AN AGENT-BASED MODEL FOR THE SIMULATION OF URBAN LAND USE CHANGE AT A CADAstral SCALE

by

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ABSTRACT

Cities are complex systems in which the diverse stakeholders, who have conflicting values and priorities, interact to directly influence the process of urban land use change. These interactions, which are characterized by a strong competition for space, can be represented by an agent-based model in order to better understand and analyze urban systems, and to forecast possible future urban land use patterns. In this study, an agent-based model that simulates the process of urban land-use change at a cadastral scale by modeling the actions of the key stakeholders in the city has been developed. The generated simulation outcomes provide various land use change scenarios and they indicate that the urban planning policies implemented in the model and the characteristics of relocating households influence the changes in land use patterns. This study contributes to the advancement of agent-based models that can assist in the process of urban land use planning.

Keywords: Agent-based Modelling, ABM, Urban Land Use Change, Geometric Transformation

Subject Terms: Geographic Information Science, GIS, Land Use Change Modelling
DEDICATION

I dedicate this thesis to all those who have held my hand and assisted me on my long educational journey. Most important on that list are my parents who taught me to always thirst for knowledge and to always broaden my horizon.
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CHAPTER 1 INTRODUCTION

1.1 Introduction

Since the seminal work by Johann H. von Thunen in 1826 (von Thünen and Hall 1966), land use models have been used to examine the relationship between the location of activities and the patterns of land use in metropolitan areas. According to Von Thunen’s model, several rings of agricultural land use activities would surround the location of the central market place and the rings closest to the market will yield products that are most profitable at the market and most difficult to transport. As the distance from the central market increases, the land use patterns change to those types that produce goods that are less profitable in the market and are much easier to transport. In 1925, the Burgess Model, also known as the concentric ring model, was developed by Ernest Burgess when he observed that wealthier families tended to live much further away from the central business district (Park and Burgess 1967). In this model, it was observed that the city is composed of concentric rings of different social classes around a central business district, with the ring closest to the centre mainly used for industrial and wholesale activities mixed with poor quality housing. As the commuting distance from the central business district increased, the rings tended to have better quality housing. Hence, it was theorised that there is a correlation between wealth and the distance from the central business district because wealthier families tended to live further away from the centre. Although the von Thunen model of land use patterns and this later model by Burgess were overly simplified in their analysis of land use patterns, they provided the
foundation upon which the later, dynamic and comprehensive models of the 1960s were built (Batty 1994).

The comprehensive models of the 1960s incorporated many of the various processes of urban dynamics but they failed to achieve their intended goals. It had been hoped that with the advent of the computer, large-scale models that required large volumes of disaggregated data could be used to model the complex urban environment and aid planners, while improving our understanding of the theory of urban dynamics. Lee’s (1973) critique of these modelling efforts is still relevant today especially in terms of understanding the theory of urban dynamics. However, progress has been made in the intervening decades in terms of computational capabilities, availability of data resources, theoretical understanding of spatial processes and the modelling methodologies (Miller et al. 2004).

Urban land use is one of several aspects that are important to planning authorities in metropolitan areas. Other aspects include transportation, housing, employment, environmental protection and infrastructure for service delivery. Using frameworks based on urban systems theory, the earlier comprehensive models, such as Lowry's (1964) model of Pittsburgh, considered these aspects as independent activity systems that had spatial interconnections. However, besides these important interconnections, these activity systems are constantly evolving due to external influences such as changes in government policy, technology, demographics and social values. When considered as a whole these factors make the city a dynamic and complex landscape.

The process of urban land use change can be seen as a dynamic system where the locations as well as the intensity of the different activities that take place in a city evolve
over time (Rodrigue et al. 2006). These activities, which are cultural, social and economic, are dependent upon the availability of services from other features of the city such as the water and transportation infrastructure. In addition, there are complex relationships that connect the different land use types in the process of land use change. For example, the relationship between commercial land use and accessibility to suppliers and consumers can be affected if there are changes in the transportation network, or if toxic industrial activities are sited next to the residences thereby forcing the consumers to relocate. These complex interdependencies between the different aspects makes it very difficult for planners to make strategic decisions concerning the delivery of services, and to understand the growth of the urban region as a whole (Levin 1991; O'Sullivan 2004; Batty 2005). Thus, the theory of complex systems becomes an important basis for modelling urban land use change because the urban landscape has many interacting factors that contribute to its highly complex evolutionary process. In addition, complex systems modelling can provide planners with more flexibility to experiment with different growth scenarios and to learn more about the relationships between the different components (Couclelis 2005).

In order to model the spatial complexity of urban land use change, cellular automata (CA) have been used extensively (Tobler 1979; White and Engelen 1993; Clarke and Gaydos 1998; Lau and Kam 2005) and more recently agent-based modeling (ABM) has also been used (Deadman and Gimblett 1994; Dean et al. 2000; Brown et al. 2004; Parker and Meretsky 2004). Both of these modelling approaches are bottom-up methods because they rely on examining the existing subcomponent relationships in a system (Torrens and Benenson 2005). Typically, CA operate on a regular grid of cells
which makes them easily compatible with remotely sensed raster data sets of the environment (White and Engelen 2000). However, modelling land use change by using CA and raster-based geospatial data introduces a significant limitation with regard to the representation of the environment, particularly in situations when objects are larger or smaller than the cell size. Also, while the use of the raster grid for CA at a regional scale can be considered acceptable (Besussi, Cecchini et al. 1998), it becomes inappropriate for modeling at the higher resolutions of city blocks or cadastral lots (Wenzhong and Pang 2000; O'Sullivan 2001; Stevens and Dragicevic 2007).

For urban land use modeling, the highest resolution data is typically at the scale of the cadastral lots, and a grid composed of irregularly shaped spatial units depicting the actual landscape parcels can be used (White and Engelen 2000). Stevens and Dragicevic (2007) have developed the iCity, a tool for simulating urban land use change, that uses a CA model operating on irregular spatial tessellations that represent cadastral parcels of a city. However, this particular model could be also improved by the use of an agent-based modelling approach that effectively represents the complex behaviour that emerges from the interactions and decision making processes among the different parties that influence land use change in a city or municipality (Parker et al. 2003). These parties can be at fixed locations or mobile within the landscape and can cause land use change when they interact. They are collectively known as agents and include, for example, policy makers, households, housing developers and commercial firms, all of whom are involved in one way or another in decision-making processes that ultimately affect land use patterns. The agents in agent-based models can have nonlinear relationships with the other components
in the system and are characterized by mutual interactions, interdependences, heterogeneity and hierarchies (Epstein 1999; Manson 2001).

Considering the strengths and advantages of using agent-based modelling and the limitations imposed by the classical formalism of cellular automata on raster grid, this research study was undertaken in order to expand on the work that was started by Stevens and Dragicevic (2007). This research extends that work by developing Agent iCity, an agent-based model that adds behavioural realism to the simulation of urban land use change by using high spatial resolution vector-based geospatial data. The data used in the Agent iCity model are irregular spatial tessellations that represent cadastral parcels in small neighbourhoods of an urban environment.

The model developed in this study can aid planners by providing scenarios of future urban land use patterns of change under various growth conditions. This agent-based model is coupled with a geographic information system (GIS) in order to access spatial analysis functions, database management and visualization capabilities. The results from the simulation show various scenarios of change in land use patterns that can happen under different urban growth conditions. The model is implemented on municipal cadastral and land use data for a small neighbourhood of the City of Chilliwack, British Columbia, a city that has experienced rapid growth in the recent past.

1.2 Research Questions and Objectives

The overall goal of this thesis is to develop an agent-based model for urban land use change at a cadastral scale that can generate meaningful land use change scenarios
under various urban growth conditions. For this research goal to be addressed fully, the thesis has the following three specific objectives:

1. Develop Agent iCity, an urban land use change model, based on the agent-based modelling approach.

2. Implement the model and generate results based on data from an actual city in the Fraser Valley, BC particularly the City of Chilliwack.

3. Use the model to perform sensitivity analysis on:
   
i. the influence of the geometric shape and orientation of the cadastral units on urban land use change processes, and
   
ii. how the changes in the social and economic conditions of the households are affecting urban land use patterns.

1.3 Study Site

The land use simulation model developed in this study was tested with data from the City of Chilliwack, BC. Chilliwack is situated within the protected arable farmland of the Fraser Valley and is also surrounded by steep mountain slopes - a set of circumstances that makes it hard to find land for urban expansion as the city population grows (CEPCO 2008). The city planners are, therefore, faced with either rezoning and subdividing the bigger blocks of agricultural land into smaller lots for residential, industrial and commercial purposes, extending growth into the mountain slopes which is very expensive and environmentally unsustainable, or densifying and intensifying the land use activities within the confines of the existing city limits.
Over the years, the City of Chilliwack has been keeping records of land use in datasets that are either compatible with ESRI GIS software (ESRI 2009) or with computer aided drafting (CAD) software from AutoDesk (AutoDesk 2009). The data in the CAD format were converted to a format that is compatible with GIS. These data are exogenous to the model and are the basis of the local interactions as represented by the agent-based model. Other data were gathered from the 2006 census data (StatCan 2009).

1.4 Thesis Overview

The second chapter of this thesis provides an overview of the background literature relevant to this research, the importance of the modeling approach chosen, as well as some of the existing urban models that have employed the agent-based modeling framework. The methodology that has been used to develop this model is presented in the third chapter and its implementation is described in detail in the fourth chapter. The outcomes from the model simulations and the sensitivity analysis tests are presented in the fifth chapter. Chapter Six, provides the general conclusions about this study together with a discussion of the limitations of the methods employed. Suggestions for areas of further study are presented in this chapter as well.
CHAPTER 2  THEORETICAL BACKGROUND

This chapter covers the literature review that provides the theoretical background for this research. It is divided into two major sections. The first major section deals with complex systems modelling and the approaches that have been used to model land use change using complex systems theory. It has two subsections with the first focused on the cellular automata approach while the second is focused on agent-based modelling. The second major section covers previous research that has been undertaken in the areas of subdividing irregular polygons since the model developed in this research also incorporates a module that subdivides irregular polygons.

2.1 Complex Systems Modelling

The study of complex systems, also referred to as adaptive complex systems, was originally motivated by investigations into the adaptation and emergence characteristics of biological systems before it was applied to the field of geographic analysis (Holland 1995). The main characteristics of complex systems are non-linearity, self-organisation, adaptation, bifurcation and emergence (Manson 2001; Parker et al. 2003; Batty and Torrens 2005).

The ability to self-organize is realized when a system changes its internal structure based on positive and negative feedback. This feedback could be as simple as attraction and repulsion mechanisms in a model, so as to better interact with its environment. Self-organisation is also linked to the emergent behaviour of complex
systems where global patterns, which are not analytically sought for or determined by looking at the subcomponents alone, emerge as a result of local subcomponent interactions in the system (O'Sullivan 2004). An example of emergent phenomena in a city is the neighbourhood segregation based on ethnicity or social class.

Complex systems also have adaptive and evolutionary mechanisms that allow them to maintain their structural organization under varying conditions. The adaptive mechanism is possible because the internal components of these systems are capable of adding new relationships or changing old relationships based on learning from previous experiences. In the case of urban land use change processes, for example, as the population increases the land use patterns are altered in order to absorb the new entrants. Complex systems are also characterized by bifurcations whereby a small change in one of the factors can result in drastic changes to the system behaviour.

These properties of complex systems, similarly observed in urban landscapes, provide a framework for designing models that rely on the idea that emergent characteristic of a system are understood by examining the relationships of the subcomponents (Parker et al. 2003; Macal and North 2005). With the increased development in computation, two modelling approaches, cellular automata (CA) and agent-based modelling, have emerged as effective tools for urban growth and urban land use change modelling (Batty and Xie 2005). Both of these modelling approaches can be used to represent an urban area as a potentially infinite collection of heterogeneous entities whose interactions define the dynamics of the city at large (Benenson 1998).
2.1.1 Cellular Automata Modelling

CA, whose roots are in the fields of physics, mathematics and computer science, are grid-based systems of interacting cells that are capable of generating complex spatial dynamic models. They were first developed by Stanislaw Ulam, then used by Alan Turing to demonstrate ideas of a self-reproducing machine (Wolfram 1994). However, it was John von Neumann who initiated the scientific study of CA when he used them to investigate self-reproducing cells in a lattice. CA were first proposed by Tobler (1979) as a method for geographical modelling and they have since been used widely to model urban growth and land use change (White and Engelen 1993; Batty 1997). Using the theory of urban economics, Semboloni (1997) developed a CA model to simulate the development of a city. In the DUEM model, CA have also been used to simulate the organic growth of a city by representing the changes in the various land use types and how activities spawn at new locations (Xie 1996; Batty et al. 1999). Among other CA models for urban land use change, the one developed by De Almeida and colleagues (2003) is based on principles of Bayesian statistics, while Li and Yeh (2002) integrated neural networks and CA.

CA use discrete time increments to characterize the continuous change of a geographical phenomena in question. At every time increment, a set of transition rules are applied to the cells to determine the cell states at the next time increment. However, even with the various modifications to this classical formalism, many CA models neither represent human decisions nor the interactions that occur among various actors in the land use change process. In order to solve this problem, some CA models consider the grid cells as a set of agents and instead use the transition rules as proxies to decisions.
making (Schelling 1971; Hegselmann 1998). Another limitation is the immobility of the
cells in the grid, which hampers effective representation of the interactions of the cells
that are at a distance from each other (Benenson et al. 2002; Torrens and Benenson
2005). The need to add behavioural realism and the modularity of the agent dynamics to
the simulation of urban land use change necessitates the use of an agent-based model.

2.1.2 Agent-based modelling

In the process of land use change, the transition from one land use type to another
comes about as the result of human or natural interactions on the landscape. By taking
this perspective, autonomous and intelligent human agents are modelled as the elemental
components in agent-based models (ABMs) for urban land use change. In ABMs, the
agents are the actors that interact and make decisions which are used to link behaviour to
the simulation space (environment) in which they operate (Bousquet and Le Page 2004;
Evans and Kelley 2004; Manson 2006).

The agents in ABMs can be designed to be autonomous and intelligent enough to
control their actions and to manage their internal states in order to achieve their goals.
Given some form of memory, such as a database table of previous states, and a list of
values that act as incentives for the possible states, an agent can be programmed by
means of iterative functions to learn and choose those states which corresponded to
higher incentives. Since it is programmed as a software object, an agent can search
another agent's attributes and compares them to its own values. Through this comparison
an agent is able to interact with other agents by evaluating its own state and exchanging
or transferring some of its attribute values to them (Itami and Gimblett 2000).
Whereas neighbouring cells in CA do not change location in the system, agents in ABMs can move in space as the model runs. Like CA, the agents in ABMs are governed by rules. However, because they can be set up to learn from previous experiences and can accommodate heterogeneity through attribute specification, they are particularly appropriate in modelling human behaviour (Zhang et al. 2008).

The use of agent-based models is particularly attractive because it offers a high degree of disaggregation in the model especially when operating with high resolution data (Brown 2006; Sengupta and Sieber 2007; Dragicevic 2008). Agent-based modelling also enables the representation of fixed and non-fixed entities in the urban landscape as individual objects with capacities to change based on local interactions and decision making (Benenson et al. 2005). There are several agent-based models for the simulation of urban land use change (Tsutsumi 1999; Kii and Doi 2005; Liu et al. 2006). However, there are only a few that are being used in practical applications for city planning and the following are examples relevant to this study.

ILUTE (Miller et al. 2004), a model for land use that is still under development, uses agent-based modelling techniques to add behavioural realism to the simulation of land use change. This model aims to simulate the growth and change in the land use patterns of an entire metropolitan region by modelling the behaviour of individuals, households and businesses. The proper abstraction of transportation and land use dynamics in addition to the dynamics of the urban labour markets and the resultant commuting patterns are emphasised. However, the representation of geographic space in the model is still a challenge and the researchers have proposed two ways to address this issue. Firstly, they have suggested to represent space by using a raster grid with a spatial
resolution of thirty meters. However, this method does not capture the actual spatial units in the city, such as cadastral parcels, that are irregular in shape and are of varying sizes. In the other method, they propose the use of geocodes to link buildings to the cadastral lots in the city such that the changes in the geometry of the cadastral lots are independent of the changes in the buildings during the course of the simulation runs. However, this method is also likely to be ineffective because in reality the changes in geometry of the parcels are intrinsically linked to the changes in buildings on the parcel. In many of the cases where a parcel's geometry is altered, it is for the purpose of adding more structures on the lot or to completely redevelop the existing structures.

The second agent-based model is UrbanSim (Waddell 2000; Waddell 2002), which was designed to simulate urban land use change and commercial floor space market dynamics. Its operation is based on the analysis of various policy scenarios that include comprehensive land-use plans, growth management regulations, minimum and maximum densities in different zones, mixed-use development, environmental restrictions on development, as well as transportation infrastructure and pricing policies, and attempts to provide a means to assess how these policies affect land use patterns in the long term.

One of the key advantages of UrbanSim is the use of the discrete choice modelling to represent the choice decisions of the agents. Discrete choice modelling techniques, based on Daniel McFadden's Random Utility Theory (McFadden 1973), provide relaxed assumptions on the choice process, and they have been used to model large and complex choice options effectively (Ben-Akiva and Lerman 1985). They differ from other choice analysis methods which consider a set of choices as a single continuous
variable. Discrete choice modelling relates the selected choice to the characteristics of the chooser and it has been used widely to add behavioural realism to models of travel demand, marketing, energy and housing.

Although the agents in the UrbanSim model are disaggregated to the level of individual households and individual jobs, the representation of space is aggregated to a grid with a spatial resolution of one hundred fifty meters. Therefore, at any point during the simulation run, in each grid cell there could be a collection of households and job opportunities. Also, during the process of urban land use change, the geometry of the cadastral parcels changes when large parcels are subdivided or small ones are merged together to allow redevelopment, an issue that is not yet addressed in UrbanSim. The geometric transformation of spatial objects is an important consideration that should be addressed in models that simulate land use change so as to represent the changing form of the land units.

2.2 Geometric Transformation of Irregular Objects in Land Use Change Modelling

In the search for an effective method of representing space and spatial interaction in simulation models, Torrens and Benenson (2005) have presented the theoretical approach of geographic automata that incorporates irregular spatial objects and agents. Geographic automata joins together the characteristics of cellular automata and agent-based modelling and thereby provides a flexible and realistic framework for representing urban landscape features such as buildings, roads, cadastral lots and human interactions and it has been implemented in the modelling of urban residential dynamics (Benenson et al. 2002; Benenson et al. 2005; Torrens 2007).
By using an approach similar to geographic automata, Stevens and Dragicevic (2007) developed a cellular automata model that uses irregular spatial units, corresponding to the actual cadastral lots in the city, to simulate land use change. Although their approach provides flexibility in the representation of geographic space, the model does not account for the changes that happen to the geometry of the cadastral lots and to the boundary extents of the neighbourhoods during the course of the simulation. In addition, this model does not explicitly represent the human decisions and their interactions within the urban environment.

As part of the efforts to continue developing the representation of irregular spatial units in models of land use and land cover change, Moreno et al (2008) and Moreno et al (2009) have also developed a cellular automata model, VecGCA, that uses irregular tessellations corresponding to different land cover features. It is an improvement on the other methods that have used irregular tessellations to represent landscape because it allows for the geometrical transformation of the irregular objects during the course of the simulation. Specifically, the state, shape and area of a geographic object will change according to a transition function that is based on the area of the other objects in the neighbourhood and their influence on the specific object. A part of the object can change state, and area portions of the object can also be joined to their adjacent neighbours.

While the VecGCA model provides for geometrical transformations of spatial objects when modelling land use change in agroforested areas, it does not explicitly represent the processes that are typical in an urban land use change environment. In the course of the development of an urban region, most of the changes that happen on the periphery are the subdivision of large tracts of land into smaller parcels for residential
purposes. This subdivision tends to be in small and compactly organised cadastral parcels whose geometrical areas are approximately the same in each local neighbourhood. In the inner city areas there may be a few parcels that are merged in order to accommodate high density structures like high-rise buildings or shopping malls and big box retail stores. This observation, therefore, necessitates the need to simulate land use change at the spatial resolution of the cadastral lots and to track the geometrical transformation at that scale.

Even though the model that is presented in this research is not a cellular automata model as the one developed by Stevens and Dragicevic (2007), it expands on their work by explicitly modelling the actions of the various stakeholders that cause land use change in the city. Like the iCity model, Agent iCity simulates land use change at a cadastral level with the assumption that the increasing population in a city directly influences the land use change process and it similarly provides a means to analyse and visualise how a city may develop under different growth scenarios. However, the iCity model uses the transition rules and the existing conditions in a local neighbourhood are used to determine how the different land use types will change by using cellular automata principles. In this approach, one implicitly mimics the residents' preferences by changing the weights that correspond to the attractiveness of the different land use types. It also assumes that the developer of the housing units has no constraints or preferences on where to construct the new dwelling units.

Agent iCity, on the other hand, has been developed to overcome some of these constraints. It has a module that automatically subdivides large parcels of land into smaller ones during the course of the simulation. It also incorporates the policies of a
planner that influence the local neighbourhoods in which development happens. In addition, heterogeneous households are modelled to show how they make their relocation choices. The developer's preferences, based on profit maximization, are also modelled.
CHAPTER 3 METHODS

This chapter explains the rationale that was used as well as the assumptions that were made in the development of the urban land use change model. It is divided into four major subsections. The first subsection explains how the urban landscape was conceptualized in terms of the geographic space and the agents. The second subsection explains how the geographic space was represented as zones and parcels while the conceptualization of the agents is explained in the third subsection. Lastly, the interactions of the agents are explained in the fourth subsection.

3.1 Key Elements of the Urban Landscape

Agent iCity is structured around the abstraction of the city as an urban landscape that is dynamic and continually changing due to the interactions of various actors within it. Similar to some of the previous models of urban land use change, the main actors in the urban landscape that are given consideration are the urban planner, the real-estate developer, the commercial retailers and the industrial manufacturers (Waddell 2002; Torrens 2006). The model simulates their interactions in a sequence of distinct time intervals in order to capture the process of urban land use change. Hence, one of the key elements of the city that is featured in the model is the environment in which these actors live and interact. This environment is represented as geographic space in a vector-based geographic information systems (GIS) data model. The second element in the city is the collection of agents that represent the selected actors in the urban landscape. These agents are seen as the principle drivers of the observed change and the growth in population.
Consequently, they are one of the most important factors affecting change in the urban landscape.

3.2 The Geographic Space

Geographic Space in Agent iCity is defined by two geospatial data layers which characterize the different boundary demarcations in the city (Figure 3-1). The demarcations correspond to the boundaries of the cadastral parcels and are represented as vector-based GIS datasets of contiguous irregular tessellations. Each of the data layers represents the irregular spatial tessellations at a different spatial resolution. The first spatial resolution represents those features that are at the zonal level where several neighbouring cadastral parcels are aggregated together according to the different municipal planning zones that are specified in the city's bylaws. A municipal planning zone is mainly used to define the nature and the extent of future developments that are permitted on the cadastral parcels within its boundaries. It is not a good indicator for the current land use activities on those parcels. For example, a municipal planning zone that is classified for single-family residential use can still have a parcel within its boundaries that is used for commercial purposes and a few others that are used for multi-family residences. The heterogeneity of land use activities within a zone is often a consequence of the historical circumstances of the city, the special exemptions given by the authorities and the planners' intentions for future development.

The second spatial resolution corresponds to the individual features at the cadastral level where each parcel's land use type and related activities are marked. The representation of the features at these two resolutions is particularly useful in modelling the planning policies and the interactions of the agents. Since the planning policies are
implemented according to planning zones, the features at the aggregated scale are more appropriate. On the other hand, given that the agents' interactions happen on the cadastral parcels, the disaggregated features are more appropriate for modeling the agents' actions.

Figure 3-1: The representation of geographic space

The irregularly shaped tessellations in the data layer that represents zone-based features are characterized by the permitted land use activities, the associated densities (i.e. maximum number of households per parcel) and the minimum parcel size in those planning zones. The land use type and the built structures on the parcel characterize the features in the data layer that represents the individual cadastral parcels.
3.3 The Agents

There are five types of agents have been developed to represent the key stakeholders who affect land use change in the city. The choice of the key stakeholders was inspired by work from previous research and also on the need to simplify the actors in the urban landscape (Waddell 2002; Torrens 2006). The agents are namely, the urban planner, the housing developer, the households, the retailers and the industrialists.

3.3.1 The Urban Planner

During the planning process of an urban area, the urban planner puts the regulatory control of the municipal government into operation. This regulatory control is policy-based and provides a general framework under which the land use change process happens. In this model, one *planning agent* is designed to simulate the activities of the city planners and its primary goal is to select and demarcate the cadastral parcels upon which future growth can happen. During the selection process, if a parcel is too large, the agent initiates a subdivision module that has been designed to split large pieces of land into roads, city blocks and to cadastral parcels. The demarcation criteria and the choice of the planning zones in which growth happens are influenced by the specific policies the user of the model may select during the course of the simulation. Three different policies that can be used to manage urban growth have been selected from those listed by Bae (2007) and they are outlined as follows:

a) *Agricultural Land Preservation*: By using this policy the *planning agent* protects land with agricultural activities from change and instead directs growth towards the other land use types in the data layers;
b) **Urban Containment:** In this policy the *planning agent* confines development within the defined boundaries of the city in order to limit sprawl into the rural fringes;

c) **Priority Growth Areas:** The *planning agent* promotes growth at specific locations in order to support urban renewal or to simply encourage increased density in those areas.

### 3.3.2 The Housing Developer

Housing developers are responsible for creating new dwellings at specific locations that have been approved by the municipality's planners. Very often the developers are primarily motivated by profit and, therefore, are sometimes reluctant to construct dwellings at some of the locations selected by the planner which they may determine to be unprofitable. In this model, the *developer agent* is designed to add residential units on the cadastral parcels in the city. The new residential units can be located on newly subdivided cadastral lots or on cadastral parcels that previously had other land use activities. The *developer agent* is motivated to make "profit" and therefore, searches through the available lots from those that have been identified by the *planning agent* to finds those that are most profitable. The *developer agent* gives selection preference to parcels that are in the neighbourhoods with the highest property values and are surrounded by desirable land use activities.

It should be noted that this is a very simplified abstraction of the dynamics of a real-estate developer in the city. Usually there are multiple housing developers who may operate in different segments of the real estate market. For example, there are those who specialise in big projects like high apartment buildings and multi-unit estate development,
and others who are small business owners and can construct one house at a time. In addition, it is the real estate developer that causes the subdivision of land under the planning regulations of the city. However, in this model it is more computationally efficient if the planning agent initiates the subdivision module.

3.3.3 The Households

The urban households are responsible for most of the changes in the land use patterns in the city. This is because as the new households enter the city, there is need to find more land for accommodation and for the other activities that are necessary for their wellbeing. The household agents are designed to represent the behavioural dynamics of household mobility and choice of residential location within the urban area. The primary goal of these agents, if their neighbourhood is no longer suitable, is to search for better residential units from those that are vacant and unoccupied; and, if conditions permit, to move to those units. The household income and the number of persons in the household characterize the different households.

3.3.4 Retailers and Industrialists (manufacturers)

In a city, the retailers and industrialists are employers of the city’s residents and the areas where their businesses are located are important activity locations. The residents may be attracted to live closer to these locations in order to easily access the employment and the services that are offered, or to live further away if the employment activities give off pollutants like noise and fumes in the immediate surroundings. The retailers and the industrialists have different behavioural dynamics depending on the specialization of their operations and the economic worth of their businesses. In this model, however, their
actions and decisions are not modelled with the assumption that the dynamics of the other agents have an overriding influence on the process of land use change. Instead, the retailer and industrial agents are developed and used to mark the locations for retail and industrial activities. In addition, they are used to relate the number of jobs in the city to the number of employable persons such that as the households increase, there is also a corresponding increase in the number of employers and locations that have retail and industrial activities. This abstraction of the city's retailers and industrialists is overly simplified and is based on the assumption that the economy of the city is doing well. Also, it assumes that the increasing population in the city will cause more employment, but in reality, it is more likely that increasing employment will cause population growth. However, the City of Chilliwack has been growing steadily and for the last few years only a small percentage of the city's workforce has been commuting outside the city for work (CEPCO 2008).

3.4 Agent Dynamics and Interactions

The model developed in this thesis has been designed to simulate the process of urban land use change by mimicking the interactions of the selected agents as the main actors that cause change in the urban landscape. The interactions of the agents are modelled as events that happen at specific time intervals during the course of the simulation.

A description of the environment in which the agents interact as well as the agents' interactions themselves are presented in this subsection. The first part describes the conceptualisation of time in the model. In the second part, a description of the neighbourhood that influences an agent's behaviour is presented. The third part describes
how the models components are linked together with the agents, while the agents' interactions are described in the fourth component.

3.4.1 Time

The spatial changes in the city happen gradually and in small increments of time. The time could be measured in hours, days, weeks, months or years depending on the phenomena under investigation. For the mobility dynamics of the households, several studies (Benenson et al. 2002; Stevens and Dragicevic 2007; Torrens 2007) have used a temporal resolution of one month, which is an appropriate time scale considering that a household, under normal circumstances can move only once a month.

Time is structured as a sequence of distinct time intervals where each interval represents a period of time in which changes happen in the landscape. The smallest time interval in the model represents a period of one month and twelve of these intervals represent a one year period. Different clocks are used to simulate the actions of the different agents. The household agents operate on a monthly clock, the developer agent operates on a six month clock while the planning agent operates on a yearly clock. The planning and developer agents have been designed to operate at longer time intervals for both computational efficiency and for the fact that they operate in the landscape based on anticipated growth rather than monthly conditions that are constantly evaluated by the household agents.

3.4.2 Neighbourhood Delineation

Each of the cadastral parcels has a unique set of neighbouring parcels that exert influence upon it. These neighbours are those parcels that fall within a specified buffer
distance from the boundary of the central parcel. The determination of the
neighbourhoods is important for calculating the neighbourhood characteristics that are
later used by the agents in the model. One of the neighbourhood characteristics this
considered in the model is the proximity score. Similar to the score designed in iCity
(Stevens and Dragicevic 2007), the proximity score is based on the parcel's closeness to
the other parcels that may have desirable or undesirable land use activities and it is used
to determine the attractiveness of a parcel. Proximity to recreation parks, schools and
commercial land-uses is desirable and will have a higher weight, while nearness to
agricultural and industrial land use types is considered undesirable and so will lower
weight values. The proximity score for each of the cadastral lots is calculated by using
the following formula:

\[ P_j = C_a A + C_i I + C_p P + C_s S + C_c C + C_r R + C_o O \]  

Equation 3-1

where: \( P_j \) - proximity score for lot \( j \)

\( A, I, P, S, C, R, O \) - weights for agricultural, industrial, parks, schools, commercial, residential, other land use types respectively,

and \( C_a, C_i, C_p, C_s, C_c, C_r, C_o \) - The count (number) of agricultural, industrial, parks, schools, commercial, residential and other parcels, respectively, in the neighbourhood.

The other neighbourhood characteristics are the average property value and the average
household income in the neighbourhood. They are both used to determine the
neighbourhood in which a particular household agent can move to. The household agents
will move to a neighbourhood whose average household income is higher than or equal to
the agent's income.
3.4.3 Sequential Flow of the Model Components

Each of the various components in the model has a specific task that it performs and has several inputs and outputs that are important for the other components. The schematic diagram in Figure 3-2 shows how the model's components are linked together. The solid lines show the sequential linkages between the model's components while the dashed lines show their inputs and outputs. The neighbourhood analyser determines the characteristics that are associated with each parcel's neighbourhood. After the neighbourhood analyser has finished its computations, the planning agent is then activated in order to select the parcels upon which future development will happen. The planning agent is then followed by the developer agent who adds residential units to the simulation. Lastly, the new household agents are added to the landscape. The household agents evaluate the neighbourhoods of the parcels that have vacant residential units to determine if they should relocate there.

A more detailed description of the planning agent's operation and its linkage to the subdivision module is shown in Figure 3-3. The agent first determines if there are any new households that are expected within the next twelve months. If new households are expected, then the parcels upon which new developments will happen are selected with priority being given to parcels that are already subdivided. However, if necessary, larger pieces of land can be subdivided into smaller cadastral parcels. The lot sizes of the newly subdivided parcels vary in the geographic space according to the bylaws governing the planning zone.
Figure 3-2: Sequential flow of the model components
Figure 3-3: Detailed decision flowchart of the Planning Agent's operation
3.4.4 Agent Interactions

The *planning agent* has been designed to operate at the two levels of data aggregation in the geographic space (Figure 3-3). The data that is at the resolution of the urban planning zones is useful in the implementation of the regulatory influence of the planning policy. This influence varies from one area to another because each planning zone has a different set of requirements for new developments. For example, parcels that are currently used for residential purposes but are under different planning zones may have different municipal regulations for future developments with regard to the maximum number of residential units per parcel and the minimum parcel size.

The dynamics of the *planning agent* are directed by a selected policy that broadly influences the locations and the land use types upon which growth should be concentrated during the course of the simulation. The policy has a list of *inclusion* land use types that the other agents can change and another list of *exclusion* land use types that should not be changed during the course of the simulation. Each of the *inclusion* land use types has a *preference weight* that represents the policy's preference to change it from its current state. In the current implementation of the model, the *preference weights* assigned to the land use classes are limited to integer values ranging from 1 to 5, where 1 represents the lowest preference and 5 represents the highest. In order to permit change, once every twelve months, the *planning agent* considers only those parcels whose land use type is in the *inclusion* list. The *change weight* of each parcel, which is the weight that determines how the actual land parcels will change, is the sum of the preference weights of the land use types that fall within its neighbourhood as shown in the following equation:
\[ W_i = \sum_{j=1}^{j=h} n w_j \]

Equation 3-2

where \( W_i \) - change weight of the parcel \( i \)
\( w_j \) - preference weight of land use type \( j \)
\( n \) - number of parcels that have land use types with preference weight \( w_j \) in the neighbourhood
\( h \) - number of the different land use types in the neighbourhood

Once the change weights for all the zones in the landscape have been calculated, they are used to assign a likelihood of change to a zone in such a way that the zone with a higher weight is more likely to change than a zone with a lower weight. Therefore, it is expected that a parcel with the largest change weight will most likely be selected for change, although there is a small likelihood that it may not be selected. The number of zones that are selected for change is determined based on the anticipated increase in the number of households over the next twelve months. If a selected zone is already fully developed or it cannot contain the anticipated growth because of the zoning bylaw limits on population density but there are still other zones to pick from, then another zone is selected. This process is repeated until there are enough zones have been selected that will contain the expected growth.

Once a zone has been successfully selected, the cadastral parcels that fall within it are chosen for development or redevelopment to suit the zoning expectations. If the parcel's area is larger than twice the expected minimum in that zone, then that parcel is further subdivided so as to fit the minimum size requirements of the corresponding zoning regulations. Each parcel is then assigned a random number of residential units that
fluctuates between the expected minimum and maximum households units for that zone. In addition, the cadastral parcels with commercial and industrial land use types are seeded with retailer and industrial agents at the beginning of the simulation.

The cadastral parcels that have been selected by the planning agent are then passed onto the developer agent who then creates the new residential units that are assigned on these parcels. The developer agent will not add residential units to a parcel if 20% or more of the parcels in that neighbourhood are unoccupied household agents. This condition mimics the preference for real estate developers to build close to existing structures. The residential units are then marked as vacant so that households can consider them for residence. A brief summary of the Planning Agent's decision making rules are as follows:

**IF** parcels are needed for development **THEN**

**FOR** all parcels whose land use class is in the inclusion list **AND** fall in a selected planning zone

**IF** parcel is subdivided and is ready for development **THEN**

**decision:** Pass it to the Developer Agent

**IF** enough parcels have been found **THEN**

**decision:** stop the search

**ELSE IF** more parcels are needed **THEN**

**FOR** all parcels whose land use class is in the inclusion list **AND** fall in a selected planning zone

**IF** parcel is large and is ready for development **THEN**

**decision:** subdivide it and pass new parcels to the developer agent

**IF** enough parcels have been found **THEN**

**decision:** stop the search
The *household agent* is motivated to move to a different cadastral parcel when the average household income in the neighbourhood becomes lower than the household's income. When the household agent decides to move it will relocate to a neighbourhood in which the average household income is higher or equal to its own income. This relocation method for the agents assumes that households are always able to acquire mortgages for new residences and that they always want to live in more affluent neighbourhoods.

In addition, the *household agent* will move to a neighbourhood as long as the average property value in the new neighbourhood is equal or higher than that of the neighbourhood in which it is currently residing. The residential unit to which a *household agent* can move must be vacant and the number of rooms in the unit must be equal to or greater than the number of people in the incoming household. In this model, it is assumed that the age of the head of the household is not one of the characteristics that influence residential choice.

At each time step, new *household agents* are added to the urban landscape according to an annual growth rate specified by the user. For simplicity, the households that are expected in a year are distributed evenly, and are added regularly, over the months of the year. In this model, the households are characterised by the number of people in the household and the household income. The number of people in the household is particularly useful in determining the amount of residential space and, hence, the residential unit in which to live. It is assumed that households can live comfortably in a residential unit whose number of bedrooms is at least equal to the number of people in a household less one. The average household income is important in
determining if the household can afford to move, or must move due to deteriorating condition within its neighbourhood.

The income values for the household agents are assigned to them by using a normal probability distribution function whose parameters, the mean and standard deviation, are derived from the data of the census dissemination area under which the agents are to be assigned at the beginning on the simulation. By changing the mean and standard deviation of this distribution, it is possible to investigate how income distribution in the city influences residential locations and, therefore, land use patterns. Similarly, a uniform distribution function is used to assign the number of persons per household to the household agent.

Each new household agent searches through the list of available residential units and finds the suitable units to which it can belong based on the neighbourhood and the unit's characteristics. One unit from this group is randomly assigned to the household. Any new households that may remain unassigned to their preferred units are 'forced' into the available vacant units in order to ensure that no households are left homeless. At the subsequent iteration, the households that did not move into their preferred locations are given first priority to move.

The decision making rules for a Household Agent to relocate can be summarised as follows:
IF $HH_{Inc} > Avg\_HH\_Inc$ AND $HH\_RU\_PropVal > Avg\_RU\_PropVal$ THEN

**decision:** $HH\_Agent$ searches for suitable vacant units

IF $Vac\_RUs$ is not Empty THEN

**decision:** $HH\_Agent$ randomly picks one residential unit from $Vac\_RUs$.

$HH\_Agent$ relocates and previous unit is marked vacant

ELSE

**decision:** $HH\_Agent$ does not relocate

ELSE

**decision:** $HH\_Agent$ does not relocate

where

$HH\_Inc$ - Household income

$HH\_RU\_PropVal$ - Value of residential unit occupied by an agent

$Avg\_HH\_Inc$ - Average household income in the agent's neighborhood

$Avg\_RU\_PropVal$ - Average property value in the agent's neighborhood

$Vac\_RUs$ - List of suitable vacant residential units

$HH\_Agent$ - Household agent

The decision making rules for a *household agent* that is new to the landscape varies slightly from the one above and can be represented as follows:

IF $HH\_Inc > Avg\_HH\_Inc$ THEN

**decision:** $HH\_Agent$ looks for $Vac\_RUs$

IF $Vac\_RUs$ is not Empty THEN

**decision:** $HH\_Agent$ randomly picks one residential unit from $Vac\_RUs$.

$HH\_Agent$ moves into the residential unit and it is marked occupied

ELSE

**decision:** $HH\_Agent$ remains without a residential unit

ELSE

**decision:** $HH\_Agent$ remains without a residential unit
Since this model is designed to simulate land use change in a small city that is experiencing growth, it is reasonable to assume that the retailer and the industrial agents will not find it necessary to relocate during the course of the few years that are modelled in the simulation. Therefore, once these agents are assigned locations in the city, they stay at the same parcel for the duration of the simulation. In the case of the retailer agents, however, more agents can be added to the same parcel to represent redevelopment. Both the retailer and the industrial agents are characterised by the number of jobs they provide to the residents of the city, but there is no direct link that associates a particular household agent to a particular job location. The removal of this direct link greatly simplifies the computational setup. It is also assumed that transportation accessibility is uniform throughout the city, an assumption that holds for a small city with low traffic volumes and reasonable public transit system like that of the study area.

In order to assign locations for the retailer and industrial agents, the land use zone specifications are followed. During the course of the simulation, the new retailer agents that may added to the landscape will locate close to existing retail locations and, similarly, the industrial agents will locate close to existing industrial locations. The development of the retail and industrial premises is excluded from the developer dynamics for simplicity. Instead when the planning agent assigns them to locations it is also implied that there are enough built structures to accommodate the agents.
CHAPTER 4  MODEL IMPLEMENTATION

This chapter explains the implementation of the Agent iCity model. It has four major subsections. In the first subsection, the different software components that together constitute Agent iCity are explained. The second subsection outlines the study area and the data used in this research. In the third subsection, the implementation for the agents is explained while the parameter settings for the model are provided in the fourth subsection.

4.1 Model Components

The model components in Agent iCity were developed by using the object-oriented programming design which enabled these components to be operationalized as parallel independent modules. These parallel modules were designed according to the presentation in Figure 4-1. Each of the modules has an independent task that it performs coherently with the other modules in order to generate simulation outcomes.

4.1.1 JUMP Plug-in

This module is used to access the Java Unified Mapping Platform (JUMP), an open source GIS application, that is used for viewing and processing spatial data in the model (JUMP 2009). JUMP has a highly modular and easily extensible design that makes it easily customizable to fit the specific needs of a user. In addition, it has an active and helpful user community that assists with technical issues.
For the purposes of this research, an open source GIS application was needed because one of the stipulations from the funding agency was the requirement to use open source software. In addition, having an open source application allows for easy sharing and implementation of the source code without any licensing fees and also enables collaborative work in order to make further improvements to the model in the future.

JUMP uses the Java class libraries from the JTS Topology suite to perform processing operations. The JTS Topology suite was developed by the same company that developed JUMP in collaboration with the British Columbia Ministry of Sustainable Resource Management. It has many robust algorithms for processing two-dimensional spatial data and it is used in many of the other Java based open source GIS applications.
4.1.2 Neighbourhood Analyser

The neighbourhood analyser performs the necessary calculations in order to determine the required attributes of a parcel's neighbourhood. These attributes are a list of neighbouring parcels for each parcel (i.e. the neighbourhood), the average household income, the average property value and the proximity score in the neighbourhood. In order to perform these calculations, the required inputs for the module are the neighbourhood radius, the cadastral parcels, the list of all the residential units and the list of all the households.

4.1.3 The Agents Module

The agents module coordinates the timing of the actions of all the agents. This coordination allows for the agents to be called only when the required inputs are available and at the right time according to the simulation clock.

4.1.4 The Subdivision Module

This component is used to subdivide large tracts of land into smaller cadastral parcels. It is called by the planning agent only when it is necessary to execute the subdivision procedure on a particular parcel. Depending on how large the parcel is, it can either be subdivided into parcels of the size of a city block or to cadastral parcels that are ready for development.

4.1.5 The Repast Executor Module

The Repast executor module is used to link the model to the Recursive Porous Agent Simulation Toolkit (Repast), also open source agent-based modeling toolkit (Repast 2009). Repast, originally developed at the University of Chicago and the
Argonne National Laboratory, is freely available for download and has been widely used in agent-based simulations (Tobias and Hofmann 2004). It was chosen because, similar to Agent iCity, it is implemented on a Java platform and it has well organized documentation and many detailed tutorials. The Repast toolkit is used to schedule the sequencing of the events related to the activation of the different modules and also for the overall management of the simulation clock. In essence, Agent iCity is a model that is tightly coupled with JUMP for the management, processing and visualization of the spatial data and with Repast for the overall organisation of the agents and their scheduling.

4.2 Study Area and Data

4.2.1 Study Area

The City of Chilliwack (Figure 4-2) was chosen as the study region because it has been experiencing rapid urban growth over the last decade (CEPCO 2008). The City is located in the Fraser Valley of British Columbia with an average growth rate between 3% and 4% over the last 10 years. In 2008, the number of households in the city had increased to 29,290 from 24,398 in 2000. It is also surrounded by the steep slopes of the West Coast mountains and it has some of the best agricultural land in the region. The rapid population growth poses serious challenges to the planners who would like to see the community develop, but at the same time protect the limited agricultural land from urban sprawl.
The implementation of the land use change model has been focused on a smaller section in the southern end of the city. A new university campus has been constructed in this area and, between 2005 and 2008, several large tracts of land that have been subdivided into smaller parcels for residential use. The location of the university in this area is likely to spur secondary growth in the near future as the university staff and students look for accommodation in the neighborhood. Retail and services businesses may also be established to serve the university community.

4.2.2 Input Data

Agent iCity operates with two geospatial data layers that have been formatted according to the Environmental Systems Research Institute (ESRI) shapefile vector data format (ESRI 1998). Both of these data layers are for the year 2005 and were provided by
the City of Chilliwack. One layer represents the planning zones in the city while the other represents the cadastral parcels of the city.

4.2.2.1 Planning Zones Layer

Each of the spatial features in this layer is characterized by a unique identification number for each zone and a zone category to which it belongs as classified by the zoning bylaws of the city. The zoning bylaws specify in detail the expected land use activities in each zone, the maximum number of households on a parcel and the minimum and maximum parcel dimensions if it was to be subdivided. However, given that there are thirty-two zone categories in these data, the categories were reclassified into eight zone classes as presented in Table 4-1 and shown in Figure 4-3.

<table>
<thead>
<tr>
<th>Planning Zone</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural</td>
<td>Zones for agricultural related</td>
</tr>
<tr>
<td>Commercial</td>
<td>Zones for commercial activities</td>
</tr>
<tr>
<td>Residential</td>
<td>Zones for current and future residential use</td>
</tr>
<tr>
<td>Industrial</td>
<td>Zones for industrial activities</td>
</tr>
<tr>
<td>Institutional</td>
<td>Zones where institutions like schools, churches, government offices are located</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>Zones for protected land such as native reserves, environmentally sensitive areas, parks and recreation facilities</td>
</tr>
<tr>
<td>Rural</td>
<td>Zones for future development. Many areas are on steep slopes or in the low lands and are lacking the infrastructure for services like water and electricity.</td>
</tr>
</tbody>
</table>

Table 4-1: Description of the planning zones
4.2.2.2 Cadastral Parcel Layer

The features in the spatial layer for cadastral parcels are characterized by two main attributes. The unique identifier helps to categorize each feature as a unique parcel in the model while the land use class identifies the types of activities that take place on each parcel. The land use classes, as presented in Table 4-2, were coded specially for this model because the original data did not have the specific activities related to each parcel. The classification coding was based on the extent of observed development on the parcels and from the details of the planning zones. The dissemination area unit identifier is used to link the cadastral parcels to the city's census data for the year 2006.
Land use Class | Description
--- | ---
Residential 1 | Residential parcels that are currently occupied
Residential 2 | For parcels that are ready for occupation. These parcels have already been subdivided.
Residential 3 | Areas for future residential use. These areas have infrastructure for services laid out but are not yet subdivided into cadastral parcels
Residential 4 | Areas where infrastructure for services in not in place and the parcels are not yet subdivided
Agricultural | Parcels on which agricultural related activities take place
Commercial | Parcels upon which commercial activities take place
Industrial | Parcels on which heavy and light industries are located
Protected | Areas that are excluded from the municipal planning process specifically the native reserves
Institutional | Parcels where institutions like schools, churches, government offices are located
Recreational | Parcels on which parks and recreation facilities are located

Table 4-2: Description of the land use classes for the cadastral parcels

4.2.2.3 Census Data

In this model census data are also used to augment the spatial data provided by the city. These data are selected from the tables of the 2006 census carried out by Statistics Canada and they include the following variables for the dissemination area corresponding to the study region:

- average household income;
- the standard error of the average household income;
- and the average number of persons in a household;
- the average property value;
- average number of bedrooms in a dwelling.

The 2006 census data used in this study was compiled in 2006 and is based on 20% sample data.
4.3 Agent Implementation

4.3.1 Household Agents

The household agents are characterised by the household income and the number of people in the household. At the start of the simulation some household agents are already existing in the landscape and they have residential units associated with them. The value of the household income that is assigned to these agents is randomly generated by a normal distribution function using values of the average income and its standard error for the particular dissemination area in which the household agent is situated. Similarly, the number of people associated with each agent are also randomly assigned by using a normal distribution function centred around values from the dissemination area.

During the course of the simulation, new household agents are added to the landscape. The income values for these incoming agents are assigned to them randomly from a normal distribution whose centre is the average income specified in parameter settings of the model. Similarly, the number of people associated with each agent is also randomly assigned by using a normal distribution function centred around values from the model’s parameter settings.

4.3.2 Planning Agent

The planning agent is characterized by the selected policy or policies that the user picks. The policies were selected based on reasonable planning outcomes that the urban planner may try to achieve. The user can select the policy at the beginning of the simulation or at any point during the course of the simulation.
4.3.3 Developer Agent

There is only one developer agent in the model, which, when selecting the parcels to develop, is motivated by making "profit" through the "sale" of residential units in places with high proximity scores or in neighbourhoods with high average property values. By using a normal probability distribution function, it assigns the property value and the number of rooms to the unit based on the values from the model's parameter settings.

4.3.4 Retailer and Industrial Agents

The number of retailer and industrial agents that are added to the simulation is based on the figures from the City of Chilliwack Community Profile prepared by the Chilliwack Economic Partners Corporation (CEPCO 2008). Chilliwack's labour force is 36,792 people which represents a participation rate of 57.5% (based on the population that is 15 years old and over). However, the combined labour force in the industrial and commercial sectors is 7.5%. A problem with this figure is that it includes a number small agricultural processors who are located on land parcels in the Agricultural land use class. It has been assumed that this discrepancy is negligible considering that the study area is much smaller than the entire City of Chilliwack. In the model, the total number of persons associated with each household agent is calculated and 7.5% must be the total number of jobs associated with the retailer and industrial agents.

4.4 Model Parameters

The growth rate used in the model was adjusted from the average of the City of Chilliwack to reflect rapid development that is expected in the study area. The criteria
used to determine the neighbourhood of each parcel is by taking a buffer distance of about 125 m from boundary of each parcel. In the area where the model is implemented, half the length of a city block is about 125 m. It is assumed that the characteristics of an area the size of a city block is enough to influence a household's decision to relocate.
CHAPTER 5  MODEL RESULTS

Multiple model simulations were performed by using vector-based geospatial datasets for the small neighbourhood that has been chosen in the city of Chilliwack in British Columbia (Figure 4-2). The neighbourhood is located in the Promontory community area, which is on the southern edge of the city and has been designated to accommodate up 10,000 people in the coming years (CEPCO 2008). It is about 14 km\(^2\) in size and is parcellled into over 1500 existing cadastral lots many of which are not yet fully developed for residential purposes. The existing land use activities on the cadastral parcels were specially classified for this model into ten different land use categories as presented in Table 4-2 and are shown in Figure 5-1.

![Land Use Classes in the Study Area](image)

Figure 5-1: Land use classes in the study area
Based on the land use classification, the *Residential 1* land use class identifies those parcels that are already occupied. It is generally expected that the development of new residential units will start in the *Residential 2* land use class where the parcels are already prepared and ready for development. After the development of the *Residential 2* land use class, the model then proceeds to the *Residential 3* land use class where service infrastructure like water and electricity has already been put in place but the parcels generally need further subdivision. The *Residential 4* land use class takes the least priority in development because these areas are generally unserviced with amenities and are located in rural areas, on steep slopes or on flood plain.

By changing the planning policies without altering the other parameters of the model, three different urban growth scenarios were generated. In Scenario 1, no specific urban planning policy was implemented in the model, which allows for development to happen on any of the land use classes. In Scenario 2, the policy that protects agricultural land by excluding the *Agricultural* land use class from conversion was implemented. Lastly, in Scenario 3 the urban containment policy that confines growth within the existing urban limits was taken into account. The parameters settings related to the average household income for the new household agents and the average value of the new residential units were set at $80,000 and $250,000, respectively, for all the three scenarios. Both of these values are rounded off to the nearest 1000 based on the average values derived from the census data for the small neighbourhood under study.

According to the Chilliwack Community Report the Promontory neighbourhood in Chilliwack has been planned to accommodate a population of 10,000 in the coming years (CEPCO 2008). Consequently, the growth rate used for the study area has been
adjusted to reflect the dynamics of a higher population growth compared to the average growth rate of the entire city. The initial number of household agents in the landscape is 720, and 1625 new agents are expected to move into the study area over a period of 5 years. These figures may not be indicative of the reality but they provide appropriate growth conditions that can be used to examine the developed model.

In this model, the new household agents that are added to the landscape are assigned an average household income that is randomly selected from a normal distribution. The mean value of this normal distribution is specified by the user in the parameter settings at the beginning of the simulation. Likewise, the new residential units that are added to the landscape are assigned a property value that is randomly selected from a normal distribution whose centre is the average property value specified by the user of the model.

5.1 Simulation Results

The simulation time step $t$, represents a period of one month. At the beginning of the simulation ($t = 0$) each cadastral parcel that belongs to the Residential 1 land use class is linked with a residential unit and is occupied by an already existing household agent. The other land use classes in the landscape are not associated with any residential units or households at this time step. During the course of the simulation, the cadastral parcels on which household agents are relocated are converted to the Residential 1 land use class.

5.1.1 Results for Scenario 1

Scenario 1 simulates the changes in the urban land use patterns without the implementation of any particular urban planning policy. In this scenario the new
residential units in the landscape are associated with the cadastral lots solely based on the preferences of the developer agent. The simulation results for this scenario are shown in Figure 5-2. The incoming household agents generally occupy the Residential 2 land use class first but as the population increases the parcels in the other land use classes are subdivided to accommodate the new household agents. Since there is no particular policy that has been implemented in this scenario, the subdivisions happen randomly solely based on the preferences of the developer agent without consideration of the land use classes. This scenario lacks the constraints that would preclude development on land use classes like Protected and Recreation. The quantitative characteristics of the three scenarios are presented in Table 5-1.

For Scenario 1, 2357 new parcels were created after 5 years. On average, a newly created parcel has an area of approximately 700 m$^2$, therefore, about 1.6 km$^2$ of land was subdivided and prepared with the necessary infrastructure for residential use. For the particular scenario, the number of new parcels is the same at $t=36$ and at $t=48$. This is because at $t=48$, the planning agent has evaluated the landscape and determined that the existing parcels can accommodate the household agents that are expected in the next 12 months and no new subdivisions are required.
Simulation Results for Scenario 1

Land use classes
- Agricultural
- Recreational
- Industrial
- Institutional
- Commercial
- Protected
- Residential 1
- Residential 2
- Residential 3
- Residential 4

Figure 5-2: Changes in land use patterns for Scenario 1
Table 5-1: Cumulative values for the parcels and household agents added to the landscape

<table>
<thead>
<tr>
<th>Time Step</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Newly Created Parcels</td>
<td>Newly Created Parcels</td>
<td>Newly Created Parcels</td>
</tr>
<tr>
<td></td>
<td>New household agents</td>
<td>New household agents</td>
<td>New household agents</td>
</tr>
<tr>
<td></td>
<td>with residential locations</td>
<td>with residential locations</td>
<td>with residential locations</td>
</tr>
<tr>
<td>t = 12</td>
<td>12</td>
<td>22</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>157</td>
<td>159</td>
<td>159</td>
</tr>
<tr>
<td>t = 24</td>
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<td></td>
<td>400</td>
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<td>917</td>
<td>448</td>
<td>801</td>
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<tr>
<td></td>
<td>691</td>
<td>681</td>
<td>702</td>
</tr>
<tr>
<td>t = 48</td>
<td>917</td>
<td>1514</td>
<td>1510</td>
</tr>
<tr>
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<td>1090</td>
<td>1083</td>
<td>1090</td>
</tr>
<tr>
<td>t = 60</td>
<td>2357</td>
<td>1514</td>
<td>2438</td>
</tr>
<tr>
<td></td>
<td>1586</td>
<td>1582</td>
<td>1586</td>
</tr>
</tbody>
</table>

5.1.2 Results for Scenario 2

The second scenario considers the protection of agricultural land from development without inhibiting development to the other residential land use classes. Therefore, this scenario permits the development of new residential units on the Residential 2, Residential 3 and Residential 4 land use classes depending on the selection preferences of the planning agent and the anticipated need for new parcels to accommodate the increasing population. The results from this simulation are shown in Figure 5-3 and they show that the policy that has been implemented directs new development towards the Residential 2, Residential 3 and Residential 4 land use classes. Parcels in Residential 2 land use class are first subdivided at $t = 24$ while the parcels in the other classes are subdivided (from $t = 36$ onwards).

In this scenario, 1514 new parcels, comprising of some 1.1 km$^2$ were created in the landscape after 5 years (Table 5-1). At $t = 60$, the number of newly subdivided parcels does not increase because of the planning agent's evaluation that no new cadastral parcels will be needed in the next 12 months. At each time step, the number of household agents...
Simulation Results for Scenario 2

Figure 5-3: Changes in land use patterns for Scenario 2
that are able to find a residential unit is comparable to that in Scenario 1, although the number of new parcels differs between the two scenarios.

5.1.3 Results for Scenario 3

In Scenario 3 the urban containment policy is implemented such that new developments are contained within the City's limits. To achieve this objective, the policy permits development to happen only on the Residential 2 and Residential 3 land use classes. These land use classes are used define the city limits because the areas they cover are already serviced with community necessities like a sewer system, water supply and electricity. Areas belonging to the Residential 4 land use class are excluded from the city boundaries because they do not have the service infrastructure in place. Also, the steep slopes and flood plain which characterise the Residential 4 land use class may not be safe for residential use. The results from this scenario are shown in Figure 5-4. As in the previous scenarios, development starts from the Residential 2 land use class before proceeding to Residential 3. There is no development onto Residential 4 in this simulation scenario.

From the numerical results presented in Table 5-1, 2438 parcels have been added to the landscape by the end of the fifth year. Unlike the previous two scenarios, the number of subdivided parcels increases in each time step.

5.1.4 Comparison of the simulation results from the three scenarios.

Table 5-1 presents the number of newly created parcels in the study area as well as the number of new household agents that have been able to find a new residential unit. For all the scenarios, the number of new household agents that are assigned residential

55
Figure 5-4: Changes in land use patterns for Scenario 3
locations is approximately the same at each time step, yet the land use patterns related to these scenarios (Figure 5-2, Figure 5-3, Figure 5-4) are quite different. In Scenario 3, the parcels that get occupied during the course of the simulation are much more clustered together (compact) compared to the other scenarios. Particularly in Scenario 1 where there is no policy being implemented, the changes in the landscape are much more spread out.

At the different time steps, the number of parcels that are added to the landscape varies from scenario to scenario. In Scenario 1, there are just a few new parcels that are added to the landscape at $t=12$. This is because the lack of a planning policies provides the planning agent with more options to locate the new household agents. This implies that the planning agent, does not detect a high demand for new subdivisions in the early time steps of the model.

No new cadastral lots are added to the landscape between $t=36$ and $t=48$ for Scenario 1 and between $t=48$ and $t=60$ for Scenario 2. This happens because the creation of new parcels is dependent on the anticipated need and the number of unoccupied parcels that already exist. In both of these cases the planning agent has evaluated that there is no need to add new cadastral parcels. This control mechanism allows the model to minimize any unnecessary subdivision of land.

5.2 Sensitivity Analysis

Sensitivity analysis is an important stage in the development of a model and was carried out to explore how the model outputs varied when the initial parameter were altered. It is particularly useful in the determination of the reliability and in the
assessment of the uncertainties in the model's results (Crosetto et al. 2000; Kocabas and Dragicevic 2006).

An exploration of the sensitivity of the model's results to variations in the household income and to variations in the average residential value was carried out. In addition, the geometric orientations of the newly subdivided cadastral lots were altered in order to see if there are any corresponding differences in the changes of the land use patterns. The urban planning policy implemented in these sensitivity analysis simulations is the same as that in Scenario 2 where the Agricultural land use class is excluded from conversion.

Figure 5-5 presents the graphical user interface developed for the Agent iCity model to facilitate the running of the simulations and to visualize the growth scenarios. Part A shows the JUMP interface that is used to manage the spatial data in the model. In addition, this interface also contains the dropdown menu through which the Repast toolkit is accessed. Part B is the control dialog from the Repast toolkit that is to control the time clock in the Agent iCity model. It starts, pauses and stops the simulation. Part C is the dialog window for the model's parameter settings. This window is used to adjust the settings for the growth rate, the neighbourhood radius, the average property value and the average household income. It is also used to specify the planning policy that is implemented by the planning agent in the model. Part D displays a Cartesian graph of the number of residential units and the number of household agents in the landscape at every time step.
Figure 5-5: The graphical user interface for Agent iCity
5.2.1 Variation of the average household income

A univariate sensitivity analysis for the household income was carried out by changing the value of the average household income while keeping the average property value for the residential units constant. Two settings for the income value were used, one at $110,000 and the other at $55,000 while maintaining the average property value at $250,000. The simulation results for the variation in average household income are shown in Figure 5-6. When the average household income is high it would be expected that many household agents would be able to find residential units and therefore the corresponding number of parcels that get occupied during the course of the simulation would be high. However, based on the parameter settings for this simulation, this is not the case.

Table 5-2 presents the comparison of the results from the parameter variations. For the high income setting, there are fewer household agents that have found a residential unit compared to the case of the low income setting. This is because the income of the new agents is much higher than the average income in the different neighbourhood of the study area which restricts the agents from settling in poor areas even if the residential units are affordable.

<table>
<thead>
<tr>
<th>Time Step</th>
<th>Variations in Income</th>
<th>Variations in Property Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High Income</td>
<td>Low Income</td>
</tr>
<tr>
<td></td>
<td>New Parcels</td>
<td>New Parcels</td>
</tr>
<tr>
<td></td>
<td>New households with</td>
<td>New households with</td>
</tr>
<tr>
<td></td>
<td>residential locations</td>
<td>residential locations</td>
</tr>
<tr>
<td>t = 12</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>105</td>
<td>117</td>
</tr>
<tr>
<td>t = 24</td>
<td>253</td>
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</tr>
<tr>
<td></td>
<td>351</td>
<td>400</td>
</tr>
<tr>
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<td></td>
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<td>22</td>
<td>275</td>
</tr>
<tr>
<td></td>
<td>139</td>
<td>446</td>
</tr>
</tbody>
</table>

Table 5-2: Results for sensitivity to variations in household income and property value
Sensitivity to the variations of the Average Household Income for a fixed Property Value

High Income
Average Income Value = $110,000
Average Property Value = $250,000

Low Income
Average Income Value = $55,000
Average Property Value = $250,000

Land use classes
- Agricultural
- Recreational
- Industrial
- Institutional
- Commercial
- Residential 1
- Residential 2
- Residential 3
- Residential 4
- Protected

Figure 5-6: Sensitivity to the variations in the average household income for the new household agents
5.2.2 Variation of the average property value

By keeping the average household income constant at $80,000 while altering the average property value, the simulation results for the model's sensitivity to the property value are shown in Table 5-2. When the average property value is set at a high value of $800,000, the number of parcels that get occupied is low. However, when the average property value is lowered to $250,000, then the number of parcels that are occupied during the course of the simulation increases because more household agents can afford the residential units on those parcels.

5.2.3 Sensitivity on the geometric orientation of the parcels

The subdivision algorithm operates by selecting the longest edge of the parent polygon (the polygon to be subdivided) and then orienting the child polygons (the newly subdivided cadastral parcels) such that their lengths are perpendicular to that edge. This implies that in multiple runs of the model, a particular parent polygon will have the same number of child polygons. In reality, however, a particular parcel can be subdivided in numerous ways depending on the intentions of the developer and the city's planning regulations.

In order examine if the model is sensitive to the way the way the parcels are subdivided, the source code was altered such that different geometric orientations of the new parcels could be obtained. For Case 1 (Figure 5-9), the orientation of the new lots is aligned to an edge that is randomly selected in each parent polygon that is to be subdivided, while in the Case 2 the orientation is determined by choosing the longest edge of the parent polygon. After running the model once for each case, the land use
Sensitivity to the variations of the Average Property Value for a fixed Household Income

High Property Value

$t = 0$

Low Property Value

$t = 12$

$t = 24$

High Property Values
Average Income Value = $80,000
Average Property Value = $800,000

Low Property Values
Average Income Value = $80,000
Average Property Value = $250,000

Land use classes
- Agricultural
- Recreational
- Industrial
- Institutional
- Commercial
- Protected
- Residential 1
- Residential 2
- Residential 3
- Residential 4

Figure 5-7: Sensitivity to the variations in the average property value for the new residential units
patterns are not distinctly different because the geometry and the orientation of the parcels are not one of the factors that a household agent considers in its relocation process. Figure 5-8 presents a detailed view of the changes in some of the parcels at the centre of the study area. In this section, at \( t=60 \), the *Residential 4* land use class is much more subdivided in Case 1 than in Case 2. Considering that many of the parent polygons are approximately proper rectangles, as evidenced in Case 2, it would be expected that the geometry of the newly subdivided cadastral parcels should be rectangular. However, several of the created parcels in Case 1 are triangular in shape. Also, a visual inspection of the parcels that are subdivided, for example, the parcel north of the *Commercial* land use class, indicates that the geometry of the parcels is differs in both cases.

![Figure 5-8: Differences in the geometric orientation of the subdivided parcels](image)

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Sensitivity to the Geometric Orientation of the Cadastral Parcels

**Case 1**

\[ t = 12 \]

\[ t = 36 \]

\[ t = 60 \]

**Case 2**

\[ t = 12 \]

\[ t = 36 \]

\[ t = 60 \]

Land use classes

- Green: Agricultural
- Light Green: Recreational
- Dark Purple: Institutional
- Pink: Residential 3
- Light Blue: Residential 2
- Orange: Residential 1
- Yellow: Commercial
- Greenish Black: Protected

Figure 5-9: Changes in land use patterns based on different geometric orientations for the cadastral parcels
5.2.4 Sensitivity on multiple runs of the model

Given that randomness is incorporated in this model, it is expected that different model outcomes will be obtained for each simulation run. After running the simulation for a larger number of times in order to get statistical independence, it is possible to determine the most likely outcome from the model. For this model, the estimates of most likely outcomes were obtained by overlaying the results from 42 simulation runs and then determining the relative frequencies associated with each of the cadastral parcels. The relative frequency of a parcel was determined based on the number of times it is occupied by a household agent during the simulation runs.

For all the 42 simulation runs, the policy that protects agricultural land was implemented and each run had 60 time steps. The average household income value for new households was set at $80,000 while average property value for the new residential units was set at $250,000. The relative frequencies for each of the cadastral parcels at various time steps are presented in Figure 5-10. At \( t = 0 \), the cadastral parcels occupied by the existing households have a value of 1 while the those that are unoccupied have a value 0. For the rest of the selected time steps, the values indicate the relative frequencies of the parcels at the respective time steps. As the time steps increase there are more parcels that are occupied hence more parcel with relative frequencies. In Figure 5-11, the relative frequency of a parcel is based on how often the parcel is occupied by a household agent for all the 60 time steps of the simulation runs. Therefore, the values in Figure 5-11 are an average of those at the different time steps in Figure 5-10 and can be used to estimate the likelihood of a particular being occupied at every twelfth time step during the course of the simulation.
Figure 5-10: The relative frequencies of the occupied parcels at selected time steps during the course of the simulation
Figure 5-11: The relative frequencies of the occupied parcels at any one time step during the course of a simulation
CHAPTER 6 DISCUSSION AND CONCLUSIONS

6.1 General Conclusions of the Thesis

Agent iCity, an agent-based model that simulates the process of urban land use change by using high resolution cadastral data was developed and presented in this thesis. The model was built around the premise that the actions of the key stakeholders in a city are responsible for the changes in the land use patterns. The key stakeholders in the city were considered to be the urban planner, the housing developer, the households in the city, as well as the commercial retailers and the industrial manufactures. In Agent iCity these stakeholders were represented as the agents and their actions were modelled in order to simulate the process of urban land use change.

The planning agent, operates by activating one of the three urban planning policies that have been implemented in the model. One of the policies is designed to mimic the conditions under which agricultural land is protected from development, the second policy aims at keeping new developments within the existing limits of the city, while the last one limits development at a specific location that the user of the model may specify.

The primary purpose of the developer agent is to add residential units to the urban landscape. This agent mimics a real-estate developer who is motivated by profit. Thus, in Agent iCity the addition of new residential units to the urban landscape is biased towards neighbourhoods with desirable land use classes, high property values and high income
values because it is assumed that these are the locations that will yield maximum profit to the developer agent.

The households that are relocating as well as those that are already existing in the city, are represented by the household agents. Each of these agents searches through the existing stock of vacant residential units to find a smaller subset whose characteristics satisfy its properties. The household agent moves into a neighbourhood where the average household income is higher or equal to its own income and into a residential unit with enough rooms to accommodate the persons in the household. The retailer and industrial agents are used to represent the number of jobs and the locations of the commercial retailers and industrial manufacturers, respectively, in the city.

In addition to the above agents, a subdivision module has been developed as part of the Agent iCity model and is used to divide large tracts of land into smaller cadastral parcels along with their access roads. This subdivision module is important in the simulation of urban land use change, particularly when using vector-based data, because in a city larger parcels are often subdivided into smaller parcels of varying dimensions.

The developed model was implemented on vector-based geospatial data for one of the neighbourhoods in the City of Chilliwack, BC. The data consisted of the existing cadastral parcels and was classified according to the City's planning zones and land use classes. Census data for the study area was used to generate the characteristics of the residential units and the properties of the household agents.

Various urban growth scenarios were created by altering the urban policies that are implemented by the planning agent. The results from the simulation of these scenarios indicate that the changes in the land use patterns are strongly influenced by the urban
policies that the model user decides to work with. Also the model's sensitivity to variations in the average household income for the new household agents and the average property value for the new residential units was tested. It was found, as it is expected in reality, that when the average household income is high more household agents are able to find residential units in the urban landscape and the spread of the residential area is larger. Conversely when the average household income is low, only a few household agents are able to find residential units in which to relocate. However, if the average income of the new household agents is much higher than the average income in the study area, only a few agents will settle in the area because they have a preference of settling in more affluent neighbourhoods.

The model is also sensitive to the setting of average property value of the residential units. When the property value is high, there are only a few household agents that are able to find a residential unit within the landscape. On the other hand, there are more household agents that are able to find a residential unit when the property value is low.

While keeping the parameter settings constant, multiple runs of the model were carried out and it was found that there were differences at a local scale in how the parcels were developed during the course of the simulation. However, the differences in the patterns land use change for the entire study area were minimal and this could be due to the limited number of runs used. It was also found that the model is not very sensitive to the geometric orientation of the newly subdivided cadastral parcels.
6.2 Future Directions

While Agent iCity successfully models the actions of the agents in the urban landscape, the methodology that was used to model the decisions of the agents does not entirely capture the behavioural complexity of the key stakeholders in the city. The representation of human behavioural dynamics in the model can be greatly improved by using discrete choice models that use the random utility theory and are often employed in econometric and transportation studies (McFadden 1973; Ben-Akiva and Lerman 1985). The modular nature of the source code for Agent iCity will not require major adjustments in order to add this improvement in the near future.

Also, Agent iCity can be extended to operate via the Web. This can be achieved by developing a Web browser extension or applet that can control the Agent iCity model from a remote computer. The simulated results from the model would also be viewed through this applet. Such a web-based version of Agent iCity would allow planners and community leaders to run the model remotely. Running the model remotely is advantageous because it is computationally intensive and it would be rather inefficient on many low-end computers. Also, the integrity of a dataset used by several people is easier maintained on a remote server.

The validation of an agent-based model is a complex research endeavour and the model presented in this thesis will have to go through the validation process as a separate project for further work on this study. Data, covering a larger period of time, for the study area must be acquired in order to accomplish some parts of the validation process. Furthermore, the subdivision algorithm that has been implemented in the model can be improved by using digital elevation datasets in order to take into consideration the
influence of the slope on the alignment of the road and the cadastral parcels. Also, when new roads are added to an area, they are usually a continuation of existing ones. This is an important feature that is yet to be addressed.

While the model is capable of creating cadastral parcels from larger tracts of land, which is a novel contribution to research, it does not have the ability to merge several small cadastral parcels into larger ones. It is particularly useful to develop another component that would allow the merger of several smaller parcels into others that are designated to higher density residential use. The merger of smaller parcels often happens when the space for the city's expansion starts run out and there is a need to intensify density within the city's boundary. An example could be the merger of a few single home cadastral parcels to put up a high rise building, multiple apartments or townhouses.

The urban planning process in a city may involve different participants who contribute different goals, skills and ideas to the process. These participants include urban planners, community activists for various interest groups and the politicians. Through a set of priorities that are associated with the land use classes and the different planning zones, a web-based environment can be created where these participants can negotiate with each other and formulate planning decisions. Each participant contributes and participates by adjusting the priority weights for the land use classes and the different planning zones in order achieve his or her goals and objectives. In such a system, Agent iCity can be a useful tool for simulating different scenarios of land use change that can be used for collaborative or participatory decision-making.
6.3 Research Contributions

The developed Agent iCity model and simulation tool is a novel contribution to the field of GeoSimulation and GIScience. It uses vector-based GIS data that represents the actual cadastral parcels in a city. The approach used is particularly useful because it allows for the examination of the changes in land use patterns at both local and can be extended to wider spatial scales. In addition, the use of vector-based irregular tessellations eliminates the problems associated with models that use raster-based data to simulate urban land use change. Also, the outputs from this model are closer in appearance to what the decision makers and planners expect compared to those that could be derived from a raster-based model.

This model can be incorporated as a part of a spatial decision support system in order to aid urban planners and community leaders in their planning process. By creating different urban growth scenarios and then simulating the land use change process, the resultant land use patterns can be used to examine the implications of particular planning policies on the general form of the city. In addition, the model can be used to examine how the changes in the demographic characteristics may affect the changes in the land use patterns.

The algorithm that subdivides large tracts of land into smaller cadastral parcels is a novel improvement with respect to the existing modelling algorithms. This algorithm provides a means to automatically subdivide an irregularly shaped polygons into smaller ones of a specified size and dimensions. Methodologies of subdividing polygons are important in simulation models where irregular spatial objects change geometry.
In summary this research study contributes to the fields of geography and GIScience by proposing a new agent-based modelling approach for the simulation of urban land use change.
REFERENCES


