A Vector-Agent Paradigm for Dynamic Urban Modelling

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ABSTRACT

In the past, researchers and model developers were restricted by their theoretical knowledge about the city and how it might be simulated as well as constrained by technological limitations. Nevertheless, the simulation environment is now appropriate for the infusion of new ideas into urban modelling. Urban simulation is a relatively unique modelling problem. The urban systems commonly represented in urban models considering different factors (economic, social, environmental …. etc.) and are notoriously difficult to simulate. It is proposed that agents are more flexible than cellular automata at modelling the city, and in turn that vector-based agents are more suitable than cell-based agents at doing the same. Therefore, this paper is intended to review the limitations raised by using cell-based models with an agent simulation system, and introduce a new paradigm for integrating vector-based spatial model with agent system.

1.0 INTRODUCTION

Computer simulation models combine theory, data and algorithms to arrive at an abstract representation of the character and functioning of a land use system for example. Ideally, once a simulation has been calibrated against a known scenario, the model may be used to make predictions about the future state of the system. Land use models are a particular class of model used to simulate how land use systems operate. They were first put to use in the outcomes of decisions affecting cities, and as a laboratory for testing ideas and hypotheses relating to urban systems. However, land use models are uncertain tools; as with any model there is a degree of abstaction in their representation of real world systems and processes (Torrens, 1997).

Computer models may be developed to understand more about how a real system works. Such models must add-flexibility to represent the real system's behaviour under a variety of conditions and constraints (Gimblett, 2002). Recently, Agent-based systems are increasing being used as advanced computer-based technologies for spatial simulation modelling. These models have been applied extensively to examine and understand the complexities of urban and land use dynamics in cities. However, the major problem is how to develop and optimize a computer simulation model that reflects the real behaviour of land use and their heterogeneity.

Most previous and current research of a computational nature focuses on developing urban models using Cellular Automata (CA) (Batty, 1998, Batty et al., 1994, 1997, 2000). Lately, Agents are starting to attract the attention of researchers in the same field through mainly in a cell-based sense (Gimblett, 2002, Jiang et al., 2002, Rodrigues, et al., 1997, 1998). The centrality of the neighbourhood concepts of its rules, and homogeneity of the regular cellular structure, are limitations for using this technique (cell-based Agent systems) for modelling the complexity of the city.

From an urban perspective, cities are facing serious problems as a result of population growth. The resultant rapid and often disorganised sprawl of large cities causes many difficulties for their inhabitants, and makes the task of spatially allocating land for development to meet a specified population target a major challenge for the planners. Traditionally, the means for determining the location and nature of new development has been through extensive research, specifically regarding urban and land use dynamics.

However, understanding the dynamics of complex systems and evaluating the impact of urban growth on land use involves procedures of modelling and simulation, which require innovative methodology and robust techniques.

This paper is intended to serve as a literature review to computational urban modelling techniques, regarding Cellular Automata and Agent-based simulation as well as introducing conceptual idea for using vector-agent as a new paradigm in urban modelling.
The paper proceeds in section 1 with a brief overview and history of urban modelling. The shortcoming of Cellular Automata in the context of urban modelling is then addressed in section 2. Section 3 will outline the merits of agent technology followed by the introduction of integrating the vector spatial model with agents system.

2.0 URBAN MODELLING

Urban models come in forms that have a complex diversity. These range in variety from basic to mathematical, with a respective diversity of theoretical foundations, purposes, and functionality of use. Much of the contemporary urban land use modelling effort has proceeded on a foundation of descriptive or analytical models that have been steadily developed since the beginning of the twentieth century. Among the more influential of these have been concentric zone theory (by EW Burgess), wedge or radial sector theory (by Hoyt), and multiple-nuclei theory (by Harris and Ullmann) (Wilson, 2000). While many of these models are weak in their capacity to describe today's cities, and limited in their predictive powers, they have provided both an important environment for urban simulation and a base upon which fashionable efforts can be built (Torrens, 1997).

Since the late 60's and early 70's, a period in which the development of elaborate mathematical models for urban planning applications emerged, new scientific and technological development has considerably changed the fields of spatial modelling and urban planning (Malcolm, 2002). The elaboration of new scientific paradigms based on such phenomena as complexity, self-organization, chaos and fractals, has generally emphasized the fact that exact prediction in complex city planning is not possible (Rotmans, et al., 1999). The main purpose of the models is to serve as thinking tools, to help the user learn about the nature and dynamic behaviour of the real world system and find out how it is critically bounded, rather than to make definite statements about the future state of the system modelled (Engelen, et al., 1999).

For systems as complex and as dynamic as cities, performing acts of planning without having some concept of how activities, land-use, and how the spatial interactions will change as the result of the intrinsic growth potential and planning interventions seems a somewhat futile exercise (Benenson, et al., 2001).
Hence, it is a major shortcoming of today's techniques not to offer the possibility of dynamic and spatial modelling in the preparation and evaluation of urban policies. This is a view supported by many authors (Batty, 1998, Eastman, et al, 1993). It is clear that many of tools with which we study the city today are deficient in their ability to fully simulate and describe the changing character of urban areas. There is a need for models that are flexible and dynamic in their simulation capabilities as is the city in its ability to evolve (Batty and Torrens, 2000). There is much potential for how we improve the urban system modelling considering the recent technology. Such an approach would build upon those areas of traditional or classical models that can serve as ground for the new urban modelling techniques.

3.0 CELLULAR AUTOMATA & CELLULAR-CITIES

Cellular Automata (CA) is a modelling technique defined on a raster space. Cell states usually represent land use or land cover, and the transition of a cell from one state to another depends on the states of the neighbourhood cells. CA have proven to be useful for dynamic modelling although studies that have attempted to include GIS have had varying success (Batty, et al., 1994, 1997). Most of this research emphasised urban simulation in order to understand the urban growth and its form. However, to build models that represent more practical geographical problems, it seems that more complex CA is required and that their dynamics need to be constrained (Engelen, et al, 1997). Moreover, GIS are an inherently static tool, and are limited for use in dynamic modelling in both their updating of cellular data and implicit cellular nature (Ward, et al., 1999). They do not include procedures for explicitly handling time, are designed to process entire arrays of data, and cannot easily address varying localized operations across the spatial grid (Gimblett, 2002).
The city is a complex system and is beyond the capability of standard CA (Jiang, et al., 2002). Previous research has made clear the limitations of the CA framework (Colonna, et al., 1998, Loibl, et al., 2002, Ward, et al.,

1999). Its homogeneous cellular structure and synchronous time advancement are too rigid to easily accommodate the diversity of processes that interact of overall system (Colonna, et al, 1998).
Urban systems incorporate a variety of spatial objects that interact with each other in complex, non-linear, and often surprising ways. Therefore, the current CA urban models are to a large degree limited to physical processes (Xie, 2003). Moreover, geographic phenomena, particularly the urban system, have extremely complex characteristics as a result of interactions among different components which make CA limited for handling such dynamic systems.

Many attempts have been made to develop a more general and flexible CA. Couclelis (1985) extended CA by separating the neighbourhood set and transition rules from each cell. In other words, each cell can possess its own set of neighbourhood and transition rules. Li and Yeh (2000) developed a sustainable urban model based on constrained CA. They argue that CA can be used to model compact cities and sustainable urban forms based on local, regional, and global constraints. In addition, the concept of grey state of a cell was proposed, which can overcome the limitations of absolute black and white cells (i.e. dead or alive) that are used in standard cellular automata. Engelen (1997) developed a model-based support tool in complex urban areas. The model based on constrained CA. They constrained the overall dynamics of the CA model by means of coupling with more traditional dynamic spatial interaction models, operating on a set of regions much larger than individual cells. Also, the transition functions are written as distance functions and represent the push and pull forces between pairs of land use. The simulation operates on urban activities using rules for spatial interaction among these activities, including predefined and changeable constraints.

Other research exhibits a great potential for handling neighbourhood relation in CA model. Takeyama and Couclelis (1997) adopt the concepts of Geo-Algebra in generalising and extending CA. In their work, CA is generalised and extended using the representations and operators of Geo-algebra.
In the same sense, Shi and Pang (2000), introduce another constraint to CA in order to handle the the limitation raised by operating the CA over a regular and uniform space using Voronoi spatial model.

However, these extended versions of CA still operate on a regular array of square cells. The neighbourhood relations among spatial objects with irregular shape and sizes, is still major problem for any spatial system.
Standard CA should be integrated with more states, infinite neighbourhoods, and more constraints with complex transition rules. More integrated technology is required for urban simulation modelling: the use of intelligent agents is the currently the best approach to model the dynamic behaviour of the land-use system (Rodrigues, et al., 1998). But the question remains, what type of spatial model can be integrated with agent system to overcome the irregularity and other limitations of CA.

4.0 AGENT TECHNOLOGY & VECTOR-BASED AGENTS

There is no one definition for an agent. As there are several fields of software development in which they are being used, it is very difficult to uniquely define them (Haugeneder et al., 1998). The most general definition is: task oriented software components that have the ability to act intelligently, either independently or collectively (Rodrigues, et al., 1998).
The concept of a spatial agent has been introduced as a specialisation of the agent concept that can reason over representations of space, and can understand space as either physical or non-physical phenomena (Rodrigues, et al., 1998). Applied to spatial models, agents become entities evolving in space and time, within an environment composed of all the passive elements of the space (Gimblett, 2002).

The research of spatial agents and GIS has received great attention in recent years (Rodrigues, et al., 1997, Ferrand, 2000, Jiang, et al., 2002, Gimblett, 2002). Most of this research focused on integrating the agent-based approach with GIS in the sense of CA for spatial simulation and spatial decision support systems. In the work of Rodregues, et al. (1998), the multi agents approach has been used for the prototype of MEGAAOT (an environmental planning application for spatial decision making). In this project the spatial processes involved only CA for simulation modelling. Whereas, the most exciting research for using multi agent based modelling with GIS was developed in collaboration with the team of the French National Geographical Institute. The project has addressed the limitation for using the agent approach with CA for dealing with complex dynamic system, which led to the conversion of the work towards a multi reactive agent system (Ferrand, 2000, Rodrigues, et al., 1998).

In fact, a multi agent system can be used either for simulating complex systems or for solving spatial problems. The use of multi agent system is a return to natural modelling, because all is needed is a simple description of

objects and processes (Ferrand, 2000). The system can be integrated with any type of information such as rules or functions, and is entirely open as it is possible to add agents of any type (Wooldridge, et al., 1995).
However the most fundamental requirement of any spatial model is handling the dynamic form and relationships of irregular spatial objects. As mentioned above (section 2) in the original CA, spatial units of irregular shapes cannot be handled. This restriction limits the applicability of the CA (and cell-based agents) for modelling the spatial processes that operate over a regular and uniform space. We believe that spatial units with irregular shape and size are not applicable in this case, but are applicable for multi agents. Issues have been raised about the tendency of adopting CA as an agent-based modelling technique.
Some research has investigated handling the spatial or mobile object as an autonomous agent. One of these research projects is the Web-based map using a Multi-Agent system by Li et al. (2002). This project addressed the possibility for handling the spatial vector objects in computer simulation as in reality. They introduce a Maplet agent. Each kind of map feature is an independent agent represented by a Maplet. Each agent has its own control flow and respond to change in its environment. It might be an argument that this application is quite far from the urban modelling context. However our main concern is to extend the idea for handling the irregular spatial object with agents system for urban modelling.

The key message of this paper is that an agent system can be adopted with a vector-based spatial model, where each land use can act as a single autonomous agent with no limitation for shape and size. Vector-based agents are a more realistic way of modelling real world (geographic) forms and processes than cell-based agents and cellular automata, due to having a spatial entity one-to-one match rather than having it discretised into many cells.
In terms of neighbourhood, Vector-based agents (based on non-space filling and generalised Voronoi polygons) have an advanced neighbourhood capability, which makes for a more realistic urban model. Spatial objects can posses an infinite number of neighbours without any limitation of distance. Whereas, the transition functions in CA must be applied to immediate neighbours only (8 square cells), so a spatial unit cannot be effected by more distance units.
This new technique of urban land use simulation can be a successful tool especially for reproducing the classical urban form theories (mentioned previously in section 1) as an initial prototype. Each class of spatial object can possess its own set of transition rules and neighbourhood relations that can be feasibly defined in numerous ways according to the real world. This allows predicting the unforeseen effects while calibrating one of these classical models with respect to others considering more constraints and rules.
Moreover, building in increasing anisotropy (e.g. from rivers, coast, terrain) from a real-world scenario to govern the behaviour of vector-based agents onto simple rules governing the growth of the city makes for an urban model that approximates to reality.
Indeed, the integration between the vector spatial model and agent-based system offers not only a more realistic way to simulate the complex behaviours of urban land use but also a significant solution to the simulation of the spatial object interactions in the real world.

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