Developing a web-based cellular automata model for urban growth simulation

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ABSTRACT

Cellular automata as an emerging technology have been adapted increasingly by geographers and planners to simulate the spatial and temporal processes of urban growth. While the literature reports many applications of cellular automata models for urban studies, in practice, the operation of the models as well as the configuration and calibration of relevant parameters used in the models were only known to the model builders. This is largely due to the constraint that most cellular automata models were developed based on desktop computer programs, either by incorporating the model within a desktop GIS environment, or developing the model independent of a desktop GIS. Consequently, there is little input from the user to test or visualise the actual operation or evaluate the applicability of the model under different conditions.

This paper presents a methodology to implement a fuzzy constrained cellular automata model of urban growth within a web-based GIS environment, using the actual urban growth of Metropolitan Sydney, Australia from 1976 to 2006 as a case study. With the web-based cellular automata model, users can visualise and test the operation of the model; they can also modify or calibrate the model's parameters to evaluate its simulation accuracies, or even feed the model with various 'what-if' conditions to generate alterative outcomes. Such a web-based modelling platform provides a useful and effective channel for government authority and stakeholders to evaluate different urban growth scenarios. It also provides an interactive environment that can foster public participation in urban planning and management.

Keywords: Cellular automata, urban growth, simulation, web-based GIS, Sydney.

1. INTRODUCTION

Cellular automata as an emerging technology have been adapted increasingly by geographers and planners to simulate the spatial and temporal processes of urban growth. Various cellular automata models have been developed and applied either as an analytical tool to explore the driving forces of urban growth or a projection tool to foresee future urban development of a region.

While the literature reports many studies on the development and applications of the CA models for urban growth simulation, with convincing results demonstrating the usefulness of the models, in practice, the operation of the models as well as the configuration and calibration of relevant parameters used in the models were only known to the model builders. This is largely due to the fact that most cellular automata models were developed based on desktop computer programs, either by incorporating the model within a desktop GIS environment, or developing the model independent from a desktop GIS. Consequently, there is little input from the user to test or visualise the actually operation of the model, or to evaluate the applicability of the model under different conditions.

The advance of web-based GIS technology has made it possible to develop simulation models over the Internet. With web-based GIS services, users will be able to visualise and test the operation of the model; they can also modify or calibrate the model's parameters to evaluate its simulation accuracies, or even feed the model with various 'what-if' conditions to generate alterative outcomes. Such web-based urban modelling platform can provide a useful and effective channel for both government and stakeholders to evaluate different urban growth scenarios. It can also provide an interactive environment to foster public participation in urban planning and management.

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This paper presents a methodology to implement a fuzzy constrained cellular automata model of urban growth within a web-based GIS environment, using the actual urban growth of Metropolitan Sydney, Australia from 1976 to 2006 as a case study. The following section presents the cellular automata modelling in general, and the fuzzy constrained cellular automata model of urban growth in specific and how the model is applied to simulate urban growth dynamics. Section 3 discusses the system architecture and the implementation of the CA model based on ESRI's ArcGIS Server technology. Finally, Section 4 concludes the paper and provides future research directions in CA based urban modelling using web-based GIS technology.

2. CELLULAR AUTOMATA MODELLING

2.1 Cellular automata model

Cellular automata modelling technique was originated as a type of computer games to simulate the dynamic process of system transitions [1][6]. This modelling technique has been used primarily in the physical and natural sciences areas such as physics, chemistry and biology; there are also increasing number of applications to study urban growth and land use change [1-5][8-23].

According to Levy (1992), a cellular automaton is a self-operating machine that 'processes information, proceeding logically, inexorably performing its next action after applying data received from outside itself in light of instructions programmed within itself' [7]. There are five basic elements of a cellular automaton. These include the cell, state of cells, neighbourhood, transition rules and time. Each cell in an urban system takes a finite state such as urban or non-urban at a certain time; the state of a cell at any time is depend on the state of the cell itself and the states of cells of its neighbourhood at the previous time according to certain transition rules. The fundamental principle of a cellular automaton can be represented as follows:

$$S_{x_{ij}}^{t+1} = f(S_{\Omega_{x_{ij}}}^{t}) \tag{2.1}$$

where $S_{x_{ij}}^{t+1}$ is the state of a cell x_{ij} at time t+1; $\Omega_{x_{ij}}$ represents a set of cells within certain neighbourhood (including itself); $S_{\Omega_{x_{ij}}}^{t}$ represents a set of states of cells $\Omega_{x_{ij}}$ at time t; and f is a function representing a set of transition rules.

Given the variation in transition rules, the model can be used to generate complex spatial patterns, representing the spatial and temporal dynamics urban growth.

2.2 The fuzzy constrained CA model

A fuzzy constrained cellular automata model was developed in a previous study to simulate the spatio-temporal process of urban growth [11]. According to the model, urban development is considered as a fuzzy process which is constrained by both internal and external forces. Internally, an area tends to continue its development if it has started to develop from rural to urban state, especially if this natural tendency is supported by development from within its neighbourhood. Externally, factors such as the physical conditions of the area, socio-economic conditions as well as institutional controls may also have an impact on the process of its development. For instance, the physical constraints such as water bodies and steep terrain may restrict or slow down the process of urban development, as do the institutional controls that may accelerate or prohibit further urban growth. The socio-economic factors such as land availability and the demand on available land, the accessibility to nodes of employment and other services and facilities such as schools, shops, public transport and the contiguity to existing urban areas also play important roles in urban development. These internal and external forces can be represented in the cellular automata model through a set of primary and secondary transition rules.

2.2.1 Primary transition rules

Based on the principle of cellular automata, the internal forces driving the process of urban development can be represented by a set of primary transition rules. That is, at a homogeneous urban space where there is no variation in either the physical conditions or economic/social/institutional constraints, if a cell has the propensity to develop into an urban state and it can receive sufficient support for such development from its neighbouring cells, then the cell will develop at a medium speed towards the urban state. Such a development process can be slowed down if its own propensity for development is weak, or if the cell does not receive sufficient support for development from its neighbourhood. On the other hand, the development can also be sped up if the cell has a strong propensity for development and/or it receives strong support for development from its neighbourhood.

In order to reflect the non-deterministic nature of those driving factors for urban development, three sets of fuzzy linguistic terms were proposed to implement the primary transition rules. One set of such terms is used to quantify the speed of development, such as ‘slow’, ‘medium’ and ‘fast’; one set to quantify the propensity of cells for further development, such as ‘moderate’, ‘strong’ and ‘weak’; and the other set to quantify the extent of neighbourhood support, such as ‘sufficient’, ‘weak’ and ‘strong’. These fuzzy linguistic terms can be modified by either the model builder or the users during the model calibration process.

2.2.2 Secondary transition rules

While the primary transition rules deal with an ideal situation where the area under study is of homogeneous nature, which hardly exist in the real world, the secondary transition rules add in the effects of other factors such as topographic features, transportation networks, socio-economic status as well as planning and human decision-making behaviours to the modelling process. Some factors, such as the provision of urban infrastructure and transportation network, will function as accelerators to speed up the process of urban development; others, such as a mountainous landscape, or an area with a lack of urban infrastructure supply may function as constraints to slow down the development process. These factors are built into the model as secondary transition rules to modify the primary rules on the transition of cell states.

For instance, if there is an accelerating factor within the neighbourhood of the cell in question, the speed of urban development of that cell will be faster, that is, from slow to medium, or from medium to fast. On the other hand, if there is a constraining factor within the neighbourhood of the cell in question, the speed of urban development of the cell will be slowed down, that is, from medium to slow, or from slow to very slow speed. If there is more than one such factor, the speed will be upgraded or downgraded two steps up or down. In the case where there exists both an accelerator and a constraint then the effect of both factors will be cancelled; hence, the speed of development will remain unchanged.

Using the metropolitan area of Sydney, Australia as an example, the cellular automata model was configured with 250 meter cell scale and a Moore neighbourhood (9 cells including the cell itself in the centre) to simulate its urban development from 1976 to 2006 under different configurations of the primary and secondary transition rules. The following section will address the implementation of the model within a web-based GIS environment.

3. THE WEB-BASED GIS MODELLING FRAMEWORK

The development of Internet technology has profoundly changed the way of human communication. With the rapid development of information technology, new and better ways have been developed for people to share information and work collaboratively amongst multiple parties, increasing the efficiency of human productivity.

Web-based GIS technology has been developing rapidly, with many GIS software vendors providing powerful web-GIS platforms for developers to build up web GIS applications. Using web GIS technology, this section presents the fuzzy constrained CA model of urban growth deployed over the Internet. The deployment of the CA model is for users to interact with the model and test different urban planning scenarios.

3.1 Model implementation

The fuzzy constrained CA model of urban growth can be implemented either within or outside a GIS platform. Using the built-in functions of ArcGIS program, the model can be realised as a geoprocessing tool to operate within the ArcGIS platform. Although this method can be built on the existing functionalities of ArcGIS which are out-of-the-box and are easy to implement, the drawback of this approach is also obvious. That is, the model cannot operate without the ArcGIS program. In addition, the coding of complex algorithm of the CA model cannot be optimized as it is difficult to change the underlying operations of ArcGIS coding. For instance, as the model will generate a new raster dataset each time when an operation is executed, this results in numerous intermediate and temporary datasets which will slow down the operation of the program. In fact, when implementing the model as a geoprocessing tool using ModelBuilder in ArcGIS, the computation time of the model was long, even for a small number of iterations.

The fuzzy constrained CA model presented in this paper was developed outside a GIS platform; it is self-contained and independent of any specific GIS platform and component. This approach provides flexibility in model construction although it takes more time and energy for the model builder to develop. As the model is independent of any GIS platform, it can be deployed almost everywhere with minimum restraint. The coding of the CA algorithms and transition rules were optimised which saves the computation time; hence the operational efficiency of the model can be improved significantly.

Using the Microsoft's free Visual Studio Express C# 2005 as a development tool, an independent module named FuzzyCA was developed to implement the fuzzy constrained CA model. There are three main components in this module; they are the Grids, Grid-Operation and CA-Algorithm. The Grids component is to manage all raster datasets, including generating, copying, saving and releasing data. The Grid-Operation component provides a number of grid operation functions, including arithmetic, conditional and logic operations. The core component of the module is the CA-Algorithm, which encapsulates all transition rules of the CA model. It receives parameter values from the user's input, and invokes the functions of Grid-Operation to process the Grids and generate result. The relationship of the three main components of the CA Module can be illustrated as Figure 1.

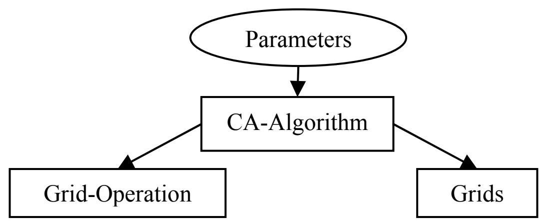

Figure 1 Three Core Components of the FuzzyCA Model

3.2 Model deployment over the Internet

In order to deploy the FuzzyCA model over the Internet, we chose to use ESRI's ArcGIS Server software program. ArcGIS Server allows users to share GIS resources across an enterprise and over the web. The ArcGIS Server services can be consumed by web browsers, mobile devices and desktop systems. It also supports many standards such as OGC and W3C like WMS, WFS, WFS-T, WCS and KML. Using ArcGIS Server it is possible to support large potential users and the services can be consumed by many clients using different web service standards.

Using the Software Development Kit (SDK) for .NET developers supported by ArcGIS Server, the following SDK components were utilised in the deployment of the FuzzyCA model to the Internet:

- ArcObjects, which was used to operate the raster datasets, and also execute map operations such as adding raster data to the map document.
- Web Application Developer Framework (ADF), which was used to build a web application of the model and deploy the model over the Internet.

The Web ADF Task Framework provides a set of interfaces and abstract classes to create custom tasks. A custom task named CA-Task was created to encapsulate CA functionalities as a distributable component. This custom task is a web control which offers an interface for users to interact with the model.

The communications between the web user on the client side and the FuzzyCA model on the server side can be described as follows (Figure 2).

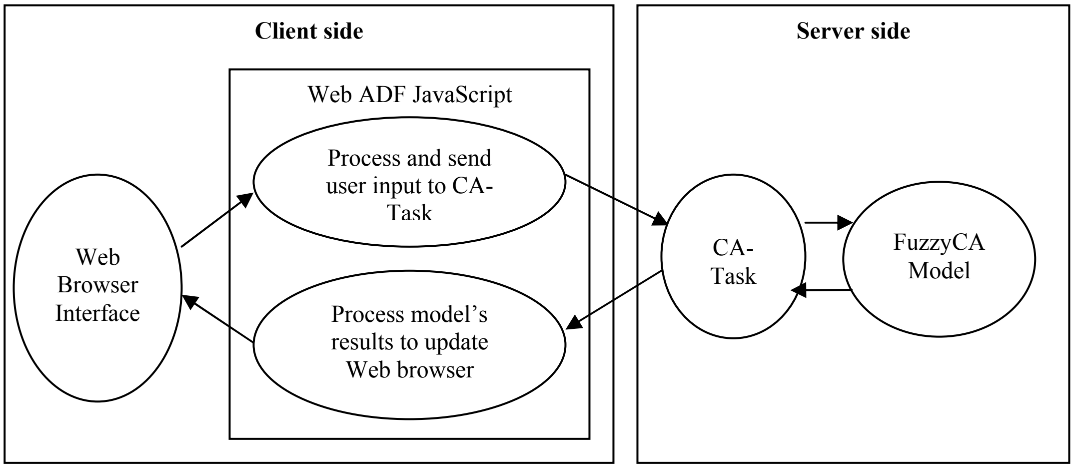

Figure 2 Communications between the User on the Client Side and the FuzzyCA Model on the Server Side

1) Users first encounter a graphic user interface (GUI) through a web browser to select transition rules and change or adjust the parameters of the model;
2) Once the user commits to start the model, the user's input will be received and processed by a Web ADF. These input will be sent to the CA-Task on the server side asynchronously;
3) Once the CA-Task receives the user's rule and parameter settings, it will commit the settings to the FuzzyCA model to start the simulation process. The FuzzyCA model is an independent module to implement the fuzzy CA transition algorithms;
4) Computation of the model with user defined rules and parameters are carried out by the FuzzyCA model. This results in a new raster dataset representing the simulated state of cells at the specified time. The model also generates a set of statistics illustrating the various simulation accuracies of the model' results. These results will be sent back to the CA-Task;
5) The CA-Task will then send the results to the web controls for processing and delivering to the user through the web browser; and
6) Upon receiving the updated information, the web browser will refresh the screen display on the user's machine. The map results generated by the model will be added to the map document as a new data layer and displayed; the simulation accuracy statistics will also be displayed as a tabular view on the user's web interface.

3.3 User interface

A graphic user interface was designed and deployed over the Internet for users to interact with the model and calibrate the model's relevant parameters (Figure 3). For instance, users can choose to set the size of the cells to 100, 250, or 500 meters, representing a high, medium or low cell resolution. They can also set the size of the neighbourhood to 2, 3 or 4 cells, representing a small, medium or large neighbourhood. The start and stop date can be changed by the user to a date between 1976 and 2006. In addition, users can also choose which transition rules to implement in the model, being primary or secondary transition rules. For instance, if no secondary rules are selected, the model will only operate based on the primary transition rules to simulate a scenario of natural urban growth within a homogeneous landscape. Users can also add in one or more secondary transition rules such as the DEM or slope factors, the transportation support factor or the urban planning control to constrain the natural urban growth process. The initial configuration of the model's parameters can be launched through user input, which may be modified during the model's calibration process.

Inputs from the user are encapsulated into the model as a custom task; it is provided as a floating panel within the web-based CA modelling environment. Users can launch the model setting panel by selecting the 'MODEL SETTING' menu and then click 'SETTING RULES'. Once the model setting is configured, they can start the simulation by clicking the Start button on the model setting panel (Figure 4).

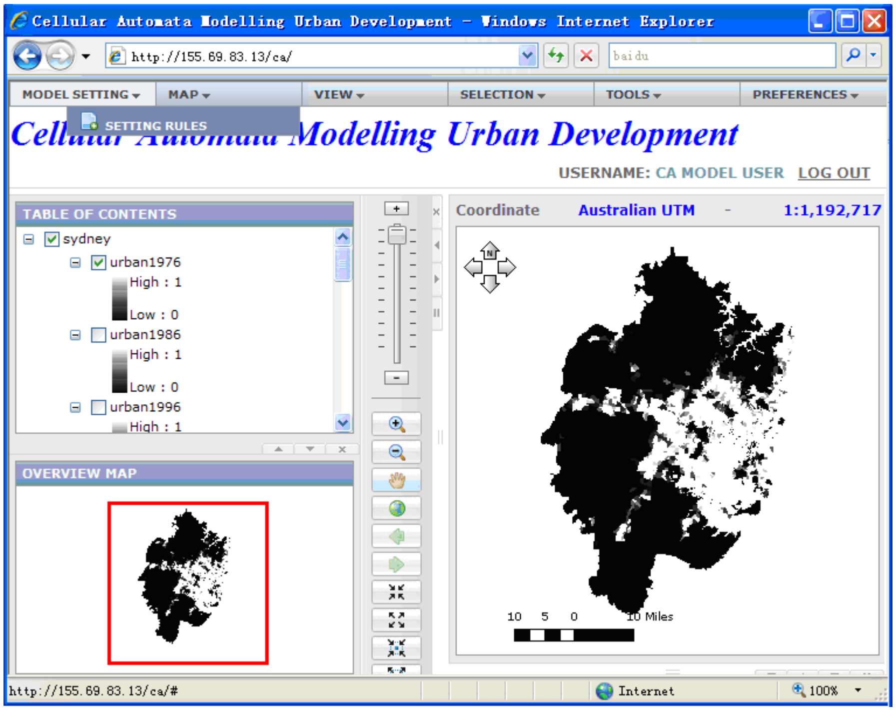

Figure 3 The Graphical User Interface

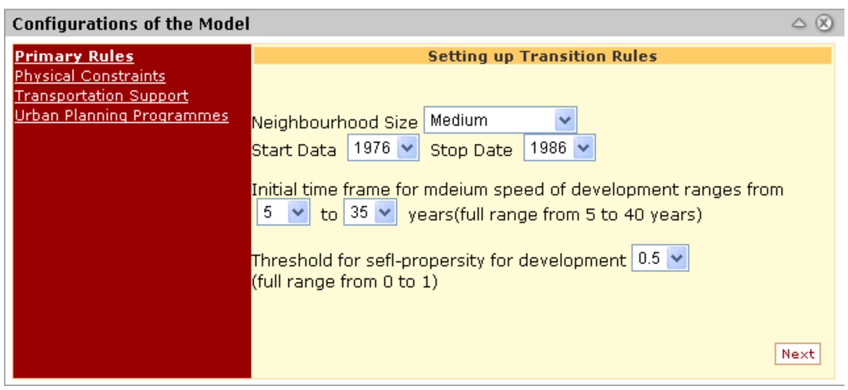

Figure 4 Configuration of the Model's Transition Rules

After the operation of the model, a new set of data will be generated and added to the map document. This new set of data displays the simulated scenario of urban growth under the conditions of the users' choice. The simulation accuracies of the model can be computed by selecting a year under the SIMULATION ACCURACY menu, and the results including the users' and producers' accuracies, the overall accuracy and Kappa coefficient of the model at the selected year will be displayed under the Result Panel (Figure 5).

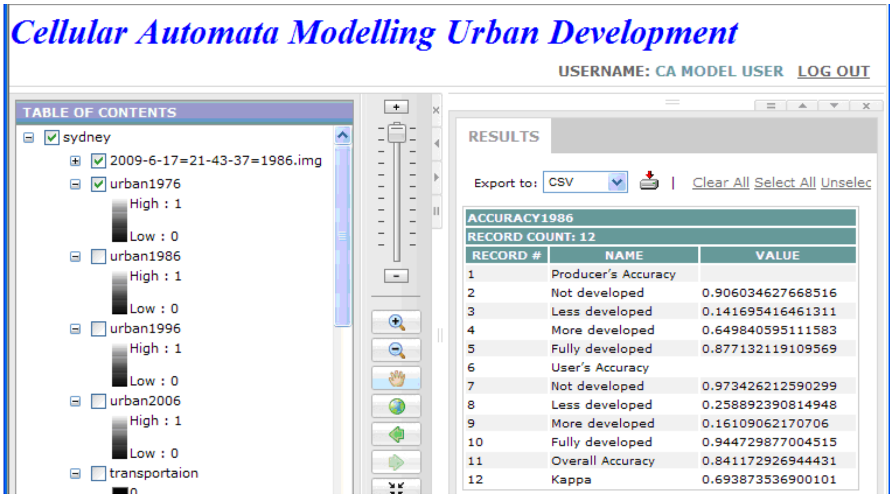

Figure 5 Simulation Accuracy Results Generated by the Model

4. CONCLUSION

So far the FuzzyCA model has only been developed and released to the Intranet where the authors are working. Once the model is fully calibrated and tested, it will be deployed to the Internet and become openly accessible by the public with an Internet connection. Vigorous testing and evaluation of the model on its usage over the Internet will need to be carried out in the near future. Specifically, we will need to evaluate the usability of the model, including the amount of time required to complete each iteration of the model with user's input; the stability of accessing the service; the flexibility of the model in responding to users' queries, as well as the number of users that can be supported simultaneously and how it may affect the processing and transmission time. The results from the usability test will be reported and discussed in a separate paper when data become available.

Furthermore, it is expected that the fuzzy CA model constructed in this research will be further advanced as a web-based modelling tool for users to engage in their own studies of urban dynamics. To this end, users will be able to not only interact with the datasets provided by the model itself to simulate the urban growth of metropolitan Sydney in Australia; they will also be able to utilise the model with their own data to evaluate the urban growth scenarios of other regions. With this capability the re-applicability of the model can be tested vigorously. Such applications of the model to understand the dynamics of urban growth as well as the underlying driving forces for such growth will contribute significantly to the development of CA models in urban research and the understanding of urban growth itself.

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