
<thead>
<tr>
<th>Majority of simulation</th>
<th>Reference Data</th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Non-urban</td>
<td>Partly-urban</td>
<td>Urban</td>
<td>Row total</td>
</tr>
<tr>
<td></td>
<td>40973</td>
<td>3602</td>
<td>2534</td>
<td>47109</td>
</tr>
<tr>
<td>Partly-urban</td>
<td>384</td>
<td>1372</td>
<td>931</td>
<td>2687</td>
</tr>
<tr>
<td>Urban</td>
<td>7</td>
<td>1072</td>
<td>15159</td>
<td>16238</td>
</tr>
<tr>
<td>Total</td>
<td>41364</td>
<td>6046</td>
<td>18624</td>
<td>66034</td>
</tr>
</tbody>
</table>

**Producer’s Accuracy (measure of omission error)**
- Non-urban: $= 40973/41364 = 99.1\%$, 0.9\% omission error
- Partly-urban: $= 1372/6046 = 22.7\%$, 77.3\% omission error
- Urban: $= 15159/18624 = 81.4\%$, 18.6\% omission error

**User’s Accuracy (measure of commission error)**
- Non-urban: $= 40973/47109 = 87.0\%$, 13.0\% commission error
- Partly-urban: $= 1372/2687 = 51.1\%$, 48.9\% commission error
- Urban: $= 15159/16238 = 93.4\%$, 6.6\% commission error

**Overall Accuracy** = 57504/66034 = 87.1\%

$K_{nat} = 73.1\%$

Table 1
Results of the error matrix analysis and $K_{nat}$ using the 1996 urban area as the reference data and the majority state of cells within a 3 by 3 neighbourhood of the simulation result from urban natural growth as the assessed data.
Note: All data shown above except for the percentage data are total number of cells in each category.
SLOPE CONSTRAINT

The slope of land is not always a critical determining factor in whether urban development will or will not occur. The impact of land slope on urban development can be relaxed if there is a high demand for land but short supply of flat land, or if there is a high income group with people preferring to live on higher elevations to obtain good views. However, the slope factor can speed up or slow down the processes of urban development to some extent. Therefore, the slope factor was introduced into the cellular automata model of urban development of Sydney. To implement this factor, it was assumed that the transition rules implemented in the urban natural growth were based on a moderate slope condition, which was defined as a slope of 3 degrees or less. If the slope of a cell gets to a critical high level, a slow pattern of development might occur to the cell. By implementing this constraint, the previous version of the model was amended as follows (Conditions A to E as defined under Urban natural growth):

For partly-urban cells,
if: the slope is moderate,
then: apply the transition rule as set in the Urban natural growth;
else if: the slope is relatively steep and Condition A,
then: apply the slow pattern of continued development;
else if: the slope is relatively steep and Conditions B or C,
then: apply the very slow pattern of continued development.

For non-urban cells,
if: the slope is moderate,
then: apply the new development rules in the Urban natural growth;
else if: the slope is relatively steep and Condition E,
then: apply the very slow pattern of new development.

By calibrating the settings of the model's parameters with the urban area data of Sydney from 1971 to 1996, a different scenario of urban development of Sydney was generated (Figure 2 and Table 2). Compared to Scenario I, Scenario II generated more development from non-urban to partly-urban areas, which matches the actual development of Sydney better than Scenario I. However, the omission errors in the partly-urban and fully urban categories were still high, which need to be reduced.

By also including the slope constraint, the overall agreement between the simulation results and the actual urban development of Sydney in 1996 was slightly improved compared to the previous results (88.4 per cent as to 87.1 per cent shown in Table 1). However, the commission errors in each category decreased, with only 463 partly-urban cells and 280 non-urban cells in the reference data committed to urban and partly-urban incorrectly in the simulation results. With this improvement, the $K_{hat}$ coefficient was increased from 73.1 per cent to 76.0 per cent. However, 3326 partly-urban cells and 3586 urban cells were still omitted from the categories they should be in, resulting in a high omission error of 62.7 per cent in the partly-urban category and also a high omission error of 19.2 per cent in the urban category. This indicates that on the one hand the slope constraint rule was capable of controlling the urban development in the steep terrain areas, resulting in the decrease of the commission errors in each category. On the other hand, the slope rule was not able to accelerate existing development or generate new development.
Hence, it was necessary to introduce new rules for the transition of cells from the non-urban to partly-urban and urban states.

Figure 2
Scenario II – Results of the simulation of Sydney’s growth, 1971 to 1996, with two snapshots showing the city’s extent in 1981 (a) and in 1996 (b). This model took into account urban natural growth and slope constrained development.
| Scenario II – Slope constrained development | Non-urban | 41077/41364 | 99.3% | 00.7% omission error |
| | Partly-urban | 2257/6046 | 37.3% | 62.7% omission error |
| | Urban | 15038/18624 | 80.8% | 19.2% omission error |
| | Non-urban | 41077/46869 | 87.6% | 12.4% commission error |
| | Partly-urban | 2257/3657 | 61.7% | 38.3% commission error |
| | Urban | 15038/15508 | 97.0% | 03.0% commission error |
| Overall Accuracy | = 88.4% |
| $K_{nat}$ | = 76.0% |

| Scenario III – Slope constrained and transportation supported development | Non-urban | 40602/41364 | 98.2% | 01.8% omission error |
| | Partly-urban | 3733/6046 | 61.7% | 38.3% omission error |
| | Urban | 16183/18624 | 86.7% | 13.1% commission error |
| | Non-urban | 40602/42172 | 96.3% | 03.7% commission error |
| | Partly-urban | 3733/5989 | 62.3% | 37.7% commission error |
| | Urban | 16183/17873 | 90.5% | 09.5% commission error |
| Overall Accuracy | = 91.7% |
| $K_{nat}$ | = 83.8% |

| Scenario IV – Slope constrained and transportation supported development together with terrain and coastal proximity attractions | Non-urban | 40066/41364 | 96.9% | 3.1% omission error |
| | Partly-urban | 5316/6046 | 87.9% | 12.1% omission error |
| | Urban | 17195/18624 | 92.3% | 7.7% omission error |
| | Non-urban | 40066/14231 | 97.2% | 2.8% commission error |
| | Partly-urban | 5316/6337 | 83.9% | 16.1% commission error |
| | Urban | 17195/18466 | 93.1% | 6.9% commission error |
| Overall Accuracy | = 94.7% |
| $K_{nat}$ | = 89.9% |

| Scenario V – Development with urban planning to release slope constraint and reinforce transportation support as well as terrain and coastal proximity attractions | Non-urban | 39957/41364 | 96.6% | 03.4% omission error |
| | Partly-urban | 5426/6046 | 89.8% | 10.2% omission error |
| | Urban | 17346/18624 | 93.1% | 06.9% omission error |
| | Non-urban | 39957/40805 | 97.9% | 02.1% commission error |
| | Partly-urban | 5426/6553 | 82.8% | 17.2% commission error |
| | Urban | 17346/18676 | 92.9% | 07.1% commission error |
| Overall Accuracy | = 95.0% |
| $K_{nat}$ | = 90.4% |

Table 2
Results of the model's simulation accuracies in 1996 under various development conditions.
TRANSPORTATION SUPPORT

Transportation (access and infrastructure) has been established as a critical factor in accelerating urban development and attracting new development. For Sydney, the early development of the region was closely tied to the development of its public transportation systems (New South Wales Department of Planning 1993). From the mid-19th century, the urban area of Sydney expanded outwards along the radial railway lines. Most urban constructions were conducted along the extensive networks of tramlines in the late 19th century. From the mid-20th century, the electrification of railways and the construction of the city’s underground railway greatly improved the overall capacity of the existing networks and encouraged commuting from greater distances. Moreover, the high level of car usage in Australian cities has enabled more extended suburban settlements in less accessible areas of Sydney. Hence, transportation is an important factor that needs to be introduced into the model.

Good transportation networks increase the accessibility of land, and land with good accessibility is more easily selected for urban development. To measure the spatial accessibility of a cell in the urban development context, a transportation density index was calculated. It was assumed that cells with a higher transportation density index had a higher level of accessibility to transport services and infrastructure. As different transportation modes and different standards of transportation have different strengths of impact or potential to attract new and accelerate existing development, a weighted transportation density index was computed. For instance, a local or residential road was allocated a base weight of one in the weighting system, a secondary road such as a connector or distributor road or a one-track railway was allocated a weight of two. Similarly, a regional principal road such as a highway or a regional through road or a multitrack railway was allocated a weight of three. The weighted transportation density index was therefore calculated by dividing the total value of the transportation weights of cells within a certain neighbourhood of a cell under consideration by the total number of its neighbouring cells.

The impacts of dual carriageways, such as freeways, or national highways on urban development are more complex. Such a carriageway may have very limited impact on local urban development if there is no exit from the carriageway to the locale. In addition, areas that are too close to the carriageways are not attractive to urban development owing to the concern over noise. With this understanding, a separate rule of transition driven by carriageways was implemented in the model based on the distance of the cell to the carriageways, which was only applicable to cells surrounding the exit/on-ramp of a dual carriageway.

To implement the rules of transportation support for urban development into the model, three fuzzy linguistic variables, ‘variables whose values are not numbers but words or statements in a natural or artificial language’ (Zadeh 1973) were used to represent the strength of transportation support a cell can receive. If a cell has a very high transportation density index, or the cell is within a certain distance of a dual carriageway, it is entitled to have a strong transportation support for urban development. If the transportation density index of a cell is not very high but is strong enough to expedite existing development or attract new development, it is entitled to have a weak transportation support. If the transportation index of a cell is very low, then the cell is entitled to have no transportation support. With a strong transportation support, a partly-urban cell might be further developed very quickly, or a non-urban cell be selected for development.
at a speed quicker than without strong transportation support. On the other hand, development can also be accelerated, or new development be initiated in areas with a weak transportation support, although this development may not be as quick as the one that has a strong transportation support. Without the support of the transportation networks, the pace of development of the cell will be controlled only by the natural growth rules and the slope constraints. For instance, if a cell can take a basic pattern of a continued development in the slope-constrained scenario of development, this cell may take a quick pattern of the continued development if it receives a weak transportation support. It might take a very quick pattern of continued development if it receives strong transportation support. Without any transportation support, the speed of development of the cell will be controlled by the basic pattern of continued development. The fuzzy thresholds of various parameters used in the model were adjusted through model calibration.

The transportation support not only speeds up the process of existing development, but also initiates new development at various speeds depending on its strength and the conditions of the cell itself and its neighbouring cells. For instance, under a moderate slope condition, if a non-urban cell receives strong transportation support and it also receives support (although not very strong) for development from its neighbourhood, a pattern of new development can occur. Even without the support from its neighbourhood, it may still be possible to develop, although at a slow speed. If the transportation support is weak, new development can be initiated at a slower speed. By implementing the rules of transportation support in the model, a different scenario of urban development in Sydney was generated (Figure 3).

Through visual comparison between modelled and actual urban growth, the results generated from the model incorporating the rules of both slope constraint and transportation supports were improved significantly compared to the actual urban development of Sydney. The model has generated most of the urban development that occurred in the west and southwest parts of Sydney. With the transportation support, the model generated an overall accuracy of 91.7 per cent and a $K_{\text{hat}}$ of 83.8 per cent (Table 2). Compared with the overall accuracy of 87.1 per cent and 88.4 per cent, or the $K_{\text{hat}}$ of 73.1 per cent and 76.0 per cent in Scenarios I and II respectively, results generated with the support of the transportation networks represented a much better match for the actual urban development of Sydney. The individual accuracy of each category improved to various extents, with a significant decrease of the omission errors of partly-urban cells from 62.7 per cent in Scenario II to 38.3 per cent in Scenario III. The omission error of the urban category also decreased from 19.2 per cent to 13.1 per cent. These improvements indicate that the model generated more development to match the actual urban development in Sydney.

Even though the model has an overall simulation accuracy of 91.7 per cent and a $K_{\text{hat}}$ coefficient of 83.8 per cent in 1996, there were still 1159 partly-urban cells being omitted from this category and another 1154 cells being committed to this category incorrectly. In addition, 2441 urban cells were omitted from the urban category and 1690 cells committed to this category incorrectly. This indicates that the model still needs to be fine-tuned either by adjusting its parameter settings or introducing new rules.
Figure 3
Scenario III – Results of the simulation of Sydney growth, 1971 to 1996, with two snapshots showing the city’s extent in 1981 (a) and in 1996 (b). This model took into account slope constrained and transportation supported development.

TERRAIN AND COASTAL PROXIMITY ATTRACTIONS

Comparing the simulation results achieved thus far with the actual urban area of Sydney as defined in Liu (1998), large differences in the Menai area south of Sydney were observed. This area is attractive to a relatively high-income sector owing to its relatively high terrain and beautiful natural environment (Cities Commission Planning Division 1974). Geographically, this area is sited in the transition between the Woronora Plateau and the Cumberland Plain. In some of
these areas, the residents may have views of the sea and the coast. To represent these conditions, new rules representing the attractiveness of terrain and coastal proximity to the urban development were proposed and added into the model.

For the non-urban cells,

if: the slope is moderate and the terrain is high enough to view the coast,
then: apply the new development rules of urban natural growth;
else if: the slope is moderate, it is within the proximity of the coast and it also receives weak support for development from its neighbourhood,
then: apply the basic pattern of new development rule;
else if: the slope is steep but the terrain is high enough to view the coast,
then: apply the very slow pattern of new development rule;
else if: the slope is relatively steep, it is within the proximity of the coast, it can receive weak support for development from its neighbourhood and it also passes a random selection,
then: apply the very slow pattern of new development.

With the spatial modelling rules incorporating terrain and coastal proximity attraction, development was generated in Menai and surrounding areas (Figure 4). Some of the cells in these areas were fully developed into an urban state and the model generated an overall accuracy of 94.7 per cent and a $K_{\text{hat}}$ coefficient of 89.9 per cent in 1996 (Table 2). Both the producer’s and the user’s accuracies on individual categories reached over 80 per cent. This demonstrates that the model provided a suitably accurate representation of the outcomes of urban development, and possibly they accounted for the processes of the urban development of Sydney over the last two and a half decades.

**URBAN PLANNING**

Three metropolitan planning schemes have been proposed and implemented in Sydney over the last three decades. These are the *Sydney Region Outline Plan* (New South Wales State Planning Authority 1968), the *Sydney into its Third Century* (New South Wales Department of Environment and Planning 1988) and the *Cities for the 21st Century* (New South Wales Department of Planning 1995). In each of these plans a number of areas were proposed for urban development within a certain time period. What would occur in areas set aside for specific types of urban development, if the plans were changed or any of the five driving factors for urban growth were modified? In this paper, the cellular automata model was used to implement rules controlling urban developments and examines the impact of variations in urban planning controls on Sydney’s urban development.

The planning rules first implemented were those representing the areas planned for urban development as independent factors. These rules assumed that if a cell was sited in an area nominated for future urban development in any of the urban planning schemes, development would be faster, or a new development be initiated. Adding these rules into the model resulted in increased development in the planned areas. These results did not match well with the actual urban development of Sydney over the same period. The reduced accuracy of the simulation results indicates that not all areas planned for urban development can actually develop at the same pace independently. Instead, urban plans were more likely to release the constraint or reinforce the support of other factors including the slope and the transportation networks.
An alternative approach of implementing the rules of urban planning was tested, which combined the impact of areas planned for urban development with other urban growth controlling factors, either through reinforcing the support of transportation and coastal proximity attractions or releasing the constraint of slope factor. For instance, if a cell has a weak propensity for development and it cannot get sufficient support for such development from its neighbourhood (Condition D), previous rules indicate that this cell will undergo a slow pattern of continued development if the slope of a cell is moderate and the transportation support is weak. However, if this cell is sited in an area planned for urban development, the speed of development of this cell will be expedited, that is, this cell will undergo a basic pattern of continued development.
For an undeveloped non-urban cell with a moderate slope and a weak transportation support, a slow pattern of new development can occur to the cell if it is sited in an unplanned area. If this cell is sited in an area planned for urban development, it may undergo a basic pattern rather than a slow pattern of new development. Through the implementation of the rules representing areas planned for urban development in conjunction with other rules, the overall accuracy and the $K_{hat}$ coefficient have slightly increased from 94.7 to 95.0 per cent and from 89.9 to 90.4 per cent respectively. The producer's accuracy on each category has also improved, although the user's accuracy decreased slightly, indicating that the model has generated more development than it should have (Table 2 and Figure 5).

Figure 5
Scenario V – Results of the simulation of Sydney's growth, 1971 to 1996, with two snapshots showing the city’s extent in 1981 (a) and in 1996 (b). This model took into account areas planned for urban development, slope constraints, level of transport support, terrain, and coastal proximity attractions.
RESULTS AND DISCUSSION

Comparing the results generated from five different scenarios indicated that by including each driving force of urban growth into the model, the simulation accuracy of the model increased (Figure 6). The improvements in the simulation accuracies were statistically significant, especially when implementing the rules representing the constraint of slope, the support of transportation networks and the attractions of terrain and coastal proximity. Each of these factors was identified as a potential major contributor to the spatial variation in urban development around Sydney over the years 1971–1996. For urban planning, it was obvious that not all areas planned for urban development were actually developed over the proposed time periods. The urban development occurred only in areas with certain degrees of accessibility and services, such as a relatively smooth terrain and a support for development from the transportation networks. Therefore, to ensure that development could actually occur as was proposed in the planning schemes, it was important to improve the local accessibility of the areas and the communications between these areas and other developed areas.

Figure 6
Real versus simulated urban development of Sydney from 1971 to 1996. The upper left (a) shows the development of urban areas, the upper right (b) shows the development of partly-urban areas, and the lower left (c) shows the development of non-urban areas.
CONCLUSIONS

This paper has demonstrated a flexible implementation of urban growth rules in a spatial cellular automata model for simulating the urban development in Sydney. Five key factors, including the self propensity for development and neighbourhood support, slope constraint, transportation support, terrain and coastal proximity attractions and urban planning support have been implemented in the model to simulate Sydney’s urban development from 1971 to 1996. These factors were introduced into the model based on the sequence of the physical constraints, socio-economic factors and institutional controls. The physical constraints such as water bodies, slope and terrain are ‘hard’ constraints on urban development; these factors cannot easily be altered by human beings. In contrast, the socio-economic factors and the institutional controls are more ‘soft’ in affecting the processes of urban development, and they are more easily changed by human forces. Whether and how an alternative sequence in the implementation of the rules would generate different outcomes were not tested; this needs further study.

Not all the factors affecting Sydney’s urban development have been considered in this model. For instance, although the transportation networks have been implemented in the model to represent accessibility, factors such as journey to work and access to other services and facilities including schools, shops, sewerage and drainage systems were not modelled. Other factors, such as urban infrastructure (drainage and sewerage systems), and community services are also recognised as contributors to the pattern of urban development in Sydney. Nevertheless, the model has produced realistic results in illustrating Sydney’s urban development.

With the flexibility of rule- based implementation within the model, more rules can be added as new ‘If-Then’ statements to fine-tune the model, provided that a good understanding of the rule is maintained and good data are collected. This flexibility of the model enables it to function not only as an analytical and heuristic tool to understand the factors controlling the processes of urban development, but also as a planning tool to experiment with various planning proposals and answer the ‘What-if’ questions in the planning practice.

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ENDNOTES

1 ie, Vitousek 1994; Batty 1995; Batty et al. 1996; Allen 1997; Batty 1998; Sui 1998.
2 ie, Couclelis 1985; White et al. 1993; White et al. 1994; Batty 1997; Batty et al. 1997; Clarke et al. 1997; Couclelis 1997; White et al. 1997a; White et al. 1997b; Clarke et al. 1998; Wu 1998a; Wu 1998b; Wu 1998c; Wu et al. 1998; Batty et al. 1999; Batty 2000; Wu et al. 2000.
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