INTEGRATION OF AN IRREGULAR CELLULAR AUTOMATA APPROACH AND GEOGRAPHIC INFORMATION SYSTEMS FOR HIGH-RESOLUTION MODELLING OF URBAN GROWTH

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ABSTRACT

Urban growth is a dynamic spatial process that is commonly modelled with complex systems theory and the cellular automata (CA) approach. The majority of CA models use the raster data structure to represent space and are often implemented as custom-built or geographic information systems (GIS)-coupled software. However, the regular grid presents a number of problems when used with high-resolution land use data composed of irregularly sized and shaped cadastral parcels. The objective of this study is to develop a CA model of urban growth using a high-resolution irregular spatial data structure with high temporal resolution. A GIS-embedded modelling tool named *iCity* was developed within a common desktop GIS to enable urban planners and stakeholders to visualize how different subdivision designs, population growth rates, and buyer preferences will influence urban development. This study contributes to the advancement of CA models and spatial decision support systems for use in urban planning.

DEDICATION

Questa tesi è dedicata ai miei nonni Bruna e Aldo Canziani che generosamente mi hanno provveduto con il mio primo computer. Le ore spese con questo computer hanno partecitato alla mia fondazione tecnica e hanno contribuito nella possibilità di questa ricerca.

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CHAPTER 1 - INTRODUCTION

1.1 Introduction

Dynamic models of urban systems were first developed in the 1960s in the form of land-use-transportation models (Batty, 1994; Torrens, 2000b) and built on classical urban models by von Thunen (Thèunen and Hall, 1966), Burgess (Park et al., 1925), Hoyt (1939), and others. Since the land-use-transportation models of the 1960s, other aspects of urban systems have been modelled, such as real estate markets (Wu, 2003) and gentrification (O'Sullivan, 2002). However, models of urban growth and land use change have been the most predominant form of urban model in the last decade with examples abundant in the literature (e.g. Batty et al., 1999; Besussi et al., 1998; Clarke et al., 1997; Landis, 1994; Silva and Clarke, 2005; White and Engelen, 2000; Wu and Webster, 1998). The proliferation of urban growth models is likely due to the rapid expansion of urban populations globally and the challenges that this expansion brings. According to the United Nations (2004), over 60 per cent of the world's population will live in urban areas by the year 2020. Even in countries of relatively low population growth there is a strong rural-to-urban migration resulting in rapidly growing cities (Clarke et al., 1997). Land markets have so far failed to produce acceptable land use patterns in growing cities and have instead encouraged a problematic form of low-density growth known as urban sprawl (Daniels and Lapping, 2005). In order to reduce future urban sprawl and its associated problems, cities require some form of central planning to guide their growth in a sustainable direction away from market-driven sprawl.

1.2 Urban Sprawl

Cities can be likened to a living organism, and as with any living organism cities grow over time. This growth is driven by an increase in population and by a population's economic potential to expand the city (Hansen, 2001). This is exhibited on the landscape as a combination of vertical and horizontal growth. Vertical growth increases densities within the developed city and may take the form of taller buildings with smaller living units or as infill development. On the other hand, horizontal growth takes place at a city's fringe, it is low density and often referred to as *sprawl.* While no uniform definition of sprawl exists, Hasse and Lathrop (2003) define sprawl as *a specific type of development with "low-density, dispersed, auto-dependent and environmentally and socially-impacting characteristics*". Sprawl occurs when low-density suburbs expand into the rural region surrounding a city, converting rural land into suburban or ex-urban developments primarily for residential use, but increasingly also for commercial and other uses (Jenerette and Wu, 2001; Munroe et al., 2005). It is recognized as an unsustainable use of scarce land and other resources, where a greater number of resources are required per resident than for development within a city's core (Hancock, 2000).

This low-density, dispersed form of urban growth creates a number of problems including traffic congestion (Ewing et al., 2003a); health problems related to decreased physical activity (Ewing et al., 2003c; Frumkin, 2002; Lopez, 2003) and motor-vehicle accidents (Ewing et al., 2003b); increased costs of public services (Carruthers and Ulfarsson, 2003); loss of agricultural and forest land (Hoffman, 2001; Lopez et al., 2001;

Munroe and York, 2003; Musaoglu et al., 2005); and loss of wildlife habitat (Martien and Trojnar, 2001). Sprawl may also decrease energy efficiency and has negative impacts on the psychological and social well-being of urban populations (Ewing, 1994, 1997) resulting from stress caused by long commuting times as well as increased pollution and its related health effects (Andersson et al., 2002).

Urban planners use a variety of tools when developing strategies and plans to mitigate these problems. Traditionally these have been prescriptive tools such as geographic information systems (GIS) (Webster, 1994) or descriptive tools such as computer aided drafting (CAD) software and 3D visualization packages (Levy, 1995), as well as traditional artist's sketches and physical 3D scale models (Appleton and Lovett, 2005). These tools, however, have had little *predictive* capability (Webster, 1994).

Despite the problems associated with sprawl, it is accepted as inevitable and has even been defended (Gordon and Richardson, 2000, 2001). Nevertheless, the correlation between urban sprawl and its negative externalities prompts most planners and local governments to attempt to curb its spread. One way this can be accomplished is by using policy instruments such as development regulations (Daniels, 2001) and taxation (Hancock, 2000) to guide and encourage urban development to take more compact forms. Testing the effectiveness of these strategies in the real world, however, is unfeasible due to the time, cost, and irreversibility of urban development. One way to asses potential success of these strategies is by using dynamic urban models and integrating them within spatial decision support systems (SDSSs) (Pettie and Pullar, 2004).

For more than twenty years, researchers have been developing modelling approaches to describe and predict urban growth. These tools are based on complex systems theory and favour the use of a CA framework to drive them (Benenson et al., 2005). However, only a few studies report on the use of CA-based models as part of spatial decision support tools for land use and urban growth management (de Kok et al., 2001; White et al., 2004).

1.3 Urban Models

According to Batty (1994), the contemporary form of urban modelling emerged at a time when urban planning was transforming from an intuitive practice into a more objective science. This was partly in response to the need to quantify and empirically justify urban decision-making, but also in response to the insecurities of the urban planning and urban geography fields in the 1960s. By developing dynamic models, researchers were able to jump into the "quantification" culture following their colleagues in related disciplines such as human ecology, mathematics, geography, operations research, linear programming, regional science, and economics (Torrens, 2000b). These contemporary models have their foundation in earlier classical models of land use.

1.3.1 Classical Urban Models

Throughout the 1800s and 1900s, a group of descriptive and analytical urban models was created (Batty, 1994). While this is by no means an exhaustive list, key models in this group include the von Thèunen model, concentric ring model, and the radial sector model of land use.

1.3.1.1 Von Thèunen Model

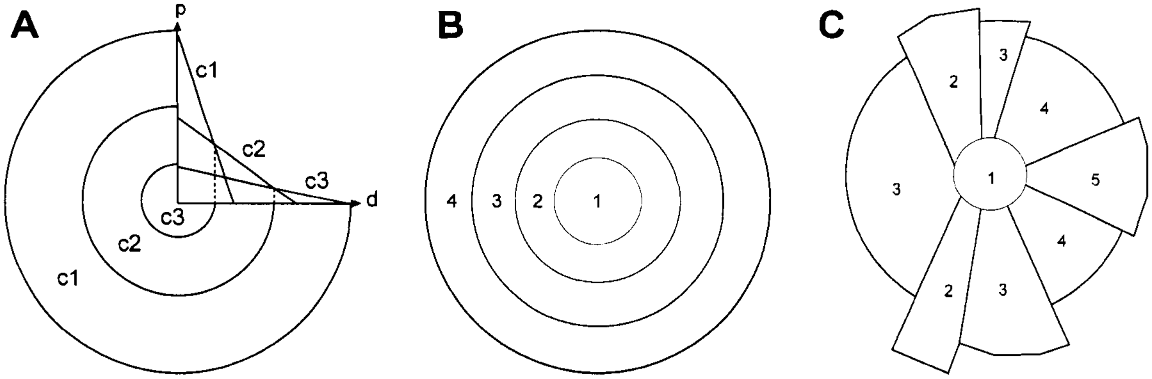
The von Thèunen model is an analytical model of an optimal agricultural land use pattern around a central market. It is based on the profit-at-market generated for the production of different agricultural goods and calculates the potential profitability of each crop at each distance from market minus production and transport costs (Crosier, 2004; Wilson, 2000). It was created before industrialization and first published in *Der isolierte Staat* in 1826 (for an English translation, see Thèunen and Hall (1966)).

The model contains a number of simplifying assumptions: the central market is located in a self-sufficient community with no external influences, the land surrounding the market is open land, the land is homogeneous (i.e. an isotropic plane), all transport takes place by horse-and-cart, and farmers are profit maximizers (Crosier, 2004).

Figure 1-1 (A) illustrates the zones of agricultural land use surrounding the central market as conceptualized by von Thèunen. Each zone is determined by the land use returning the highest rent at each distance from the market. This model is an optimization model as it suggests optimal land use at a given location. It can be considered 1.5-dimensional as it assumes that land use is identical in all directions radiating outward from a central market.

1.3.1.2 Concentric Ring Model

Concentric ring theory was developed by E.W. Burgess and R.E. Park in the mid-1920s and attempts to describe the natural succession of people through different zones of a city (Brown, 2004). Based on the historical development of Chicago throughout the 1890s, the model assumes that the city grows outward from a central core in concentric rings of development (Figure 1-1 (B)). Working class residents are thought to live in



c1 = crop 1 (e.g. tomatoes)
c2 = crop 2 (e.g. wheat)
c3 = crop 3 (e.g. cattle)
p = profit of selling crop per unit area
d = distance to market

1, 2, 3, and 4 represent concentric rings of land uses surrounding a city core.

1, 2, 3, 4, and 5 represent the land uses radiating outwards from the central core of the city along transportation routes.

Figure 1-1 Classical urban models. A) von Thèunen model showing optimal land use around a central market. The graph portion of the model shows profit (rent) gained from varying agricultural land uses as distance increases away from the central market; B) Burgess' concentric rings model shows concentric zones of land use around a central core; and C) Hoyt's radial sector model shows areas of high rent housing (sectors 4 and 5) and low rent housing (sectors 2 and 3) radiating outward from the central core along transportation routes.

the inner-most residential ring and move outwards as their socioeconomic situation improves (Wilson, 2000). Unlike the von Thèunen model, the concentric ring model is descriptive rather than analytical; however, it shares a similar 1.5-dimensionality with von Thèunen's model. It was first published in 1925 in The City (Park et al., 1925).

1.3.1.3 Radial Sector Model

Hoyt (1939) showed how the concentric ring model had to be modified to incorporate sectoral differentiation. He proposed the radial sector model suggesting that similar types of residential land use occupy wedge-shaped sectors extending along transportation corridors from the city center outwards (Briassoulis, 2000). In his model, high-rent housing occupies specific sectors with rents decreasing as one moves away from the high-rent housing sector. Low-rent housing occupies sectors extending from the core in a similar fashion (Figure 1-1 (C)). Hoyt included direction into his model making it a fully two dimensional representation of land use patterns; however, his failure to including employment influences on residential location has been identified as a serious flaw (Harvey, 2000).

These classical models and their associated theories are often criticised for their over-simplicity, unrealistic assumptions, and inapplicability to the structure of today's cities and surrounding regions (Briassoulis, 2000). For example, von Thèunen's model ignores all other factors determining agricultural land use such as the quality of the land and access to irrigation, both of which may impose serious constraints. Both the von Thèunen and concentric ring models also ignore the effect of transportation systems on urban land use (Torrens, 2000b). Hoyt's inclusion of transportation in his radial sector model is his major innovation, resulting in a more realistic asymmetrical representation of the city. Another criticism is that none of these models consider polycentric (i.e. multi-nuclear) cities which are increasingly becoming the norm. However, the most significant limitation of these models is that the theories behind the classical urban models can only describe a city at one moment in time. They are insufficient to model dynamic change. As such, a new theory was needed, one which could take into account the dynamic nature of urban land use. In the 1960s and 1970s, modellers of urban systems turned to complexity theory to help them understand and model dynamic processes in cities.

1.4 Complex Systems and Cellular Automata

Cities exhibit self organization. That is, their internal components organize themselves in a manner that cannot be attributed to outside influences (Portugali, 2000). This is not to say that outside influences do not exist, but rather that they do not determine or cause the behaviour of the internal elements. In the case of cities, examples of the internal elements could be residents, families, and firms. Since self-organization is a central property of complex systems, complex systems theory can be applied to model self-organizing systems such as cities (Wilson, 2000).

The distinction between complex and simple systems is the number of variables required to describe them: simple systems need only a few variables while complex systems require many (Weaver, 1948). Wilson (2000) further describes complex systems as those that are made up of a number of strongly connected interacting parts. One of the main characteristics of complex systems is their emergent properties. Emergent properties are the global patterns that are exhibited from the local interactions of a system's individual components (Wolfram, 2002). These can be seen in the way cities self-organize into neighbourhoods of similar socio-economic status and the city-wide patterns of land use that emerge from of this (Torrens, 2000a).

One of the most commonly used methods to model complex systems is cellular automata (CA). Cellular automata have their roots in Allan Turing's theory of self-reproducing machines, John von Neumann's later demonstration of such machines, and John Conway's Game of Life (Gardner, 1970; 1971). However, Waldo Tobler (1979) was the first to note the potential of CA models for use in geography. The popularity of CA in geographical applications is likely due to (1) the alternative to CA being differential equations which often make computation very tedious (Portugali, 2000), and (2) the availability of data in raster format inherently compatible with CA models (White and Engelen, 2000). While popular in urban modelling, cellular automata have also been used in a wide range of other spatially-aware fields to tackle problems such as epidemic propagation and vaccination (Sirakoulis et al., 2000), pedestrian traffic flow in fire evacuation (Kirchner and Schadschneider, 2002; Yang et al., 2002), land use optimization in afforestation areas (Strange et al., 2002), the effects of global warming on the distribution of insect populations (Karafyllidis, 1998), migration and influence dynamics (Flache and Hegselmann, 2001), and the spread of forest fires (Clarke et al., 1994; Song et al., 2001) among others.

White and Engelen (2000) describe cellular automata as one of the simplest forms of spatial model that are particularly suited to modelling complex systems. In the traditional form of CA, there are five main components: the grid, time steps, cell states, a neighbourhood, and transition rules. The *grid* is usually composed of equally sized square cells, however other regular tessellations such as hexagons have also been used (Phipps, 1989). *Time* is divided into discrete time steps.

Each cell is described by a single *state* or attribute appropriate to the phenomena modelled. Some models use a binary set of states such as {*developed land*, *undeveloped land*} (Cheng and Masser, 2004) while others use multiple states, such as {*housing*, *industry*, *commerce*, *streets*, *vacant land*} (Batty et al., 1999). It is important to note that any cell can be represented by only one state at any given time and that the grid is assumed to be homogeneous in all other respects.

The *neighbourhood* of each cell defines the geographical domain of influence (Tobler, 1979) and traditionally takes the form of either the von Neuman neighbourhood (the four adjacent cells to the N, S, E, and W) or the Moore neighbourhood (the four adjacent cells plus the four diagonally adjacent cells) (White and Engelen, 2000). The *transition rules* examine the cells in the neighbourhood to determine if and how the central cell will change state at the next time step. Together, these five components form the basis of all cellular automata models.

1.5 Research Problem

While the simplicity of the traditional cellular automata approach is seen as one of its benefits, it presents a number of challenges when applied to urban growth. The first part of the research problem deals with these challenges while the second involves implementation of CA models.

1.5.1 Simplifying Assumptions of the Classical Cellular Automata Method

Classical cellular automata involves a number of simplifying assumptions that make it problematic when used to model urban growth (Torrens, 2000a). The first simplification concerns the grid which is assumed to be an isotropic plane where topography, geology, and all other features remain constant except for the variable of interest (e.g. land use). Natural and built environments, however, are not isotropic planes and many factors influence land use dynamics at a given location (e.g. topography, vicinity to transportation routes, geology, susceptibility to flooding, perceived crime rates, and property values). Second, classical CA are able to run infinitely, representing unconstrained growth which is unlikely in reality.

Third, classical CA models use a raster grid of cells which cannot accurately represent irregularly sized and shaped cadastral units of urban land. Land use is often represented by municipal governments at the cadastral parcel scale, with each parcel having an irregular size and shape. Generalizing across these units of land with a regular grid could result in transformed data depending on where raster cell boundaries fell in relation to actual land use boundaries. This may result in different patterns leading to different conclusions, a result of the modifiable areal unit problem which occurs when the same data are aggregated at different resolutions or using different areal units (Openshaw, 1983, 1984; White and Engelen, 2000).

Fourth, the discrete time steps of classical CA cannot accurately represent different rates of change for different cell states. As applied to urban growth, a cell is either *undeveloped* or *developed* and the time for development remains the same (usually one time step) regardless of the cell's developed land use. In reality, different land uses take different lengths of time to develop and therefore different areas of a city may develop asynchronously. That is, development occurs at different times and at different rates in different places. This is considered *asynchronous growth.*

Due to these assumptions, most urban models relax or extend the traditional definition of cellular automata (Couclelis, 1985; Torrens, 2000a). There are many examples in the urban growth literature of models relaxing the homogeneous grid assumption (Batty and Xie, 1999; Engelen et al., 1993; White et al., 1997; Wu, 2003) and addressing the problem of unconstrained growth (White and Engelen, 2000; White et al., 1997; Yeh and Li, 2001). A few examples outside the urban growth field exist that use an irregular spatial structure to overcome the problems of the raster data structure generalizing across irregular spatial units (O'Sullivan 2001a, 2001b, 2002); however, these methods cannot be directly applied to urban growth modelling due to their method of defining the neighbourhood. O'Sullivan's (2002) model of gentrification defines the CA neighbourhood using a graph structure created from Delaunay (Boots, 1999) triangulation where each land parcel is essentially reduced to a point. This is inappropriate for use with urban growth due to the wide variety of sizes and shapes of land parcels and other units of land use, such as roads; therefore, this study builds on current urban modelling theory and addresses issues concerning the regular raster spatial structure and the need to represent asynchronous growth.

1.5.2 Model Implementation

The second part of the research problem concerns how models are implemented. Most urban CA models have been implemented using custom-built software (Stevens et al, 2005). Developing custom-built software requires a high degree of specialization and time leading to higher cost. Additional problems of data compatibility and lack of advanced GIS analysis functions also exist. The GIS-analysis problem has been addressed to some degree by the creation of various levels of GIS-coupled models (Batty et al., 1999; Clarke and Gaydos, 1998; Parks and Wagner, 1997; Yeh and Li, 2001) but these models do not address the problem of spatial data compatibility and have only been used within a raster-based GIS framework.

1.6 Research Objectives

The objectives of this thesis address the above problems by developing a CA model of urban growth capable of using irregular spatial units, representing asynchronous growth, and using high resolution spatial data at the cadastral scale in the vector GIS format. Furthermore, the model had to be embedded within common desktop GIS software to demonstrate how GIS can be used as a model implementation tool to aid the development of spatio-temporal models. To accomplish these objectives, the research was divided into three parts:

1. Development of a conceptual model for high spatial and temporal resolution modelling of urban growth, including mechanisms to represent synchronous and asynchronous growth and an irregular spatial data structure such as cadastral land parcels.
2. Development of *iCity*, a prototype software for full implementation of the conceptual model within a GIS software framework.
3. Examination of the model and prototype by generating results using realistic scenarios and spatial data from a real urban area.

1.7 Study Site

A study site located in the City of Saskatoon, Saskatchewan, Canada, was chosen on which to examine the proposed urban growth model. Saskatoon is located on the banks of the South Saskatchewan River in townships 36 and 37, range 5 and township 36, range 6, west of the third meridian (City of Saskatoon, 2005; ISC of Sask., 1994) or at approximately 52.24° N, 106.67° W. It is home to approximately 205 900 residents and occupies an area of 148 km^2 (Statistics Canada, 2005).

The study site is currently exhibiting a dynamic growth process and is located in the north east part of the city. It includes the neighbourhoods of Sutherland, Forest Grove, Silverspring, Arbor Creek, Erindale, Willowgrow, the NE Development Area and the Sutherland Industrial District, in addition to a number of agricultural fields within the city limits. The area is bounded by College Drive to the south, Circle Drive to the west, and the city limits to the north and east. The Sutherland neighbourhood was once the centre of a small town of the same name, and as a result this area of Saskatoon has a wide range of land uses including residential, parks, commercial, industrial, and includes a small central business district.

1.8 Thesis Overview

The second thesis chapter presents a synthesis of the current status of urban CA research, including the limitations of current cellular automata models and an overview of the current work that has been conducted using irregular cellular automata. The proposed conceptual model is presented along with a discussion of how the various cellular automata components are implemented within it. Results from simulations under two sets of scenarios are given to demonstrate the model's ability to generate outputs under different buyer preference scenarios and using different neighbourhood designs as spatial inputs. Results demonstrating asynchronous growth are also presented. A technical description of the proposed GIS-based software modelling tool, named *iCity* (Irregular City), is presented in the Appendix.

Chapter three concludes the thesis by summarizing the results from the research, discussing benefits and limitations to the methods employed, and presenting suggestions for further research.

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CHAPTER 2 - A GIS-BASED IRREGULAR CELLULAR AUTOMATA MODEL FOR URBAN GROWTH[1]

2.1 Abstract

This study proposes an alternative cellular automata (CA) model which relaxes the traditional CA regular square grid and synchronous growth. It can be applied to high-resolution representations of land use in and around an urban area. The model uses high-resolution spatial data in the form of irregularly sized and shaped land parcels and incorporates synchronous and asynchronous development to more realistically model urban growth at the land parcel scale. The model allows urban planners and other stakeholders to evaluate how different subdivision designs will influence development under varying population growth rates and buyer preferences. A model prototype has been developed in a common desktop GIS and applied to a rapidly developing area of a mid-sized Canadian city.

2.2 Introduction

With high levels of urbanization occurring world-wide (United Nations, 2004), it is important for the well-being of the urban and rural populations as well as the natural environment that cities be developed in a sustainable and liveable manner. Complex

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[1] A modified version of this chapter has been submitted to the journal *Environment and Planning B: Planning and Design* under the co-authorship of Suzana Dragicevic.

systems theory is used as a theoretical framework for studying and understanding how cities grow in response to a multitude of factors in much the same way that it is used to explain how natural systems react to continuous change (Batty and Xie, 1999; Silva and Clarke, 2005). Cellular automata are one of the simplest forms of complex systems model (White and Engelen, 2000) that are suitable for modelling spatial phenomena such as urban growth. They operate in an abstract universe with space represented by an infinite grid of cells and time by a set of discrete time steps. The grid is usually composed of equally sized square cells, though hexagons have also been used (Phipps, 1989) and triangles proposed (Torrens, 2000). Each cell contains a single value that represents the state of the phenomena in question, for example, land use. At each time step, a set of simple local rules is applied to each cell to determine its state at the following time step. The transition rules examine the cells in the neighbourhood to determine if and how the central cell will change state at the following iteration (Batty, 1997). Neighbourhoods are traditionally defined as either the von Neuman (the four adjacent cells to the N, S, E, and W) or the Moore neighbourhood (the four adjacent cells plus the four diagonally adjacent cells) (White and Engelen, 2000). Together, these five components make up a traditional cellular automata model.

Cellular automata models have been used to model urban growth at regional scales (Clarke and Gaydos, 1998; Clarke et al., 1997; Engelen et al., 1995; Landis, 1994) down to finer-scales of smaller regions and cities (Cheng and Masser, 2004; Li and Yeh, 2000; White et al., 1997; Yeh and Li, 2001). The use of a regular raster grid in these models creates areas of assumed homogeneous land use that may contain variability in reality. Therefore, a regular grid of cells cannot precisely represent irregular patches of land or cadastral units, such as those that compose urban environments. While the raster spatial structure has been said to be an acceptable generalization (Besussi et al., 1998) it becomes less appropriate when the spatial resolution is increased. As resolution increases, subdivisions, census tract boundaries, postal code areas, city neighbourhoods, and even individual land parcels can be identified, all with irregular size and shape. If a regular grid were to generalize across these homogeneous land units, information would be lost or transformed depending on where the raster cell boundaries fell in relation to actual land use boundaries. Two images of the same area with cells slightly offset would yield different representations as a result of the modifiable areal unit problem (Openshaw, 1983, 1984). White and Engelen (2000) suggest that an irregular spatial framework should be used to overcome this problem.

Currently, most urban CA models represent growth occurring at the same rate for the entire study site. When a cell begins to develop, it is fully developed at the next time step. However, in reality not all land uses are developed at the same speed as others and do not begin at the same time. Single-family homes may take several months to build while an apartment building may take a year or more and new residential developments start at different times at different locations in the same city. This variability in temporal dynamics needs to be accounted for in high resolution models where different speeds and rates of change occur at different locations in urban areas (Dragicevic et al., 2001; Liu and Andersson, 2004).

The objective of this study is to propose a CA model of urban growth using an irregular spatial structure with high spatial and temporal resolution. To overcome the limitations of existing raster-based and irregular CA models, the *iCity* model prototype has been developed and fully integrated within a common desktop geographical information system (GIS) using data in the vector format.

2.2.1 Irregular CA

Tobler (1984) proposed resolution elements (resels) as an irregular spatial structure combining aspects of vector and raster data representations. The resel method could be adapted to run very simple irregular CA, but lacks a graphical display method and has no means by which to define a standard neighbourhood. Further, Moore (2000) built on this structure and offered examples of different image-processing filters for use with resel data. While the literature has long suggested using irregular structures in CA modelling (Couclelis, 1985), there have been only a few researchers implementing it in practice. Perhaps this is due to the computationally intensive operations required to search irregular neighbourhoods, the overhead associated with the vector data structure most appropriate to representing irregular shapes, or the complexity involved in defining some of its basic components such as the neighbourhood and irregular grid.

The few examples of irregular CA all use Voronoi polygons or the related Delaunay triangulation to divide space. Voronoi polygons divide space into regions surrounding objects such that any point in an object's polygon is closer to that object than to any other object, while Delaunay triangulation is a triangulation of the points in a Voronoi diagram where the circumcircle of each triangle is an empty triangle (Boots 1999). Shi and Pang (2000) and Pang and Shi's (2002) CA extension used Voronoi polygons in order to model dynamic topological relationships. Objects sharing Voronoi polygon edges were considered neighbours and could affect each other through the transition rules. Flache and Hegselmann's (2001) work on migration and influence dynamics concluded that some implications of their CA model became apparent only after using a randomly generated irregular spatial structure. Both Flache and Hegselmann (2001) and Pang and Shi (2002) use the Voronoi spatial structure of dividing space into irregular units, however, the resulting polygons do not represent useful units such as cadastral land parcels or urban administrative areas such as postal codes areas or census tracts.

In an urban example, O'Sullivan (2001a; 2001b; 2002) used land parcels as an irregular grid and a graph-structure generated using Delaunay triangulation (from the land parcel centroids) to model the neighbourhoods in his model of urban gentrification. While based on useful spatial units, this framework would be problematic if used in a model of urban growth, however, as additional land units between the individual property parcels (e.g. roads, parks, railways, ponds) and more appropriate neighbourhood definitions would be required to incorporate influence at a distance rather than simple adjacency.

Due to the complexity required in implementing such modifications to traditional CA, most urban CA models have been implemented using custom-built software (Batty et al., 1999; White et al., 1997). This has created its own challenges relating to the high degree of specialization and time required to develop such CA modelling tools, problems of data compatibility, and lack of advanced GIS analysis functions in the custom applications.

2.3 Model Implementation Tools

Model Implementation Tools (MITs) are the software tools with which modellers can operationalize their conceptual models. MITs can be categorized based on their flexibility and ease-of-use (Stevens et al., 2005). MITs that are easy to use often contain hard-coded logic specific to one conceptual model, thus offering little or no flexibility. Batty et al (1999)'s Dynamic Urban Evolutionary Model (DUEM) and White and Engelen (2000)'s LeefOmgevingsVerkenner (Environment Explore) fall into this category. While powerful tools for their respective purposes, they offer little to the user whose requirements do not explicitly match those of the software developers. However, if a user's needs can be met by these hard-coded MITs, they can often be more cost-effective than the alternatives.

On the other extreme are general-purpose programming languages such as C++, Java, and Visual Basic. These offer the most flexibility but require that not only the model logic be programmed, but also that data handling, user interface, visualization, and analysis functions be programmed, adding considerable cost due to the time and expertise required to use them.

Between these two extremes exists another category of MIT: specialized modeling environments. These environments offer the developer one or more tools with which to implement models, including *specialized modeling languages* such as those found within SELES (Fall and Fall, 2001), CAGE (Blecic et al., 2005), SpaSim (Moreno et al., 2002), and UrbanSim (Waddell 2002); *software development kits (SDKs)* that allow for the customization of existing software using general-purpose programming languages, such as ArcObjects (ESRI, 2004b, 2005a) and the SDKs included within GEONAMICA (RIKS, 2005) and the Idrisi Kilimanjaro GIS (Clark Labs, 2005); and *visual model builders* such as Idrisi's Macro Modeller (Clark Labs, 2005) and ArcGIS's Model Builder (ESRI, 2004a).

These environments can be further categorized based on whether they are part of a GIS (e.g. ArcObjects, Idrisis's Macro Modeller, ArcGIS's Model Builder) or whether they exist as stand-alone environments (e.g. SpaSim, UrbanSim, SELES, CAGE, GEONAMICA). Stand-alone environments have limited functionality in terms of spatial data analysis and support only a limited set of spatial data formats but do not require GIS software to run. They are also currently limited to functioning on a regular spatial structure. On the other hand, GIS-based environments provide a wealth of analysis tools and the ability to use a wide range of industry-standard spatial data formats all within the same environment. The more flexibility given to the user by a modelling environment, the less the user will benefit from the specialized software (Benenson et al., 2005).

The cost of obtaining and using a specialized modelling environment varies widely depending on the tool selected. Some tools such as CAGE, SpaSim, and UrbanSim are in the public domain or open source while others such as GEONAMICA, ArcGIS, and Idrisi are proprietary commercial applications that can be relatively costly if purchased solely for a single modelling project. Organizations without existing licenses for proprietary commercial software may want to explore the public domain packages before investing in expensive commercial software. When assessing the total cost of implementing a model, the software developer's familiarity with specific GIS software or modelling tools should be considered as the time spent learning new software may incur costs in excess of purchasing software with which the developer is already familiar.

The proposed modeling tool, *iCity*, was developed using a GIS-based SDK and a general-purpose programming language. This provided a high level of flexibility in addition to being moderately easy to use and enabled the CA model procedures to be embedded within the GIS.

2.4 Method

Most CA models of urban growth attempt to determine or predict the general patterns of land use that are likely to emerge given certain economic, social, or regulatory conditions. In contrast, this model can be used by planners and stakeholders to analyze and visualize how a city may develop using different neighbourhood designs at the land parcel level and under various growth rates, residential densities, and resident preferences. Land parcels at the cadastral level were chosen to represent space as it was determined that they more realistically represent the irregular nature of urban land use areas than raster cells. As they are the smallest unit of land use, their adoption removes the problems associated with raster cells misrepresenting boundaries at a low resolution or requiring multiple cells to represent one discrete unit at a high resolution. Along with this high spatial resolution, there is a requirement to model at a high temporal resolution to better represent the reality of rapid urban development. Therefore, a high temporal resolution is adopted to acknowledge the different length of time it takes to develop different land uses. A number of parameters can be adjusted to tailor the transition rules and neighbourhoods to a user's specific needs.

The model consists of two sub-models, global and local (Figure 2-1). A set of global parameters, including the modeled area's starting population and growth rate, is input to the global sub-model in the form of numerical values by planners, developers, or other stakeholders. The local sub-model receives the global sub-models' output, a set of local influence scores representing how neighbouring land uses influence a parcel's

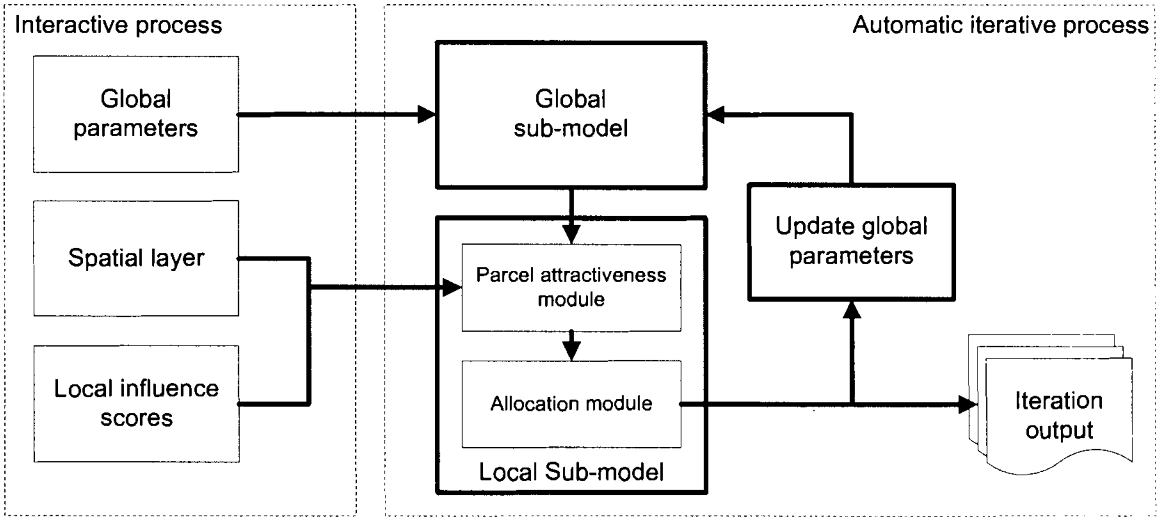


Figure 2-1 **Flow chart of the model showing the inputs (on the left) and the iterative process and output (on the right).**

development, and land parcel spatial data. The spatial data provides the land parcels' current or proposed land uses and their development level to the local sub-model. The development level is set to either *developed* or *undeveloped* at the initial time. At later iterations, the development level may also signify a stage of development (e.g. second month of twelve months). The local sub-model then generates an output permitting the visualization of the development stages of all the land parcels in the study area at a given point in time. Both sub-models update the global parameters which are then provided to the global sub-model for the next iteration.

2.4.1 Global Sub-Model

The global sub-model uses the initial population of the city or region and its growth rate in order to determine the expected future population. This sub-model updates a number of global parameters including the expected population in *n* growth stages, the number of housing units that need to begin construction at the current growth stage to house the expected population, and the city's current population. The first variable calculated is p_{t+n}, the expected population at growth stage n, defined as:

$$p_{t+n} = p_t \cdot g^n \tag{2-1}$$

where t is the current growth stage, p_t is the population of the area represented by the spatial layer at growth stage t, n is the number of growth stages it takes to develop the most common residential land use, and g is the user-input growth rate where $g > 1$ representing a positive growth rate as the model is not currently designed to model urban recession. If residential buildings take longer than one growth stage to develop, it is assumed that developers will begin their construction in anticipation of future population increases. This maximizes the developers' profits and minimizes housing shortages. As some residential units, such as apartment buildings, may take longer than the number of growth stages required to develop the most common residential land use, there may be an un-housed population which is assumed to live in temporary accommodation until their housing has been fully constructed. The next value calculated is h_t, the number of housing units that should begin construction at growth stage t, defined as:

$$h_t = p_{t+n} - p_t - h_{t-1} \tag{2-2}$$

where p_{t+n} is the expected population after n growth stages as determined by equation (1), p_t is the current population at growth stage t, and h_{t-1} is the number of units that began construction at the previous growth stage. At the initial growth stage $h_t = 0$, but in subsequent stages the local sub-model updates the value of h_t. The last variable that is calculated is p_{t+1}, the population count for the next growth stage:

$$p_{t+1} = p_t \cdot g \tag{2-3}$$

where p_t is the population at growth stage t, and g is the population growth rate where

$g > 1$. Once these three values are calculated they are used as input to the local sub-model (figure 2-1).

2.4.2 Local Sub-Model

The local sub-model is composed of two modules (figure 2-1). The first module calculates an attractiveness factor for each undeveloped residential land parcel adjacent to a road while the second module develops all land use parcels based on their transition rules which take into account the attractiveness scores for the residential parcels. It is within these two modules that the traditional CA components of neighbourhood and transition rules are found.

2.4.2.1 Parcel Attractiveness Module

The parcel attractiveness module receives inputs from the land parcel spatial layer and the set of local influence scores and their parameters describing the conditions under which the scores should be assigned. The influence scores are added to the parcel's attractiveness score if the condition is met. Negative factors will have negative score values. If none of the conditions are met for each influencing land use, a score of zero is usually assigned. The attractiveness scores summarize the conditions in a residential parcel's neighbourhood and are used by the transition rules. The total attractiveness of residential parcel j, denoted as a_j, is defined as

$$a_j = b_j + c_j + l_j + q_j + r_j \tag{2-4}$$

where b_j, c_j, l_j, and q_j are the scores that parcel j receives with regards to its proximity to park, commercial, light industrial, and heavy industrial land respectively, and r_j is the score received for its adjacency to existing developed or developing residential land.

These are the most common land uses in a suburban neighbourhood that are thought to influence the development of residential land.

Commercial and park lands do not use attractiveness scores but instead rely on more simple transition rules examining the conditions in their neighbourhoods directly. Table 2-1 shows the three developable land uses, the land uses that influence their development, and their transition rules. Each undeveloped parcel that meets the conditions set forth in the transition rules will have its development state incremented by one development stage, while already developing parcels will be automatically incremented by one development stage until they are fully developed. Each development stage represents a unit of time (e.g. a week, month, or year) under which development occurs. The number of development stages for complete development of a parcel varies based on its land use type. For example, parks could take two development stages, medium residential six stages, or for those land use types that need a longer time for development, such as commercial or high-density residential (e.g. apartments), twelve stages.

2.4.2.1.1 Neighbourhoods

In both calculation of the attractiveness scores for residential land parcels and more direct transition rules of the commercial and park parcels, the neighbourhood conditions of each parcel must be examined. While traditional CA use the Moore or von Neuman neighbourhoods, or an extended version of each, irregular CA must use alternative neighbourhood definitions to deal with non-uniform number of neighbours for each cell and the irregular size of individual cells. This model proposes three irregular neighbourhoods suited to land parcel proximity functions: adjacency neighbourhood, distance neighbourhood, and clipped distance neighbourhood (Figure 2-2). The adjacency

Developable Land Use	**Influencing neighbouring land uses**	**Transition Rules**
Residential (high, medium, and low)	park commercial light industrial heavy industrial roads	**For undeveloped residential property adjacent to a developed road:** *Begin* construction of undeveloped residential property in order of their attractiveness. *Begin* constructing only what will be required by the expected future population. **For developing residential property:** *Continue* construction of the residential property.
Commercial	commercial roads	**For undeveloped commercial parcels adjacent to a developed road:** *If* the neighbourhood of a commercial property contains a sufficient population to sustain it and *if* the neighbourhood is not already saturated with other commercial properties *then begin* developing the property. **For developing commercial parcels:** *Continue* construction of the developing commercial properties.
Parks	residential	**For undeveloped parks:** *If* an undeveloped park is adjacent to a specified area of developing residential properties *then begin* developing the park. **For developing parks:** *Continue* construction of developing park land.

Table 2-1 Developable land uses and their transition rules.

neighbourhood of parcel *j* contains all parcels which share a point or line with parcel *j* and can be likened to the traditional Moore neighbourhood. The distance neighbourhood contains all parcels which are within a certain distance of parcel *j*'s outer border. The notion *within a certain distance* can be defined in two ways. For a parcel to be considered within a distance of *d* metres of parcel *j*, for example, it may have to reside entirely within the *d* metre limit, or it may only have to be partially within the *d* metre limit. The clipped distance neighbourhood is similar to the distance neighbourhood except that it clips the distance neighbourhood returning only the portion of the outer parcels which lie within the specified distance. This allows the transition rules to determine the area of each land use that lies within a specified distance from cell *j*.

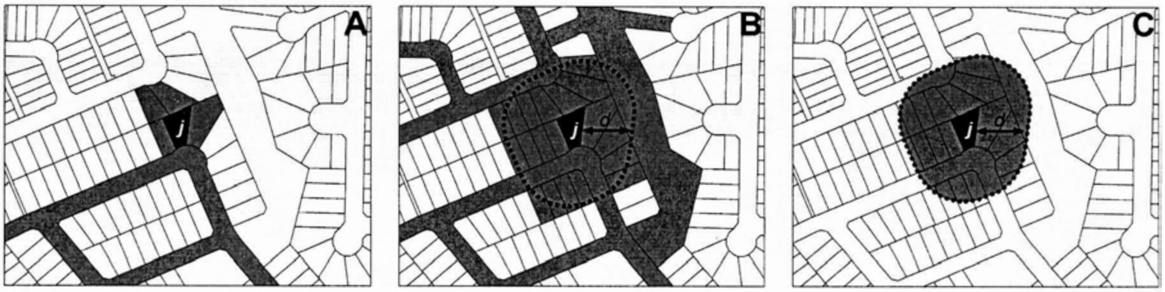


Figure 2-2 **Three irregular cellular automata neighbourhoods implemented in *iCity*. The grey polygons indicate those polygons in the neighbourhood of polygon j. (A) the adjacency neighbourhood includes all polygons which share a common edge or point with polygon j, (B) the distance neighbourhood includes all polygons that fall completely or partially within d map units of polygon j, and (C) the clipped distance neighbourhood includes all polygons that fall within d map units of polygon j plus the portions of polygons partially within d map units of polygon j.**

The different neighbourhoods can be used for a variety of functions. For example, the adjacency neighbourhood can determine whether or not a park is adjacent to residential land parcel *j*. The distance neighbourhood enables the model to determine whether or not commercial land is within *d* distance of residential land parcel *j*, and the clipped distance neighbourhood can determine the number of residents within *d* distance of commercial land parcel *j*.

2.4.2.2 Allocation Module

The allocation module increments the development state of all currently developing land parcels by one growth stage and then begins developing the required number of undeveloped residential parcels in order of attractiveness. The attractiveness score represents how attractive a given residential parcel will be to a potential home buyer. It is assumed that developers will build on these land parcels first in order to maximize revenues. While this may not represent all cases in reality, it was a necessary assumption to maintain simple model logic to facilitate examining the irregular and asynchronous characteristics of the model. The residential parcels are followed by parks and commercial parcels. These three classes of land use are the most common in the suburban neighbourhoods examined. As each new residential parcel is developed, the model subtracts the number of people expected to occupy parcel k_j, from the number of people requiring housing h_t (equation 2). The value for k_j can be calculated as:

$$k_j = s_j \cdot m \tag{2-5}$$

where s_j is the calculated surface area of parcel j, and m is the average number of residents per unit area for that land use. When h_t (equation 2) reaches zero, signifying sufficient housing has been developed to house the expected population, the parcel development stops for the current growth stage. If the model runs out of parcels before h_t reaches zero, new roads will be constructed, attractiveness factors calculated for the land parcels adjacent to the new roads, and development will continue until sufficient housing has begun development to house the expected population. The decision of which roads to construct is a function of their Euclidian distance from the CBD which is considered a surrogate for travel time. Roads closest to the CBD will be developed before roads further away. In this way, the model operates at two scales, the land parcel scale and the neighbourhood or street scale. It therefore can simulate asynchronous growth.

Asynchronous growth takes place when multiple areas are under development at the same time. Since different land uses take different lengths of time to develop, it is likely that growth will occur in several places at the same time. This ability for asynchronous growth is implicitly embedded in the allocation module through the mechanisms used to construct additional roads when all parcels adjacent to developed roads have already begun development. The new roads developed may not be adjacent to currently developing land parcels if there is a proposed new road (i.e. a road with its development level attribute set to fully undeveloped) closer to the CBD in another part of the modelled area.

Parcels of park land, representing suburban neighbourhood parks and green spaces representing green pedestrian alley ways, begin development when a specified threshold of residential parcels has begun development within a specified distance. Commercial parcels, on the other hand, begin development when a specified number of people live within their neighbourhood and only if the number of commercial lots already under development does not saturate the market. Therefore, only a sustainable level of commercial land will be developed in any neighbourhood reducing the likelihood of abandoned commercial lots. Both commercial, park and other greenspace parcels depend on the residential population in their vicinity in order to be developed; therefore, this model is considered resident-driven as the residential population drives the growth of all land uses. Although urban developers and planners may heavily influence decisions on what land will be developed, it is assumed their decisions are based on the public's demands and preferences in order to maximize profits.

2.4.3 Calibration

The model's influence parameters have to be calibrated in order to simulate current economic conditions and housing preferences using historical land parcel data. Appropriate values for these can be obtained from stakeholder or expert focus groups for model input. The growth rate should also be calibrated based on current or hypothetical conditions and can be used to represent changes in economic conditions as a proxy for land demand. Once calibrated, alternative neighbourhood designs with different mixes of land use and street layout can be input in order to examine how the spatial configuration of neighbourhoods will impact development.

2.5 Results

In order to test the proposed model and explore how a recently updated GIS software package can be used for high-resolution irregular CA modelling, the *iCity* prototype was developed as a fully-integrated extension to ArcGIS 9 (ESRI, 2004a). A study site in the City of Saskatoon, Canada, was chosen to examine the *iCity* model and generate the simulation results.

Saskatoon is located in south-central Saskatchewan on the South Saskatchewan River and is home to approximately 205,900 residents (City of Saskatoon, 2005), occupying an area of 148 km^2 (Statistics Canada, 2005). The part of the city that was selected to test the model (figure 2-3) is currently exhibiting dynamic change and includes the neighbourhoods of Sutherland, Forest Grove, Silverspring, Arbor Creek, Erindale, Willowgrove, as well as the NE Development Area and the Sutherland Industrial District. This area is bounded by College Drive to the south, Circle Drive to the west, and the city limits to the north and east, and was selected due to the sharp boundary between the developed suburban land and surrounding agricultural fields. Additionally, this area once included the separate town of Sutherland and therefore has distinct commercial and industrial districts as well as new residential neighbourhoods which allows for a greater variety of land uses.

The model was tested using vector land parcel spatial data obtained from the City of Saskatoon. These data contain zoning information for each land parcel that were used to reclassify the parcels into the unique land use classes of residential high density,

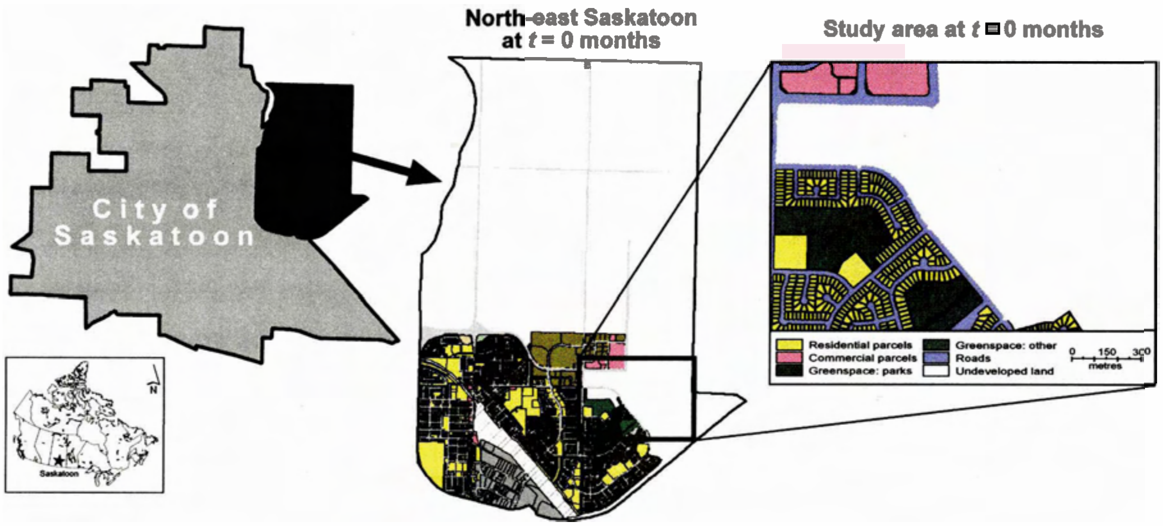
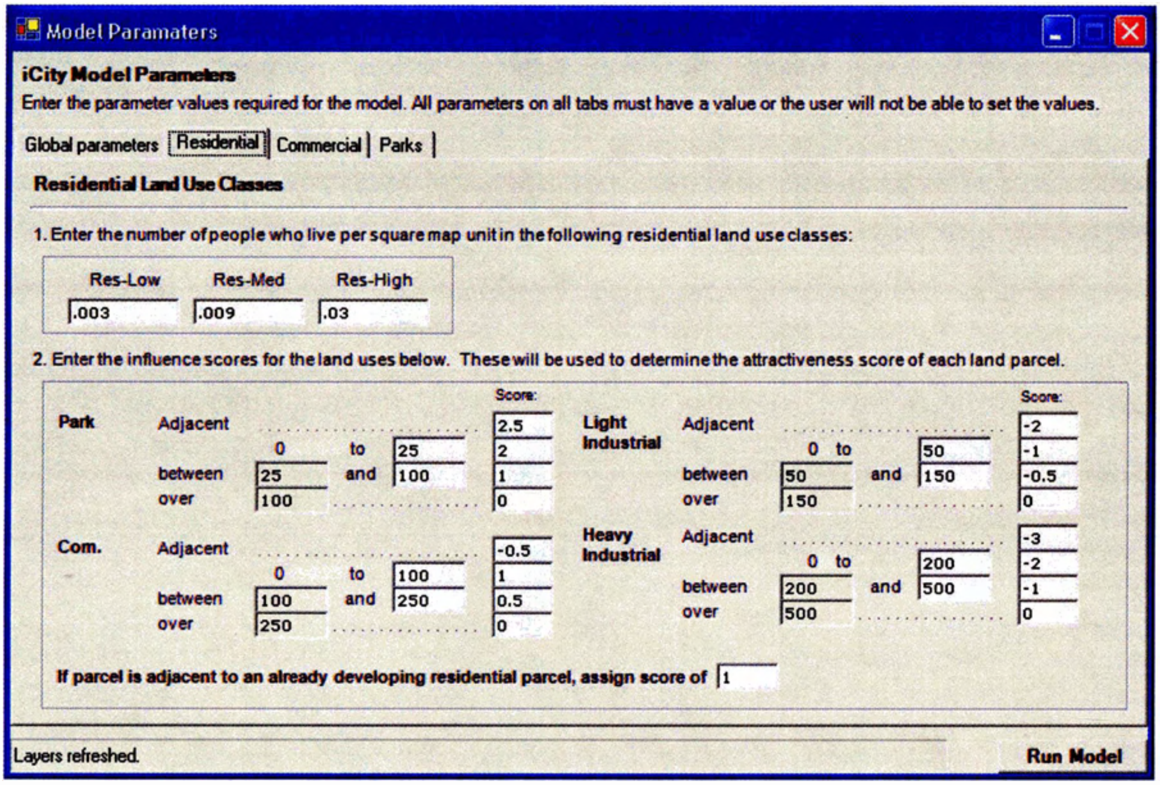


Figure 2-3 Study area shown at the initial time (t = 0 months).

residential medium density, residential low density, greenspace: park, greenspace: other, commercial, industrial high density, industrial low density, railways, and agricultural land. A number of recently developed neighbourhoods were selected and the development-level states for their land parcels and roads were set to the *undeveloped* land use state. The road polygons which were set to undeveloped at the initial time were split into polygons for each section of road forming small sub-neighbourhoods. These sub-neighbourhoods were composed of a small number of streets or one complex street with all its bays, courts, crescents, and ways. This approximated the state of the area before these sub-neighbourhoods were developed and provided an effective way to employ undeveloped streets and land parcels in a realistic pattern.

2.5.1 The *iCity* User Interface

The *iCity* prototype provides an interactive graphical user interface that is accessed from within the GIS (figure 2-4). The global tab allows the user to easily set the global options and parameters, such as selecting the initial GIS data containing land use



iCity Model Parameters

Enter the parameter values required for the model. All parameters on all tabs must have a value or the user will not be able to set the values.

Residential Land Use Classes

1. Enter the number of people who live per square map unit in the following residential land use classes:

Res-Low	Res-Med	Res-High
.003	.009	.03

2. Enter the influence scores for the land uses below. These will be used to determine the attractiveness score of each land parcel.

					Score:
Park	Adjacent				2.5
		0	to	25	2
	between	25	and	100	1
	over	100			0
Com.	Adjacent				-0.5
		0	to	100	1
	between	100	and	250	0.5
	over	250			0
Light Industrial	Adjacent				-2
		0	to	50	-1
	between	50	and	150	-0.5
	over	150			0
Heavy Industrial	Adjacent				-3
		0	to	200	-2
	between	200	and	500	-1
	over	500			0

If parcel is adjacent to an already developing residential parcel, assign score of 1

Layers refreshed.

Figure 2-4 ***iCity* user interface for assigning the influence scores and associated parameters for residential land parcels.**

parcels, specifying the location to save the model outputs, the number of months to simulate, the initial population for the area, and the area's annual or monthly growth rate. As depicted in figure 2-4, tabs also exist for each developable land use: residential, commercial, and parks.

The residential tab allows the user to enter the average population density for each of the three residential sub-classes (low, medium, and high), as well as the influence scores and associated distance parameters for land uses that affect a resident's decision on where to live. Using the parameters and scores shown in figure 2-4 one can approximate the values for equation (4) under varying circumstances. For example, $b_j = 2.5$ if parcel j were adjacent to a park, $b_j = 2$ if parcel j were not adjacent to a park but between 0 and 25 map units from a park, and $b_j = 1$ if parcel j were between 25 and 100 map units from a park, but not adjacent or within 25 map units of a park. The score values are considered relative to each other and can be any real number between -50 and 50 due to model constraints. For example, a score of +3 for adjacency to park land and a score of +1.5 for adjacency to commercial land would signify that a resident considers adjacency to park land twice as important as adjacency to commercial land. Extreme values were used when calibrating the influence scores and adjusted until meaningful results were obtained.

The commercial and park tabs receive the inputs required by their transition rules as presented in table 2-1. The *iCity* prototype redraws the display after each development stage to permit visualization of the development process. Technical details of the *iCity* software are provided in the Appendix.

2.5.2 Simulations

The proposed irregular CA model was tested using two sets of scenarios to provide variability of model outcomes when (1) the growth rate and residential preference parameters were different, and (2) when different neighbourhood designs were input. These scenarios were generated with development restricted to the smallest part of the study area (figure 2-3). In order to show the asynchronous growth properties of the model, results were also obtained for the larger north-east area of Saskatoon.

In all these scenarios the average development time for a residential parcel (*n* in equations (1) and (2)) was chosen to be 6 months, a reasonable length of time to develop the wood-frame houses common in suburban neighbourhoods of western-Canadian cities. One model iteration was chosen to be equal to one month due to the typical dynamics of building construction in the study area. However, other lengths of time can be represented in the model depending on the dynamics of different types of urban development found elsewhere. Parks and other greenspaces had a development time of 2 months while roads could be developed as needed. There were no undeveloped commercial land parcels in the study area. The initial population for the study area was set at 20800 inhabitants and was derived from the population of its respective 2001 census tracts.

2.5.2.1 Growth Rate and Residential Preference Scenarios

2.5.2.1.1 Growth Rate - Park User Scenario

The Park User Scenario assumes that all new residents place value on living close to parks and commercial properties, but prefer not to live directly adjacent to commercial land. The influence scores were set accordingly and based on reasonable estimates of how a residential property's proximity to various land uses would affect its attractiveness to a potential resident with these pro-park preferences. Figure 2-5 shows the results for this scenario using growth rates of 2%, 1%, and 0.5%, while the residential land influence scores were held constant. A 1% growth rate is the current rate of growth in this area of Saskatoon (Statistics Canada, 2005) while the 2% and 0.5% rates were chosen to illustrate faster- and slower-than-normal development. The park influence score b in equation (4) is 2.5 for parcels adjacent to a park, 2 for parcels between 0m and 25m from a park, 1 for parcels between 25m and 100m from a park, and 0 for parcels greater than 100m from a park. The commercial influence score c is -0.5 for parcels adjacent to commercial land, 1 for parcels between 0m and 100m from commercial land, 0.5 for parcels between 100m and 250m from commercial land, and 0 for parcels more than 250m from commercial land. The influence scores for light and heavy industrial land (l

and *q* respectively) are shown in figure 2-4 but did not influence the output for the study area as it is not near any industrial land. An adjacency score *r* of 1 is given to those parcels adjacent to an already developing parcel.

Figure 2-5 depicts the model outputs for 6 months, 12 months, and 22 months for three growth rates under this scenario. Using the 2% growth rate, nearly all parcels had begun development by $t = 6$ months, and all undeveloped parcels had started by $t = 8$ months. In comparison, using a 0.5% growth rate only a few parcels along two roads had begun development after 6 months and it was not until 22 months that all parcels had started to develop. The simulation using the 1% growth rate shows a situation between

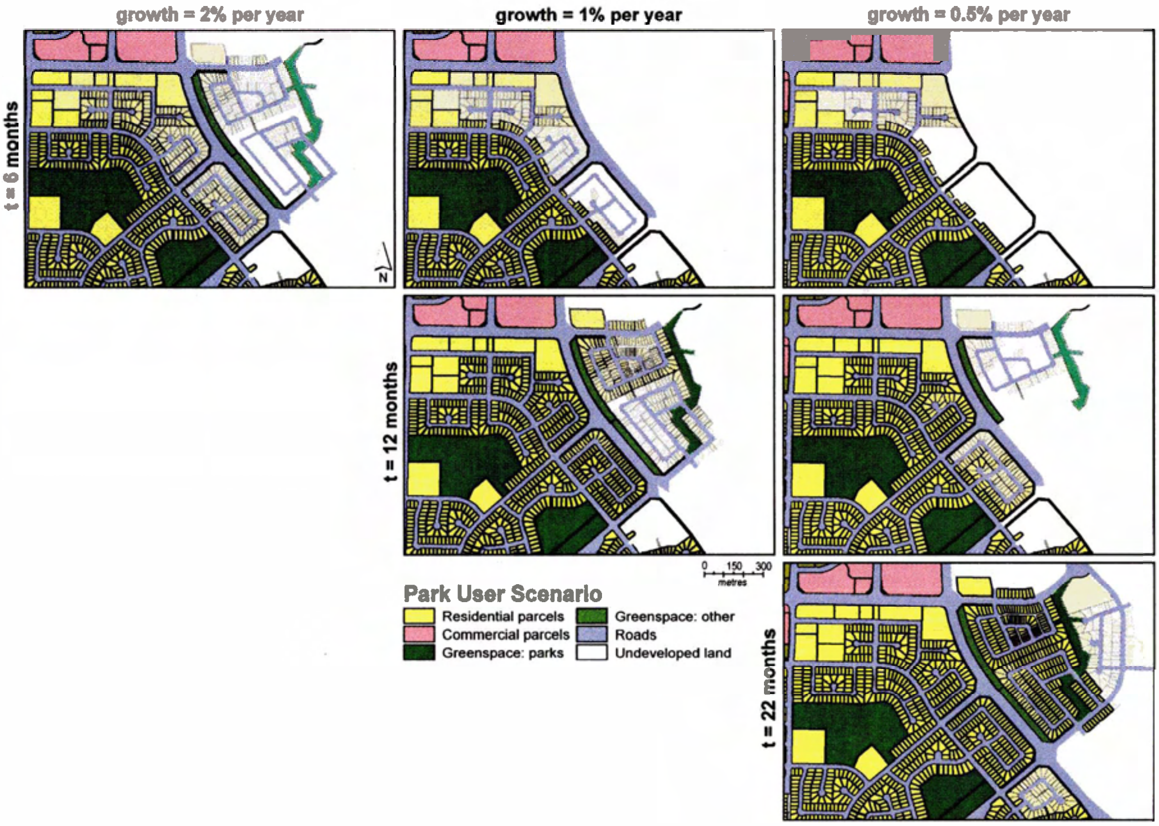


Figure 2-5 Model outputs under the Park User Scenario comparing annual population growth rates of 2%, 1% and 0.5%.

these two extremes. As expected, under all growth rates it can be seen that parcels adjacent to or near parks begin developing before parcels further away.

2.5.2.1.2 Residential Preferences - Commercial User Scenario

The Commercial User Scenario was developed to simulate growth under two conditions. First, it simulates development when residents prefer to live close to commercial amenities but not adjacent to them. Second, it simulates development when residents do not want to live adjacent to, or too close to, parks due to their negative externalities, yet still prefer to have access to them. The influence scores were set accordingly. Under this scenario, the park influence score b in equation (4) is -3 for parcels adjacent to a park, -1.5 for parcels between 0m and 25m from a park, 1 for parcels between 25m and 100m from a park, and 0 for parcels greater than 100m from a park. The commercial influence score c is -0.5 for parcels adjacent to commercial land, 3 for parcels between 0m and 100m from commercial land, 2 for parcels between 100m and 250m from commercial land, and 0 for parcels more than 250m from commercial land. An adjacency score, r, of 1 is given to those parcels adjacent to an already developing parcel. The influence scores for light industrial l and heavy industrial q land uses remain the same as for the park user scenario (figure 2-4) since industrial land will be perceived equally as negatively by both the commercial and park users.

Outputs were generated under the commercial user scenario for an annual growth rate of 0.5%. Development after 6, 12, and 22 months is shown in figure 2-6 to facilitate comparison with the 0.5% growth rate simulation under the park user scenario. After 6 months the development in the two scenarios was relatively similar due to the restricted number of parcels adjacent to roads at the initial time, but when additional roads were

Figure 2-6 Model outputs under the Commercial User Scenario with an annual population growth rate of 0.5%.

built the parcels farthest from the parks begin developing first due to the scenario's bias against parcels close to parks.

2.5.2.2 Neighbourhood Design Scenarios

Three neighbourhood designs scenarios were created to examine how urban growth would occur using different neighbourhood designs. High-density, medium-density, and low-density neighbourhood designs were input to the model (figure 2-7). In these scenarios the population growth rate was held constant at 1% per year.

The residential preferences of all new residents were assumed to be identical to those of the Park User Scenario (see section 2.5.2.1.1) and therefore the influence scores have the same values as that scenario.

The residential parcels used as input in the low-density scenario were twice the size of those used in the medium-density scenario but housed half the number of residents. In this scenario, the low, medium, and high density residential land parcels contained an average of 0.15, 0.45, and 1.5 residents per are (input as 0.0015, 0.0045, and 0.015 residents per square metre) respectively. When generating results for the medium- and high-density scenarios average densities of 0.3, 0.9, and 3 residents per are were used for low, medium, and high density residential land uses (input as 0.003, 0.009, and 0.03 residents per square metre) respectively. The area to be developed was approximately 1.2 square kilometres.

Model simulation results indicate different scenario outcomes (Figure 2-7). In the low density scenario, eight months were needed before all the parcels had started developing, creating housing for a total of 955 residents. In the medium density scenario 15 months were needed until all parcels had started to develop, with housing for 1983 residents. The high density scenario, consisting of mainly multi-story apartments, required 25 months for all parcels to begin development and was able to house 5716 residents. All three scenarios exhibited development as expected and in a similar pattern, starting adjacent to the already developed area and moving outwards. The main

Figure 2-7 Simulation outputs for scenarios simulating low-density, medium-density, and high-density neighbourhood designs.

difference between the scenarios was the length of time to begin developing all the units and the number of people each was able to house.

2.5.2.3 Asynchronous Development

In order to represent growth patterns more realistically, *iCity* is designed to model asynchronous growth where different neighbourhoods can be at different stages of development at the same time. This is facilitated by the use of the development states showing different development stages.

Figure 2-8 shows the north east area of Saskatoon under the 2% growth rate park user scenario. It differs from the 2% growth rate simulation in figure 2-5 as development is not restricted to the small study area.

After 5 months, development is starting on the northern edge of the developed area, after 10 months this neighbourhood continues to develop and another area has started (). At 15 months the first area to begin developing has finished, the second area to

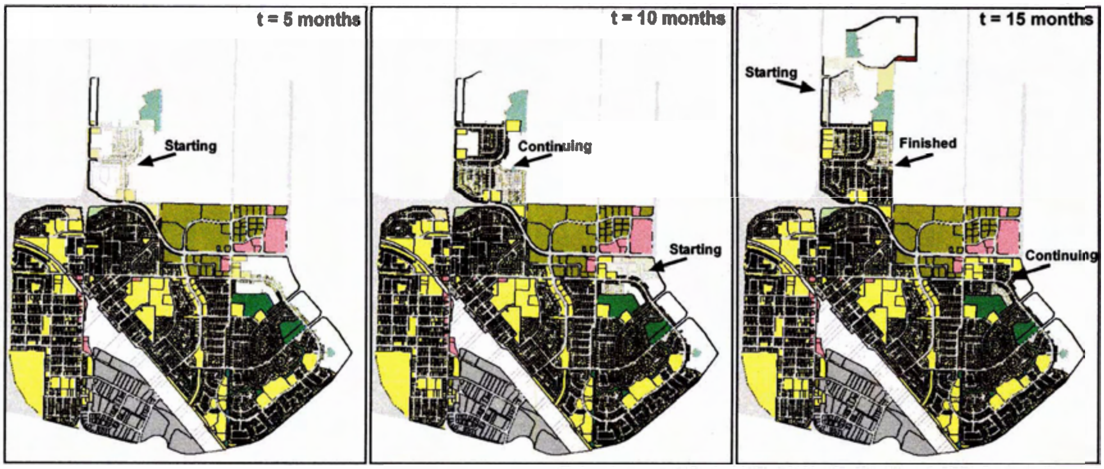


Figure 2-8 **Model outputs depicting asynchronous growth in the north-east area of Saskatoon. After 5 months, a neighbourhood in the north part of the area begins development. At 10 months a second area begins developing while the first one continues. At 15 months the first area has finished developing, the second area continues, and a new area to the north of the first begins.**

start is still under development, and a third area, to the north of the first, starts to develop. In a larger region, there could be numerous neighbourhoods developing at similar times.

2.6 Conclusion

This study proposes an irregular vector-based CA model, fully operational in a GIS environment to overcome the limitations of existing cellular automata approaches for urban growth modelling.

The model uses polygons in the vector GIS data format that correspond to cadastral land parcels to overcome the problems associated with the raster representation of commonly used discrete spatial units. The adapted neighbourhood definitions as well as the implementation of the rules, time steps, and cell states, emphasize how the basic CA elements can be incorporated into an irregular spatial structure. The *iCity* prototype was able to successfully represent asynchronous growth due to its high temporal resolution and its development states realistically representing stages of the urban development process.

The flexibility of *iCity* resides on the possibility for the user to vary the values of the influence scores for various land uses which influence residential development. These scores can be determined by focus groups or experts and represent the value residents attach to various land uses surrounding their homes. Therefore, *iCity* shows the potential for irregular cellular automata models embedded in GIS to be used as powerful spatial decision support tools.

The *iCity* prototype has also demonstrated that GIS is a useful model implementation tool for irregular vector-based cellular automata models and that although current GIS are not capable of implementing such models with easy-to-use graphical tools, their powerful application programming interfaces and reusable software components, such as ESRI's ArcObjects, allow for the added functionality to be built. Reusable software components are pre-written software classes that can be accessed by programmers and incorporated into their own software. Embedded models such as *iCity* will enable planners, urban developers and stakeholders to easily adjust parameters and run models using a familiar GIS-interface. They also allow for the user to perform additional spatial analysis on the results, to provide cartographic outputs, and the ability to combine various geospatial datasets commonly used in land use planning.

The *iCity* prototype can be applied to other cities or regions with minor modifications to either the software, to recognize city-specific land uses, or to a region's spatial data in order for it to match the land use classes required by the model.

This proposed model has demonstrated the potential to aid urban planners and other stakeholders to visualize and better understand the dynamic changes occurring in their urban environments. In addition, development of the *iCity* prototype has demonstrated that current GIS software can facilitate development of such models. Suggestions for future work include implementing a more robust model logic, including economic factors in housing preferences and the use of street networks to calculate distance to the CBD instead of simple Euclidean distance. Additionally, the model can be enhanced to automatically construct new urban cadastral parcels from much larger rural parcels surrounding the city according to user-input neighbourhood design preferences.

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CHAPTER 3 - CONCLUSIONS

3.1 General Conclusions

This research focussed on the creation of a GIS-based irregular cellular automata model capable of representing synchronous and asynchronous growth and using irregular spatial units represented by vector GIS data. This was successfully accomplished through (1) the development of the conceptual model, (2) its implementation as a prototype tool, *iCity*, within a common desktop GIS, and (3) the examination of outputs generated by the prototype tool.

The conceptual model was developed using complex systems theory and extended the classical formalism of cellular automata to include mechanisms to represent asynchronous growth and to incorporate an irregular spatial structure. Asynchronous growth occurs when development takes place in different parts of an area simultaneously but not necessarily beginning at the same time. This is facilitated by the high temporal resolution allowing a land parcel's growth to be represented in discrete stages. Traditionally, CA models begin and end development of a cell in one discrete stage (for example, one year), but the high temporal resolution used in the *iCity* prototype tool can represent time at different granularities such as months and thereby better represent stages of partial urban development.

In order to implement an irregular spatial structure, vector GIS data were used and the CA neighbourhood and transition rules had to be modified accordingly. Three neighbourhood definitions were developed and successfully incorporated into the conceptual model. The proposed neighbourhoods included (1) the land parcels adjacent to the target parcel, (2) the land parcels either fully or partially within a specific distance of the target parcel, and (3) the land within a specified distance of the target parcel. The transition rules contained constraining mechanisms to limit growth and ensured that the residential land parcels were developed in order of attractiveness as determined by user-supplied influence scores. These scores represent the general preferences of prospective buyers, developers, or planners and can be determined by expert groups or focus groups of made up of residents or other stakeholders. For this study, the scores were estimated and based on values expected to be supplied by residents. Future neighbourhood designs were pre-determined and input into the model before the simulations were generated representing the top-down zoning process prescribed by city officials. This modelling tool can be used in a GIS-based collaborative and participatory planning process.

The conceptual model was successfully operationalized within a common desktop GIS in the form of an ArcGIS (ESRI, 2004a) extension named *iCity*. The model implementation tools used to create *iCity* included ESRI's Software Developer's Kit (ESRI, 2004b) and ArcObjects (ESRI, 2005), Microsoft's Visual Basic .NET (Microsoft, 2005) and the ESRI ArcMap GIS software (ESRI, 2004a). The method of implementing *iCity* allowed full advantage to be taken of the functions built-in to ArcGIS, including file handling and access to the spatial data loaded in GIS thus reducing the time and effort required to implement the model. An interactive user-interface was also created allowing the user to manipulate the transition rules through the influence scores, residential densities, and other parameters.

A number of scenarios were developed to experiment with model outputs when different growth rates, residential parameters, and neighbourhood designs were used as model inputs. The first scenario assumed that residents generally prefer to live close to parks while the second assumed residents prefer to live close to commercial areas. The results showed the model functioning as expected under the various growth rates and resident preferences. Three more scenarios were developed using different neighbourhood designs for low density, medium density, and high density development. These designs were input to the model in the form of vector GIS layers while growth rates and residential preferences were held constant. The outputs of these scenarios also followed expected patterns: the low-density neighbourhood design resulted in a rapid development of the study area but housed relatively few people when compared to the high density design.

3.2 Contributions

This research contributes to the fields of GIScience, geography, and urban planning by extending the cellular automata modelling framework, adding dynamic capabilities to GIS software, and proposing a prototype tool that can be used as a spatial decision support system for urban planning.

The extensions to the CA modelling framework include the development of a conceptual CA model able to overcome the limitations of traditional cellular automata. This study suggests using asynchronous growth with a high temporal resolution and proposes that high-resolution irregular spatial structures should be used if a meaningful irregular structure exists (e.g. cadastral land parcels).

An ongoing problem with most GIS software has been their inadequate representation of the temporal dimension of geographic data (Stevens et al., 2005). The *iCity* prototype builds on standard GIS functionality enabling dynamic changes and the processes that drive them to be represented directly within the GIS. This extends the functionality of GIS by making it a more versatile and useful tool. It also provides modellers with a platform that greatly facilitates many aspects of model development and provides model users with a familiar environment in which to run dynamic spatial models.

Lastly, this research contributes a GIS-based prototype software tool, *iCity*, which can be used by urban planners or stakeholders to examine how urban growth may proceed given different neighbourhood designs and under various growth rates, density scenarios, and buyer preferences. The prototype is fully integrated within a common desktop GIS system and therefore utilizes industry-standard spatial data formats commonly used in municipal planning departments. The tool can either be used as a stand-alone tool for urban planning or integrated within a more comprehensive spatial decision support system. The *iCity* software tool is in the public domain and available by contacting the author.

3.3 Future Directions

This research was successful in implementing its goals of developing a conceptual model and operationalizing it within a GIS, however both these components were necessarily limited in their complexity for the purposes of examining the irregular CA and asynchronous growth components and should be extended for use in a production or decision-making environment. Therefore, a number of areas of further research are suggested.

First, the conceptual model's logic should be expanded. The model currently develops land parcels assuming all residents are of equal socio-economic status and only take surrounding land use and Euclidean distance from the central business district into consideration when selecting a location to build a new home. Including street network analysis to more accurately represent travel times in addition to economic factors, such as resident income and market value of cadastral lots, which inevitably influence residential land use decisions, will greatly enhance the model's predictive power. Additionally, the model logic can be extended by expanding attractiveness score calculation to include additional factors and land uses applicable to a wider variety of environments. For example, terms representing physical features such as slope and underlying geology could be included, as well as more abstract terms indicating hazard risk (e.g. flooding) or the probability of human risks such as break-ins.

Second, the implementation of the model, *iCity*, lacked computational optimization resulting in long processing times when running the model even for a small area of a city. While some of the code cannot be optimized due to its encasement within ArcObjects, it is suggested that all components of the model be examined to determine whether there is a more efficient decision structure or GIS operation that can produce the same result in order to increase the speed of operation.

Third, it is suggested that future research develop an algorithm to automatically construct small urban land parcels from the larger parcels found in rural areas based on user-supplied rule-based criteria for neighbourhood design.

Fourth, the visualization component should be extended to add a third dimension in order to intuitively show the gradual development of land parcels as well as enable the model to take advantage of 3-dimensional analytical capabilities such as viewshed analysis. For example, stages of development could be shown by different building heights and viewshed analysis could be used to help determine a property's attractiveness score. It is suggested that a 3-dimensional GIS be used for the same reasons cited for using a GIS to develop the model prototype in this study.

Fifth, the model's user-interface could be developed as a web-based application thereby facilitating decentralized collaborative planning and decision-making by participants unable to physically meet.

Lastly, but perhaps the most profound progression from this research relates to a paradigm shift in urban modelling resulting from the desire to increase the resolution of models. While it can be argued that the proposed model already incorporates the highest spatial resolution suitable for modelling urban growth by using disaggregated units of land use (the cadastral parcel) and that the model already incorporates a high temporal resolution, the representation of *decisions* made is still at a highly aggregated level. The individual components that interact in a city to generate the emergent forms are implicitly represented in CA models and as such they are represented in aggregate. In the proposed model, residential location preferences are aggregated whereas reality suggests that different residents will actually have very varied preferences. The natural progression is therefore towards *agent-based models* that can model the decisions of individual autonomous interacting agents (e.g. people, families, firms) on top of a regular or irregular grid of cells that represent land use. In CA, the cell is the agent and the agent is the cell while in agent-based modelling no such connection exists; agents are free to move around the landscape (Batty, 2003). While many types of agents exist, they can generally be described as self-directed objects that can satisfy internal goals or objectives through internal rule-based behaviours (Brown et al., 2005). Agents are autonomous; they can communicate; and they make goal-oriented decisions based on interactions with other agents and the environment (Parker et al., 2003).

Each agent has a location (x,y), a set of attributes {a, b, c...z} and a number of behaviours. The location of an agent represents its place in space and its set of attributes describes the agent. Different types of agents can have different attributes. For example, a *resident* agent may have an *age*, *income*, and *family status* attributes while a *firm* agent may have a *number of employees*, *required zoning*, and *required lot size*. The behaviours can also vary by agent type. A *resident* may have a *cohabitate* behaviour which results in two residents coming together to live in one residential unit. A resident's *rent* method may change the *rented* attribute of a *residential* unit to "true" thereby preventing other resident agents from occupying the same unit. In turn the residential unit's *collect_rent* method may deduct rent at a regular interval from any occupying *residential* agents. If an agent is unable to pay rent, the *residential* unit may call its *evict_resident* method which moves the *resident* agent outside the residential unit and changes the units *rented* attribute to "false". Currently, a number of agent-based models exist in the geographic literature (Brown et al., 2005; Portugali and Benenson, 1997; Sanders et al., 1997) but their use has not yet been widely adopted nor fully integrated within GIS frameworks.

In conclusion, the methods proposed in this research have demonstrated the potential to aid urban planners, land developers, and other stakeholders to better understand and plan the dynamic changes occurring in their urban environments. The development of the *iCity* prototype has demonstrated that current GIS software can facilitate the development of irregular CA models for use in spatial decision support systems. It is the intent that such models be further refined and used by urban planners to help create sustainable forms of urban growth to improve the quality of life of urban residents as well as minimize damage to the natural environment. This research also presents a foundation on which the next stage of urban modelling, agent-based models, can be developed in vector-based GIS environments.

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APPENDIX: THE *ICITY* PROTOTYPE

The *iCity* prototype was developed to explore how a recently updated GIS software package can be used for integrating a high-resolution irregular CA modelling approach with a common desktop GIS to aid urban planning. According to *iCity*, an urban area is divided into discrete land use units based on cadastral parcel lines. The land uses include residential (low, medium, and high density), commercial, road, greenspaces – park, greenspaces – other, light industrial, and heavy industrial. Each cadastral parcel is also given an attribute representing its level of development from fully undeveloped to fully developed land. The user inputs spatial data representing the current land uses of an urban area and future neighbourhood designs. In addition, a number of parameters are entered such as the area's population and growth rate. At each discrete unit of time, called a growth stage, a parcel's level of development will either remain the same or be incremented by one stage according to a set of user-input parameters.

Implementation

GIS-Based SDK

The GIS used to implement the model was ESRI's ArcGIS 9 (ESRI, 2004a). ArcGIS was selected due to its well-documented ArcObjects libraries and SDK (ESRI, 2004b, 2005a) as well as its wide use in municipal governments where such models are likely to be used. ArcObjects provides application programming interfaces (APIs) that allow a model developer to programmatically access ArcGIS to automate repetitive tasks and extend its functionality using third-party Component Object Model-compliant (COM-compliant) programming languages such as Visual Basic, C++, Java, or Python (figure A-1). Because ArcObjects are the same software libraries on which the ArcGIS suite of applications are built, any function available in ArcGIS can be implemented programmatically through ArcObjects.

This approach offered three major benefits. First, the software developer was relieved from many programming tasks as the majority of software classes needed had already been created. ArcObjects is divided into dynamic link libraries (DLLs) containing groups of software classes representing the different components of the ArcGIS suite. For example, the geodatabase library contains object classes representing a wide range of tactile components such as a featureclass, a feature, and a field. These each have a number of methods and properties that can be used to read, write, or manipulate data contained in featureclasses, features, or fields within the GIS (figure A-2)

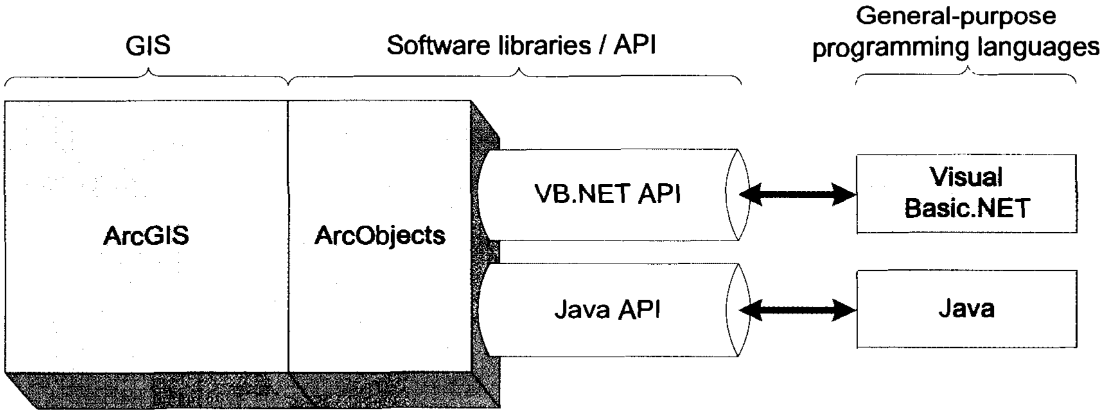


Figure A-1 The three main components of a GIS-embedded CA model such as *iCity*

Second, these object classes allowed the developer to focus on implementing the model at a high level which is closer to the conceptual model. Instead of storing spatial data in memory using arrays and accessing it by row and column numbers, the featureclass object, for example, stores the spatial data and methods relating to a feature class and allowed the programmer to search the *featureclass* to return the specific *feature* required. The feature object could then be used to return the value from a specific field contained within the feature. For example, if a featureclass contained the cadastral land parcels in a city, the search method of the featureclass could be called to return the parcel feature with a specified ID. In turn, the parcel feature's *field value* method could be called to return the value from its "land use" field. In this way, the programmer accesses data, as well as user interface, geoprocessing, and other software components in a manner analogous to how it would be done manually through the GIS. This aided the software developer in translating a set of manually performed steps into automatically executed code.

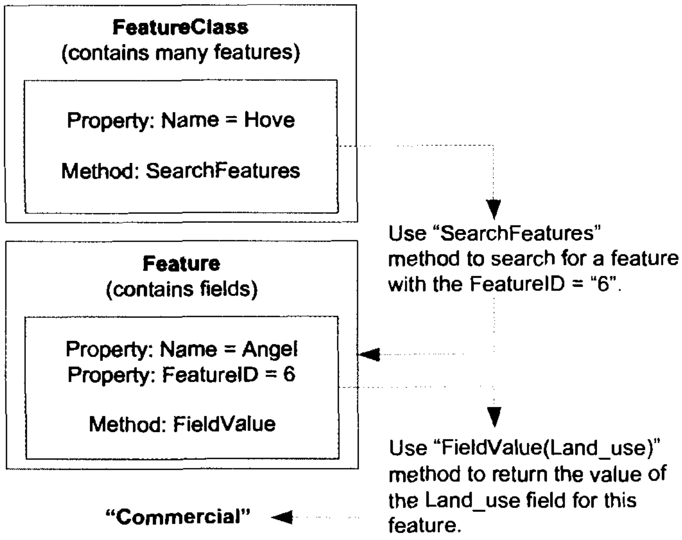


Figure A-2 Objects, methods, and properties in ArcObjects.

Third, ArcObjects allowed the model to be embedded within the GIS. While loosely coupled models require the model to pass data between the GIS and the model software by writing output to disk, an embedded approach allows the model to directly access and manipulate any spatial or attribute data that ArcMap has open in memory. For example, the developer avoided the need to write file handling routines to open the various software-specific spatial file formats from disk, instead simply accessing the layers directly from the GIS regardless of the file format used to physically store the data on disk. The model becomes part of the GIS as opposed to a separate component. This increases performance as physical disk writes and potentially complex data conversions take longer than accessing data directly in memory. While this improves efficiency in areas such as data handling, optimization in other areas is not always possible due to the hidden nature of the code contained within the ArcObjects libraries.

General-Purpose Programming Language

While ArcObjects can be accessed using any COM-compliant programming language, the choice of which language to use is best made based on the experience of the developer. Because most of the code executed is from within the ArcObjects themselves, there is little performance gain in using a traditionally faster language, such as C++, over a slower one, such as Visual Basic 6 (ESRI, 2004b). Using a language that is already known to the developer will eliminate the need to learn a new language unnecessarily.

For new software developers, however, there is an advantage to selecting one of the versions of the Visual Basic programming language. Visual Basic for Applications (VBA) is built-in to ArcGIS and requires no external development environment. As a result, the majority of users contributing code to the ESRI Developer Network (ESRI, 2005b) on-line community do so using the Visual Basic for Applications language or the related Visual Basic 6 or Visual Basic .NET languages (the latter two require an external development environment). This has resulted in a wealth of code samples and highly active user-driven support forums. Due to the complexity of ArcObjects, it is often helpful to seek advice from other users or search the user forums to see if a solution to a similar problem has previously been posted. While the solutions to many problems will be similar in any COM-compliant language, most solutions are posted in the Visual Basic context and therefore can be taken directly without the need for translation.

Conceptual Model

The *iCity* model is designed to allow planners, developers, and other stakeholders to simulate and visualize urban growth at the cadastral land parcel scale given different neighbourhood designs and under various growth rates, density scenarios, and resident preferences. The cadastral land parcel scale was chosen because the boundaries between dissimilar urban land uses typically coincide with cadastral boundaries. Data at this level are also readily available from municipal GISs in vector format. Due to the high spatial resolution of the GIS data used, the model also uses a high temporal resolution to acknowledge the different lengths of time it takes to convert undeveloped land into different urban land uses. A temporal resolution commonly used in CA models may divide time into yearly time steps whereas a high temporal resolution uses weeks or months.

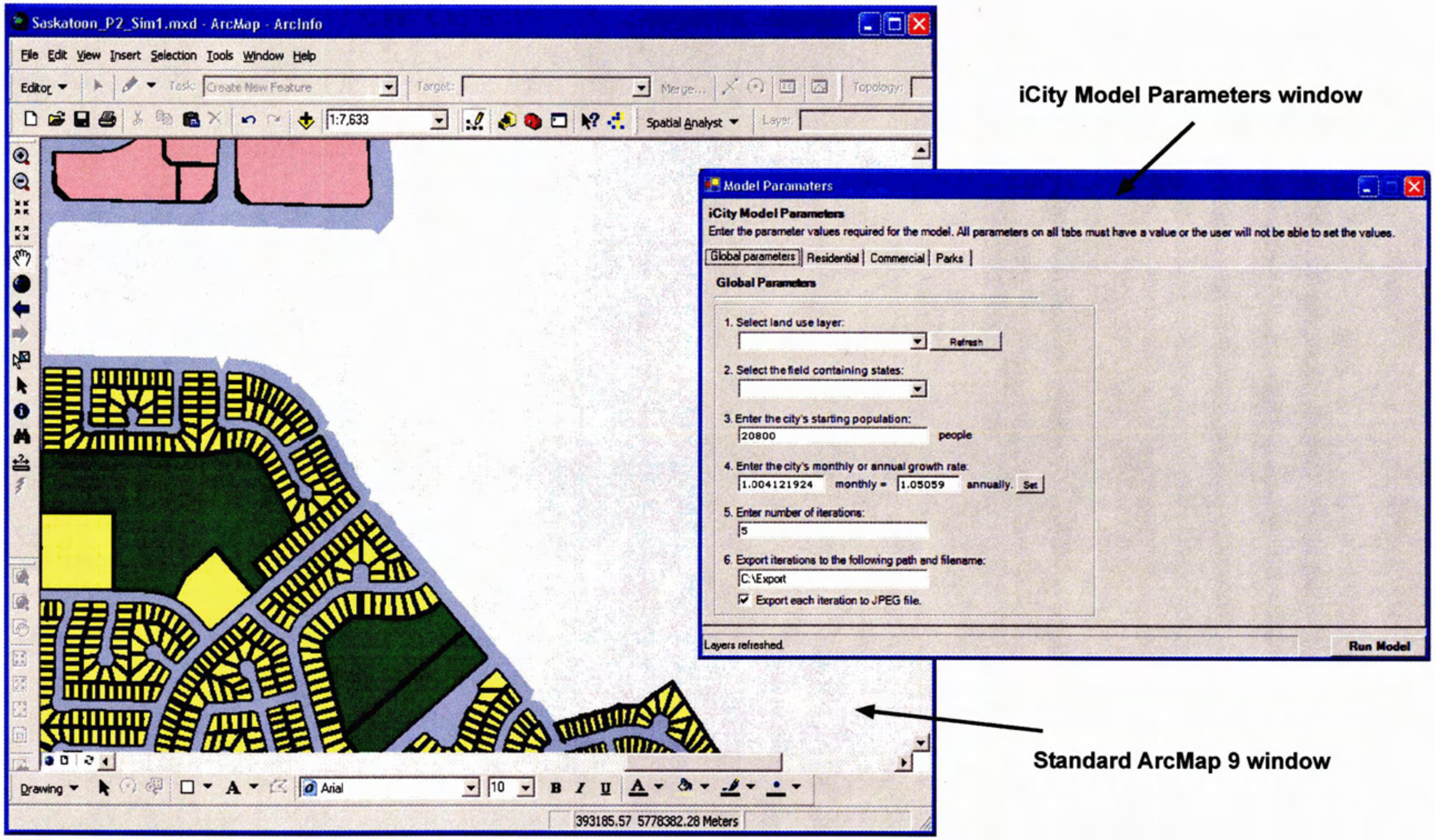
The following sections explain the conceptual model from the point of view of the user. First, the various components of the user interface are presented followed by an explanation of how they contribute to the proposed model. The user interface is made up of two components: the *iCity Model Parameters* window and the standard *ArcMap* window (figure A-3). The spatial land use layer is loaded into ArcMap using its *File* menu or *Add Data* button and then the *Model Parameters* window is opened by clicking on the *iCity* icon on the ArcMap toolbar. The *Model Parameters* window consists of four tabs, each used for a different class of parameters: *global parameters*, *residential*, *commercial*, and *park*. Only land uses that the model assigns to parcels have parameters associated with them. The parameters entered in each of these tabs are summarized in table A-1 and explained in the sections below. Once the parameters have been entered the model is run using the *Run Model* button. Updates to the model's status are displayed in the ArcMap status bar giving visual cues as to the model's progression and speed, and the changing states of the landscape are displayed in ArcMap's *data view* window.

Global Parameters

The global parameters tab has six options (table A-1). A pull-down menu allows the user to select which currently loaded layer contains the land use polygons. The user then selects the field within this layer that contains the attribute data representing each polygon's land use. The initial population of the area is entered followed by the city's monthly or annual growth rate and finally the number of iterations and the filename for each iteration's output is supplied. Each model iteration represents one growth stage which corresponds to one unit of model time required for development to occur.

Residential Land-Use Parameters

The residential parameters are divided into two parts: residential densities and influence scores (table A-1). The residential densities parameters allow the user to adjust the average population per square map unit for the low-density residential, medium-density residential, and high-density residential land use classes which are used to determine the number of residents that will occupy each residential parcel. The densities are determined by the user based on current or proposed residential population densities. The influences scores are used to calculate the attractiveness of each residential land parcel which is used to determine the order in which the residential parcels will be developed.



iCity Model Parameters

Enter the parameter values required for the model. All parameters on all tabs must have a value or the user will not be able to set the values.

Global parameters | Residential | Commercial | Parks

Global Parameters

1. Select land use layer:
2. Select the field containing states:
3. Enter the city's starting population: 20800 people
4. Enter the city's monthly or annual growth rate: 1.004121924 monthly = 1.05059 annually.
5. Enter number of iterations: 5
6. Export iterations to the following path and filename: C:\Export

☑ Export each iteration to JPEG file.

Layers refreshed.

Figure A-3 ArcMap graphical user interface (GUI) with the *iCity* Model Parameters window. File management and visualization is contained in the Standard ArcMap 9 window while the model parameters are entered in the *iCity* Model Parameters window. The Standard ArcMap 9 window depicts the initial state (t = 0 months) of the study area.

Commercial Land-Use Parameters

The commercial parameters consist of three values that must be entered in order to determine when and if a commercial land parcel will be developed: the population threshold, neighbourhood distance, and the maximum commercial land per 10000 residents (table A-1). The population threshold specifies the minimum number of residents that must be living within the neighbourhood distance of *d* map units before the commercial parcel begins development. The maximum commercial land per 10000 residents is calculated within the neighbourhood area of *d* map units. These parameters ensure that a sufficient market exists for a commercial land parcel and that the market will not be saturated and should be determined by the user based on market conditions specific to the area modelled.

Park Land-Use Parameters

The parks tab has two parameters which determine if and when a park will begin development: population threshold and the neighbourhood distance (table A-1). The population threshold determines the number of people that must be living within a neighbourhood distance of *d* map units from the park before it starts developing. Generally the population threshold and neighbourhood distance will be small assuming that a park will begin developing when development occurs in its immediate vicinity.

Sub Models

The user-input parameters presented above are used by a number of sub-models to simulate the growth. The decision structure of these sub-models is shown in figure A-4. The global sub-model calculates the population forecast which is used by the residential allocation sub-model when determining the number of residential land parcels needed to begin developing at each iteration. At the end of each iteration, the population for the next growth stage is calculated.

The allocation sub-models examine the cadastral land parcel data, which includes both current and proposed parcels, to determine which undeveloped parcels will begin development at the current growth stage. The allocation sub-models then increment development by one growth stage for those parcels already under development and begin developing the new parcels.

The residential allocation sub-model is divided into two parts. First, it calculates attractiveness scores for each residential land parcel that is adjacent to a developed road. The scores are calculated based on weights given to various conditions in the parcel's neighbourhood, such as its proximity to park, commercial, and industrial land uses (table A-1). These weights can be determined by expert groups of planners or by focus groups composed of residents or developers, or a combination depending on whose decisions the modeller intends to simulate. A parcel's attractiveness score represents an average preference of all decision makers consulted as varying individual decisions cannot be represented by this model.

Second, the residential allocation sub-model begins developing the number of housing units required to house the expected future population and assumes that all new residents will be housed in new

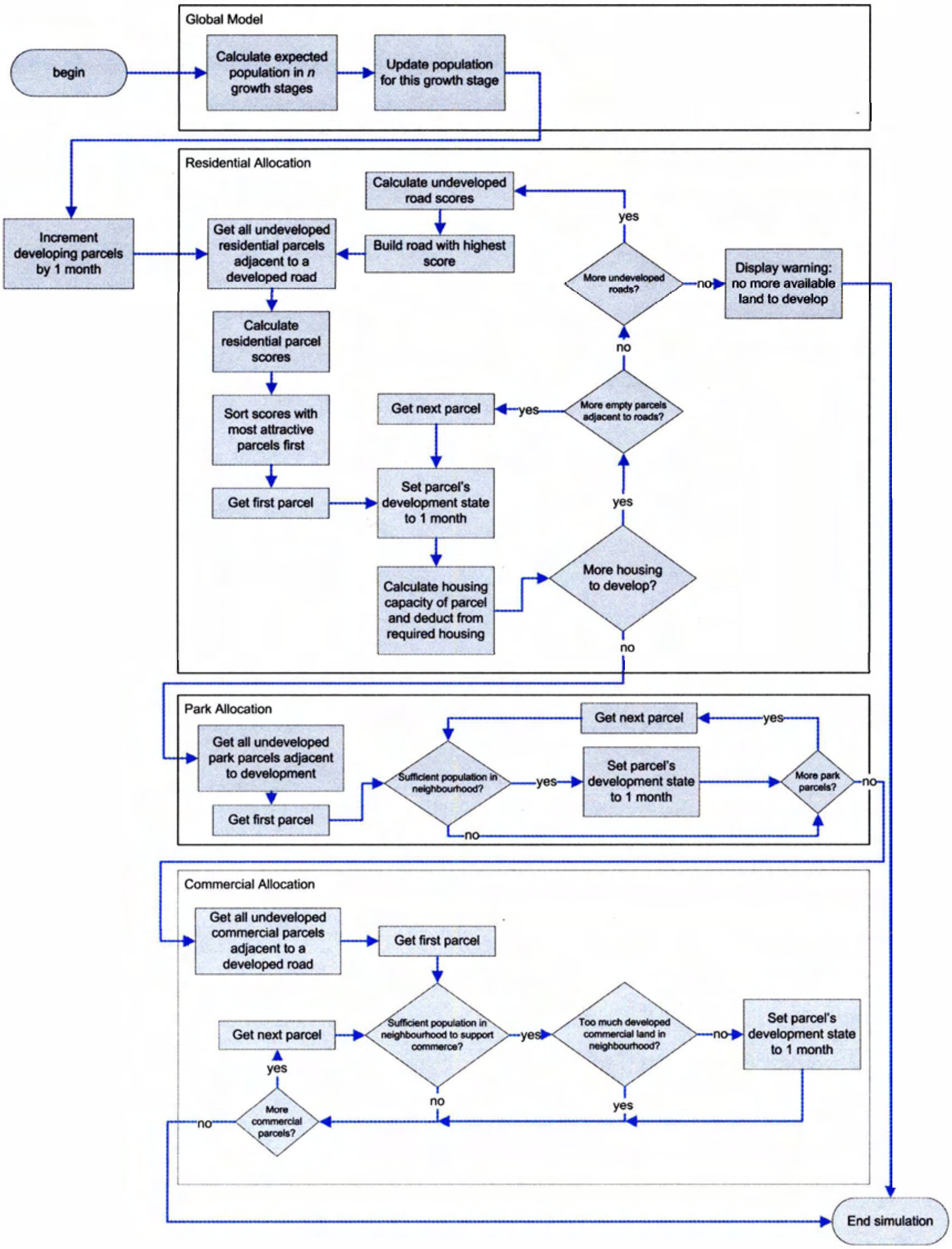


Figure A-4 Decision structure of the model as implemented in *iCity*.

Table A-1 Model Parameters

Tab	Parameter	Description
Global Parameters	Land use layer	The spatial data layer containing the irregular spatial structure (i.e. land use parcels).
	Field containing the states	The field within the land use layer that contains the cell states (i.e. the current land use).
	City's starting population	The population of the study area at the initial time.
	City's growth rate	The growth rate, either monthly or yearly, of the study area.
	Number of iterations	The number of time steps to run the model.
	Export path	The base filename and path for the model outputs. By default, the model ouputs .TIFF images of each iteration.
	JPEG export	Selecting this box tells the model to also export JPEG images of each iteration.
Residential	Res-Low	The average number of people per square map unit in the low-density residential land use class.
	Res-Med	The average number of people per square map unit in the medium-density residential land use class.
	Res-High	The average number of people per square map unit in the high-density residential land use class.
	Influence scores: Park	These values are added to the attractiveness factor of residential land parcel *j* if the a park land parcel is within the specified distance of parcel *j*.
	Influence scores: Commercial	These values are added to the attractiveness factor of residential land parcel *j* if the a commercial land parcel is within the specified distance of parcel *j*.
	Influence scores: Light Industrial	These values are added to the attractiveness factor of residential land parcel *j* if the a light industrial land parcel is within the specified distance of parcel *j*.
	Influence scores: Heavy Industrial	These values are added to the attractiveness factor of residential land parcel *j* if the a heavy industrial land parcel is within the specified distance of parcel *j*.
Commercial	Population threshold	The minimum number of residents within a radius of *d* map units that must be satisfied in order for the commercial parcel to begin development. This ensures the commercial land parcel has a market.
	Neighbourhood distance	The radius of *d* map units used in conjunction with the population threshold above.
	Maximum commercial land per 10000 residents.	The maximum amount of commercial land per 10000 residents within the neighbourhood distance of *d* map units. This acts as a saturation level at which additional commercial land would over-saturate the market.
Park	Population threshold	The number of residents that must be present within a neighbourhood distance of *d* map units in order for the park to begin development.
	Neighbourhood distance	The radius of *d* map units used in conjunction with the population threshold above.

suburban developments as opposed to a portion of new residents being housed in previously urban areas redeveloped to a higher density. One housing unit can house one resident, and one land parcel may be considered multiple housing units depending on its size and type (i.e. a residential-low parcel will have fewer housing units than a residential-high parcel of the same surface area).

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