Residential property developers in urban agent-based models: Competition, behaviour and the resulting spatial landscape

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It is not the mountain we conquer, but ourselves.

Sir Edmund Hillary

Abstract

While it is widely acknowledged that property developers are the most important agent in the urban development process, existing urban agent-based models often fail to examine the diversity of their types, strategies and behaviours and the resulting effects this differentiation has at a spatial level.

To examine this, a spatial multi-agent model that accounted for the variation in how developers purchase and subdivide land was created. Developer agents within the model all accessed the same set of behaviours, but implemented them differently based upon the capital available to the developer. These behaviours include how developers: assess the property market, evaluate parcels for purchase, evaluate the timing of subdivision, manage their risk, and focus transactions within a defined territory. To enable the subdivision of parcels, a hierarchical landscape was created that provided the framework for developer agents to understand, analyse and enact the mechanism of subdivision on the urban environment.

Using this agent-based model, two experiments were conducted. The first experiment varied the level of developer competition to examine how the diversity of capital affects the development of the urban landscape. The second experiment compared the default heterogeneous application of the behavioural traits with a homogeneous application to explore the resulting affects on the pattern of development. This was done to both understand the importance of the behaviours but to also explore the way in which heterogeneity affects urban agent-based models.

The resulting contributions to the field of urban modelling vary from methodological to more applied knowledge. Methodologically, this research has developed a more accurate representation of space that enables a realistic form of residential property development to be modelled. In addition the research moved away from the mathematical formalism found in other urban models and developed a more process-based approach that enables more behaviourally focused agents to be included.

Building on the methodological achievements, the research answered a range of applied questions that highlight the importance of residential developers when examining the changes in urban growth and form. These focused on how varying levels of developer competition can shape the resulting development pattern, and the role that developer behavioural heterogeneity has in shaping the form of urban development, particularly around the importance of satisficing in their decisions.

From this analysis, it is clear that residential developers play a substantial role in shaping the resulting urban landscape, through the structure and composition of the residential developer market as well as the spatial application of their behavioural activities.

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One of the great joys of writing a thesis is the collaboration with a wide range of people who have supported the work. This section allows me to acknowledge those people who helped me to complete the work you hold before you.

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The process of writing a doctoral thesis is made more bearable when you can share your successes and failures with people who are going through or have gone through the same process. The 4th floor open plan PhD office and the people that have come and gone meant that there was always someone to talk to, listen to and often laugh with. My friends and colleagues at Landcare Research, most of who have been through the same process, also deserve my appreciation. Roger, Kyle, Corina, Tara, David, Amit, Jane, Christina, Indra, Claire, Maryann, Petra, Eric, Hiroki, Enni, Brandon, Keith, Jinfeng, Alison, Kathryn, Jeremy, Eva, Nalanie, Oshadhi, Suzie, Mags and both Robyns' – the support and interactions with you made going through this process much more enjoyable.

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Glossary

ABM	Agent-based models
ASCII	American Standard Code for Information Interchange
BSP	Binary Space Partitioning
CA	Cellular Automata
DRAM	Disaggregate Residential Allocation Model
DS	Developer Set
DUEM	Dynamic Urban Evolutionary Model
GIS	Geographic Information System
HHI	Herfindahl-Hirschman Index
IAN	Image Analysis
LIDAR	Light Detection and Ranging
LUCC	Land Use and Land Cover Change
ODD	Overview, Design Concepts, and Details
PCA	Principal Component Analysis
PLUM	Projective Land Use Model
PNG	Portable Network Graphics
SLEUTH	Slope, Landuse, Exclusion, Urban extent, Transportation and Hillshade
SLUCE	Spatial Land Use Change and Ecological Effects at the Rural-Urban Interface

1 Introduction

> Developers are the central actors in the development process, because their actions determine the what, when, and for whom of residential development: what land will be considered for development, when improvements will begin, and for whom the project will be developed
>
> (Bookout 1990, p. 9)

The expanding edge of the city has a distinct appeal for many urban homeowners, primarily because of the more affordable prices and low-density lifestyle it can provide. As land on the urban fringe is subdivided by residential property developers to meet this demand, the resulting landscape can be viewed as a fragmented patchwork of developed and undeveloped land. Development also occurs within the existing urban area, a process which reshapes the form of existing neighbourhoods through changes in population density and parcel size. Current and forecasted urban growth trends will increase the pressure on the urban landscape to cater for the increase in urban dwellers, making the goal of a sustainable city even harder to achieve.

Issues surrounding sustainable development (such as congestion, air pollution and commuting times) can be viewed as a consequence of the pattern of growth rather than the amount of growth (Ligmann-Zielinska et al. 2008, Randolph 2004, Roseland and Connelly 2005). Sustainable city initiatives need to be more focused on sustainable growth patterns, with a key focus on the more efficient use of existing land within the city's urban limits (Roseland and Connelly 2005, Song 2005). To achieve these changes a major shift in the behaviour of key actors within the process of development is required (Williams et al. 2000).

Existing perspectives on development of land within the city's urban limits focus on the demand-side factors of urban growth. These demand-side factors, particularly householder behaviour, are sometimes still considered to be the driving forces of land-use change (Clark and Dieleman 1996, Kaiser 1968, Kaiser and Weiss 1970).

While these factors undoubtedly play a role in urban growth, it is the residential property developer who decides, based upon endogenous and exogenous factors (such as householder behaviour and demand), where and when to develop parcels of land. Consumers can only choose from among the housing choices that are provided by developers. Understanding the process through which developers choose land for development could allow for increased land use efficiency and more sustainable growth.

The process through which the production of space for commercial and residential development is accomplished (known as the urban development process) was given little acknowledgement within scientific literature until the last two decades (Coiacetto 2000, Guy and Henneberry 2000, Healey and Barrett 1990, Wadley 2004). Healey and Barrett (1990) reinforce the view that knowledge of the urban development processes is critical to the understanding of urban development and our attempts at managing these processes.

Existing investigation into conceptual models of the urban development process has focused on two key areas. Initially, a neo-classical equilibrium perspective where the structure of society creates an expectation that the various agents involved in the process will work collectively at 'the right time, in the right place and at the right price' (Healey 1991a, p.222). The second is an agency perspective that focuses on the 'actors' in the development process, the roles they play and the interests that guide their strategies in the conversion of land (Gore and Nicholson 1991, Healey 1991a). This agency perspective continues to underpin the importance of developers through their position at a nexus between all other actors in the process.

While their behaviour and actions are often high-profile (a key example within the New Zealand context is the Stonefields residential development (Orsman 2006) within the old Winstones Quarry in St Johns, Auckland), the behaviour and actions of property developers are not a major focus in academic literature. This appears to be because of the widely held belief that developers act as explicit profit maximisers who do not make decisions that would reduce their profit (Skaburskis and Tomalty 2000, Watkins 1999). Through the analysis of empirical studies into developers and their behaviour, it is apparent that developers are satisficers who weigh a number of factors while attempting to maximise their utility. Satisficing is a decision-making strategy that attempts to meet a pre-defined minimum requirement, rather than to identify an optimal solution (Kapteyn et al. 1979, Manson 2006). In this approach a developer sets a minimum requirement for their next development that, if attained, will be "good enough". The developer then seeks a parcel that meets or exceeds the minimum requirements. Given the importance of developers in the urban development process, it is surprising that there is both a lack of research into the satisficing nature of developers and a tendency to treat developers as an ‘undifferentiated whole’, as if all developers were identical (Coiacetto 2000).

Consequently, when addressing the issues of ineffectually allocated urban growth, spatial urban models need to account for the roles, behaviours and interactions of developers while also integrating the unique process that is urban development. Including these aspects seem reasonable, although for reasons of complexity or because of a lack of understanding about their importance, they have been ignored or over simplified. If spatial urban models do account for these aspects, they can be used to plan for a more sustainable city through understanding and accounting for the behaviour of a key actor in the development process.

Early spatial models of urban growth were labelled as unrealistic, with cities becoming more decentralised with accompanying changes in the underlying social structure (Hall 1983). However the fundamental problem with these models is that the processes behind the changes were ignored. Urban development was construed as an abstract process with supply and demand always in equilibrium, a far cry from the reality of urban growth (Healey 1991a). This procedurally static approach to modelling urban growth tried to be prescriptive or predictive in nature where understanding the underlying processes of growth held less value than the forecasted output of the model.

In moving from a static approach to a dynamic understanding of the processes that contribute to urban growth, approaches such as cellular automata and agent-based modelling have revitalised the ways in which we conceptualise and model urban phenomena (Torrens and Benenson 2005). Linkages between the conceptual models of the urban development process and agent-based modelling are readily apparent. This approach also facilitates the ability to embed the process of urban development within a model of urban growth. Consequently, this research aims to use an agent-based modelling approach to the urban development process incorporating the roles and behaviours of residential property developers.

1.1 Research issues and goals

Based on the wide range of ideas that this research will cover (property and planning, behavioural theory, behavioural economics, spatial economics, and sociology) it is necessary to outline the thesis position this document will take. The underlying direction of this thesis is from an urban modelling perspective, exploring and theorising the role of people in urban modelling and in particular the role of agent-based models to enable a greater understanding of the urban development process.

In support of this research direction, a number of research questions should be addressed through the results of this thesis:

- What changes in development pattern are evident when developer stratification (based on their level of available capital) is introduced to a multi-agent model of the urban development process? How do these development patterns compare with other implementations?
- What changes to the development patterns are evident when the ratio and numbers of small and large developers within the model are altered? Is there a marked difference in sprawl/expansion for certain developer competition ratios?
- Do developer behavioural traits shape the resulting landscape? Which behavioural traits hinder or help the creation of a sustainable urban form through a more clustered urban development pattern?

To answer these questions, the research aims to explore and resolve a number of issues. The first is the under-representation in existing spatial urban models of both the processes which drive urban growth and the actors that enact it. The second is combining an understanding of the urban development process with the unique role of residential property developers. This will place developers at the centre of the urban development process while linking developer's decisions with the resulting land-use patterns. The third issue is the analysis and development of a typology of core developer behaviour. This was undertaken because of the existing narrow academic view of developer behaviour and was carried out through the analysis of the sparse empirical studies of residential property developers. Using both a typology of developer behaviour and an understanding of the urban development process, the fourth issue is the integration of developer agency within a spatial model of the urban development process. Finally, this research requires a representation of space that enables the process of urban development to occur on a cadastral landscape. To resolve these issues, a number of methodological objectives need to be met:

1. Development of a typology of residential property developer behaviour.
2. Development of an agent-based model implementing the key stages of the urban development process.
3. Implementation of the developer behaviours within the agent-based model.
4. The creation of a spatial representation that allows developer agents to understand and enact the process of development on the landscape, while also providing an abstract representation of an urban cadastral structure.
5. Development of a method to examine the changes in the urban landscape arising from the inclusion of developer agency.

Once these methodological issues have been resolved, this research has two clear goals:

- To examine how differing levels of property developer competition affect the urban landscape through an examination of the change in urban growth and form

- To examine the importance of property developer behaviour with a specific focus on how developer behavioural traits affect the resulting urban landscape.

Thus, this research aims to add to our understanding of the importance and/or role of developers in the production of the built environment, while also investigating the integration of ‘process’ within models of urban growth. Based on the results from the model of developer behaviour, this research will also comment on the importance of rules that limit, and/or encourage, development opportunities (council requirements and restrictions) and the resources distributed via the financial system (financial institutions who lend money for development).

1.2 Structure of dissertation

The dissertation is composed of nine chapters. Chapter 2 begins with the modelling approaches used to examine urban growth. The review of urban modelling covers initial and abstract monocentric interpretations of the city through to comprehensive and highly realistic models of the city. A key critique of these models is the lack of ‘process’ surrounding urban growth. This leads to a detailed analysis of the spatial tools that can be used to examine the role of developers and their behaviour within urban growth. Cellular automata and agent-based modelling are examined as ways to model the urban development process and the role residential developers have within it. Finally, existing urban models that incorporate residential developers are reviewed, with a specific focus on the heterogeneity of the developers, the integration of process, and the representation of space.

Chapter 3 begins with a definition of the urban development process, set in the context of the structure and agency debate. The chapter then reviews the three modelling perspectives used to explain the role of the urban development process. The chapter finishes with a key emphasis on those agency models which claim that the actors and their behaviours are the most important aspect of the process.

Chapter 4 develops this direction through a comprehensive discussion of the role that residential property developers have within the process. This is further discussed through an examination of the form of the developer market based on the amount of capital available to each developer, colloquially referred to as ‘size’. The empirical review continues with a conceptual stratification of key developer behaviours based on the size of developers.

Using the Overview, Design Concepts, Details (ODD) protocol (Grimm et al. 2006, Grimm et al. *unpubl. manuscript*), Chapter 5 provides a detailed description of the agent-based model of residential property developers created for this research. The chapter begins with a review of the modelling platforms and the representations of agents, time and process to be implemented within the resulting model. While the ODD protocol is a ‘dry’ description of the model, it explains in detail the components and structure of the agent-based model to enable better understanding of how the model behaves and the subsequent results.

Chapter 6 covers the creation and use of binary space partitioning (BSP) trees to create a spatial representation that allows developer agents to understand and enact the process of development on the landscape. The approach also provides an abstract representation of an urban cadastral structure on which the model of developer behaviour will act. The chapter begins with the reasons why such an approach was required. This is followed by a review of tree-based data structures and some existing applications. The chapter then describes both a theoretical and applied implementation of how BSP trees were used to create the urban spatial pattern. The resulting urban patterns are examined with particular reference to the distance-weighted equation used to create the patterns. Other ways of implementing the binary tree are shown through the use of ‘partitioning maps’ based on abstract and real-world data. The chapter examines the additional support that the formalised node structure of a BSP tree provides for an agent-based model of property developer behaviour and how the landscape is used to examine the changes caused by the agents over a model run.

Chapter 7 begins with a review of how the key parameters of the model were set. The chapter then focuses on the investigation of how developer competition plays a role in shaping the city. This is followed by a discussion on how the experiment is designed, with a particular focus on the sets of developers used in the experiment. After this, the experimental results are reviewed and discussed for each of the three types of results;

- overview results based on the structural metrics from the landscape's BSP tree;
- landscape metrics based on the urban/non-urban landscape exported after initialisation, and at the end of each time-step, with a particular focus on the shape of urban growth;
- landscape metrics based on the parcel size landscape which was also exported after initialisation, and at the end of each time-step, with a particular focus on the form of the resulting landscape.

After all of the results are presented, the chapter concludes with a detailed review of the various developer and landscape responses to competition.

Chapter 8 investigates how satisficing and the behavioural heterogeneity of developers affect development patterns. The experimental design is covered in detail with a key focus on how the five behavioural traits are applied to the developers in a homogeneous fashion. This section also describes how a heterogeneous baseline is used to derive the change caused by a homogeneous application of the behaviour. The results and discussion sections follow the same pattern described above for Chapter 7. After all of the results are presented, the chapter concludes with a detailed review of how the pattern of development is altered through the homogeneous application of the five behavioural traits.

Chapter 9, reviews the thesis as a whole, through a review of the issues resolved, the implications for urban modelling based on the advances in the methodology discussed in this thesis and the two experiments undertaken in the course of this research. In addition a number of future research directions are defined which would continue to explore some underlying questions around urban modelling.

2 Modelling urban growth: Residential property development as a complex spatial system

> This 'new wave' of [urban models] opens up exciting possibilities for simulating systems of all descriptions, and in particular, the simulation of behavioural processes and the structures that they generate
>
> (Torrens 2003b, p. 212)

Modern urban regions are highly complex entities. Despite the difficulty of modelling every relevant aspect of an urban region, researchers have produced a rich variety of models dealing with interrelated processes of urban growth, process and change. The city, as a spatial system, grows in two ways – through compaction and expansion (Batty and Xie 2005). Expansion leads to more space being occupied and compaction results in increasing density and intensity (Batty and Xie 2005). These dual processes of growth result in a number of complex geographic systems (such as land use, sprawl, and land cover change) that have posed, and will continue to pose challenges for researchers to investigate (Torrens 2003b). Models are a useful analytical tool when examining the dynamics of a complex system. Their nature enables a complex system to be broken down into its component parts and examined from the 'bottom up'. Although a model as a whole is a generalisation of reality, the relationships between the various components of the model enable relationships and dynamic factors to be explored.

The field of urban modelling has a relatively short history when compared with other disciplines. Development of the field began in the early 1960s alongside the introduction of computers to the field of planning. This was heralded as "a tool of such revolutionary new potential that it may have an effect in redefining the process of planning itself" (Harris 1968, p. 223). Unfortunately, the large-scale urban model never reached the goals that was set for it and was severely criticised in the early 1970s for the numerous problems that seemed impossible to overcome (Lee 1973). While the criticism hindered the development of the field, it also allowed the computing tools to catch up to the theoretical requirements for the models. Simultaneously, new methods of modelling and simulation have been introduced and adapted from other disciplines to allow a greater insight into the systems and structures of the urban city. Batty (2005) and Benenson and Torrens (2004a) review the recent developments in this area.

2.1 Urban models before 1973

Much of the theory of urban modelling has been based upon the work of early researchers such as von Thunen (1826), Burgess (1925) and Christaller (1933, 1972). These models provided the general basis from which contemporary urban modelling has developed, and examining them is the key to understanding the recent growth of the discipline. The advantages seen in these early models is obvious, von Thunen's (1826) agricultural land-use model (Figure 2.1) examined the balance between land costs for production and the economic constraints of transporting the products to the market, transforming the existing notion of city structure.

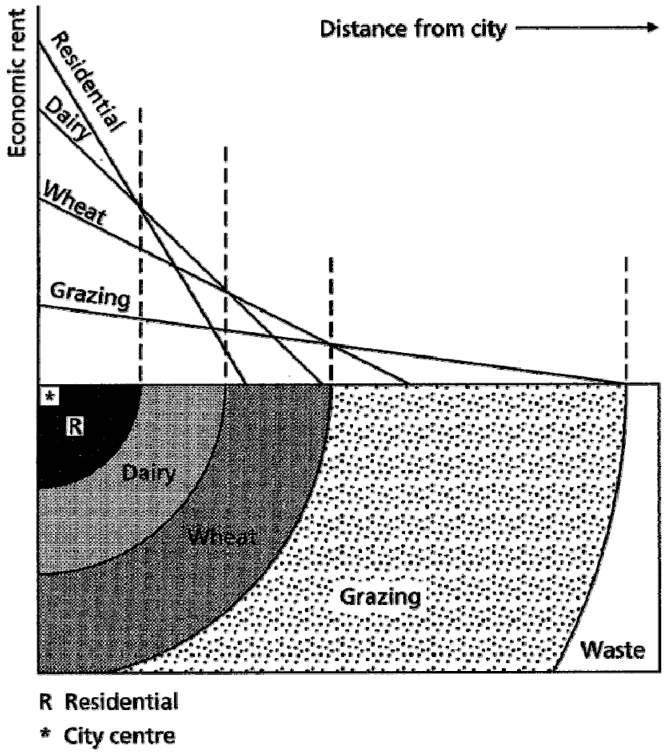

Figure 2.1: von Thunen's agricultural land-use model (Source: Mayhew 2004)

Burgess (1925) examined the patterns of land use within Chicago and developed a descriptive model of urban land use and expansion focusing on the notion of concentric development of urban land use and growth. Christaller (1933, 1972) developed Central Place Theory to explain the distributional and hierarchal development of urban settlements with a particular focus on the spatial concepts of *centrality*, *threshold* and *range* (Mayhew 2004).

These early models of urban land use and growth are steeped in mathematical and economic theory (Batty 2005, Benenson and Torrens 2004a). Later, a new phase of models examining urban growth was developed that theorised that the city was a study in equilibrium and that the patterns seen in these models indicated stability between the various processes being modelled (Batty and Xie 2005). Equation-based urban growth models, such as Morril's (1968) model of the wavelike nature of urban growth, were focused more on simulating urban growth's equilibrium outcomes than on understanding the dynamics of the system (Batty 2005). Other models, such as Alonso's (1964) monocentric spatial structure model (Figure 2.2),

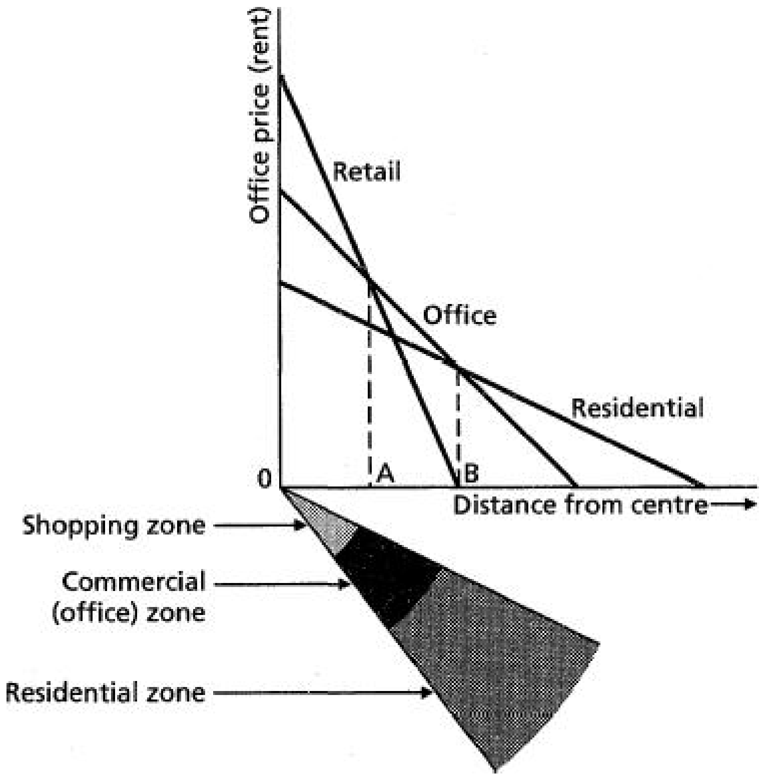

Figure 2.2: Alonso's monocentric spatial structure model (Source: Mayhew 2004)

worked towards equilibrium when examining urban land-use patterns and urban sprawl. These abstract and unrealistic monocentric models are focused on the outcomes of the models and not the processes within the models. This fixation on the outcome of the process rather than on understanding it continued within equilibrium models for the next thirty years.

Up to the 1960s models of the urban system were confined to theory; however, in the early 1960s the "quantitative revolution" in urban regional and geographical analysis set the stage for the introduction of computers into the field of planning. The introduction of computers provided the drive for large-scale urban models to move from theory and into the applied domain. With this divergence, contemporary applied urban models of land use and transportation were soon developed, formalised and introduced (Batty 1976). The core components of these 'traditional' land-use and transport models drew on theories that stemmed from the Chicago School of urban studies (Carter 1981). As Torrens (2001, p. 6) highlights:

> These theories were formulated, for the most part, in a time in which cities were quite different than their current manifestations. In terms of activity, the conceptualization of cities was that they were largely dominated by centralized modes of production. Structurally, cities were considered to be monocentric, organized with a dominant and often singular center that was surrounded by satellites of nucleated activity that orbited on the periphery, dispersing monotonically with distance from the urban core.

One of the key models that followed this conceptualisation was Ira Lowry's model of a metropolis (1964), which was built on the idea of a centralised city and a spatial interaction/gravity framework common during that period. The model describes the structure of a metropolis's urban spatial structure (in the original case, Pittsburgh) in terms of activities and their corresponding land uses (Lowry 1964). The model assumed that with everything else being equal, the place of employment determines the place of residence. The residential population requires a number of services that determine the location of service employment and therefore the housing location for the service employees (Oryani and Harris 1996). Constructed and developed abstractly the model disregards the role of the urban development process. Within the model, the growth of the residential housing zone is seen to be meeting an equilibrium state (supply will always meet demand) that is both unrealistic and over-simplified. Lowry's model has been revised numerous times and its theory can still be seen in more recent models such as the Projective Land Use Model (PLUM) (Goldner 1968, Putman 1979, 1995), the Time Oriented Metropolitan Model (Crecine 1964), and the Disaggregate Residential Allocation Model (DRAM) (Putman 1995). Lowry's model (and its derivatives) is well-constructed and examined but, like earlier models, the process of growth is weakly-represented, examined and understood.

While applied models such as Lowry's were initially welcomed, they soon encountered problems that re-evaluated their role within planning. Critics began to label the centralised core model type as unrealistic – urban areas were becoming more decentralised with changes in the social structure of cities (transportation, sprawl, suburbia) (Hall 1983). In fact, while these aggregate scale – top down approaches to modelling the urban system provided an understanding that was up till then absent, a growing number of researchers were becoming critical of the entire approach (Hall 1983, Lee 1973, 1994, Sayer 1976).

2.2 Critiques of urban models

In line with these critiques, most early attempts at modelling the urban system were complex mathematical models based on a number of equations (usually economic in nature) that attempted to detail the various functions and processes that occur within the urban area (Batty 2005, Benenson and Torrens 2004a). This type of approach to modelling required two key resources to work well, substantial amounts of data and computational power, both of which were not available at the time. Such a lack of resources quickly led to a decline in the modelling of urban systems and a rise in valid criticisms of the 'large-scale urban model' approach.

Two key critiques of urban modelling in the early to mid-1970s (Lee 1973, Sayer 1976) broached the growing dislike of existing urban models. Both reviews critique the issues and direction of the development of urban models. Although the critique was a by-product of the expectations of what urban models should do (Batty 1979), the critique went further to offer a “series of criteria that a ‘good’ urban model should satisfy” (Benenson and Torrens 2004a, p. 87). Lee’s (1973) critique discusses ‘seven deadly sins’, which he believed stood in the way of the modelling toolkit of the time (Benenson and Torrens 2004a). Lee (1973) stated that these sins are ‘the fundamental flaws in attempts to construct and use large models’. Interestingly, while these sins outlined the problems within the large-scale urban modelling approach, they also provided a list that outlines the needs for the future direction of large scale urban models. His critique, labelled the ‘seven deadly sins’ covers:

> **Hypercomprehensiveness** – where the models were constructed to replicate immensely complex systems that were intended to be multi-purpose in nature.
>
> **Grossness** – the requirement for very detailed microscopic data led to models that were expensive, both computationally and in the amount of time required to compile the necessary microscopic data. Lee noted that this made the model results less interesting to broader scale policy makers.
>
> **Hungriness** – along with the requirement for microscopic data, a huge amount of microscopic data was required for the resulting models. When Lee wrote the critique, he described a 30,000 record dataset as being large. Current models and computer platforms regularly handle datasets of this size, if not much larger.
>
> **Wrongheadedness** – a key fallacy within large-scale urban models. Lee thought that existing large-scale urban models were based on poor theories and understanding of the overall system. This led to a model that was poorly constructed, with equations and statements that distorted the models results.
>
> **Complicatedness** – with the drive to be as comprehensive as possible, hundreds of interactions were built into early large-scale urban models. With the additional linkages, the system became more and more complex. Research into the understanding and comprehension of how these additional linkages provided value to the model was non-existent.
>
> **Mechanicalness** – In the ‘70s computers were not as ‘user-friendly’ as they are currently. Large-scale urban models run on a computer of the

time were extremely time intensive and involved highly specialised tasks that required access to some of the more advanced computers of the time.

Expensiveness – the time required to gather, compile, develop, run and finally analyse the results of a large-scale urban model was an expensive process. This expense in both time and resources limited the initial models to well-funded agencies.

The second critique by Sayer (1976) takes a similar path, although he is particularly critical of the mathematical formalism, static equilibrium and urban economics approach taken by the early urban-scale models (O'Sullivan 2004). Sayer states that this approach to urban models, created a need for larger models that required more and more resources, resources which at the time were unavailable. As O'Sullivan (2004) comments, Sayer (1976) endorsed a move towards a 'Structualist' approach to urban models that moved away from the "technical aspects of theoretically inadequate models, and onto the political-economic processes driving urban change" (p. 288). This change would force modellers to "include far more in our models than we can handle, so that we may start from trying to understand some small subsystem, and in our search for a system closure [...] end up modeling the entire urban system." (Sayer 1976, p. 249).

These critiques, along with later work by White (1977), Allen and Sanglier (1978, 1979), Tobler (1979), and Couclelis (1985) instigated a rethink of the modelling of urban systems, moving away from the static mathematical equilibrium models and towards a dynamic, process-based appreciation of the numerous systems and structures within the city (Batty 2005, Benenson and Torrens 2004a). Interestingly, recent critiques also highlight many of the same issues. Torrens (2001) discussed 6 key weaknesses of current urban models when compared with newer models that follow the computational approaches currently being developed: their centralised approach; poor treatment of dynamics; weak attention to detail; shortcomings in usability; reduced flexibility; and the lack of realism apparent within the models. A number of these weaknesses can be viewed as evolved forms of Lee's seven sins, which highlights that while we have moved on computationally, there is continual progress to be made to advance the theory behind urban models.

2.3 The rise of comprehensive urban models

After the critiques of the 1970's, Batty (2004, p. 327) states that "the subsequent twenty years was a period of massive retrenchment as planning became less strategic and more localised and the use of technology in this top-down 'brave new world' manner fell out of fashion". Wegener (1994, p. 17) saw that "nowhere in the world have large-scale urban models become a routine ingredient of metropolitan plan making". While metropolitan planners began to shun large-scale urban models, Lee's "paper coincided with the burgeoning of a research tradition, and although the original surge of practical applications subsided, the applications diffused across the globe" (Batty 1994, p. 7). In particular, researchers outside the United States began to acknowledge the values of large-scale 'comprehensive' urban models (Batty 1994, Wegener 1994). Alongside the continuing academic interest in these types of models, researchers continued to develop a number of localised urban models to satisfy the needs of planning agencies at various levels of local and regional government (See Wegener's 1994 article for an overview of these models).

Most of these comprehensive urban models attempted to understand the spatial behaviour of firms and households, while also examining the resulting spatial interaction such as population migration, residential and service locational choice, and commuting trip distribution. After initial research around a gravity law and entropy maximisation approach (Wilson 1970), McFadden's random utility theory (Domencich and McFadden 1975, McFadden and Reid 1975) associated the spatial econometric approach of comprehensive urban models in micro-economic theory.

While comprehensive urban models are still popular today, there are a number of critiques which continue to be unresolved. Like most of the early models previously discussed, these models continue to be mostly mathematical in nature, working to meet an equilibrium in the model (i.e. between population and city growth). This approach fixates purely on the results/forecast of the model but fails to examine and understand the process that caused the change. It is this aspect of these spatial econometrics and comprehensive urban models that has drawn the most criticism (Benenson and Torrens 2004a). Spatially, these models focus on the locational decisions for each firm/household being made between fixed zones throughout the city, rather than a continuous Euclidean space. This approach was initially used to limit the matrix of decisions for each firm/household because of the lack of computing power. While the zones used in these types of models are now smaller (matched by an increase in computing power), the decisions are still invariably made between fixed zones which contribute to a level of spatial inaccuracy within the results.

2.4 Complexity in urban systems

Traditional urban models were driven by policy based on the issues that dominated the 1960s – urban growth and travel behaviour, both of which remain important today. These conventional spatial models are focused on the interactions between coarsely considered units of space and describing the interactions in an aggregate way (Torrens 2006a). Recent computational models, while still focusing on these 1960s issues, have begun to examine the city as an emergent complex system that requires a bottom-up approach to modelling (Batty 2004).

New techniques, theories and ideas, drawn from computer science and the field of complexity studies, have revitalised the ways in which we conceptualise and model real-world phenomena (Torrens 2001). This recent move towards approaches that understand complexity seems late, because geographers already thought of cities as examples of complex systems in the late ‘70s (Wilson 1979). However, the move towards these new approaches was hampered by the dominant comprehensive integrated modelling approach during that time (Benenson and Torrens 2004a, Wilson 1979).

To be classed as a complex system, a system should exhibit properties that are beyond convergence to a globally stable equilibrium (Portugali 2000). Most simple systems are linear in nature, always tending towards a steady equilibrium state, and their reaction to changes in the system are straightforward and will eventually settle again into an equilibrium state. A complex system is inherently nonlinear and open in nature, numerous small-scale interactions leading to a dynamic understanding of the system. Page (1997) explains that computational models allow the study of complex, dynamic worlds because they themselves are dynamic.

Initial investigations into cities as a complex systems, such as Epstein and Axtell's (1996) societal investigation called "SugarScape", attempted to model a society from the perspective that rules like kinship, learning, social exclusion, and disease were society's building blocks. This 'bottom up' approach to modelling complex systems is common in geocomputational methods. The method focuses on the individual agents or entities rather than attempting to simulate the overall condition of the system in a 'top down' approach. The development of these computational approaches can be seen as a direct response to Openshaw's (1994, 1995) challenge to develop a range of methodologies in human geography that seek computational solutions to problems involving numeric and symbolic data (Parker et al. 2003).

Based on these early investigations, urban systems are now widely regarded as complex systems (Portugali 2000) that can be explained and simulated more effectively through the use of tools designed to understand complexity (Benenson and Torrens 2004a). Prior to this, urban modelling was seen as relatively static (when compared with other disciplines such as, ecology, environmental science, biology, physics, and economics) and lacking the techniques to understand the complex systems within the city (Torrens 2003a). Many of these concepts and methodologies formed under the banners of cellular automata and agent-based models.

Cellular Automata

Cellular Automata (CA) are mathematical models for examining complex natural systems that contain numerous simple components and depend on local-scale interactions (Wolfram 1984a). While CA was first developed in computing (Sipper 1997), they are now used in a wide variety of disciplines. In urban studies, CA are best used to represent the dispersal of activity and characteristics between discrete spatial units of urban infrastructure (See Figure 2.3 for a graphical representation) (Torrens and O'Sullivan 2001) The conceptual basis for CA was developed in the 1940s when John von Neumann (1951) began his work on understanding and exploring the self-producing structures in nature in a mathematical context (Benenson and Torrens 2004a, White and Engelen 1993). His work alongside Turing's (1936) 'computational machine' provided most of the theory for modern day CA.

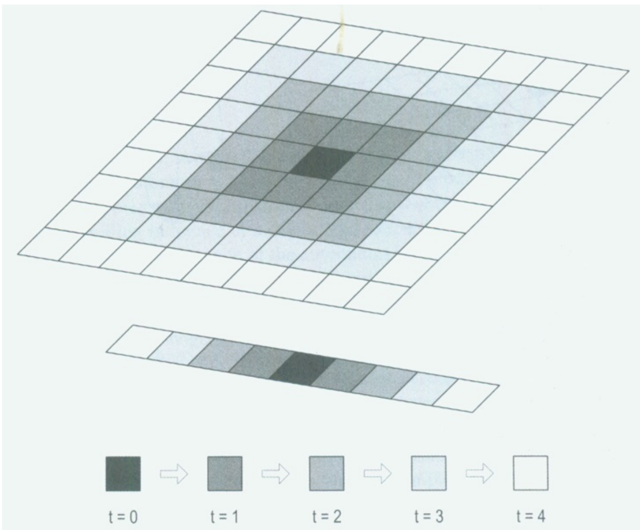

Figure 2.3: Stylised representation of dispersal within a cellular automata model (t = time step) (Source: Benenson and Torrens 2004a)

A Cellular Automaton is a finite state machine that exists in some form of tessellated cell space, hence the term 'cellular' (Torrens and O'Sullivan 2001). Levy (1992, p. 15) states that "an automaton is a machine that processes information, proceeding logically, inexorably performing its next action after applying data received from outside itself in light of instructions programmed within itself". CA-based models comprise five key elements, all of which are required to be classified as a cellular automata (Couclelis 1985, Torrens and O'Sullivan 2001, Wolfram 1984b): lattice; cells; states; neighbourhoods; and transition rules. While time is naturally inherent in the nature of CA (because transition rules require knowledge of 'prior cell states'), Torrens (2001) included it as a sixth element within CA models.

In 1970, John Conway developed the 'Game of Life', which provided new interest in the area of CA (Gardner 1970). Conway's motivation behind the 'Game of Life' was to study the microscopic spatial dynamics of population through a simple set of rules (Berlekamp et al. 1982). Benenson and Torrens (2004a, p. 101) highlighted that the Game of Life introduced complexity to a wider audience, moving away from the realm of physicists and mathematicians and "introduced CA as an interdisciplinary tool for representing complex spatial systems and investigating their dynamics". Tobler (1970, 1979) became the first geographer to recognise the advantages of CA and begin to implement it within his research. Tobler (1979) created a link between the state of an individual cell and the state of its neighbouring cells, creating a locational dependence between the two. This link made it possible to use a two-dimensional cell-space to represent and stimulate real-world spatial dynamics.

While Tobler (1979) was the first geographer who understood the benefits of CA in solving geographical problems, it was Wolfram (Wolfram 1984a, b) who demonstrated that the origins of the complexity within natural systems might be understood through the use of CA. Wolfram's work influenced the development of CA within geography, resulting in the use of CA in studies, such as wildfire propagation (Clarke et al. 1994), population dynamics (Couclelis 1988), urban spatial patterns (Candau et al. 2000, Clarke and Gaydos 1998, Clarke et al. 1997), land-use changes (Batty and Xie 1994, White and Engelen 1993), and urban growth (Cheng and Masser 2003, Torrens 2006b). From a geographic perspective, the benefits in the use of CA are their attention to detail, an inherently spatial design (Torrens and O'Sullivan 2001), and their natural affinity with raster data (Couclelis 1997) and object-oriented programming (Torrens and O'Sullivan 2001). When looking at the area of urban growth models, various models have been developed that incorporate CA.

The Dynamic Urban Evolutionary Model (DUEM) was initially developed as part of Xie's (1994) dissertation work but was further expanded by Batty and Xie's (1994) simulations of suburban residential sprawl in Amherst, New York ,and to the greater Detroit region (Batty and Xie 1999). DUEM differs from other CA models because it deals with a comprehensive set of land uses. Each of the land uses has one of three phases initiated, matures and then declines. Changes in land use are driven by land supply through two processes, land use encourages other land uses to surround it and the transformation of one land use to another at the same location (Batty and Xie 1999). While the model is built on the principles of real estate development, there are no links to a well-formed housing market and real-life supply and demand dynamics of development process are effectively ignored.

SLEUTH (Clarke and Gaydos 1998, Clarke et al. 1997), which stands for Slope, Landuse, Exclusion, Urban extent, Transportation and Hillshade, is a CA model that aims to be a general and simple tool for the high-resolution simulation of urban growth (Benenson and Torrens 2004a). SLEUTH has been developed as two subcomponents, one of which models the urban and non-urban growth of the city, and the other of which models the dynamics that affect land-use change. The success of the model can be seen in its application to various locations around the world (Clarke et al. 1997, Esnard and Yang 2002, Jantz et al. 2004, Leao et al. 2004, Silva and Clarke 2005, Yang et al. 2003).

White and Engelen (1993, 1997, 2000) have used CA to explore the spatial structure and temporal dimension of urban land use and to test general theories of the structural evolution of cities. The cellular model-generated patterns for each land-use type were then compared with data from a set of USA cities. Results showed good representations of actual urban form, suggesting that CA approaches make it possible to achieve a high level of realistic spatial data representation. In another instance, White et al. (1997) implemented a CA model to predict the land use of the city of Cincinnati in USA. While these models were successful on one level, their temporal (fixed cycle length of 100 years) and spatial (focused only on a limited part of the city) scope were limited.

Criticisms of CA are that they take only a bottom-up approach, and account for local effects that generally define the overall representation of the space. The constituents of urban systems do not exhibit only bottom-up behaviour (e.g., urban planning decisions, national policies, macro-economy, and so on). Furthermore, CA is restricted to general rules and does not create its own dynamic. In real urban contexts not all changes in systems are driven by the same force or mechanism. It is clear that urban elements can react differently to general rules. From the perspective of this research, a key shortfall of the approach is that while the models “inductively assume that the actions of human agents are important [they] do not expressly model decisions” (Parker et al. 2003, p. 316). While “cellular models have proven utility for modelling ecological aspects of [Land-use and land-cover change, …] they face challenges when incorporating human decision making” (Parker et al. 2003, p. 316). The addition of complex rule sets can account for a number of these decision making shortfalls (White and Engelen 2000), but creates a hybrid approach that is incomparable to most cellular automata (Torrens and O'Sullivan 2001).

Agent-based models

Agent-based models (ABM) are a valued technique in representing disaggregated decision making. As their name suggests, agent-based models (also referred to as multi-agent systems) attempt to model the behaviour of a complex system by representing the behaviour of the various agents that make up the system (Klosterman and Pettit 2005). Within the urban environment, ABM are best suited to simulating individuals and/or groups with behaviour and traits and the capacity for spatial mobility and communication (See Figure 2.4 for a graphical representation) (Benenson and Torrens 2004a, Jager and Janssen 2003). Like CA, ABM also have origins in computer science, although they are a more recent development that arose out of an abundance of computing power (Ferber 1999). An agent-based model is a computer-based representation of a system comprised of multiple, interacting actors called agents (Brown et al. 2005, Ferber 1999, Page 2008). Agents are discrete entities defined in terms of both their attributes and behaviour and by what the model is examining (Brown et al. 2005). The roles the agent (or agents) will simulate are usually anyone who makes decisions or takes actions that affect the underlying system state (Evans et al. 2005, Page 2008). It is claimed that agent-based models have the potential to advance most disciplines they are applied to, as they include more realistic assumptions about behaviour, structure and timing than previous methods of modelling (Page 2008).

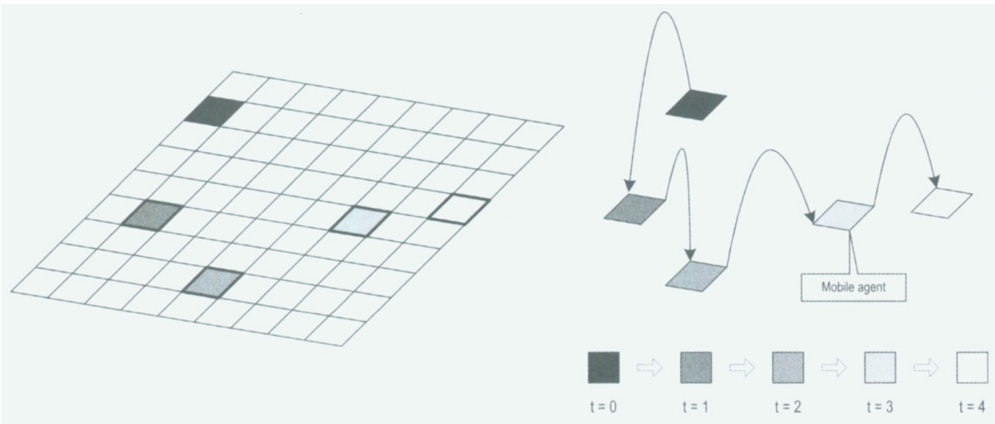

Figure 2.4: Stylised representation of an agent moving in an agent model (t = time step) (Source: Benenson and Torrens 2004a)

Numerous disciplines have adopted agent-based models to varying effect. Economics (Luna and Stefansson 2000), pedestrian movement (Batty et al. 2003, Haklay et al. 2001, Kerridge et al. 2001), ecology (Hogeweg and Hesper 1983, Reynolds 1987), and of course geography (Antona et al. 1998, Bousquet et al. 1998) have all integrated the approach into their disciplines. In geography, urban models implementing ABM are now numerous (Benenson 1998, 2004, Dijkstra et al. 2000, Haklay et al. 2001, Torrens 2006b), because they are particularly well suited for representing complex spatial interactions under heterogeneous conditions and for modelling decentralised, autonomous decision making (Parker et al. 2003).

While the structure of multi-agent systems might differ between disciplines, when investigating urban phenomena (such as urban sprawl, land use – land cover change and the urban development process) they usually consist of two components: a cellular model that represents the landscape (which could be cadastral, neighbourhoods, soil quality, land cover) that is being investigated, and an agent-based framework that simulates the decision making and interactions of the actors in the model. The agents are spatially mobile, they are programmed to navigate through the landscape and interact with their neighbours and also with the landscape (Torrens 2001). Behaviour, types and goals can be embedded within the agents to mimic the agent's real-world counterparts. In the context of this research, agents would be developers with a goal to develop parcels of land in the landscape of a property market while making a profit. Types of developers, based on the size of their operations, could also be included in the model. The differences in size affect how the developer behaves, from assessment of a parcel for development to the number of properties a developer could develop at a time and the introduction of territoriality to the model.

At a minimum, agents must react to changes in the environment around them (Torrens 2001), the limits to the behaviour of the agents in a ABM are an open question (Parker et al. 2003). Traditional urban models are derived from rational utility theory in which a land-use pattern can be explained in terms of actors who maximise their utility. While every intention should be made to incorporate a range of agent behaviours, the inclusion of numerous detailed and complex behaviours creates a substantial hurdle for the programmer. The creation of agents that are 'perfectly rational' in the way they behave, which would be based on both their previous actions and the actions of their neighbours, would be "a highly-dimensional, fully recursive programming problem" (Parker et al. 2003, p. 317).

The notion of 'bounded rationality' aims to recognise the unique environment in agent-based models and restrict the complexity behind the human decision making process while still moving the agents towards achieving their predefined goals

(Gigerenzer and Todd 1999, Manson 2006, Simon 1997, Tversky and Kahneman 1990). Bounded rationality can be employed within ABM through genetic algorithms (Arifovic 1994), heuristics (Deadman and Schlager 2002), and reinforcement learning (Duffy 2001, Laine and Busemeyer 2004a, b).

Despite a number of advantages, ABM are not as widespread as CA. Most of the urban models developed are academically driven with little commercial impact (as yet). Relevant multi-agent implementations such as the University of Michigan's Spatial Land Use Change and Ecological Effects at the Rural-Urban Interface (or SLUCE) model (Brown et al. 2004, 2005, Brown and Robinson 2006, Fernandez et al. 2005), CityDev (Semboloni et al. 2004), and Benguigui et al (2001a, b) approach the simulation of the city from the perspective that the behaviour and actions of the actors within the process are the fundamental building blocks of the model.

In this vein, land-use and land-cover change (LUCC) models have been adapting agent-based approaches to enable the simulation and analysis of a variety of LUCC scenarios. The benefit for LUCC models in this approach is the explicit focus on human decision making, which is important for examining the role and interactions of the actors which drive LUCC. An excellent review of multi-agent systems in LUCC can be found in Parker et al. (2003). In creating a multi-agent/land-use and land-cover model, two distinct components are combined. The first is a cellular model that represents the landscape about which actors make decisions. The second component is an agent-based model that outlines the decision-making architecture of the key actors within the system. The two components are integrated through the development of dependencies and feedback loops between the agents and the landscape (Parker et al. 2003). The numerous interacting components in these types of models generate behaviour that can be observed, compared and evaluated in light of ideas from complexity theory (Manson 2001).

2.5 Developers and the urban development process within urban models

The urban development process and the role property developers play in this process is an example of a complex urban system; dynamic linkages between multiple competing agents; numerous agent types with varying behaviours; and a fluctuating and extrinsic property market that raises uncertainty. It is therefore unsurprising to find that developers and the urban development process are usually overlooked in spatial urban models. When developers are explicitly included in a model, their behaviour and the process in which they convert land is usually subsumed within a 'black box' structure.

The most thorough implementation of developer behaviour within a CA model is Webster and Wu's (1999a, b) model. Developers (along with householders) were constructed to be explicit profit maximisers through the creation of relevant cellular automata transition rules. Although the model focused on a homogeneous representation of developers, the rules enabled an understanding of how developers select locations based on the profitability of the location, and implemented a form of residual valuation into the process of site selection.

As in CA models, existing agent-based models overlook the importance of developers in the process by approaching development as an abstract process where the household agents 'demand' a residential development and it is 'supplied' without examining any actors within the process. A more promising approach is Semboloni et al.'s (2004) implementation of developers. Developer agents are explicitly included in the model although their behaviour explicitly represents developers as profit maximisers through limiting their behaviour to a residual parcel valuation where maximum return on investment is required. In addition, the model treats developers as a single unit with no differentiation in types, behaviour or strategies.

Benguigui et al.'s (2001a, b) model is another of the very few multi-agent models to explicitly define developers and their behaviour. In contrast to CityDev, the model removes all expectation of profit from the developers, instead choosing to implement a behaviour focused on territoriality. The agents randomly select potential development sites to 'visit' in a constrained area surrounding the previous development. After a number of iterations and once a site has been 'visited' by the developer a predefined number of times, the land parcel is instantly developed. The lack of any economic behaviour in the agents is surprising but the model showcases an implementation of other non-economic forms of developer behaviour. As in all the models discussed previously, developer agents are homogeneous with no differentiation by size.

One of the more interesting agent-based implementations of developers was undertaken by Ligmann-Zielinska (2009). Ligmann-Zielinska used attitude utility functions to define a developer's risk position and investigated the effect that the positions had on the resulting land use pattern. While the initial experiment focused on a single developer agent, later experiments investigated the effects on the land use pattern with three agents with heterogeneous risk positions. The results from these experiments showed that certain risk positions resulted in a either a more compact or dispersed land-use pattern. Heterogeneous risk patterns across the three developers produced only a slight variation compared to a homogeneous set of risk positions. The model implemented by Ligmann-Zielinska is a credible investigation into how developer behavioural rules and their resulting locational decisions shape the landscape. Ligmann-Zielinska acknowledges that the simplistic behavioural rules used in existing agent-based implementations of developers is "too crude to capture the complex process of individual location decisions" (2009, p. 231).

2.6 Representations of space in urban models

A distinction also needs to be made regarding how space is represented in urban spatial models. Most urban models use an abstract representation of space to define the urban area with the level of abstraction dependent on the scale and the focus of the model. This abstraction ranges from the common cellular landscape that is in research-focused urban models (Batty and Xie 1994, 2005, Brown and Robinson 2006, Brown et al. 2008, Clarke et al. 1997, Engelen et al. 1997, Ligmann-Zielinska 2009, Semboloni et al. 2004, White et al. 1997) through to more complex representations that produce an identifiable urban cadastral landscape such as cellular graph-theory (O'Sullivan 2001), links to vector information through a Geographic Information System (GIS) (Benenson and Torrens 2004a, Crooks in press, Parker 2005) or geographical vector agents (Hammam et al. 2007).

From an urban perspective the advantages and disadvantages of the cellular approach to representing space is well documented (Batty et al. 1998). The key point in a cellular approach is that it removes a level of geometric detail and oversimplifies the complex geometries of the city (Batty 2005, Crooks 2007). For a cellular urban landscape, a cell either represents a parcel or it represents an area that includes numerous parcels of land. When a change in the cell’s state occurs, the cell changes stage and consequently the representation implies that the parcels beneath change state as well. This approach overlooks any understanding of the mechanism or structure of the activity that caused the change. Other approaches, such as the few models that spatially define individual parcels, represent space in a more recognisable way but the approach is rigid in its implementation. The models only allow the whole parcel to switch states (i.e. converting from ‘undeveloped’ to ‘developed’) ignoring the way in which the parcel might have multiple uses or levels of development.

In both approaches, the process of urban development is restricted by the representation of space defined in the model. As this thesis is developing a theoretical understanding of the way in which property developers shape the urban landscape, implementing either of these approaches will not enable a clearer understanding of the impacts of developers and their behaviour on urban growth. A spatial representation that allows developer agents to understand and enact the process of development is required to meet the goals of this research.

2.7 Conclusion

The quality of models investigating urban systems has developed alongside our increased understanding of how the system operates. Early models focused on the growth and structure of the city, through mathematical- and equilibrium-type models. These early models provided answers about how the city grows or its structure but are unable to explain the processes that caused it. The growing critique of this approach led to a re-evaluation of how the system should be viewed. Because of this critique, urban systems are now widely regarded as complex adaptive systems that can be explained and simulated more effectively through the use of computational tools like agent-based models.

Agent-based models introduce the concepts of space, distance and time, while allowing actor behaviour and types to be implemented. The inherent integration of agents and their behaviour within the model creates an explicit process that can be altered to mimic how the process unfolds in the real world. While these tools enable the process of development to be implemented in a structured way, an understanding of how the process, and the actors within the process, operates is required to implement such a model.

Chapter 3 explores the property and planning literature with a specific focus on the theoretical and conceptual implementations of the process which can link with the complexity tools described in this chapter. Understanding the process of urban development enables the move away from the 'black box' mathematical formalism that formed the basis of early urban models and towards a greater understanding of the way in which cities grow.

For the most part, the role of the developer within urban modelling has been largely ignored. When developers are included in some early implementations, the level of heterogeneity in their types and behaviours are largely ignored. Therefore, it is important to investigate and implement a more realistic representation of agents within an agent-based model of the urban development process. Chapter 4 explores the role of residential property developers in the urban development process with a key focus on their behaviours which shape development.

After reviewing these two gaps, an agent-based approach can be used to create a model of the urban development process. The resulting model will enable an exploration into how developer competition and behaviour affect development patterns.

3 Urban development: Property, process and models

at the right place, the right time and the right price

(Healey 1991a, p. 222)

Cities require the production of space in the form of buildings and space for numerous activities. The process by which the production of space for commercial and residential development is accomplished has been given little acknowledgement within scientific literature until the last two decades (Coiacetto 2000, Guy and Henneberry 2000, Healey and Barrett 1990, Wadley 2004). As Healey and Barrett (1990) discuss, knowledge of the urban development processes by which the built environment is produced and used is critical to the understanding of urban development and our attempts at managing these processes.

At a cursory glance, the urban development process consists of a number of roles – landowners, construction, finance, developers, and statutory bodies, to name a few. In addition, the process includes a number of institutions such as land, property and zoning within which the processes of production and consumption are framed. Reviews of previous research into conceptual models of the urban development process form three main approaches to understanding the process – neo-classical equilibrium, event-sequence and agency models (Gore and Nicholson 1991, Healey 1991a). Most research has focused on an idealised mechanical view of the urban development process (equilibrium or event-sequence models), an approach that fails to recognise the relationships between roles and institutions and the complex effects they have on each other (Doak and Karadimitriou 2007, Gore and Nicholson 1991, Healey 1991a).

To overcome this issue, the sociological concept 'Structure and Agency', introduced by Healey and Barrett (1990), investigates the complex nature of the urban development process by examining the strategies, action and interests of key actors and how they interact with the broader structural forces (Adams et al. 1998). Agency as discussed under the banner of 'Structure and Agency' has distinct similarities to the 'agency' of software agents in an agent-based model (O'Sullivan and Haklay 2000). Consequently, when investigating the agency of the actors within the urban development process, existing empirical research into the roles and behaviours of the various actors associated with the process is critical to the development of a model that realistically represents the process.

3.1 Structure and Agency

The debate on the influence of Structure and Agency is central to sociology. The key discussion revolves around the primacy between the two sides – does social structure shape an individual's behaviour or does the behaviour (i.e. the agency) of individuals shape the structures that surround them? Three broad theoretical positions have been formed to respond to this question. The first is a position where "social life is largely determined by social structure, and that individual agency can be explained mostly as the outcome of structure" (Jary and Jary 2000, p. 615). The second position takes the opposite view, where individuals have the capacity to construct and reconstruct the worlds and structures with which they interact (Jary and Jary 2000, Lukes 1973). The final and most prevalent position in recent work focuses on the complementary nature of the two processes, recognising the importance of structural determinacy and individual agency (Berger and Luckmann 1967, Bhaskar 1978, Giddens 1984).

For the purposes of this thesis the theme of Structure and Agency is based on the framework behind Giddens's (1984) Structuration theory, a theory which points to a 'duality of structure' where "social structure is the medium and the outcome of social action" (Jary and Jary 2000, p. 614). In this framework, structure is defined as "the structuring properties [which allow] the 'binding' of space–time in social systems, the properties which make it possible for discernibly similar social practices to exist across varying spans of time and space, and which lend to 'systematic' form" (Giddens 1984, p. 17). Agency is defined as the act of human action or behaviour, collective or individual, which makes a difference to a social outcome. Giddens's framework views agency operating in conjunction with structure to create a structure that 'enables' as well as 'constrains' (Giddens 1984). This leads to "systems (structures) [that] are reproduced through the rules and resources which individual agents draw upon in the production and reproduction of social life" (Healey and Barrett 1990, p. 93).

3.2 Integration of Structure and Agency within property research

Over a decade ago, a number of reviews (Gore and Nicholson 1991, Healey 1991a) examined the then current theoretical opinion of property development. These reviews concluded that the existing theories and models were unable to address the growing role that behaviour, interaction and relationships of and between actors had within the urban development process. In particular, the existing approaches (neo-classical location theory and land economics) were unable to address the way in which actors "behave in deploying resources to realise specific investments … and the broader processes which drive the strategies and interests of the various actors involved" (Healey and Barrett 1990, p. 89). As a result, in an attempt to stimulate interest in the processes of the production of the built environment, Healey and Barrett (1990) extended Anthony Giddens's Structuration theory into the context of development processes. Giddens's theory argues for a relational approach between structure and agency, where structure is established through the actions of the agents in the process: "deploying, acknowledging, challenging and potentially transforming resources, rules and ideas as they frame and pursue their own strategies" (Healey and Barrett 1990, p. 90).

Healey and Barrett (1990) state that the lack of research into the urban development process has meant that "many analysts of spatial change have treated the conversion of economic and social processes into land use change and built form as essentially unproblematic" (p. 94). This neo-classical position expects that the various agents involved in the development process would work collectively at the right time, in the right place, and at the right price based on market signals such as land and property prices alongside potential rents (Healey 1991b, Lichfield and

Darin-Drabkin 1980, Massey 1984). However, as Healey and Barrett (1990, p. 94) state, “empirical research shows that the relationship between demand and supply in the various processes which constitute the production of the built environment is problematic in many ways”.

The main shortcoming with the neo-classical position is that it places undue importance on the existing social structure of society and removes all reference to the agency of the actors within the process, similar to the structuralism and functionalism of sociological theories discussed previously. The opposing position endorses a behavioural view that emphasises the roles of the various actors within the process and the importance of their decisions (Barrett and Whitting 1983, Bryant et al. 1982, Drewett 1973, Goodchild and Munton 1985). Consequently, this position aligns with individualism and the ability for individuals to operate independently of structure.

As in the case of the sociological theory behind structure and agency, the third position recognises the importance of both approaches to the urban development process. This position aims to integrate the development agencies in development events and the interactions these agencies have between themselves and other agents of the urban development process (Guy and Henneberry 2000, Healey and Barrett 1990). A new institutional model of the urban development process was born out of this position and has been adopted into the mainstream (Ball 1998, Ball et al. 1998, Guy and Henneberry 2000, Healey 1992) but there still appears to be some debate about the level of ‘agency’ that is involved in the process (Ball 2002, Guy and Henneberry 2000). A more recent move was Guy and Henneberry’s (2000) argument in favour of a ‘cultural institutionalist’ approach to the process, an approach that should be “dynamic, deeply contextual and contingent both on the particular aims and objectives of development actors, and on a shifting market framework which may enable or constrain development strategies” (p. 2413). Their approach would examine the relationship between culture and capital through the unpacking of the cultural frames through which investment strategies are made (Guy and Henneberry

2000). Through this deconstruction, it is apparent that a "relatively small number of decision-makers serve to structure socially property market processes" (Guy and Henneberry 2000, p. 2413).

Historically, the rise in studies examining specific parts of the urban development process has underlined the complexity of the development process. Studies have investigated the construction industry, building material industry, financial sector, and the "whole spectrum of social and economic activity in relation to the demands and needs for land, buildings and location" (Healey and Barrett 1990, p. 91). These 'institutional' approaches have provided detailed information about each aspect of the building development process, while also providing a platform to examine and hypothesise about the interaction between the various parts of the process.

3.3 Conceptual models of the urban development process

Two key reviews (Gore and Nicholson 1991, Healey 1991a) provide a starting point to understand the existing approaches to the urban development process. The models reviewed fall into two broad theoretical assumptions, neo-classical and Marxist economic viewpoints (Guy and Henneberry 1998, Healey 1991a), both of which address similar issues, but involve separate 'languages' (Guy and Henneberry 1998, Needham 1994). While both reviews cover much the same territory, their conflicting approach to the value of the previous work highlights the historical debate (which still exists today) between the two theoretical positions.

Healey's (1991a) overarching aim for her review was to develop a more holistic representation of the process that balanced the economic pressures of the process with the perceived need to include social processes in our understanding of the urban development process. The review (Healey 1991a) is the second in a series of three papers Healey wrote following Healey and Barrett's (1990) introduction of Giddens' Structuration theory to property research and before the development of her institutional model of the development process (Healey 1992). Gore and

Nicholson (1991) presented a divisive review that disregarded most Marxist models in that “the concern to develop such an all-embracing approach means that specific empirical applications are weakly developed […], or take a back seat altogether” (p. 725). Their review, while not explicitly endorsing an approach, placed an implied importance on a neo-classical approach. Recently, Guy and Henneberry (2000) tried to resolve the continuing debate (see Ball 2002 for the continuation of the debate, Guy and Henneberry 2002a) in stating that “whatever approach is adopted, any economic analysis needs to be populated with development agencies involved in the development events and needs to deal with the relations between them” (p. 2400).

This debate showcases how academic disciplines began to align themselves within the debate over the urban development process. While some disciplines (such as economics) are firmly entrenched on one side of the argument, most disciplines such as geography, planning and sociology are more prepared to highlight the benefits of each viewpoint and understand that a single approach to modelling the urban development process might not adequately represent reality (Healey 1991a). A hybrid position that acknowledges both viewpoints would achieve the best outcome. Gore and Nicholson (1991) come to the conclusion that “different types of model… offer different levels of understanding [and] there is no reason to dismiss any of them out of hand” (in Guy and Henneberry 1998, p. 6). It is important to note that whatever theoretical perspective is used, they “must be operationalised within a wider methodological framework” (Guy and Henneberry 1998, p. 6), an area that this thesis will endeavour to implement.

Within the framework of these two theoretical perspectives, conceptual models of the urban development process fall into three approaches, Economic Processes, Development Events and Development Agencies. As Coiacetto (2000) points out, the existing modelling approaches emphasise the importance of the context or structure within which actors, and the agency of the actors, are influenced and bound by development processes. Interestingly, while the context in which actors are influenced is found within all three approaches, actors and their agency are explicitly referenced in only one of the three types of models (as seen in Table 3.1). Therefore the creation of an agent-based model of urban development naturally aligns with the Development Agencies approach. However, as the process in which urban development occurs is inherent in the surrounding economic processes and development events listed below, it is important to review the other two approaches to the modelling of the urban development process.

Theoretical Assumptions	Economic Processes (*Equilibrium*)	Development Events (*Event-Sequence*)	Development Agencies (*Agency*)
Neo-classical	Demand, supply, price mechanism, Transactions, investment, Rational utility maximisation (Harvey 1981b)	Land purchase Arrangement of finance Construction Occupation (Goodchild and Munton 1985)	Land dealer Developer Builder Firms (Bryant et al. 1982)
Marxist	Capital accumulation Circuits of capital Capital switching (Harvey 1981a)	Loan of interest – bearing capital Direction of industrial or commercial capital (Boddy 1981)	Former landed property Industrial landownership Financial landownership (Massey and Catalano 1978)

Table 3.1: Conceptual models of the urban development process. Reproduced from Guy and Henneberry (1998), which in turn was based on Healey (1991a).

The three approaches are in effect “different ways of developing the analysis of actors and institutions operating in markets structured by the demand and supply of commodities” (Healey 1991a, p. 221), therefore the differences between the three approaches are changes in emphasis rather than changes in the basic theoretical assumptions.

Neo-classical equilibrium models

The underlying assumption of these types of models is that the catalyst for the development process is the demand for new property. As Healey (1991a, p. 221-222) states in her review of these types of models, “[s]ufficient stock (supply) should be brought forward to meet demand, in the real estate adage, ‘at the right place, the right time and the right price’ ”. The new land is then processed through rent and yield calculations and the subsequent land and property valuations to create a product. Transactions and investment into the urban development process are activated by market signals such as land and property prices; actors who ‘read’ these signals the best while developing will be successful (Healey 1991a). These types of models focus on the economic adage of supply and demand, equilibrium is reached when the demand for new housing is met by the supply of housing, and if further imbalances occur more housing is produced to meet the demand (Harvey 1981a). While problems can occur with the process, such as ‘supply’ side issues like monopoly land ownership (Markusen and Scheffman 1978), conceptually the “development activity itself is seen as relatively unproblematic” (Healey 1991a, p. 222).

However, this approach to the urban development process is not unproblematic. Healey (1991a) outlines a range of issues with this approach, such as the model being unable to understand diverse forms of demand (such as user and investor), the non-economic interests of the actors involved in development not being accounted for, the difficulty in assessing the financial viability of a potential development and the lack of complexity within the development process itself. This leads Healey (1991a, p. 223) to conclude that equilibrium models “are only helpful in understanding the development process for standard types of project in relatively stable conditions where active property markets exist”. Decision makers within these models are crudely conceptualised whereby relationships are mechanistically described and outcomes are deterministically derived (Guy and Henneberry 1998). Using developers as an example, Key et al. (1994, p. 65) state that they are “responding mechanically to the market signals provided by current prices and price changes, […] developers are simple price takers, who on average do not succeed in anticipating turning points in the market”.

Guy and Harris (1997) pursue this topic further stating that property research, in adopting such “...an economistic tradition... has pursued an inexorable path towards a mechanistic and deterministic interpretation of the world [and] a reductionist approach to analysis... defined in terms of accuracy of prediction” (Guy and Henneberry 1998, p. 130). This reductionist approach has reduced “the social world to technique, the extent of which is only exceeded by an emptiness of meaning” (Beck 1992, p. 158, in Guy and Harris 1997). Guy and Harris (1997) contend that the neo-classical approach necessitates a deeper, more qualitative understanding of the property market to be developed. This is because the existing approach is fixated on the measurement of the market, which does not mean that the market is understood.

Fisher and Collins (1997) argue that while the development process has been analysed by neo-classical economists such as Jack Harvey (1981b) and Marxists such as David Harvey (1981a), the structural models that have been created (Demand and supply, Rational utility maximization, Capital switching and Circuits of Capital to name a few) do not delve into the specifics of development and could be classified as ‘one-dimensional’.

Finally, the process of abstracting the system to an equation-based equilibrium model effectively homogenises the actors through the assumption that human behaviour can be captured by simple mathematical functions (Arthur 2006). In effect, an equilibrium model assumes that all actors within the model are perfectly rational, exhausting all informational resources to the point that they have no incentive to alter their decision. In reality however, informational asymmetry is commonplace, constantly affecting the structure of the market through the demand and supply of commodities.

Event-sequence models

Event-sequence models are the second stage of models that investigate the urban development process by examining the complexity of the process by analysing the constituent *events*, such as evaluation, preparation, implementation and disposal (Barrett et al. 1978, Birrell and Shi Bin 1997, Cadman and Austin-Crowe 1978, Gore and Nicholson 1985, Radcliffe 1978). While early event-sequence models were 'rough and ready' in their representation of the process (Gore and Nicholson 1991), the aim of these types of models is to conceptualise a framework of events for more detailed further analysis. A later, more comprehensive, description of the process using an event-sequence model (Goodchild and Munton 1985, p. 65) stated that "the development process begins when a parcel of land is considered suitable for a different or more intensive use, and is completed when the necessary changes have taken place and land is re-occupied". These changes are outlined as:

1) the maturing of circumstances that makes possible a change in the use of land, for example, the construction of a new road or the selection of a settlement for expansion.
2) purchase of the land by a person prepared to develop it.
3) preparation of the land for development, including both 'physical' construction work and 'abstract' operations such as establishing legal title to the land.
4) preparation of the development scheme, including obtaining all the necessary consents, especially planning permission.
5) arrangement of finance to carry out the development.
6) construction of the development scheme.
7) its occupation by either the developer, a new owner or a tenant.

(summarised in Goodchild and Munton 1985, p. 65, Lichfield 1956)

This approach to the event-sequence model recognised that actors play numerous roles within the process, that the sites of development are varied, and that these events do not always follow a set sequence. This approach to the urban development process began to illustrate the complexity of the process and facilitates further investigation into the 'pipeline' of development that focuses on the potential blockages to a development (Barrett et al. 1978). However, as Healey (1991a, p. 224) states, these models "provide little help in explaining why a development process takes the form that it does in a particular case". Consequently, while event-sequence models provide an insight into the urban development process, their closed rigid form makes it difficult to capture the unique nature of the actors within the process (Gore and Nicholson 1991).

Agency models

Agency models, as Healey (1991a) highlights, focus on the 'actors' in the development process, the roles they play, and the interests that guide their strategies. These models bridge the gap between the detailed process of urban development found in event-sequence models and the interactions of the actors within the process. While there are numerous roles within the urban development process such as Landowners (Goodchild and Munton 1985), Estate Agents (McNamara 1984), Investors (Nappi-Choulet 2006), and Surveyors (McNamara and Turner 1987), Developers are seen as the central player mainly because they are a key-coordinator that drives development (Adams et al. 2001, Antwi and Henneberry 1995, Coiacetto 2000, 2001, Craven 1975, Drewett 1973, Gillen and Fisher 2002, Goldberg 1974, Goldberg and Ulinder 1976, Hawes 1982, Kaiser and Weiss 1970, Lichfield and Darin-Drabkin 1980, MacLaran 2003a, Schler 1966, Winarso 2000).

As Healey (1991a, p. 224) explains, when "activated by perceptions of potential yields, the developer assembles the inputs to production, organizes the production process and markets the product" – a process that is captured in Drewett's (1973) model of residential development (Figure 3.1). This model, along with Kaiser and Weiss's (1970) model of land conversion (Figure 3.2), provides a simplistic representation of an actor's behaviour and the network of other actors within the process. When examining both, it is clear that the role of developers is critical to the process. These models are classified by Healey (1991b) as the first approach to developing the agency model of the process.

The second approach to the agency model was later elaborations such as Barrett, Stewart, and Underwood (1978) and Bryant, Russwurm, and McLellan (1982) (Figure 3.3). This second approach highlighted the complex and numerous events that

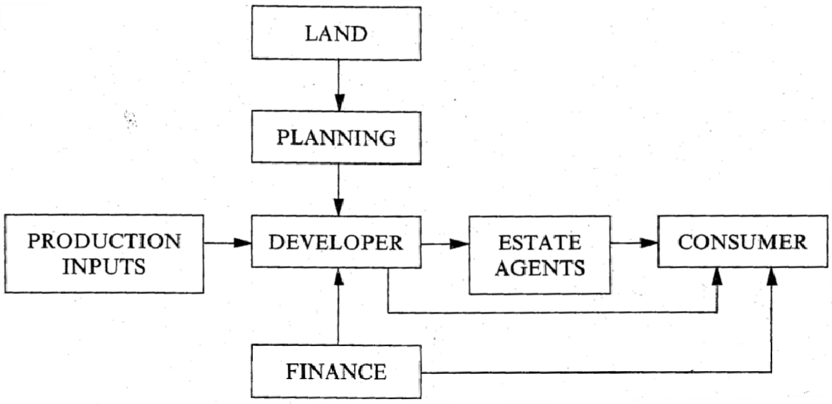

Figure 3.1: Drewett's (1973) model of residential development (Source: Healey 1991a)

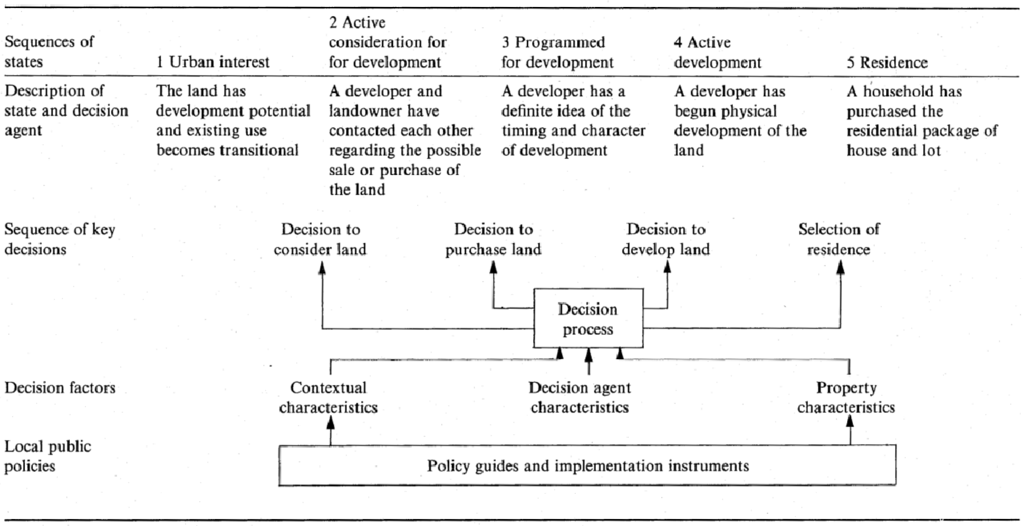

Figure 3.2: Kaiser and Weiss's (1970) model of land conversion (Source: Healey 1991a)

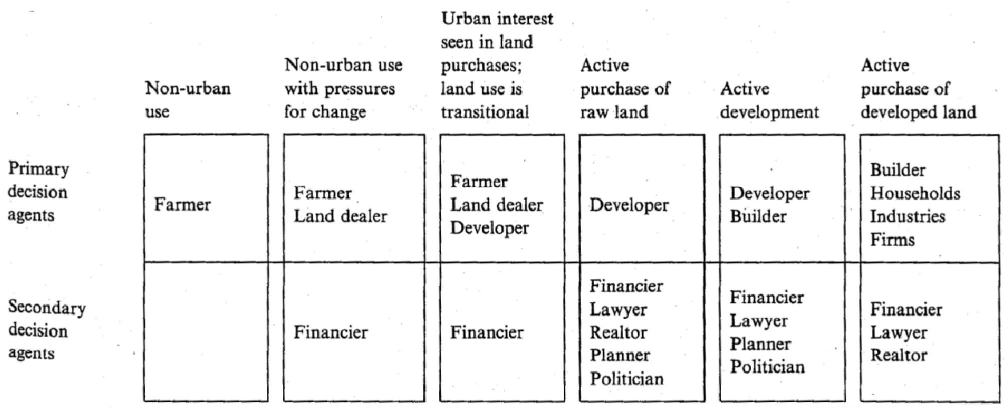

Figure 3.3: Bryant, Russwurm, and McLellan's (1982) agency model of residential development (Source: Healey 1991a)

surround the urban development process as well as the diverse nature of the actors. The final approach focuses on the behaviour and 'interests' of agents within the urban development process, an area synthesized by McNamara's (1983, 1988) suggestion that actors' social relations with the mode of production and the socio-political system define the interests or behaviour that they exhibit (Healey 1991a). This approach alludes to the discussion within the theoretical concept of 'Structure and Agency' and aligns with Giddens's (1984) Structuration theory.

As part of their earlier work, Healey and Barrett (1990) created a framework, rooted within the concept of 'Structure and Agency' and Structuration theory, which has been adopted by researchers wishing to pursue a more 'agent' orientated approach to the urban development process (Adams 1994, Doak and Karadimitriou 2007, Guy and Henneberry 2000, Healey 1992, 1998a, b). The framework embodies the structure within the *resources* to which agents might have access, the *rules* which govern their behaviour, and the *ideas* that are available to them in developing their strategies within the urban development process:

> (a) the resources for development, as channelled via the financial system and the interrelation of supply and demand
>
> (b) the politico juridical rules which limit the construction of development opportunities
>
> (c) the ideas and values people hold about what they should build, what they would like to occupy and what kind of environment they seek.
>
> (Healey and Barrett 1990, p. 94)

Healey (1992) developed this framework into an institutional model of the urban development process which argued that there is a need to

> establish the link between structure and agency empirically through relating the construction of roles, the strategies and interests if agencies, to the material resources, institutional rules and organizing ideas which agents acknowledge implicitly and explicitly in what they do.
>
> (Healey 1992, p. 35)

Doak and Karadimitriou (2007) have outlined the role played by the move towards complexity in the urban development process, in that prospects open up when we assume their constituents can make complex systems whose emergent properties are more than the sum of the parts and whose behaviour is inherently difficult to predict. Placing this within a property context, Doak and Karadimitriou (2007, p. 209) explain that "the agents and networks involved in property development can be seen as constituents of structures that perform complex processes" and that "[t]hese structures interact, forming new more complex structures and networks". Therefore development "can be conceptualised as a process of transformation: a complex system, a 'dissipative' structure involving developers, planners, landowners, state agencies etc" (Doak and Karadimitriou 2007, p. 209). Their discussion highlights the concept of 'dualism' of structure and agency within the urban development process, which aligns with Giddens's (1984) Structuration theory.

3.4 Conclusion

Gottdiener (1994, p. 197) states that "no single model of political economy, either from a Marxian (Harvey 1981a) or from a neo-Ricardian perspective (Scott 1980), can be used to deduce the present-day sociospatial patterns or multi nucleated regional development". The introduction of Structure and Agency fulfilled Healey and Barrett's (1990) aim to stimulate interest in the processes of the production of the built environment. The subsequent classification and development of new approaches to examining the urban development process (Equilibrium, Event Sequence, and Agency) ignited a comprehensive examination of the area. While there are merits in each of the approaches discussed in the chapter, the clear choice is to adopt an Agency approach to the urban development process. The rationale for this decision is that the agency of developers plays a distinct role in how they choose and consume land for development. The ways in which a developer's agency is manifested can be seen in the behaviour, choices and process a developer goes through when developing land. The next stage is to understand the behaviour of developers and the structure of the development industry, both of which are discussed in the next chapter.

4 Developers and their role in the urban development process

> To developers, the urban landscape represents a profitability surface that is highly differentiated geographically
>
> (MacLaran 2003b, p. 45)

Developers are seen as a nexus within the urban development process (Coiacetto 2000, Drewett 1973, Gillen and Fisher 2002, Hawes 1982, Kaiser 1966, Schler 1966). Kaiser (1966) graphically illustrates the central role developers have within the process (Figure 4.1). Surprisingly, while the importance of developers within the urban development process is commonly accepted there is a lack of empirical research into their behaviour and a tendency with urban development process research to treat developers as an "undifferentiated whole, as if all developers were the same" (Coiacetto 2000, p. 353).

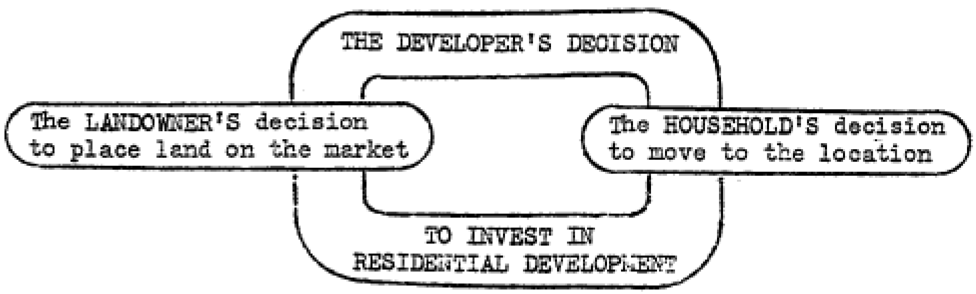

Figure 4.1: Central role of the developer (Kaiser 1966)

While their behaviour and actions are often high-profile, the behaviour and actions of developers are not a focus in academic literature. Demand-side factors, particularly householder behaviour and its associated indicators, such as socio-economic status, race, mobility and migration, were, and sometimes still are, considered to be the driving forces to land use change (Clark and Dieleman 1996, Kaiser 1968, Kaiser and Weiss 1970). Literature on the economics of sprawl continues to focus on the impacts local government are forced to bear, rather than the costs and actions faced by other actors within the urban development process (Mohamed 2003). In the literature, developers are discussed as explicit profit maximisers who do not make decisions that would reduce their profit (Skaburskis and Tomalty 2000, Watkins 1999). Such research ignores the role, behaviours and interactions of developers in the urban development process, an area of research which has slowly gained acceptance (Bookout 1990, Coiacetto 2001, Gillen and Fisher 2002, Kenney 1972, Peiser 1984). According to Bookout (1990):

> Developers are the central actors in the development process, because their actions determine the what, when, and for whom of residential development: what land will be considered for development, when improvements will begin, and for whom the project will be developed.
>
> (Bookout 1990, p. 7)

While the move towards examining the role and behaviour of the developers within the process is valid, Clawson (1971) states that “private housing development for a private market is first, last and all the time a business operation, conducted for profit, and the merit of decisions is always judged by the effect upon profit” (p. 59). Based on Clawson’s statement one could assume that a profit maximising perspective in this case is a valid one, although the recent understanding of behavioural economics, bounded rationality and in particular the role of satisficing (Conlisk 1996, Kahneman 2003, Manson 2006, Simon 1997), highlights the need to include the other factors that weigh in the decision making process.

A profit maximiser perspective on developer behaviour appears in one of the two main types of model examining the urban development process: neo-classical equilibrium models. The neo-classical equilibrium model (Lichfield and Darin-Drabkin 1980, Massey 1984) expects that the various agents involved in the urban development process work collectively to develop land in an efficient manner (Healey and Barrett 1990). Developers are seen as mechanical – maximising their profit by efficiently responding to market signals, although they are usually unsuccessful in anticipating turning points within the market (Key et al. 1994). From an empirical perspective, the models' neo-classical relationship between supply and demand is problematic in that it places undue importance upon the existing structure of society, and has removed all reference to the agency of the developers within the process (Guy and Henneberry 2000, Healey and Barrett 1990).

The preferred alternative to gain a more qualitative understanding of the urban development process is to employ a form of agency model that addresses the way in which developers behave in deploying their resources to realise an investment. It is unsurprising that most agency models focus upon the key role developers have in the development process (Adams et al. 2001, Antwi and Henneberry 1995, Gillen and Fisher 2002).

Historically, economists investigate actor preference and choice using rational choice theory, where all choices come with complete information in relation to the costs and benefits for each decision (Schwartz et al. 2002). This information would enable an actor to act rationally when deciding, maximising their utility and in the case of developers increasing their profit. In the case of a property developer, the level of information that would need to be supplied are aspects such as the exact state of the property market for each time step in the model.

Economists now acknowledge that people routinely ignore the principles of rational choice and that the assumption of complete information is unrealistic (Kahneman and Tversky 1979, 1984, Tversky and Kahneman 1981). Satisficing was proposed as a way to acknowledge the limitations of a maximising perspective and allowing a more realistic approach. Satisficing is based on the fact that an actor has a threshold of acceptability when making decisions. Once an option exceeds this threshold the actor would accept it. Satisficing behaviour does not pursue the best option but a good enough option (Schwartz et al. 2002).

MacLaran's (2003b) overview of the property development sector provides a comprehensive review of the developers' role within the urban development process. As seen in the previous discussion on event-sequence and agency models of the process, the stages and activities a developer goes through to develop land is well known. The developer scouts for opportunities, assesses the resulting parcels against both price and risk, designs the plans for development (including securing development permission), secures funding, builds, and finally markets' and sells the final product (Goodchild and Munton 1985). While this is the optimal process a developer goes though, the process is not fixed and is often adjusted based on interactions with other agents (Dewey 1997). While the economic and political structures affect the way in which developers operate (Adams et al. 2001), these structures are outside of the scope of the thesis.

4.1 Empirical research into developer types

Given the importance of developers in the process, it is surprising that there is a lack of empirical research into their behaviour, and a tendency to treat them as an 'undifferentiated whole', as if all developers were identical (Coiacetto 2000). While the literature on models of the urban development process implicitly supports this, treating developers as an 'undifferentiated whole' is not supported by the broader property and planning literature. Clawson (1971) qualifies her earlier statement on the profit making nature of developers, by noting a recurring theme that she has observed – developers behave differently based on the level of financial resources available to them. These resources usually define the size of their development operation. In the rest of this thesis, 'size' refers to this distinction.

Clawson's observation is reinforced by three sets of empirical research – Schler's (1966) early empirical review of developer types in the greater Kansas City area began to highlight a number of clear distinctions in developer behaviour based on the size of their development operation; Dowall's (1984) investigation into urban development around the San Francisco Bay area that began to discuss the changes in land use impacts based on developer size; and Coiacetto's (2001) research on developer types and behaviour in two adjoining local government areas along the northern coast of New South Wales.

Larger developers (termed 'commercial' by Schler) are focused more at a metropolitan-wide scale of development opportunities. Unconcerned by local influences, they generally have a background in the building and construction fields and have grown to be a major provider of housing (Coiacetto 2001). These developers are oriented to provide quantity to the market, sacrificing distinct housing look to ensure economy of scale savings in their many similar housing products.

In Schler's (1966) eyes, smaller 'marginal' type developers are an extreme example of local-focused development, working within their own area, which they know intimately, usually because they are residents of the area in which they carry out their development. They are inexperienced in the process of land development and the structure of the development operation is loosely defined, which leads to increased transaction costs (Dowall 1984). The types of developments undertaken mimic the local styles and trends (Coiacetto 2001). These marginal developers primarily focus on fringe development of the urban core and surrounding exurban areas, in areas where they "see an opportunity for easy profit making in the subdivision of land" (Schler 1966, p. 114).

This differentiation based on size leads to literature on industrial market typologies that range from the highly competitive, through gradations of oligopoly, to a monopoly (Figure 4.2). There is a common misconception that the industrial organisation of the development industry is either dominated by a small number of large developers (tight oligopoly) or a highly competitive industry with numerous smaller developers (Coiacetto 2006, 2009). In reality, the industry is oligopolistic with regional factors accounting for the level of dominance the larger developers hold (Coiacetto 2009, Healey 1998b).

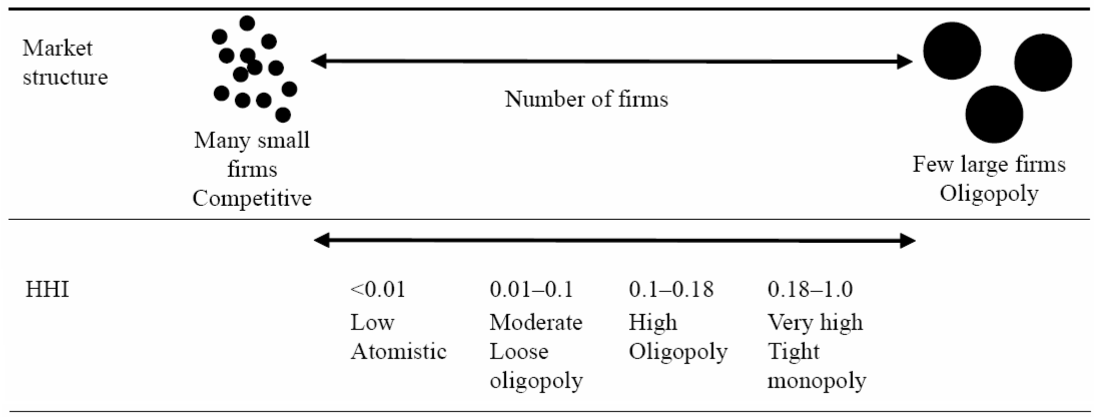

Figure 4.2: Market structure for the development industry (Source: Coiacetto (2007, 2009) adapted from Buzzelli (2001)). HHI stands for the Herfindahl-Hirschman Index, a measure of the size of firms in relation to the industry and a commonly used indicator of the amount of competition within an industry

4.2 Large vs. Small – Size-based stratification of developer behaviour

While not as commonplace today, post-war land-use patterns were affected by large institutional developers known as 'place-makers' (Eichler 1982, Frost 2001, Mohamed 2003, Weiss 1987). These developers were enormous in their scope and created entirely new communities from the ground up with large investments in infrastructure such as roads, power and water services (Mohamed 2003). Place-maker developers were more evident in USA with the closest New Zealand counterparts being current large scale developers like LandCo who are currently developing the 110 hectare Stonefields residential development (Orsman 2006).

Recently, government investments into infrastructure have obviated the need for present-day private place-makers (Mohamed 2003). Large developers have adopted the role left vacant by the 'place-makers' at the core of the city's 'growth machine' (Logan and Molotch 1987, Molotch 1976). Smaller developers enter the market primarily to capitalise on locations that are not of any commercial interest to the larger developers (Coiacetto 2006).

The way in which developers undertake development can be viewed as a behavioural trait associated with their size. The remainder of this section outlines the way in which core developer behaviours are differentiated based on developer size. Table 4.1 summarises some of these core behaviours.

The decision to purchase sites for development is the most important decision a developer will make. Drewett (1973, p. 168) states that “it is an investment decision and a locational decision, the combination of which will determine the likely marketing success of the project and thus the gross return on the capital employed”. From an economic standpoint, most developers use a form of *residual valuation* to calculate a parcel’s profitability (Drewett 1973, Morley 2002). A residual valuation can be expressed as a simple equation of:

$$Profit = \ future\ selling\ price - (current\ purchase\ price + improvements)$$

While the concept of the residual valuation is straightforward, the expertise of the developers in how they estimate both the site value and costs of development affects its resulting accuracy significantly (Morley 2002). As Antwi and Henneberry (1995, p. 218) state “considerable uncertainty is involved in assessing future gain, and distortions are produced by the valuation and appraisal methods used by developers to assess risk and reward”. This expertise/uncertainty can be aligned with the level of financial resources (detailed property and planning documentation, local sales records, etc.) devoted to the assessment of the parcel. Smaller developers with smaller development budgets are therefore more variable in their residual value calculation and the assessment of the property market (Guy and Henneberry 2002b).

From a neo-classical perspective, the residual valuation by itself is used to define developers as explicit profit maximisers. However, developers assess a variety of endogenous and exogenous attributes inherent in each development opportunity. While exogenous factors such as the existing overall property market and zoning are evaluated, the endogenous factors such as the physical characteristics of the parcel are usually the most important (Goodchild and Munton 1985). The inclusion of these factors represents a move towards a profit satisficing position. As Weiss et al. (1966), state

> locational decision process emphasizes the *ad hoc* nature of the process in contrast to a systematic rational decision-making model. The process seldom seems to involve an explicit weighting of alternatives by developers. More typically, the developer selects the most favourable site on the basis of preliminary considerations, evaluates the feasibility of the site and either purchases the site or moves on to an evaluation of other sites in a similar manner.
>
> (p. 28, in Drewett 1973)

Locationally, parcels that are closer to desirable facilities are more attractive to developers because risk in the resulting product being unattractive to the market is minimised (MacLaran 2003a, Mohamed 2009, Speir and Stephenson 2002). From a social structure perspective, the fact that land is fixed locationally contributes to the inelasticity of supply (Bryant et al. 1982). The subsequent demand is commonly reflected in the increased land values for these parcels. The parcel's location is less critical for larger developers because they can create their own 'location' and amenities, similar to the earlier 'place-makers' described above (Coiacetto 2007).

This ties in with MacLaran's (2003a) belief that the economics of construction favour large development sites and that small or irregular lot sizes represent higher risk and are therefore more costly to develop. In this vein, residential brownfield development (the redevelopment of land with an existing urban land use into housing) is often constrained, because of the level of return on investment, to smaller developers or specialist subsidiaries. This level of return is directly tied to the scale of development, so brownfield opportunities at a certain spatial scale will attract attention from larger developers even with the increased risk involved in the site's development.

SMALL DEVELOPER APPROACH	BEHAVIOUR	LARGE DEVELOPER APPROACH
Inaccurate, focused on local area rather than wider property market. Lack of financial resources also makes their assessment inaccurate.	**Market Knowledge**	The financial resources available usually mean forecasting and or other techniques are used to increase accuracy of market assessment.
Knowledge of local attributes of the parcel offsets less detailed approach to the residual value calculation.	**Parcel Knowledge**	As above. The financial resources put into the residual value calculation usually means assessment of parcel profit is more accurate.
‘Gut’ instinct type approach to managing risk. More successful based on experience level of developers.	**Risk**	Usually measured and planned approach to development. Will not shy away from risk, but dependent on the reward.
Less prevalent, because amount of capital tied up in future development restricts level of current development.	**Landbanking**	Commonly used to ensure a steady stream of development projects and ability to purchase large parcels with high expected returns.
Mimics previous successful developments and moves away from previous unsuccessful development opportunities.	**Habit Persistence**	Choice and type of development based on best choice at time of development.
Critically important, often a ‘make or break’ type of scenario. Commonly requires development soon after purchase.	**Timing**	Able to handle a mistimed development because of increased financial resources. Might hold back development until better time.
Small in size and local to developer’s home, Development operations are predominantly focused within territory.	**Territoriality**	Large area of interest to the point of no real territory. Developments are chosen based on factors other than territory.

Table 4.1: Summary of key developer behaviour

Risk avoidance is another widely accepted practice among developers (Baerwald 1981, Kenney 1972, Leung 1987, Wiewel et al. 1999). In direct contrast to MacLaran's thoughts, Peiser (1984) contends that developers prefer smaller projects because of the reduced risk and lower amounts of capital required. Regardless, observations made by Barnard and Butcher (1989), Goldberg and Ulinder (1974, 1976), and Robinson and Robinson (1986) all point to cost avoidance behaviour being implemented by developers to minimise the risks of development. Hepner (1983) also shows that in certain areas, developers choose locations that minimise costs regardless of household preferences and the level of profit the location provides.

This profit satisficing approach is supported by the literature in that the maximisation of profit is not always a primary concern for developers (Baerwald 1981, Kenney 1972, Somerville 1999). Developers are satisficers with bounded rationality, content with reasonable aspirations that are achievable through simple decision rules (Mohamed 2006). One consequence of satisficing behaviour is that developers prefer projects on greenfield sites that take a shorter time to build and sell (Daniels 1999). Profit 'satisficing' behaviour is particularly relevant for smaller developers because of the costs and uncertainties involved with their developments (Mohamed 2006). Mohamed (2009) also postulates that smaller 'satisficing' developers contribute to inefficient land use through the underutilisation of existing services and infrastructure. This underutilisation results in smaller developers undertaking low-density and leapfrogging-type development (Mohamed 2009), where developers skip over parcels adjacent to the urban core to obtain land for development at a lower price.

This leapfrogging nature of property development has also been attributed to the activity of landbanking, in which land is speculatively purchased with the intention of future subdivision. Landbanking is a commonly used tactic to strategically secure land for future projects (Adams and Watkins 2002, MacLaran 2003a). Seen as a risk minimisation strategy, landbanking is usually undertaken by developers who have access to a large and secure source of funding, allowing the security of future options while continuing their existing operations. The financial capabilities of large powerful developers also allow them to find ways around planning restrictions, find loopholes in existing legislation, or strongly oppose new legislation (Feagin 1983, Logan and Molotch 1987, Stone and Sanders 1987, Warner and Molotch 1995).

Larger developers are better capitalised and use their knowledge of the regulatory processes, or their financial power, to outbid smaller developers (Dowall 1984). From a spatial behaviour perspective, large developers prefer to locate closer to public utilities, services, zoned areas, and the central business district (Hepner 1983, Kaiser 1968, Weiss 1987). This preference in location is based on their access to the initial capital required to invest in these areas that are regulated to require public facilities, an approach that protects their investment (Baerwald 1981, Hepner 1983).

Unlike their larger counterparts, smaller developers constantly find it difficult to stay in business because of increasing ‘up front’ costs of development (Dowall 1984). While all developers encounter issues surrounding access to capital and control over their cash flows, smaller developers are particularly affected by the constraints this places on their business (Chan 1999). In response to this pressure, there appears to be a divergence in the smaller developers’ behaviour with some becoming more conservative, taking fewer risks in site selection, and mimicking the spatial and economic decisions of larger developers (Gober and Burns 2002). From a spatial perspective, smaller developers tend to locate on either the peripheral areas of high demand, areas occupied by the larger developers, or at dispersed locations throughout the market (Somerville 1999). Lacking the financial and organisational power of larger developers, smaller developers are more dependent on local connections and knowledge (Leung 1987).

This territorial dependence on local well-known locations for development may persist even if financial opportunities are greater elsewhere (Baerwald 1981, Kenney 1972, Somerville 1999). Numerous papers have defined this localised preference further, with most authors finding that familiarity with regulations, financial backers or other localised agents (such as builders) is regarded by the small developers as being key to their success (Baerwald 1981, Hepner 1983, Somerville 1999). In addition to their preference to be 'local' they also prefer projects that are similar to their previous 'successful' developments (Kenney 1972). Peiser (1990) contends that these localised and repetitive behaviours are at the insistence of conservative financial backers. When smaller developers do engage in business outside the local area or dramatically alter the process that has been successful in the past it is usually a response to external shocks, such as increased regulations (Byun and Esparza 2005, Dowall 1984) or financial pressure (Mohamed 2006).

Smaller, locally oriented developers are also strongly aligned with other local agents, therefore the "regionalization and negotiation of [development] opportunities and influences are generally confined to [the developer's] immediate experiences" (Schler 1966, p. 164). This distinction highlights the smaller developers' reliance in decision making on their previous successes and failures over the wider market conditions (Baerwald 1981). This can be seen in the habit-persistence behaviour and 'gut instinct'-type decisions made by developers (Adams et al. 2001, Antwi and Henneberry 1995, Baerwald 1981, Daniels 1999, Henneberry and Rowley 2002, Kenney 1972, Mohamed 2009, Peiser 1984, 1990). These types of behaviours indicate that profit satisficing is more prevalent in smaller developers (Mohamed 2009). Larger developers compare opportunities across a larger territory, an approach that inherently includes an assessment of the overall property market, ensuring a more balanced decision on the suitability of parcel purchase or development. Consequently, larger developers are more able to pursue profit maximising behaviour (Mohamed 2009).

The timing of bringing a development to market is critical to all developers. To larger developers with more financial resources to cover economically lean times, correct timing might be of less importance (MacLaran 2003a), although even large developers with numerous unsold parcels for substantial periods will place a strain on the developer's financial position. The case is even worse for smaller developers, with the lack of a financial ‘cushion’, “bringing a project to the market at a time of oversupply [or a falling market] can have ruinous consequences” (MacLaran 2003a, p. 53). As Adams et al. (2001) highlight, these consequences are sometimes unavoidable where a developer who requires liquid funds to continue development may be forced to sell a development at an inopportune time. A developer with access to more liquid sources of capital might not be in such a position.

4.3 Conclusion

Developers are seen as central to the urban development process (Coiacetto 2000, Drewett 1973, Gillen and Fisher 2002, Hawes 1982, Kaiser 1966, Schler 1966). While developers are clearly important to the urban development process, existing research mainly focuses on their role and tasks, and research into their types, strategies and behaviours is limited (Coiacetto 2001). In particular, there is a tendency to treat the development industry as an ‘undifferentiated whole’, an approach that is clearly a fallacy. Additional research into developer behaviour has highlighted a number of attributes about how developers act that are stratified by the size of the developer (such as motives, objectives, information needs, approaches and strategies) (Coiacetto 2001, Dowall 1984, Schler 1966). Dowall (1984) went on to show that the stratification of the industry based on developer size can have land-use implications. These implications are directly related to the way in which the developers behave.

This chapter reviewed a number of behavioural characteristics that are based on the size of the developer. These behaviours are primarily financial in nature, ranging from their accuracy and ability to read market signals (in particular their ability to assess an increasing or decreasing market), to accuracy in undertaking the Residual Value calculation for parcel evaluation, and to the financial resources available for forecasting (large) compared with the more variable ‘gut instinct’ approach of small developers. How the developer manages the exposure to risk is another critical behaviour. Two other behaviours – habit persistence (mimicking development projects which were successful in the past) and territoriality (smaller developers rely upon local knowledge and connections to find land, larger developers are less territorial in nature) – are less directly financial.

A common perception of developers is that they are all profit maximisers. If this was the case, and every decision they made maximised their return, an equilibrium type model of the urban development process would be viable. However, as soon as a single decision is made that does not maximise the developer's profit, a model that examines *why* that and all other decisions were made, is the most appropriate option. In the real world there is little evidence that all developers are profit maximisers, consequently a model accounting for the variety of decision making by developers is the most appropriate option for examining the behaviour and resulting urban form that developers of varying size produce.

Using this typology, this research will focus on the implementation and understanding of how developers of various sizes behave within the urban development process and how their size-shaped behaviour affects the spatial consumption of land.

5 Behaviour and modelling: An agent-based model of residential property developers

> Much of the behavior of systems rests on relationships and interactions
>
> (Forrester 1969, p. 114)

The three previous chapters underpinned the direction of this research and therefore a short review of what was found is prudent. Chapter 2 undertook a review of existing mathematical- and equilibrium-type spatial urban models and came to the conclusion that these types of models focused on the growth and structure of the city structure but were unable to explain the processes that caused it. Subsequent critiques of urban modelling highlighted the lack of vision in how the system is viewed. Examining the process of urban development enabled a move away from the 'black box' mathematical formalism that formed the basis of early urban models and towards a greater understanding of the way in which cities grow. Furthermore it was observed that the role of the actors within urban modelling was largely ignored. On the rare occasions that they are included, the heterogeneity in their behaviour is largely ignored. Underlying these observations it was recognised that the rise of computational tools, such as agent-based models, enabled agents and their behaviour to be defined within a wider process which would allow the urban system to be explored in more detail and to mimic how the process unfolds in the real world.

Building on the lack of process within existing spatial urban models, Chapter 3 reviewed the conceptual models and theories regarding the urban development process developed in the property and planning literature. The review focused on the links between the conceptual theories of structure and agency in urban development and also in the variety of conceptual models that have been developed. One type of conceptual model, Agency, focused on the role that key agents had within the process while also acknowledging the detailed process surrounding the agent's behaviour and choices. An obvious link can be drawn between the agency conceptual model and the methodological approach of agent-based modelling. Even more critical, the urban development process that is enshrined in the agency conceptual model is easily adapted to a spatial agent-based model that would enable an greater understanding of the process of change within the urban system.

Chapter 4 examined and developed a typology of developer behaviour. This was undertaken because of the existing narrow academic view of developer behaviour and was carried out through the analysis of the sparse empirical studies of residential property developers. While developers were widely seen as a central part of the process of urban development, existing research mainly focused on their role and the types of tasks undertaken. Research into developer types, strategies and behaviours was limited with Coiacetto (2000) stating that property and planning literature tends to treat residential property developers as an "undifferentiated whole, as if all developers were the same" (p. 353). Interestingly, this statement can also be made about the lack of variation seen in any of the existing urban models that explicitly include property developers.

With the move towards implementing an agent-based model that is based on the property and planning literature's agency conceptual model, a detailed typology of their behaviour was required. The resulting typology found that the application of numerous behavioural traits is closely linked to the level of available capital. This size-based stratification of developer behaviour led to a number of behaviours being developed for inclusion in the resulting model. Underlying these behaviours was the philosophical decision to implement the developer agents as profit satisficers, moving away from widely-held perspective that developers act as explicit profit maximisers. This decision was based on both the behaviours reviewed (in particular the way developers manage their risk position) and the rise in behavioural economics and bounded rationality as both a way to understand behavioural responses but to also model them. At the end of this chapter there was a clear link between developer behaviour and how the resulting land-use patterns could be effected though an alteration in that behaviour.

Using both a typology of developer behaviour and an understanding of the urban development process, a spatial model of the urban development process was created that explicitly examined the role that developer competition and behaviour have within the process. To create this model, two unique approaches were used that will be discussed over the next two chapters; a process driven agent-based model of developer behaviour (this chapter); and a binary space partitioning tree that allows developer agents to understand and enact the process of development on the landscape, while also providing an abstract representation of an urban cadastral structure (Chapter 6).

This chapter examines the creation of the agent-based model of developer behaviour and the implementation of the developer agents, through three distinct stages. The first stage covers the selection of the modelling platform used within the research. The second provides a brief discussion about how representation in the model is handled. The final stage is a detailed description of the agent-based model itself using the ODD – Overview, Design Concepts, and Details protocol (Grimm et al. 2006, Grimm et al. *unpubl. manuscript*).

5.1 Platform

Several authors (notably Najlis et al. 2001, Railsback et al. 2006, Robertson 2005, Tobias and Hofmann 2004) outline various criteria that should be considered before selecting a toolkit for agent-based model development. Items such as ease of programming; the size of the community; the language in which the package is implemented; the way in which space and topological relationships are represented; the mechanism for scheduling and sequencing events; and the ability to represent multiple levels and scales, should all be considered when choosing a platform for development. A survey of the literature resulted in a substantial number of platforms for agent-based model development. After reviewing the many options in relation with the above criteria and the requirements for the model, a short list was developed.

SWARM – Agent-Based Model (Minar et al. 1996)

Swarm is a widely recognised agent-based development environment for social science research, developed by researchers at the Santa Fe Institute. Substantial work has been created using SWARM, which simplifies the learning procedure as a large number of libraries have been developed through previous work. Linking the agent framework to the 'landscape' could be difficult as not much work has been undertaken in importing and linking geospatial data. There are a number of implementations – C++, Java and Python.

RePast – Agent-Based Model (North et al. 2006)

RePast stands for REcursive Porous Agent Simulation Toolkit, and was developed at the University of Chicago and Argonne National Laboratories. Very similar in design to the SWARM model but arguably more user friendly in its interface. Prior models have implemented the ability to import data between RePast and geospatial information. This makes RePast a very favourable option. As with SWARM, RePast has a number of implementations – C++, Java and Python.

NetLogo – Cellular Automata and Agent-Based Model (Wilensky 1999)

Developed by Northwestern University's Center for Connected Learning, NetLogo has been in development just over a decade with the platform being a variant of the original StarLogo modelling platform (Colella et al. 2001). Unlike the C++, Java and Python languages used in the previous two models, NetLogo's programming language is an interpreted language running over a Java core. This approach allows models to be developed extremely quickly then refined to meet the requirements of the research, at the expense of processing time. Consequently, recent evaluations have listed it as one of the best tools to use for the prototyping of agent-based models (Railsback et al. 2006). The platform is actively developed with a wide and active user community.

Based on these three options, I expected development to move away from the initial use of the NetLogo platform (in developing the model's representation of space discussed in the subsequent chapter) towards a RePast implementation. The primary motivation for this expectation was increased computational load inherent in NetLogo's design (NetLogo is a programming language which is interpreted into Java, which in itself is an interpreted programming language). When developing the model's representation of space, the substantial flexibility of NetLogo became apparent. This flexibility combined with the ability to run multiple instances of

NetLogo on a cluster (to undertake the numerous runs associated with research of this type) provided the opportunity to continue development using this platform.

In addition, as the model intended to develop a theoretical, *in silico*, perspective rather than a spatially accurate real-world one, the approach suited NetLogo's design. As in most modelling platforms, state variables of any agent in the simulation can be monitored in real time and exported for further analysis. In this area a key advantage over RePast and Swarm was the inclusion of the BehaviourSpace tool, which allows comprehensive and easily designed parameter sweeping to manage and automate this process. Initially, one drawback in the use of NetLogo was the ability for importing and exporting spatial information but with the addition of a GIS extension (Russell and Wilensky 2008) this constraint was removed.

In the end, NetLogo (Wilensky 1999) was selected because of its large user community, quality of documentation, and the 'sandbox' modelling environment that is both easy to use and, with the use of a computer cluster, fast enough to prototype the intended model (Railsback et al. 2006).

5.2 Representations

How aspects of the model are represented within it is critical to understanding how the model works. While the ODD protocol covers some of these aspects, the approach used is brief, focusing on how the model was implemented rather than covering why an approach was taken.

Spatial

Space is represented through a unique binary space partitioning (BSP) approach that creates the spatial framework on which the agent-based model operates. Using the BSP process, the landscape evolves in three distinct ways, spread out over both the initialisation and operational phases of the model.

Within the initialisation phase of the model, the creation of the landscape begins by using a binary space partitioning approach to create an initial uniform matrix landscape. A procedurally constrained use of the BSP approach is then used to grow a more realistic city on top of the matrix landscape. At this stage an initial landscape has been created that mimics an existing city fabric and allows developer agents and their behaviour to be examined. The aim of initialising the landscape in this way is to create an existing urban cadastral fabric within which developer behaviour can be examined.

Once the agent-based aspect of the model is started, the model moves from the initialisation to the operational phase of the model. Within the operational phase, the final way in which the landscape evolves, through the process of the developers choosing parcels to purchase and subdivide, is undertaken. Once a developer agent has decided on the intensity of development for the parcel, the unconstrained binary space partitioning process is applied to the parcel being subdivided (through the `developer-building-behaviour` subroutine). Once the landscape has been initialised, this is the only way in which the landscape is changed.

For a detailed review of how the BSP approach is used to create the landscapes, the reader is referred to Chapter 6 to examine the details of how the BSP approach was implemented.

Agents

Agents are the decision-making units – i.e. the individuals, households, firms and government agencies (and any other units) who actually cause the urban area to exist and develop over time through their activities (Miller 2004). In the development of agents, the notion of ‘strong’ and ‘weak’ human agency is used to define the level of agent detail (Ferber 1999). In examining the role of relationships between agents in urban systems, a level of ‘weak’ agency, where agent-agent relationships are defined as simply as possible, is usually pursued (Benenson and Torrens 2004b). Current research into urban systems considers urban systems to be constructed through the collective behaviour of numerous weakly defined agents (Benenson and Torrens 2004b).

Data for determining attribute values and behavioural rules for the developer agents in the model were obtained from observations and empirical studies in the literature on developer behaviour. This resulted in a typology of developer behaviour based on their role in altering the resulting development patterns (Chapter 4). The way in which these core behaviours are applied can be linked with the level of financial resources available to them. The level and ratio of developer capital in the model can be systematically varied across a plausible range to show the sensitivity of landscape outcomes to variations in the distribution of capital. Numerous replicate runs were performed to evaluate model consistency and to minimise the amount of stochastic variability seen in a single or small runs.

Process

Processes are the structure that drives the urban system; they are the way in which the actions of the active agents (such as the development of land for residential housing) are deconstructed into their smaller components (for the above example – funding secured, purchase of land, clearing site, subdivision of land, construction, and sale). Responding to Sayer’s (1976) critique in the level of mathematical formalism within urban models, where processes are abstracted to equations, this research will embed the urban development process in the resulting agent-based model.

Representing the urban development process within a multi-agent model is one of the main goals for this research. Growth patterns are largely a function of the availability of developable sites. The model will randomly select a number of potential sites to come 'onto the market' at the start of each iteration. Agents will assess these potential sites for purchase. Sites selected are purchased and then assessed for development. If development of the parcel is not ideal, the parcel is land-banked until the developer ascertains the best time for development. The developer, using endogenous and exogenous factors, decides on the level (or form) of development. Once developed, the parcels are sold.

Time

Within the model time is subsumed through the ‘tick’ reporter in the NetLogo platform. Within the model, a tick is incremented when all developer agents have had the opportunity to undertake purchase, subdivision and development behaviour. While not critical to the end result, a tick is informally classed as a six-month block of time based on the length of time necessary to perform similar developments in the real world. The order in which developers undertake their behaviour is covered in more detail in the ODD protocol section below.

5.3 Model verification

As Heath, Hill and Ciarallo (2009) discuss, using a model to gain insight into a real system reinforces the need that the model is an accurate representation of that real system. Since all models are in effect a ‘satisficing’ application of this reality (Stanislaw 1986), the focus needs to be on ensuring the model is an appropriate representation of the system for the questions being investigated (Heath et al. 2009, Sargent 2005).

In a recent debate on the discipline of modelling, and in particular the use of agent-based modelling, Thompson and Derr (2009) state that “models don't stand or fall on their detailed verisimilitude, but on their capacity to capture the essence of what is already known about a phenomenon and to generate expectations concerning what more might be discovered if the scientist were to look where the model pointed” (p. 1). Such an approach would lead to the development of a model where theoretically significant properties or behaviours of the modelled phenomenon are discovered (Thompson and Derr 2009).

In line with these opinions, the previous chapters have provided an understanding of the conceptually important elements of the phenomenon of urban development, in particular an understanding of the process of development (Chapter 3) and the role and behaviour of residential property developers in enacting development (Chapter 4). The landscape on which the model runs is a satisficed representation of a real-world cadastral landscape (Chapter 6). The satisficed representation simplifies the creation of an initial cadastral landscape and also creates a framework which allows the developer to understand and quantify the scale of development. The combination of all three elements captures the essence of urban development while enabling questions of developer market structure and behaviour to be investigated.

In converting the conceptual model into a computational one, a pattern-oriented approach (Grimm et al. 2005), where entities at a lower level of the system guide the formulation, parameterisation and testing of the model, is used. At the computational stage, the micro-scale dynamics of the model were validated through the evaluation of a developer's choice in the subroutines that compose the behaviour of the agent. Developers were traced through the urban development process and forced to examine parcels in line with their state variables and associated behaviours. The results of this verified the logical flow and sequencing of the process, behaviour and interaction in the model. To enable an understanding as to why a developer performed a certain decision, overall model dynamics were verified through a visual and statistical inspection of the spatial impacts of developer behaviour and the detailed commenting of individual developer decisions. The verbose outputs from the development version of the model were reviewed for a small number of iterations to confirm and trace errors and issues within the model structure.

The use of the pattern-oriented approach to model development ensures the model is structurally realistic, making it less sensitive to parameter uncertainty (Grimm and Railsback 2005, Grimm et al. 2005). This in turn increases the credibility of the model because it indicates that the most important system mechanics have been captured (Grimm et al. 2005).

5.4 ODD protocol

The model description below follows the ODD (Overview, Design concepts, Details) protocol (Figure 5.1) for describing individual and agent-based models (Grimm et al. 2006, Grimm et al. *unpubl. manuscript*). Established in 2006 and revised in 2009, the protocol provides a robust framework to make agent-based model descriptions easier to comprehend while reducing scientific criticism of the approach through increased reproducibility (Grimm et al. 2006). The protocol has been widely used since its release, with in excess of 50 articles implementing their model description using ODD (Grimm et al. *unpubl. manuscript*). In regards to this research, the ODD protocol was found to be suitable in describing three widely cited, agent-based social simulation models of land-use change (Polhill et al. 2008).

Based on feedback, the protocol has recently been revised to incorporate the unique aspects of spatial social simulation models (Grimm et al. *unpubl. manuscript*). While the protocol is commonly thought to be overly technical and sometimes redundant in its approach, it is used because it reduces the complex nature of this agent-based model to a more understandable end product.

Overview	Purpose
	ENTITIES, state variables, and scales
	Process overview and scheduling
Design Concepts	Design concepts - Emergence - Adaptation - OBJECTIVES - LEARNING - Prediction - Sensing - Interaction - Stochasticity - Collectives - Observation
Details	Initialization
	Input
	Submodels

Figure 5.1: The ODD protocol – sourced from Grimm et al. (*unpubl. manuscript*)

Overview

Purpose

This model is a spatial multi-agent model of the purchase, subdivision, building, and disposal behaviours of residential property developers. The model is designed to examine the effects on the urban cadastral form through the implementation of an explicit urban development process and incorporation of individual developer behaviour. Developer agents in the model all access the same set of behaviours, but implement them differently based on the capital available to the developer. The behaviour included in the model covers variations in how they assess the property market, evaluate parcels for purchase, evaluate the timing of subdivision, manage their risk and focus transactions within a defined territory. The purpose and resulting use of this model are two-fold:

- To examine how differing levels of property developer competition affect the urban landscape through an examination of the change in urban growth and form

- To examine the importance of property developer behaviour with a specific focus on how developer behavioural traits affect the resulting urban landscape.

It is important to note that the restructuring of the urban cadastral form through developer locational decisions is the main output of the model. This model only examines the decisions made in the conversion of cadastral form through subdivision, not the resulting quality of the new housing stock and the resulting preference for homeowners' willingness to pay for the stock.

Entities, state variables, and scales

The model is composed of a cellular landscape upon which the entities act. This model has three entities – *Cells*, *Nodes* and *Developers*. A *cell* is a spatial representation of an area of land. Single or multiple cells can constitute a cadastral parcel of land. The *node* entity, located at the geometric centre of each parcel of land, controls the cadastral parcel information. The creation of the landscape and the roles played by *cells* and *nodes* are covered in more detail in the subsequent chapter. In this model, the developer entity is the only decision-making agent in the model. The primary behaviour of *developers* is the selection, purchase, subdivision, and disposal of cadastral parcels to provide profit for the developer. State variables for the three entities are listed in Tables 5.1, 5.2 and 5.3.

Table 5.1: State variables for each developer

State Variable	*Description*
ID	Unique identifier of the developer
Coordinates	X and Y coordinates of the developer's location. Fixed at the initialisation. Used in the calculation of a developer's territory
Capital	Amount of capital accessible to the developer to undertake development activities. If the model uses an active market, then this value is updated at the end of each time step based on the success of the developer
Attitude	Attitude value used throughout the behavioural process. The value represents the risk attitude of the developer and is used to evaluate the purchase and development of parcels. Constrained between 0 and 1.
Accuracy	Scaled value based upon the developers capital value. Constrained between 0.01 and the accuracy-variance value. If the model uses a dynamic market, the capital value is altered then the value is revised at the end of each time step.
Territory	Area of landscape in which the developer primarily selects opportunities for development. Size of territory is based on the developer's capital, with larger developers having a larger territory. Stored as BSP tree node rather than a number of cells

Table 5.2: State variables for each node

State Variable	*Description*
ID	Unique identifier of the node
Coordinates	X and Y coordinates of the nodes location. Fixed at the initialisation
Parent	Unique identifier of the node which is the parent of this parcel
Children	Two unique identifiers of the nodes who are children of this parcel
Level	Level of the binary tree with which this node is associated. Relates directly to the size of the parcel
My-Patches	A number of spatially adjacent cells linked to the node, the combination of which makes up the parcel

Square? Horizontal?	Attributes required the creation of the spatial binary partitioning tree. Required to enable the process of subdivision
Leaf-node	A Boolean value that signifies whether the parcel is a visible part of the BSP tree in the two dimensional representation of the landscape
Corner-coord	The cell in the parcel that is closest to the root node

Table 5.3: State variables for each cell

State Variable	*Description*
Coordinates	X and Y coordinates of the nodes location. Fixed at the initialisation
Distance-attraction Neighbourhood-attraction Local-attraction	A relative indicator of attractiveness of each cell to the developers. Distance-attraction is a linear decay from the root node (value of 1) to the furthest point within the landscape (value of 0). Neighbourhood-attraction uses the BSP tree to define a set of neighbourhoods which are randomly assigned a unique scaled value between 0 and 1. Local-attraction based on a random value for each cell between 0 and 1. The value is diffused to smooth the abrupt edges the random approach produces.
Combined-attraction	Using the three attraction layers, a combined layer is created using a series of weightings defined by the user. The resulting layer is then rescaled to a value between 0 and 1. For each parcel (which contains one or more of these cells) the sum of the combined-attraction values is used as a proxy for the parcel's value. This value is used throughout the model.

While not critical to the end result, the temporal scale of the model (In NetLogo terms 'a tick') is informally classed as a six-month block of time based on the average length of time to perform a residential development in the real world. From a spatial perspective, a single cell is classed within the model as 400 m^2. This spatial scale is based on the average, smallest free-standing residential parcel in a New Zealand context defined through the smallest allowable parcel size for the most common residential zoning plan in the Auckland region (Gamble 2010). Through an analysis of the cadastral land data for the Auckland region, the average residential parcel size is roughly 800 m^2 (756 m^2). These two values (400 and 800 m^2) align with the 'power of 2' rule implemented in the spatial BSP tree and discussed in the subsequent chapter.

Process overview and scheduling

Prior to the agent-based model commencing, the initial cadastral landscape and extent of urban development is exported for comparison with these outputs at the end of the run. Each time step begins with the synchronous adjustment of a number of variables (both state and procedural), to the property market, developer perception of the current market, and parcel-based attributes. A percentage of the available parcels are selected as available for development which are then, along with the developers, processed through the developer purchase, subdivision and building behaviour. Using pseudo-code, the process for each time step is scheduled in the following way:

```
For each time-step (tick)
      Calculate market-adjustments for the landscape and
      developers
      Calculate a developer-assessment-of-market for all
      developers, to ensure each developer has the same
      viewpoint for all analyses in the time-step
      Randomly select a number of parcels that are up for
      sale this round (sites-avail)
      For all parcels in sites-avail calculate the
      surrounding density of cadastral parcels (average-
      level-in-radius) for use in the development
      behaviour
      In a random order, ask each developer to undertake
      the development behaviour. First, evaluate the
      available parcels for purchase and then calculate if
      the developer wishes to subdivide any parcels it
      owns. If the developer decides to subdivide, ask the
      developer to calculate the resulting form of
```

```
    development. (developer-purchase-behaviour,
    developer-subdivision-behaviour and developer-
    building-behaviour respectively)
    Update plots and recalculate metrics for next tick
    (parcel-size-hist-plot and measure-distance-to-urban)
    Advance the tick value by 1 and export the world for
    later analysis (export-levels, export-urban and
    export-change)
end
```

As seen in the pseudo-code, the order in which the developers undertake their actions is selected at random and changes for each time-step. There is no priority, based on capital or any other attribute performed at any stage. At the end of each time step, the cadastral information stored within the BSP tree is cleaned and plots and reporters are calculated.

Design concepts

Emergence

The model was designed to explore the change in development location and cadastral form based on developer market structure and behaviour. Therefore changes are expected in the resulting spatial outputs of the model such as the resulting range of development and the development of clusters of urban development well away from the core urban area. These patterns arise based on the collective decisions of the developers based on the accuracy and range of information available to each developer. It is important to note that the 'value' of each cadastral parcel is shaped through the sum of the *combined-attraction* attributes for all cells within the parcel. This 'value' attribute, along with the level of capital available to the developer, inherently constrains the range of decision-making opportunities each developer has.

Adaptation

While all developers have access to the same behaviour, they implement it in different ways, there is a key adaptive trait included in the model. Developers use the *attitude* state variable to decide if development should go ahead at the various stages of the urban development process. If the market is set to be dynamic, this *attitude* variable is altered for all developers at the end of each tick, based on the success of the developer and the current utilisation of their capital resources. This variation in attitude is in response to the developer's perceived level of risk, it makes the developers more discerning in times of economic uncertainty while less so when they have utilised a large proportion of their capital in static land holdings (through landbanking). If the market in the model is fixed, then this *attitude* state variable is fixed to its initialised level throughout the model run.

Objectives

The overall objective of all developers is to make profitable developments so as to increase their capital for future developments. Each developer is assigned attributes controlling how behaviours are implemented in assessing parcels for future profit. Profit is measured through a comparison of the purchase and disposal prices after increases in line with the market have been included. As this model is investigating the spatial (location and form) outcomes of developer market structure and behaviour, housing stock is assumed to be equal in quality and cost and therefore is not included in the disposal price.

Learning

As outlined above, all developers have the ability to change their *attitude* variable if the market is dynamic. The variable is based on three aspects – the successes and failures of their previous developments, their assumption of the market direction, and the utilisation level of their capital. If developers are generally successful and see the market going up in the future, they will be more open to development on a wider range of parcels. On the other hand, the combination of recent failures or a decreasing market will make the developers more cautious and reserved about the development opportunities presented to them.

Prediction

Developer prediction is accomplished through their *accuracy* variable. This variable is based on the level of capital to which each developer has access. It is assumed in the model that the developer with the most capital has access to a wide range of resources to improve their accuracy in assessing the market and future parcel values. If the market within the model is set to be dynamic, then the *accuracy* variable updates at the end of each time step based on the developer's new level of capital. If the market in the model is fixed, the developers' capital is also fixed and the variable does not change after initialisation. At the start of each time step, the *accuracy* variable is used to define a normal distribution for the future market value from which a random draw is taken to be the developers' 'guess' of the future state of the market. This 'guess' as to the market direction for the time step is used throughout the developer selection and subdivision behaviour rounds.

Sensing

The main environmental and state variable each developer is able to 'sense' is the current valuation of any parcel it is assessing for the developer building behaviour. In addition, each developer implicitly 'senses' all parcels up for sale in its territory state variable (Implemented through the BSP tree concept of `LEVEL` – see subsequent chapter for more information). Even though the developer 'senses' all these parcels available for development, the process of the purchase behaviour only assesses them one at a time, finishing once the developer has found a parcel that satisfies current criteria.

Interaction

There are no direct interactions between developers. However, there is indirect interaction through the selection of parcels and the resulting development of parcels.

Because all developers draw from the communal `sites-avail` pool, if two developers would have selected the same parcel to be developed, then the developer who was randomly selected to perform their actions earlier in the behavioural queue would select that parcel. Consequently, the second developer would choose a different parcel (or none) for development.

In addition, if a developer subdivides a parcel close to a parcel being landbanked by another developer, this action indirectly alters the developer's assessment of the landbanked parcel through its proximity to the form of the subdivided parcel. There are direct interactions between each developer and the cadastral parcels they are evaluating and subdividing. Developers can purchase, hold, sell and, most importantly, subdivide any cadastral parcel through interacting with the parcel's corresponding *node*. Through interaction with the *node*, developers are also able to assess a number of variables that are used to calculate the utility of each parcel for development.

Stochasticity

A large proportion of the model is designed to be stochastic and uses NetLogo's random number generator to enable this. The model's structure is designed to replicate the urban development process with a number of stochastic elements used to model events and behaviour with a specified frequency. An example is described in the adaptation section where the *accuracy* state variable for each developer is used in a stochastic random draw from a normal distribution to ensure a constant market outlook for all development decisions that time-step. One of the two layers that contribute to the 'value' of land is based on a random value between 0 & 1. A stochastic element is included along with two other attributes to provide variability in assessing an already purchased parcel for development (within the `suitability-parcel-development` subroutine described below). Completely fixed aspects of the model are the initialisation variables, such as the level of developer competition and the types of behaviours that are in effect for the model run.

Observation

While the development of the landscape can be observed visually, the complexity of the landscape means the underlying structure of development can be missed. Consequently, a number of spatial and aspatial outputs are created for further external analysis. The spatial outputs cover initial and resulting form and area of the urban area along with the areas of change in the urban structure (see section 6.6 for more details of these outputs). The aspatial outputs are internally calculated metrics (within NetLogo) measuring the structure and configuration of the landscape.

Details

Initialisation

After setting the random-seed value and a variety of model initialisation variables (See Appendix A for variables and their use), the landscape for the model is created using a binary space partitioning tree as a surrogate for an urban cadastral pattern (See Chapter 6 for a comprehensive outline on how these are created). Subsequent steps initialise the value for each cell through the calculation of an 'attractiveness' attribute based on a combination of linear decay distance, neighbourhood preference, and a stochastic value that represents local preference. The value for each parcel in the resulting BSP tree landscape is then based on the sum of the 'attractiveness' attribute for all cells within the parcel. Then overall market values are calculated for the duration of the model. These values can either be stochastically derived or a fixed growth value can be used.

Developer entities are one of the final aspects to be initialised within the model. The creation of developers involves the specification of numerous primary and secondary state variables (secondary state variables are derived from primary state variables). Since the way in which capital is used in urban development is a key interest in the model, the distribution of capital is a critical aspect of the initialisation stage. There are two ways capital can be implemented – either through stochastically derived Yule-Simon preferential attachment process (Simon 1955) or through a fixed allotment process that creates a set distribution of capital among the developers. This process defines the number of developers who will act in the model.

After the creation of the developers, two metrics are calculated: the Herfindahl-Hirschman Index (Hirschman 1945) and a measure of distance between each cell to the closest urban cell. The minimum distance to an urban cell metric is averaged across all non-urban cells and is used (along with other metrics) to record change in the landscape. The Herfindahl-Hirschman Index (HHI) is used to calculate the level of developer competition to enable comparisons to be drawn between runs with varying developer market structures (Hirschman 1945). The index is defined as the sum of the squares of the market share for each firm (Equation 5.1).

$$HHI = \sum_{i=1}^{N} S_i^2$$

Equation 5.1: Equation to create a Herfindahl-Hirschman Index (HHI). S = market share

Additional parameters controlling the developer dynamics within the model are specified at the beginning of the run. These Boolean parameters control the way in which the developer behavioural traits are applied. `Assess-Accuracy` controls how the developer is assigned the *accuracy* state variable. If true, the developer assigns the *accuracy* variable in line with the level of capital resources to which the developer has access. If false, all developers have the same *accuracy* state variable. This does not mean that all developers calculate the same value for each parcel, but rather that the developers are all equal in the variability in how they calculate a parcel's value. `Parcel-Assessment` controls the information inputs into the calculation of the desirability of a parcel for purchase. If the variable is false, then the developer only assesses the overall trend of the market, and if it is increasing the parcel is promoted for development. If the variable is true the calculation is more detailed, with the overall trend of the market, the potential number of houses which could be developed on the parcel, the average parcel size of the surrounding parcels, and the parcel's distance to an urban cell all being assessed. `Subdivision` controls the decision to subdivide a developer owned parcel of land. If the variable is false, the assessment only examines the current profit margin. Otherwise, the assessment of profit is examined alongside the gap between the parcel's size and the average surrounding parcel size, and a random stochastic element. The `Territoriality` controls the size of each developer's territory within which the majority of parcels are selected for assessment (through altering the *Territory* state variable). If false, all developers have the same very large territory. If true, the developers are assigned a territory in line with their level of capital (large developers drawing from at least half, if not the whole of the landscape with smaller developers having small neighbourhood-sized territories). The final Boolean value, `Riskiness`, controls the initialisation of the developer's *attitude* variable. If false, all developers are fixed at the initialised value with no differentiation in *attitude* within the model. If true, the *attitude* variable for each developer is stratified in association with their level of capital. Larger developers will have a higher *attitude* value and are therefore more discerning when assessing parcels for purchase. Smaller developers with a lower *attitude* will therefore be more 'risky' through an increased chance of selecting more marginal development opportunities.

Input

This model does not use input data to represent time-varying processes.

Submodels

This section is used to cover the key processes highlighted in the Process overview and scheduling section in more detail. All names in the `Courier New` font can be found in the model's code (Appendix B) for further explanation of how they operate. Each subroutine is commented on within the code to allow the flow of the model to be understood. The model's export and reporting commands are not included here based on their role in describing the model state rather than the running of the model.

`developer-assessment-of-market`

Report a random value from a normal distribution when using the model's *market-future* variable as the mean and the developer's *accuracy* variable as the standard deviation. The value is stored as a developer variable for the current time-step.

`sites-avail`

Report a random percentage of parcels that are not currently owned by a developer. The percentage is set through the global `per-parcels-up-for-sale` variable which is set before initialisation.

`average-level-in-radius`

For each parcel, report the average level for all nodes within a distance 1.5 times the distance between the parcel's node and one of its corners. Run here on all parcels within `sites-avail` to decrease the model's running time substantially. Stored as a parcel variable.

Each developer undertakes the three behavioural stages in order before the next developer undertaking the behaviours.

```
developer-purchase-behaviour
developer-subdivision-behaviour
developer-building-behaviour
```

Since these three behaviours are run in sequence and are closely interlinked they will be discussed as a single subroutine. Because of the nature of these subroutines, the description begins with a review of the process using pseudo-code, while following up with a more detailed description of each step. In addition, a flowchart (Figure 5.2) has been included that outlines the steps undertaken by each developer for each time-step in the model.

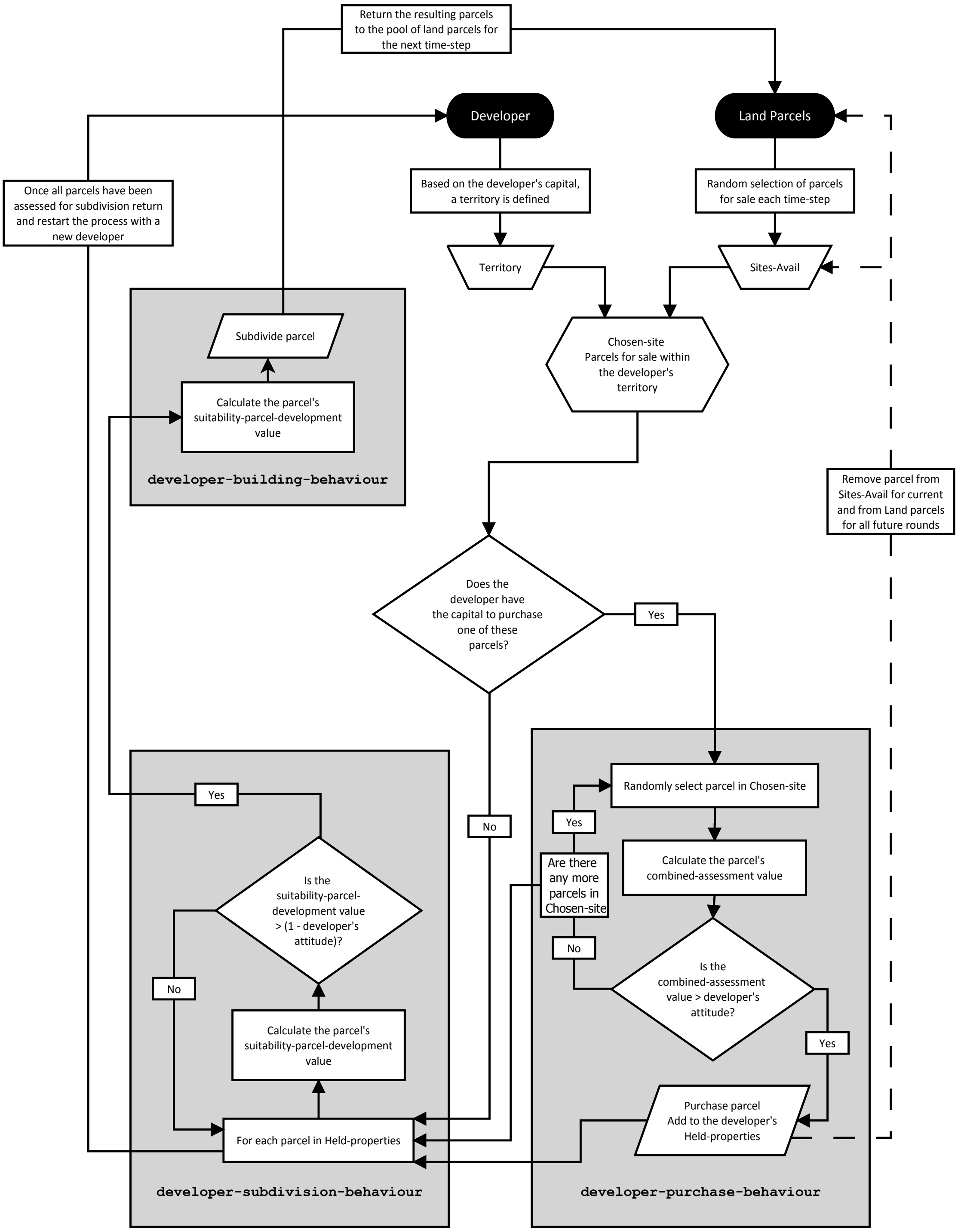

Figure 5.2: Flowchart outlining the process each developer undertakes when developing in each time-step

For each developer

developer-purchase-behaviour

Calculate territory size and number of parcels within the territory. Calculate the developer's *dev-opp-limit* to 25% of the parcels within its territory

Calculate if developer can afford any parcels within the *sites-avail* collection of parcels. If not, then halt this section and move onto the next behaviour

Compare *sites-avail* with parcels in the developer's territory. Put common ones in a collective (*chosen-site*). If required, increase number of parcels in *chosen-site* randomly selected from outside their territory so to meet the developer's *dev-opp-limit*

For each parcel in *chosen-site (in random order)*

Calculate *combined-assessment* for the parcel. If *combined-assessment* value is > the *'attitude'* of the developer then purchase this parcel and halt the evaluation on all remaining parcels.

Add selected parcel (if one is selected) to the *held-properties* of the developer and run developer-subdivision-behaviour

developer-subdivision-behaviour

For each parcel in held-properties

Calculate their *suitability-parcel-development* value. All parcels which have a value > than the inverse of the developer's 'attitude' value (1-attitude) are submitted to the developer-building-behaviour

If no parcels meet this requirement the behaviour round is complete and the next developer begins its behaviour round.

developer-building-behaviour

Calculate the average level of the surrounding nodes (*level-surr-nodes*). Using this value and a bounded stochastic value, calculate the new level of development. Using these values and the unconstrained BSP approach, initiate the subdivision routine (*split*). Update the BSP tree attributes. If the market is dynamic incorporate the profit/loss from the parcel with the developer's capital.

Beginning with the `developer-purchase-behaviour` and using the territory assigned to the developer at the initialisation stage, an opportunity limit (`dev-opp-limit`) is set based on the number of parcels within their territory. A quick check is made to see if the developer can afford any of these parcels through comparing the 'capital' of the developer with the minimum 'parcel-value' of the parcels from the `sites-avail` reporter. If not, this behaviour is halted. All parcels in the `sites-avail` reporter are then compared with their territory. Parcels found in both are included in the parcels to be assessed for purchase (`chosen-site`). If the resulting number of parcels is less than `dev-opp-limit`, then random parcels outside the developer territory are included from `sites-avail` to meet the opportunity limit. This approach mimics how developers would respond to a lack of development opportunities within their territory.

In a random order, each parcel in `chosen-site` is assessed based on four criteria (`combined-assessment`): overall trend of the market; the potential number of houses that could be developed on the parcel; the average parcel size of the surrounding parcels; and the parcel's distance to an urban parcel. All values are scaled to between 0 and 1. Combining and rescaling the four values produces a value that is compared against the developer's *attitude* variable. If the parcel's value is higher, the parcel is purchased and stored in the developer's `held-property` variable and is removed from the `sites-avail` collective. Once a parcel has been selected for purchase, the subroutine is halted and the remaining parcels are not evaluated for purchase. This 'one parcel per time step' rule was based on developers maximising their utility through the application of their capital in line with economies of scale. While the approach implemented within the model is a slight abstraction of reality, this approach is in line with the behavioural literature on developers (Chapter 4). The `developer-subdivision-behaviour` is then run.

The `developer-subdivision-behaviour` begins with a comparison of all parcels owned by the developer. This comparison (`suitability-parcel-development`) returns a value between 0 and 1 that evaluates the current development potential of the parcel and the estimated profit of the parcel based on the developer's 'accuracy' in assessing the market since the parcel's purchase. A single stochastic value is also included 25% of the time to represent a 'shock' state with the developer. Using a subdivision threshold (which represents the inverse of the developer's *attitude* variable), each parcel that has a higher value than the threshold will be subdivided and is run through the `developer-building-behaviour`. If no parcels meet this requirement then the developer's behavioural round is over and the next developer begins. For reference, a 'soft' limit on the number of parcels an agent is allowed to 'own' is included in the model. This is done though a small reduction in each developer's threshold for subdivision for each parcel they currently 'own' that exceeds five parcels.

The `developer-building-behaviour` starts with the calculation of the level of the surrounding parcels. Then, using a bounded stochastic process, the developer selects a level of development that is at least the average level of the surrounding nodes. The node is then submitted to the subdivision subroutine for the formal division of parcels. Once the formal subdivision of the parcel has finished, the BSP tree attributes are updated while the profit or loss from the development of the parcel is incorporated into the developer's capital variable.

All parcels owned by a developer are run through the `developer-subdivision-behaviour` to be assessed for subdivision. Once all parcels have either been subdivided or assessed for subdivision, the behaviour round for this developer ceases and the next randomly selected developer begins.

5.5 Conclusion

Through the use of the ODD protocol, this chapter described the structure of the multi-agent model of residential developer behaviour. In addition, questions about the choice of the modelling platform and the representation of key elements within the model have been answered. The following chapter will explain how the unique structure of the landscape that the agent-based model runs on is created and how the underlying framework of the landscape is used by developers to subdivide land. The chapter also outlines how the landscape is exported and used to examine the resulting structural changes in the model caused by developer competition and behaviour.

6 Urban landscapes and developer subdivision through binary space partitioning

For the human mind, the tree is the easiest vehicle for complex thoughts.
But the city is not, cannot and must not be a tree

If we make cities which are trees, they will cut our life within to pieces

(Alexander 1965, p. 62)

It might seem strange to start the chapter with a quote that disputes the basic premise of how this research structures the urban landscape. However, it is interesting to note that the primary process of property development is the cutting of land into pieces within which we play out our life. The most common piece of land developed is the residential home and it is a common goal for most people to own their own home. People choose the location and type of housing to satisfy the requirements of their life. From this perspective, residential subdivision can be seen as the necessary 'cutting' of land to enable life to be lived. From an abstract perspective, residential subdivision can also be seen as a tree, because at one point in time the numerous lots of a new subdivision were a single parcel of land. While it is not the intention of this chapter to dispute Alexander's claim, this thesis will pursue the belief that the city can be viewed as a tree in a particular way, primarily for the reason that he states – the city is a complex system and a tree is a useful method for its visualisation.

In creating a model to examine how developer market structure and behaviour have an effect on development patterns, two key components are required. The first is an agent-based model that represents the decision-making architecture of the types of residential developers. The second is a representation of space that enables the developer agents to make decisions, in the case of this research the landscape would represent cadastral parcels. These two components are integrated through the development of dependencies and feedback loops between the agents and the landscape (Parker et al. 2003), creating demand and areas of attractiveness for the developer. The interacting components in these types of models generate behaviour that can be observed, compared and evaluated (Manson 2001). In creating the types of developers there are set differences (imposed differences in the agents structure) and behavioural differences (Jager and Janssen 2003, Occelli and Staricco 2005).

Creating a realistic representation of urban cadastral spatial patterns is problematic. Using existing development as a starting point for testing models of urban growth may introduce inherent biases based on the city chosen. To remove these biases, a method for repeatedly generating a plausible urban cadastral pattern is required. Binary space partitioning (BSP) trees have been used to quickly generate a representation of the cadastral spatial pattern seen in cities (Morgan and O'Sullivan 2009). This approach, which has links to quadtrees and binary trees used in computer science, introduces the standard topologic elements (leaf nodes, children, root node, ancestors, descendants and levels) while also incorporating the spatial element of territory. This BSP tree approach can be used to create many similar and realistic urban spatial patterns on which an agent-based model of the purchase, subdivision, building and disposal behaviours of property developers would operate.

The subdivision of land is a key aspect of urban development. Consequently, a secondary motivation for implementing a BSP tree approach was the ability for the developer agents to be able to understand, analyse and enact the mechanism of subdivision within the resulting urban pattern. From a programming perspective, implementing agent decision-making to assess when a developer should develop a parcel is relatively straightforward, but converting that decision to how a subdivision should be spatially arranged is more demanding. This chapter discusses the use of binary space partitioning (BSP) trees to resolve both these requirements.

The last section of this chapter covers the landscape types that can be exported for analysis and the process through which these landscapes are analysed to examine how development activities alter the landscape.

6.1 Spatial representation

In creating a BSP tree to represent urban landscapes for the model, an early decision was made to develop the model with an abstract raster representation of space. Space in an agent-based model serves two purposes: first it bounds the agents and second it defines the spatial relationships between the agents (Crooks 2007), in this case the ownership of cadastral parcels. From a social science perspective, a cellular representation of space is the most widely used approach for the creation of spatially explicit agent-based models. Raster, the most common implementation of cellular space, is a uniform matrix of cells organised into rows and columns where each cell holds information about the landscape within the cell. Multiple layers of information can be added to the raster space as attributes to represent different characteristics of the space. In the case of this research, the information could be layers such as land use, attractiveness and land value.

As discussed in Chapter 2, from an urban perspective the advantages and disadvantages of cellular approach are well documented (Batty et al. 1998). The key point in this approach is that it removes a level of geometric detail and oversimplifies the complex geometries of the city (Batty 2005, Crooks 2007). While agreeing with this viewpoint for operational models, Benenson et al. (2005) state that for a theoretical application of a spatial agent-based model, the points of a cellular grid will suffice. Even so, the inflexibility of a cellular grid restricts the process of urban development through the inability to allow actions, such as subdivision, to be performed on the landscape. Creating a spatial representation that allows developer agents to understand and enact the process of development was required to meet the goals of this research. The approach that was found that met these requirements begins with the tree like data-structures found in computer science.

6.2 Tree data-structures

Tree data-structures are widely acknowledged as “the most important nonlinear structure arising in computer algorithms” (Knuth 1997, p. 308). From a general perspective, a tree-structure represents a linked relationship between nodes (Figure 6.1). A *node* is a basic unit within a tree data-structure. It is a placeholder for data but can also contain links to other nodes which in themselves can link to other nodes. The two-way formalised *link* in the tree data structure joins *parent* nodes with their *children* (usually a one-to-many relationship) and vice-versa (always a one-to-one relationship). The initial topmost node of the tree, called the *root-node*, is a unique node as it does not have a *parent* node; however, all subsequent nodes can be reached from it by following the links. The number of children each node has defines the *degree* of the node; a *node* that has four *children* has a *degree* of 4. A *node* that has a *degree* of 0, and hence no children, is called a *leaf-node*. For a formal description of tree data-structures, see Knuth (1997 – section 2.3) and Weiss (2002, p. 105–108).

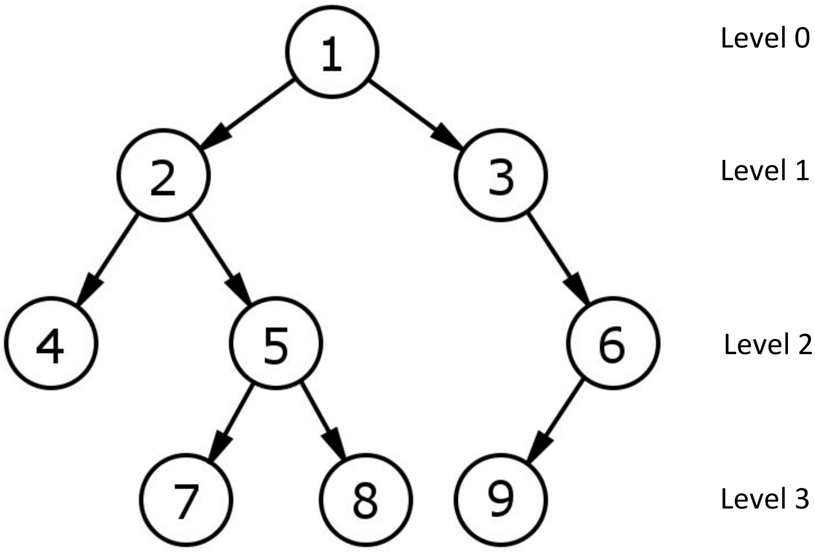

Figure 6.1: Basic tree data-structure, in this case a binary tree. Node 1 is the root-node, with nodes 4, 7, 8 and 9 being leaf-nodes. Node 5 has two children, nodes 7 and 8. Node 6 is the parent of node 9.

Binary trees are trees where no node can have more than two children (Weiss 2002). There are numerous implementations of binary trees in theory and in practice (Amatulli et al. 2006, Cormen et al. 2001, Knuth 1997, Matsuyama et al. 1984, Samet 2006, Surkan and Kelton 1974). The term 'space partitioning' represents the class of hierarchical tree-based data-structures that split a Euclidian space into two or more distinct regions (Aref and Ilyas 2001). The number of partitions and the way the space is split differ between tree data-structures. The process results in non-overlapping regions where any point from the original space can be explicitly assigned to one of the regions. As Aref and Ilyas (2001) point out, if the principle of splitting the space is dependent on the input data, the splitting is *data-driven*, while if it is dependent on the space, the splitting is *space-driven*. Two relevant *space-driven* partitioning trees are quadtrees and binary space partitioning trees.

A *quadtree* (Figure 6.2) is a rooted tree in which every internal node has the possibility of either four children or none (Samet 1984). Each node in the quadtree refers to a region on 2D space (called quadrants – usually labelled NE, NW, SW and SE). Quadtrees can be viewed as a spatial alternative to a binary tree where 2D space is partitioned recursively into four orthogonally split equal-sized quadrants to cover the relevant data.

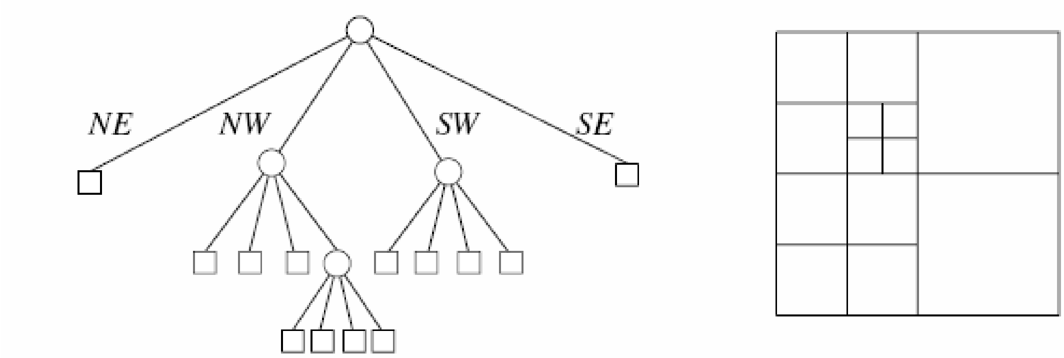

Figure 6.2: Quadtree implementation. Image sourced from de Berg et al. (2008)

Quadtrees were one of the first data structures for higher dimensional data, developed by Finkel and Bentley (1974). Since then, there have been a number of papers discussing quadtrees. Most applications are found in computer graphics and image analysis, but Geographic Information Science implement quadtrees extensively, such as in the visualization of 3-dimensional urban scenes (Ai and Zhang 2007, Koldas et al. 2007, Lee et al. 2006) or terrain visualization (Pérez et al. 2004, Zhao et al. 2006). A current ubiquitous example of quadtrees can be seen in online map databases such as Google Maps and Microsoft's TerraServer (Barclay et al. 2000).

Binary space partitioning (BSP) trees represent a recursive, hierarchical partitioning (or subdivision) of n-dimensional space into two convex subspaces until the partitioning satisfies a pre-existing requirement (Fuchs et al. 1980, Huerta et al. 1997). A BSP tree can also be viewed as a rooted binary tree designed to organise objects within a space through the allocation of an ordered level of space (Figure 6.3). Therefore each leaf node within the underlying binary tree corresponds to one of the resulting subdivided spaces.

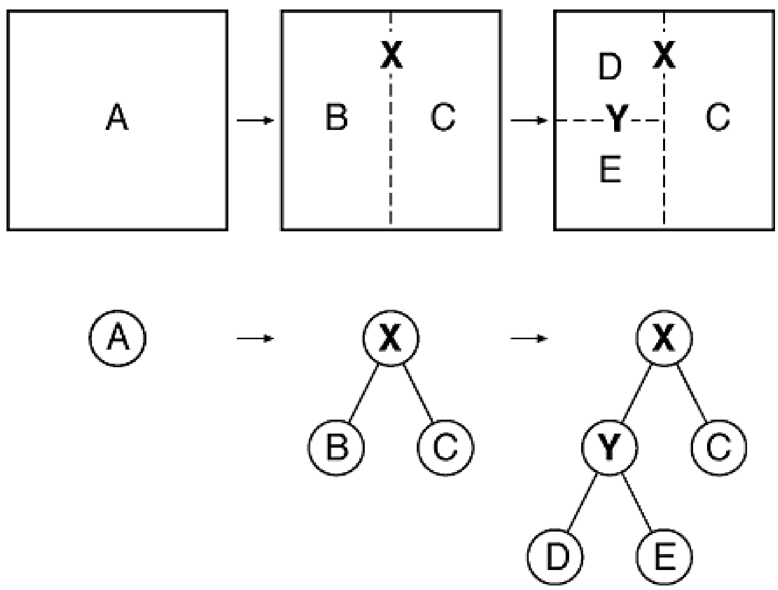

Figure 6.3: Binary space partitioning. Image sourced from (Wade 2001)

BSP Trees are widely used. Their main application is in computer graphics, with examples including the generation of 3D visualisations (Budge et al. 2008, Gordon and Chen 1991, Ize et al. 2008, Lee et al. 2008) shadow generation (Chin and Feiner 1989), removal of obscured objects (Fuchs et al. 1980) and collision detection in 3D spaces (Melax 2000). Geographic applications of BSP trees are found in the visualization of 3-dimensional urban scenes (Ai and Zhang 2007, Koldas et al. 2007, Lee et al. 2006) and have recently been used to create 3D models from LIDAR data (Sohn et al. 2008).

6.3 Theoretical implementation

To examine the way in which the BSP tree is generated to represent an urban spatial pattern, a pseudo-code summary of the actual implementation is presented in Figure 6.4.

```
CITY AND BINARY TREE GENERATION

 1   Let WORLD-SIZE be the size of the grid on which the tree will generate
 2
 3   Let CITY-SIZE be the size of the city you wish to generate (as a proportion)
 4
 5   Let LEVELS be the maximum level of development
 6
 7   Create single node (ROOT) at the centre of the world
 8      Set TERRITORY = all grid-cells
 9      Set CORNER-COORD = grid-cell closest to ROOT
10      Set CHILDREN = null
11      Set PARENT = null
12      Set IS-LEAF = false
13      Set LEVEL = 0
14
15   Set CURRENT-LEVEL = 1
16
17   WHILE [ CURRENT-LEVEL <= LEVELS ]
18      FOREACH node with [ IS-LEAF = false and CHILDREN = null ]
19         DO
20            IF ( Random Floating Number between 0 - 1 ) < CITY-SIZE -
21            ( distance from nodes' CORNER-COORD to ROOT / maximum distance to ROOT )
22               Create child-1-node
23                  Set PARENT = the calling node
24                  Set TERRITORY = orthogonal half of TERRITORY of PARENT
25                  Set CORNER-COORD = grid-cell within TERRITORY which is closest to ROOT
26                  Set IS-LEAF = false
27                  Set LEVEL = CURRENT-LEVEL
28               Create child-2-node
29                  Set PARENT = the calling node
30                  Set TERRITORY = other orthogonal half of TERRITORY of PARENT
31                  Set CORNER-COORD = grid-cell within TERRITORY which is closest to ROOT
32                  Set IS-LEAF = false
33                  Set LEVEL = CURRENT-LEVEL
34               Ask PARENT to Set CHILDREN = child-1 and child-2
35            ELSE
36               [ set IS-LEAF = true ]
37            ENDIFELSE
38         ENDDO
39      ENDFOREACH
40      Set CURRENT-LEVEL = CURRENT-LEVEL + 1
41   ENDWHILE
```

Figure 6.4: Pseudo-code of BSP tree implementation

Initially three external parameters must be defined before generating the pattern (lines 1–5). The first is `WORLD-SIZE`, which controls the grid on which the tree will generate. The tree requires a cellular space whose edge length is an exact power of 2. The second is `CITY-SIZE`, which controls the size of the urban core in the generated urban pattern. Finally, LEVELS is used to limit the number of levels the binary tree will create. From an urban cadastral pattern perspective, the LEVELS parameter controls the maximum density of the parcels in the pattern.

Once the three parameters have been set and the process has begun, the root node is created and assigned attributes such as its NODE-LEVEL (which will be 0), whether it is a leaf-node (IS-LEAF) and the links to its CHILDREN and PARENT nodes (lines 7–13). In addition to these attributes, the node also has two spatial attributes, TERRITORY (at this stage the node is assigned all of the grid cells) and the CORNER-COORD (the individual grid-cell which is closest to the root node).

The algorithm tracks the number of levels of partitioning that have occurred using the variable CURRENT-LEVEL. While CURRENT-LEVEL is less than or equal to LEVELS the partitioning code executes (lines 17 and 18.). At this stage all non-leaf nodes (IS-LEAF = False) that do not have any children (CHILDREN = null), are evaluated against a linear distance-weighted equation (Equation 6.1) with a probability of partitioning dependent on their distance to the root node. It should be noted that using both the IS-LEAF and CHILDREN tests are not required to create a BSP tree (the IS-LEAF test will suffice), but both are required when the developer agents use the BSP approach to subdivide parcels.

$$\Delta_{\mathrm{d}} = \frac{\mathrm{d}_{\mathrm{root}}}{\mathrm{d}_{\mathrm{max}}}$$

Equation 6.1: Linear distance-weighted equation

The distance-weighed equation (lines 20 and 21) is calculated as follows: first, the distance between nodes' CORNER-COORD and the root node ($\mathrm{d}_{\mathrm{root}}$) is divided by the maximum distance to the root node (the distance from the corner of the world to the root node or $\mathrm{d}_{\mathrm{max}}$). This creates a value (Δ_{d}) that is then subtracted from existing value within the CITY-SIZE variable (lines 20 and 21 and Equation 6.2).

$$\mathbf{U(0,1)} < (\ \mathbf{CITY\text{-}SIZE}\ -\ \Delta_{\mathbf{d}})$$

Equation 6.2: Wider function which governs the partitioning of the tree data structure

At this stage, if the uniformly distributed random number (defined in Equation 6.2 as $\mathrm{U}(0,1)$) is the higher of the two numbers, this branch of the binary tree is halted at this node and the nodes leaf-node attribute (`IS-LEAF`) is set to true (line 36). However, if the random number is less than the result of the distance-weighed equation, the binary tree continues. The use of the `CITY-SIZE` variable allows the user to define the size of the central urban core in the resulting urban pattern. Any value exceeding 1.00 will force a proportional area surrounding the `ROOT` node to be partitioned down to a level matching the `LEVELS` variable.

If partitioning occurs, two new nodes are created, and are linked to their parent through their `PARENT` attribute (lines 22–33). Using the link to the parent, the existing parent's territory is orthogonally halved and assigned to each new node. Three attributes are set for the new node. The node's `LEVEL` is set to `CURRENT-LEVEL`; `IS-LEAF` is set to false; and the `CORNER-COORD` attribute is set to the new node's closest grid-cell to the root-node (`ROOT`). Finally, the `PARENT` node is updated to reflect the two children that have been created (line 34).

After the partitioning of all of the nodes that meet, the `IS-LEAF = False` and `CHILDREN = null` criteria are completed, the `CURRENT-LEVEL` variable is increased by 1, and the process begins again (line 40). When `CURRENT-LEVEL` equals the required `LEVELS` parameter value, execution terminates.

6.4 Implementation within NetLogo

The modelling platform used to implement this approach is NetLogo, a multi-agent modelling platform developed by Northwestern University (Sklar 2007, Wilensky 1999). As discussed in Chapter 5, NetLogo is a 'sandbox' type modelling environment that is both easy to use and fast enough to prototype theoretical models (Railsback et al. 2006). NetLogo contains two types of agents, turtles and patches. Turtles are agents that move around in the world. The 'world' is a two dimensional plane divided into a uniform grid of cells known as a patch within NetLogo. Consequently, each patch is a square piece of "ground" over which turtles can move, interact, and undertake activities.

Using these two types of agents, a BSP tree can be created. The nodes of the binary tree are represented as turtles that are located at the centre of the parcel they are representing. Parcels are the visual representation of the leaf-nodes within the binary tree. In this framework, parcels consist of a number of patches. Given the binary nature of the BSP tree, every parcel will be restricted to numbers of patches that are an exact power of two, from a single patch to the entire 'world' if the tree only contains a root node. Note that this is in line with the world dimensions being an exact power of two.

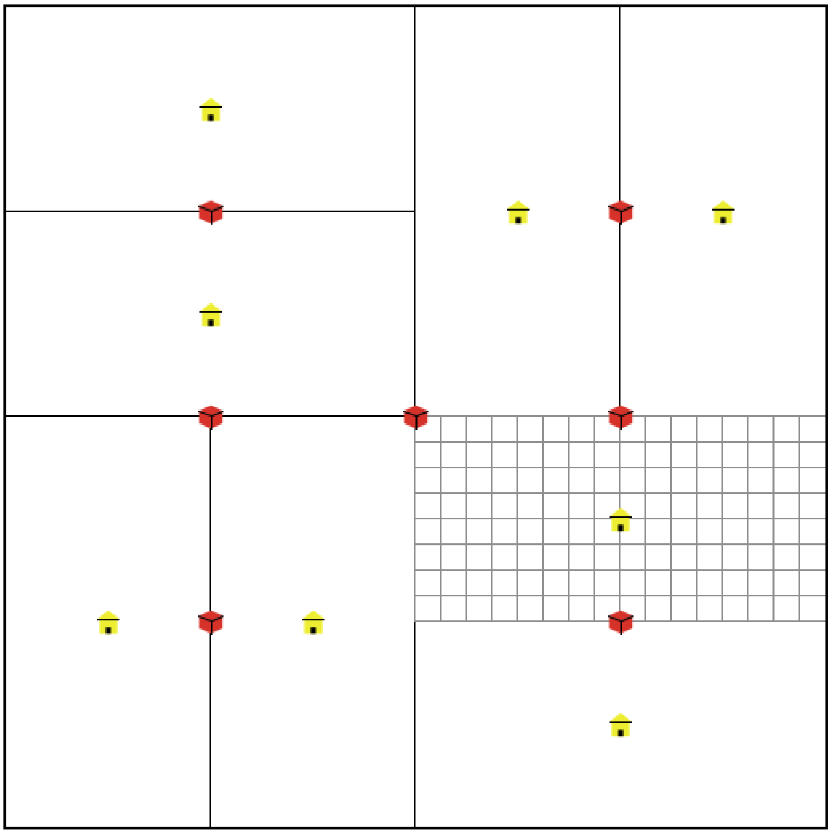

Figure 6.5: Four level BSP tree represented in NetLogo.

Figure 6.5 shows a four-level BSP tree created within NetLogo. Leaf nodes are represented as yellow houses, with non-leaf nodes being represented as red boxes. The `ROOT` node is shown at the centre of the image. Each node has a spatial 'territory' called a parcel. A parcel consists of a number of patches. In the image, one parcel has highlighted all their associated patches for reference (in this case, 128 associated patches).

From a procedural perspective, the code to create a BSP Tree in NetLogo is generally in line with the process described in the pseudo-code (see Appendix B to review the code). The two key changes are the `MAX-PARCEL-SIZE` variable and the additional code and attributes used to accurately partition each node's territory.

Implementing the BSP tree exactly as described in the theoretical implementation section allows cases where a node close to the root node is not further partitioned, resulting in unrealistic situation where a very large cadastral parcel is in the city's 'downtown'. To avoid this problem, the tree is partitioned down to set `LEVEL` determined by the `MAX-PARCEL-SIZE` variable. Once this has been carried out, further partitioning is dependent on the distance-weighed equation being invoked. This addition improves the comparison between the resulting BSP trees and real urban spatial patterns.

Additional code in the NetLogo implementation ensures that the splitting of the trees is performed correctly. Two additional node attributes (`Horz?` and `Square?`) are Boolean variables used to capture the orientation of the node's parcel. If the parcel is square, a random decision is made in regards to the parcel splitting either North–South or East–West. If `Horz?` is true, then the parcel is oriented East–West and will be subdivided North–South to bring it back to a square. If `Horz?` is false, the parcel is oriented North–South and the subdivision will be East–West.

6.5 Results

The results of the BSP tree implementation are extremely varied, even based on the simple three parameters discussed earlier in this chapter. This provides the variety of patterns required for use within the agent-based model.

The initial impression is that the implementation produces a mono-centric urban spatial structure (Figure 6.6), in line with the fractal city growth that Batty and Longley (1994) discuss. The fringe of the urban core has an increasing prevalence of larger parcels, but spindles of development extrude out into the relatively undeveloped land. These spindles of smaller parcel size resemble the intensive development along transport corridors seen in numerous cities. From the perspective of its use within the developer behaviour model, the resulting landscape provides a wide variety of opportunities (urban core, fringe, exurban and greenfield areas) for the developer to assess, purchase and subdivide.

The resulting spindles of smaller parcels out from the central core (seen in both Figure 6.6 and Figure 6.8) and areas that resemble exurban settlements arise because of the iterative process within the BSP tree. If a large parcel, well outside the central core, is successful in the distance-weighted equation, the parcel's two children will also have an opportunity to be partitioned themselves. This process creates an iterative feedback effect that increases the chance that part of the original parcel is partitioned down to the next level of the tree. Through the use of the `CITY-SIZE` parameter, the size of the urban core can be varied to suit any configuration required. Figure 6.7 highlights this variation.

The inherent flexibility of the BSP implementation can be scaled up to simulate a large 'city' structure (in excess of 200,000 urban parcels). However, with each additional level added to the tree (which increases the quality and size of the modelled landscape) the computational overhead in creating the BSP tree doubles. With a full binary tree implementation, each additional level on the tree increases

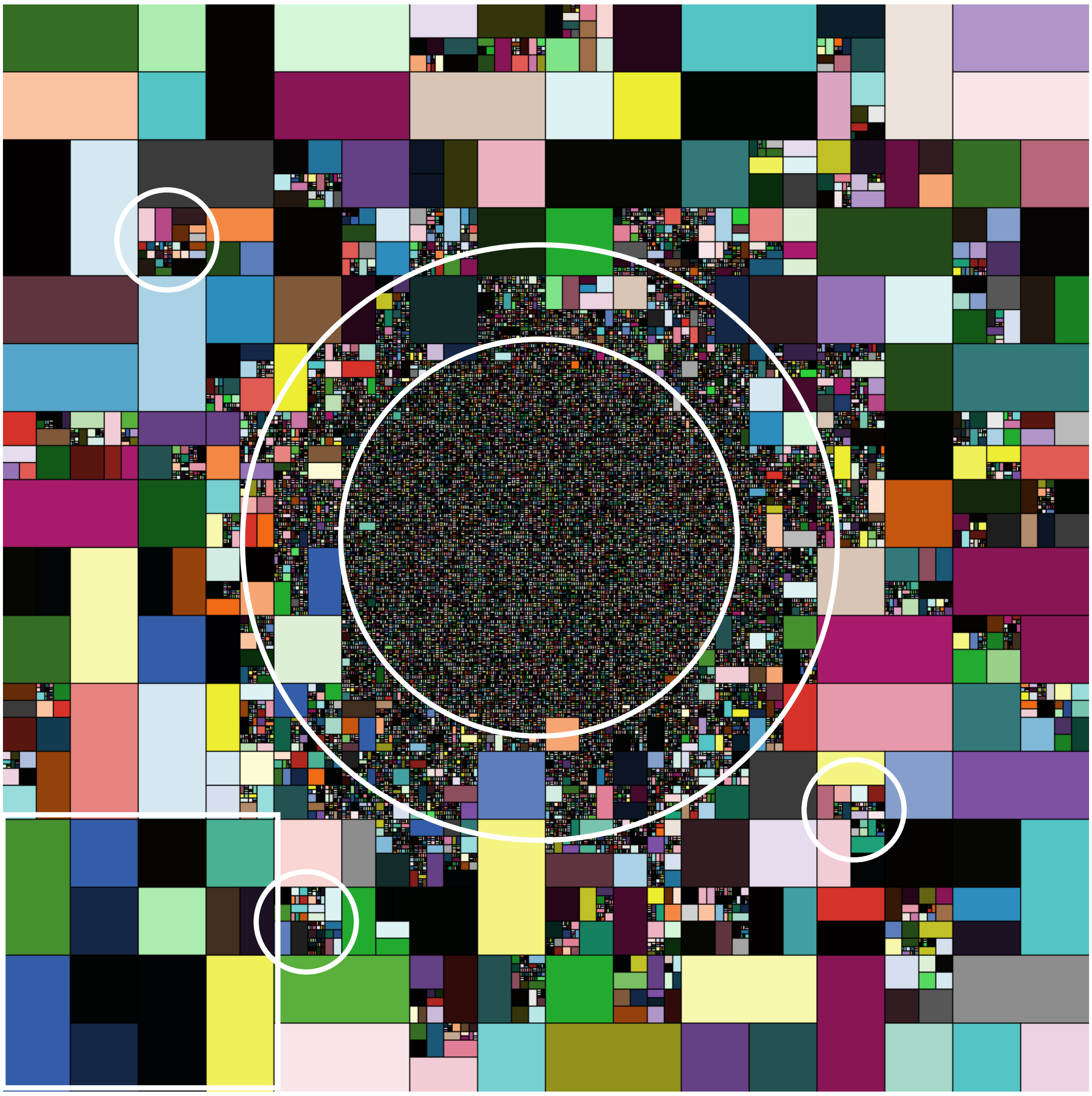

Figure 6.6: Representative forms of the resulting urban landscape. Note in this image all parcels are outlined for visibility. (Inner circle = urban core; Outer circle = urban fringe; Small circles = exurban; Square = greenfield)

the number of nodes by *n*+1 where *n* is the number of existing nodes in the entire tree.

To overcome this computational overhead, the BSP tree can be configured to create a landscape that is an exact quarter of the mono-centric city (Figure 6.8). This approach still follows the same process as that used to create the images seen in Figures 6.6 and 6.7. In implementing a quarter landscape, the benefit of a BSP approach is readily apparent. The only change to the model is in placement of the initial root node to one of the corners and away from the centre of the 'world'. This

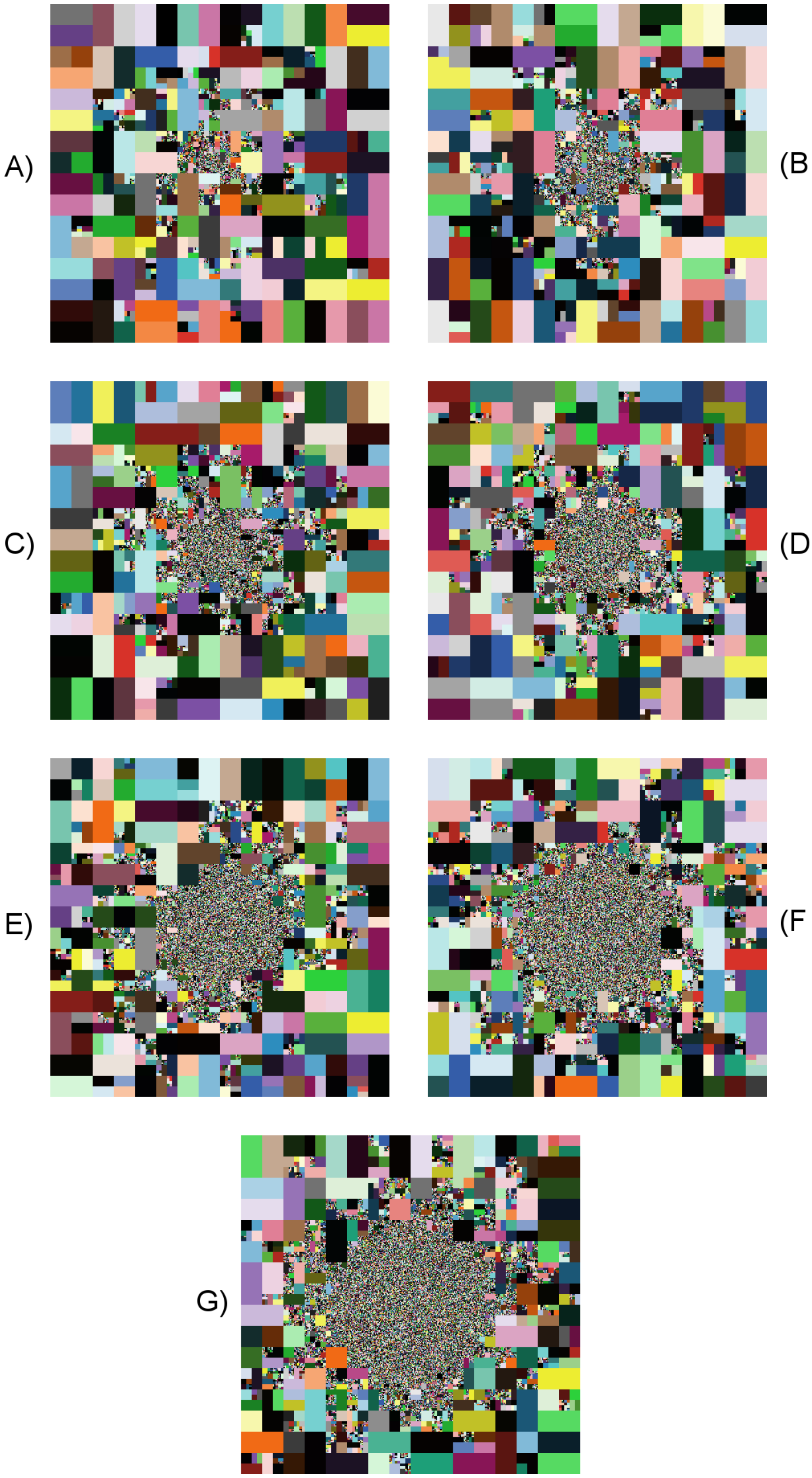

Figure 6.7: Urban Patterns resulting from a BSP tree using a distance-weighted linear equation. Using the `CITY-SIZE` parameter increases the size of the city (A – no extra weighting (1.00) through to G – a `CITY-SIZE` value of 1.30).

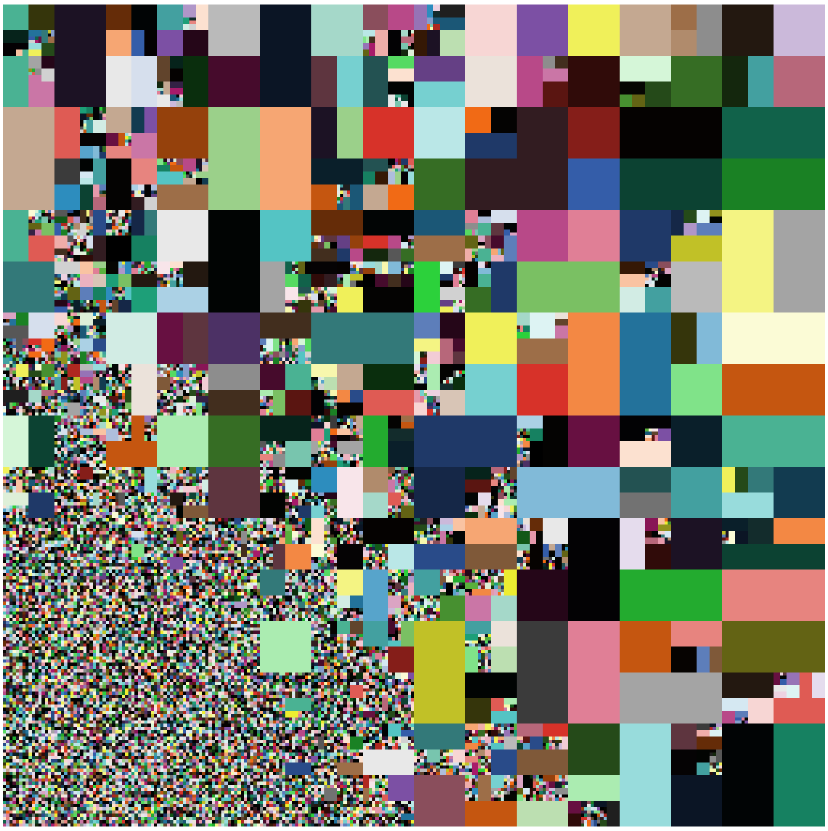

Figure 6.8: BSP tree with the lower left corner as the root-node

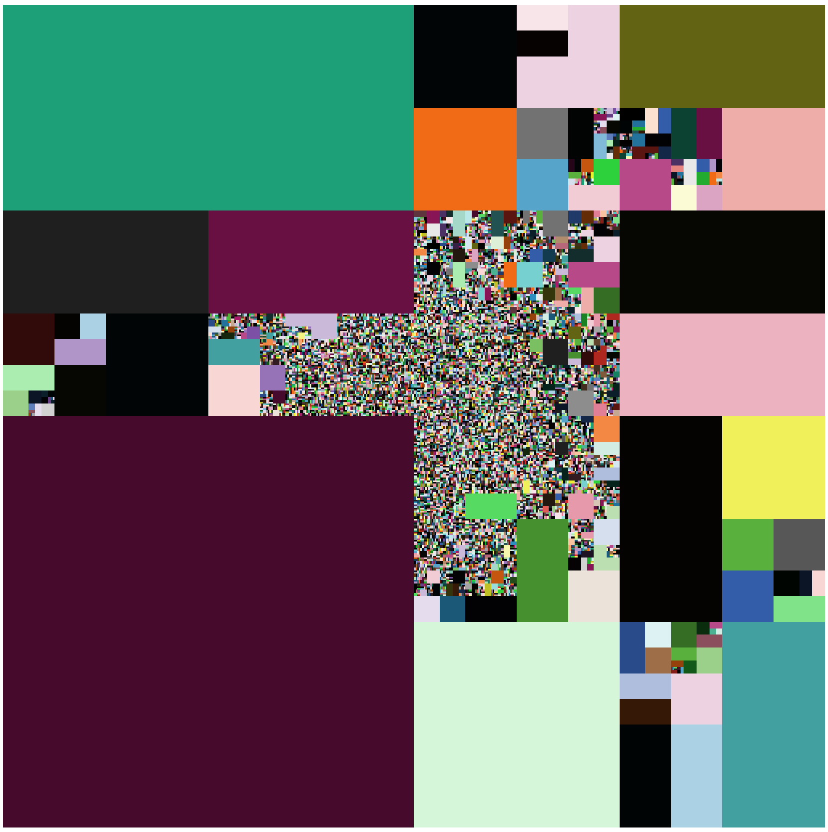

Figure 6.9: Un-seeded BSP Tree within NetLogo

change in landscape increases the speed at which the landscape is created while also improving the execution time of the model that runs on this landscape (because of the smaller number of nodes to analyse and process). Results from the agent-based model can still be extrapolated to a wider 'city' if required.

The BSP tree approach also has limitations. As previously described, if the tree is not forced to partition through the use of the `MAX-PARCEL-SIZE` variable, BSP trees where a node close to the root node is not partitioned sometimes result in unrealistic situations where a very large cadastral parcel is in the city's 'downtown' (Figure 6.9). Consequently, the `MAX-PARCEL-SIZE` variable is usually set to a more representative value that at the most creates parcels that contain 512 or 256 patches.

Because the creation of the BSP tree is reliant on a substantial number of random number requests within the distance-weighted equation, altering NetLogo's random seed value will produce different spatial patterns for each seed value. This gives the model scientific repeatability through the ability to create the same cadastral pattern for testing various behavioural or competition traits.

Pattern variations

The underlying structure of the BSP tree approach allows for substantial variation in the types of patterns generated. There are two approaches to creating the patterns, equation-based or map-based. While the above implementation uses a linear weighting, altering the equation produces a variety of alternate patterns.

Figure 6.10 highlights the resulting patterns when the distance-weighted equation is altered. Moving from left to right, the images show an increased core city area that corresponds to an increased value of the `CITY-SIZE` parameter. The first line of images is the linear implementation described above (Equation 6.1). The second line of images shows a natural logarithmic ($\log_e$) transform (Equation 6.3). This equation produces a sharp drop off in the size of the parcels, effectively ignoring any parcel outside the area forced to partition because of the `CITY-SIZE` parameter.

$$\Delta_{\mathrm{d}} = \left(\log_e \frac{\mathrm{d_{root}}}{\mathrm{d_{max}}}\right)$$

Equation 6.3: Natural logarithmic transform of the distance weighted equation

The third line of images implements a sine function on the distance-weighted function (Equation 6.4). This equation produces a disparate pattern with no central core and development occurring in strings at right angles with existing development. The pattern is reminiscent of development located in close proximity to transportation infrastructure such as highways or railway lines. The pattern becomes increasingly dense, with an increased `CITY-SIZE` parameter.

$$\Delta_{\mathrm{d}} = \left(\sin \frac{\mathrm{d_{root}}}{\mathrm{d_{max}}}\right)$$

Equation 6.4: Sine function of the distance weighted equation

Finally, a combination of two functions ($\log_e$ and cosine) produces an inverse pattern to the distance-weighted linear equation (Equation 6.5), where development surrounds an existing 'rural' area. This landscape pattern could also be used to examine the interactions of multiple urban cores on the resulting development pattern.

$$\Delta_{\mathrm{d}} = \left(\cos \frac{\mathrm{d_{root}}}{(\log_{\mathrm{e}} \mathrm{d_{max}})}\right)$$

Equation 6.5: Combined Cosine and natural logarithmic transform of the distance weighted equation

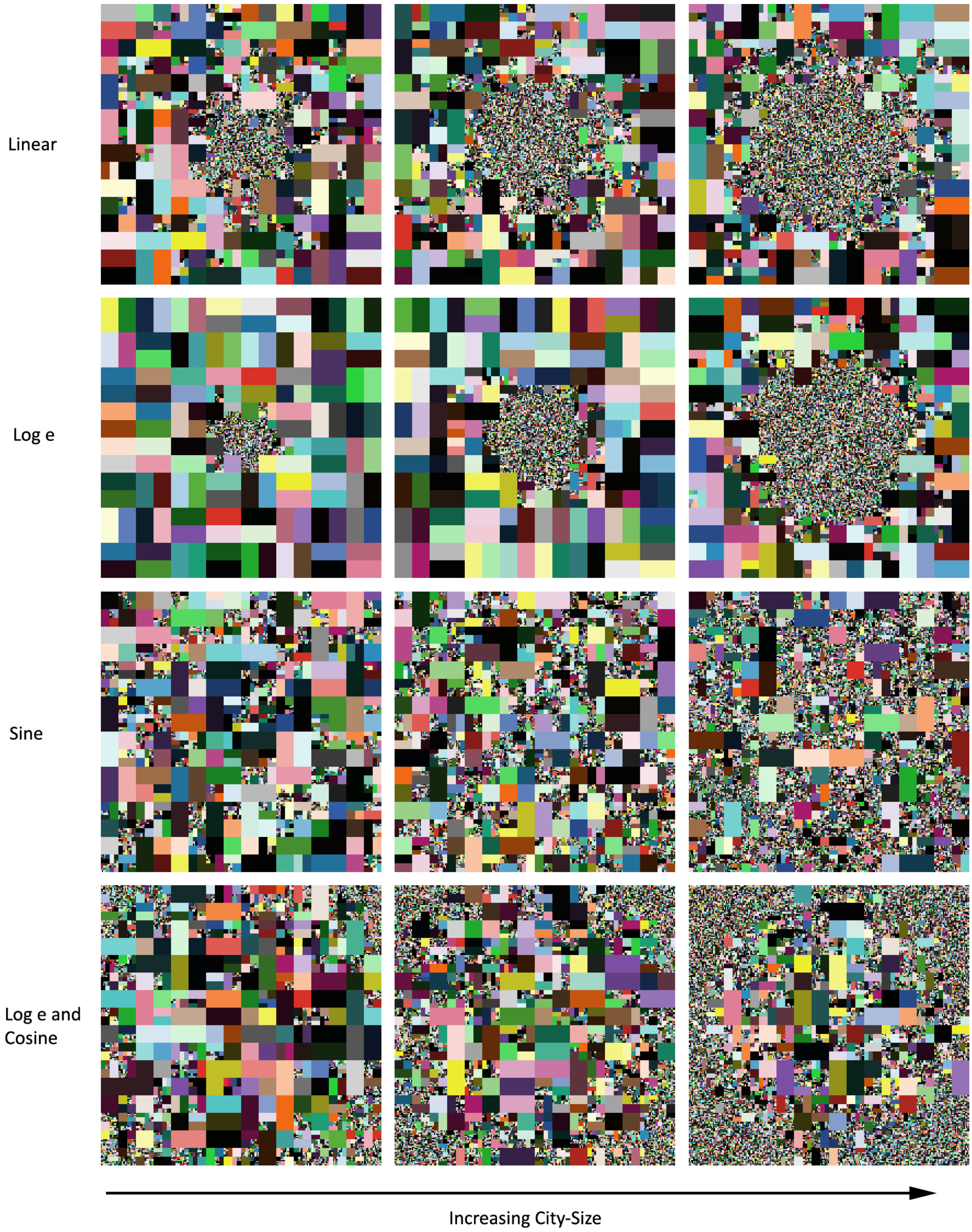

Figure 6.10: Resulting patterns from changes in the equation used in its creation

Controlling the fractal nature of the resulting urban landscape can be accomplished through including a power transform on the distance-weighted equation. Figure 6.11 shows the resulting patterns of these increases alongside an increase in the `CITY-SIZE` parameter. All the resulting landscapes show the common monocentric pattern, with the strength of this pattern decreasing with lower levels of `CITY-`

SIZE parameter. The increase in power produces a more fractal arrangement of smaller 'urban' parcels. As with the distance-weighted linear equation, the trees produced using the BSP approach are unique as they require a supply of random numbers. Altering NetLogo's random seed value before the creation of the BSP tree will produce a different spatial pattern for each seed value.

$$\Delta_{\mathrm{d}} = \left(\frac{\mathrm{d}_{\mathrm{root}}}{\mathrm{d}_{\mathrm{max}}}\right)^{x}$$

Equation 6.6: Power transform of the distance weighted equation where x signifies the power used.

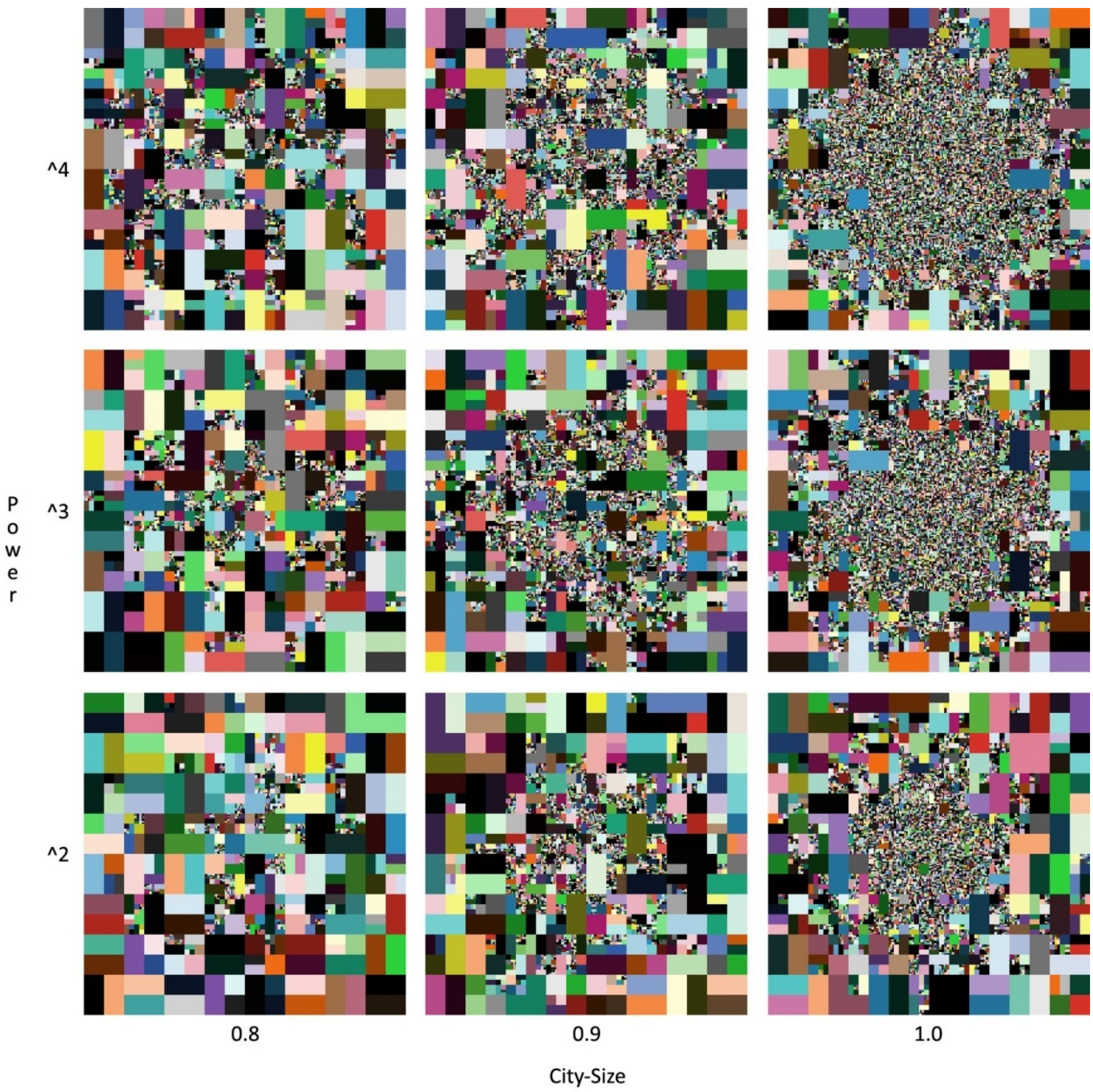

Figure 6.11: Changes in the resulting pattern with increase in power transform used

Partitioning maps

Instead of an equation-based approach to building the BSP tree, a map of areas that should be partitioned can be used to shape the tree to a user's specification. Using the cellular environment inherent within NetLogo each cell can be given a weighting that signifies the LEVEL of the tree down to which this cell should be partitioned. In the partitioning process each NODE, using its CORNER-COORD cell, queries a LEVEL value from the partitioning map. The NODE will continue to partition until the node's LEVEL value is equal to the partitioning map LEVELS value.

Figure 6.12 showcases this approach, with the partitioning maps on the left and resulting BSP trees on the right. The upper left image shows a linear decay distance map (decreasing cell values away from the centre of the image) with the resulting BSP tree shown on the upper right. The resulting BSP tree mimics the decay with increasing parcel sizes outwards from the ROOT of the tree. Darker areas on the lower left image represent areas to be partitioned more intensively. The resulting BSP tree (lower right) shows this with areas corresponding with the darker patches being partitioned more comprehensively than the lighter areas.

With the addition of NetLogo's GIS extension (Russell and Wilensky 2008) cadastral data can be imported into NetLogo to form a partitioning map for a real-world area. Each vector cadastral record is rounded to a number of pre-determined parcel areas (Such as 400, 800, 1600, 3200 square metres, etc.) and given a LEVEL value associated to each parcel area. These parcel sizes are in line with the 'power of 2' requirements of the BSP tree approach. The vector dataset is then converted to a raster data format and exported as an ASCII grid. The grid is then imported into the NetLogo modelling environment as a partitioning map. The upper image in Figure 6.13 shows an ASCII grid of the cadastral parcel sizes for the Auckland region when imported into NetLogo. The lower image shows the resulting BSP tree when using the partitioning map approach. Darker colours in both images signify larger parcel sizes. The red areas on both images are where land is classed as reserve or institutional, such as roads, in the cadastral data.

While a real-world implementation of a BSP tree does not produce a true 1:1 representation, the process still allows comparisons with the partitioning map. While the orientation and number of parcels are dissimilar, the size and nature of the parcels are similar enough to produce a plausible approximation of the cadastral pattern of Auckland. The agglomeration of the smaller parcel areas in the city causes the geometric distortion caused by the raster representation of space used by the BSP tree to be minimised. Greenfield areas such as the Waitakere and Hunua ranges (labelled 'A' and 'B' respectively) consist of large parcel sizes in line with the real-world parcel sizes, but the geometric distortion appears more pronounced because of the irregularly shaped real-world parcels.

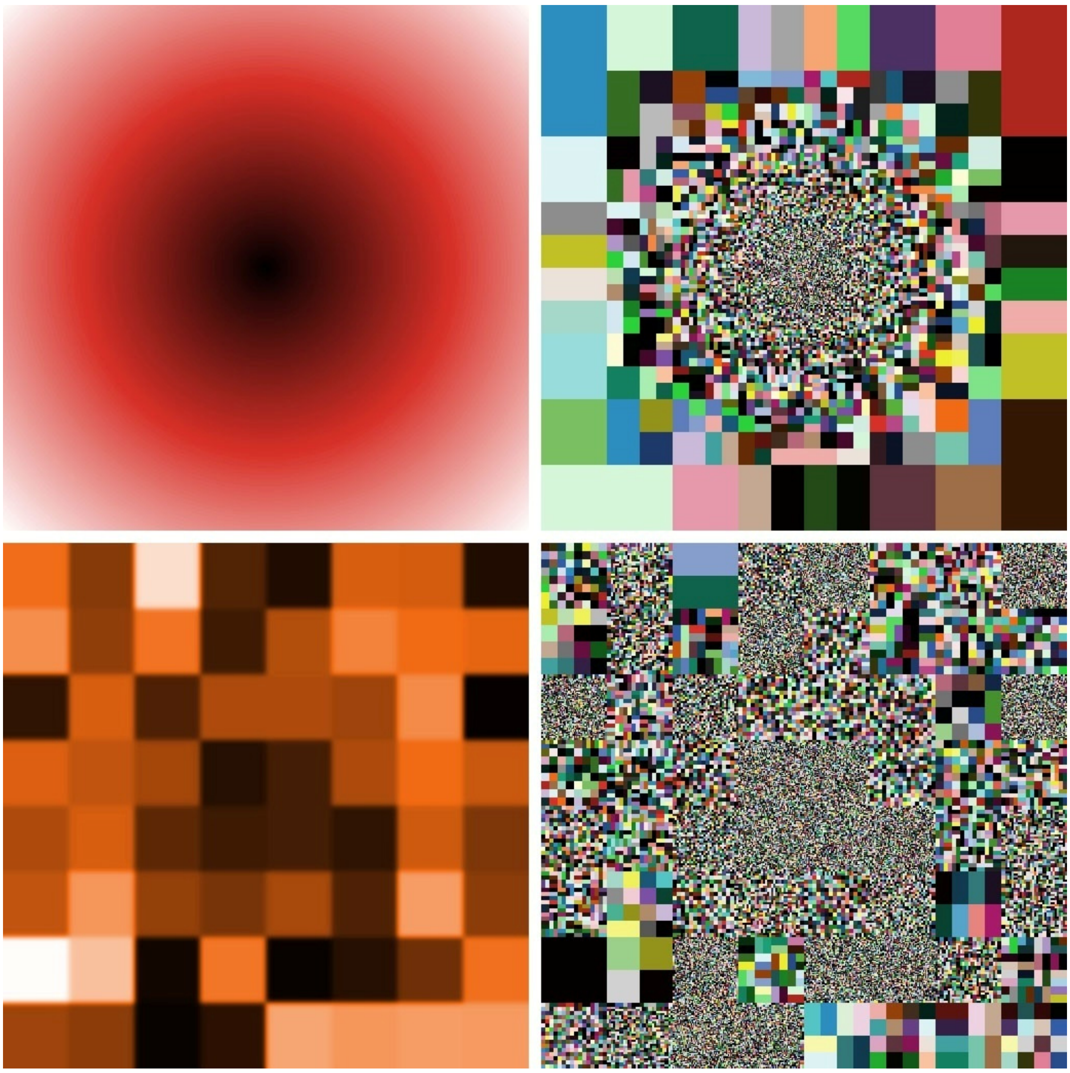

Figure 6.12: Development maps for shaping the BSP tree

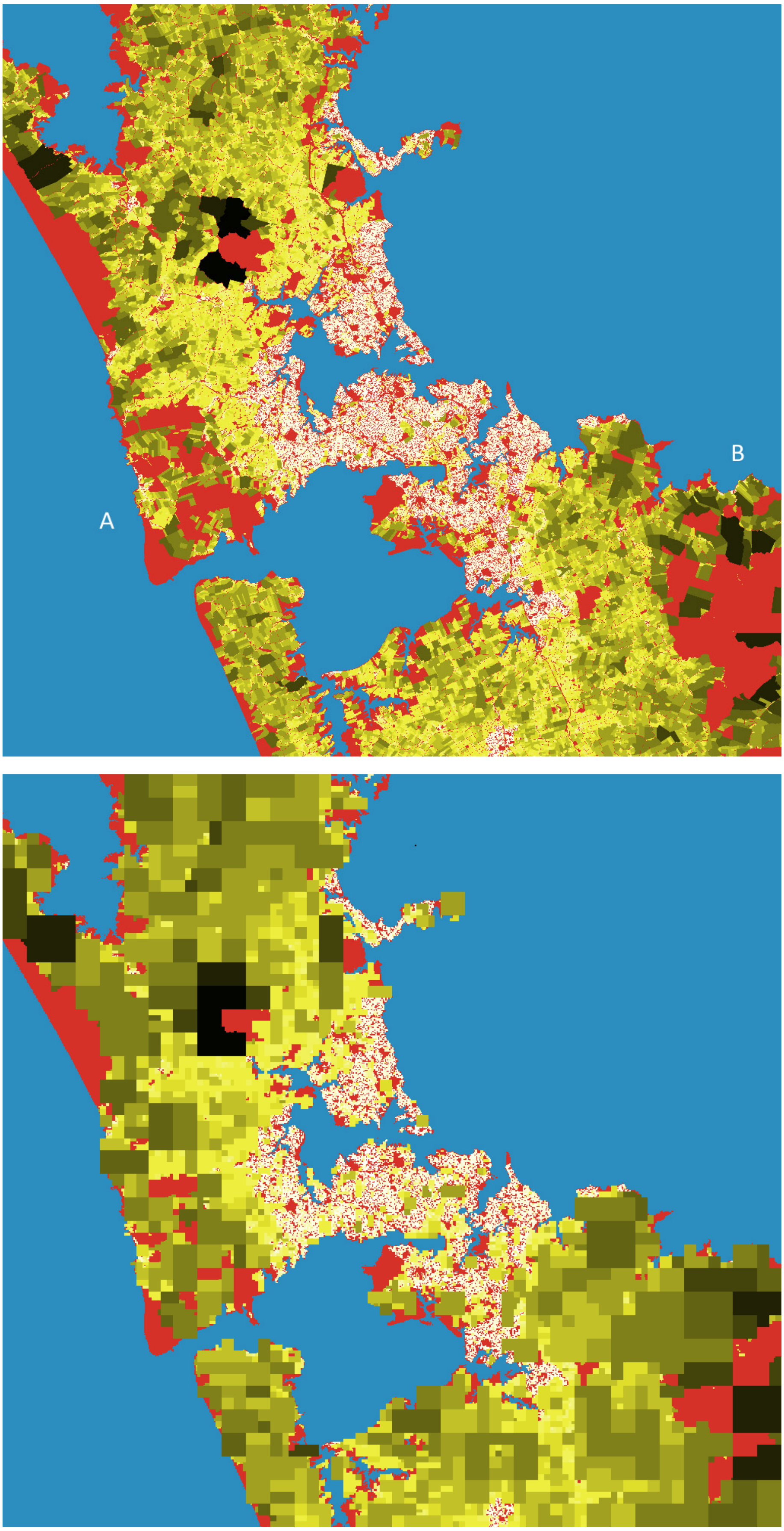

Figure 6.13: Real world implementation of a BSP tree on Auckland cadastral data.

Subdivision

As discussed at the beginning of this chapter, the motivation for implementing a BSP tree approach was two-fold. Primarily to create a method to repeatedly generate plausible urban patterns, but also to create a framework that allows developer agents to understand, analyse and enact the mechanism of subdivision within the BSP tree landscape. The approach succeeds in both areas, allowing the generation of urban patterns while also being inherently recursive to allow a developer to subdivide a single parcel into multiple smaller ones.

Once a developer has selected a parcel and decided on the intensity of development, the partitioning process inherent within the BSP tree is used to subdivide a parcel. The developer agent submits the node selected for subdivision and the desired parcel size (identified through the node's `LEVEL` variable). The partitioning code is performed in an iterative loop, initially on the original `NODE` but then on all the subsequent descendants of the `NODE` until the descendants of the original node reach the same `LEVEL` as the developer requested (Figure 6.14).

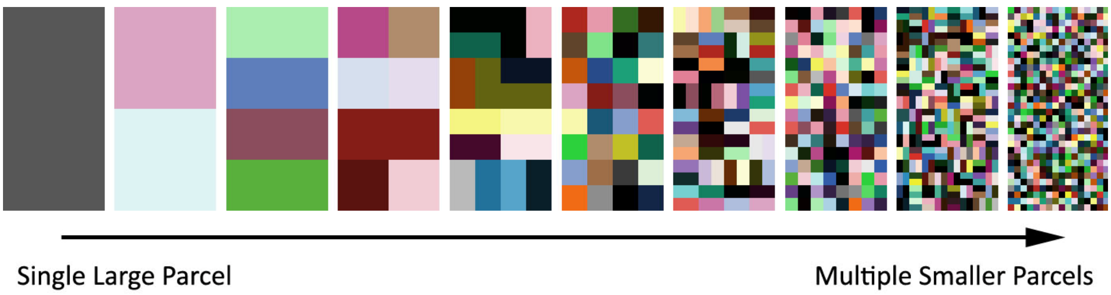

Figure 6.14: Example of a nine level subdivision process using the BSP process

`NODES` within the BSP tree can be controlled through the use of the node's `IS-LEAF` Boolean variable. Setting this variable to `TRUE` allows areas of the landscape to be made unavailable for partitioning. An example of this can be seen in the real-world implementation of the BSP tree (Figure 6.13) where parcels that are red are where the node lies on a raster cell that is listed as 'reserve' land in the cadastral database.

The benefits of using a BSP tree structure are evident when incorporating developer agents in the model. While the most obvious is the ability for developers to define and develop a parcel, the formalised node structure enables the implementation of developer territoriality, neighbourhood attractiveness, and spatial metrics for analysis in the agent-based model. Through the allocation of a node within the BSP tree, developers are assigned a non-exclusive territory over which they get the right to assess all parcels in their territory available for purchase. In the same vein, neighbourhoods, which play a role in the valuation of the parcels, are created through assigning a weighting at a certain level of the BSP Tree. Within the developer decision-making process the BSP tree is regularly queried to examine the density (calculated through the `LEVEL` attribute of the BSP tree) of the surrounding parcels to ascertain a node's developmental value. Finally, aspects of the BSP tree are used to develop spatial metrics to understand the effects developers' decision making have on the landscape.

6.6 Outputs to results

While the development of the landscape can be observed visually, the complexity of the landscape means the underlying structure of development can be missed. Consequently, a number of spatial and aspatial outputs are created for further external analysis. Using the GIS Extension developed for NetLogo (Russell and Wilensky 2008), two key spatial outputs are exported – **URBAN** and **LEVEL**. All three spatial outputs are ASCII grids, which in a text format represent the values currently in each cell of a raster landscape.

The **URBAN** grid is a Boolean representation of the binary tree where the `LEVEL` of the tree is lower than a predefined value. Each raster cell is queried as to the `LEVEL` of their representative `NODE`, if the node's level is equal to or greater than the defined variable (in this case `BASE-LEVEL` – 2) then the cell's export value is set to 1, otherwise it is set to 0. Figure 6.15 shows this landscape with a binary red/white colour scheme for the areas classified as urban/non-urban respectively.

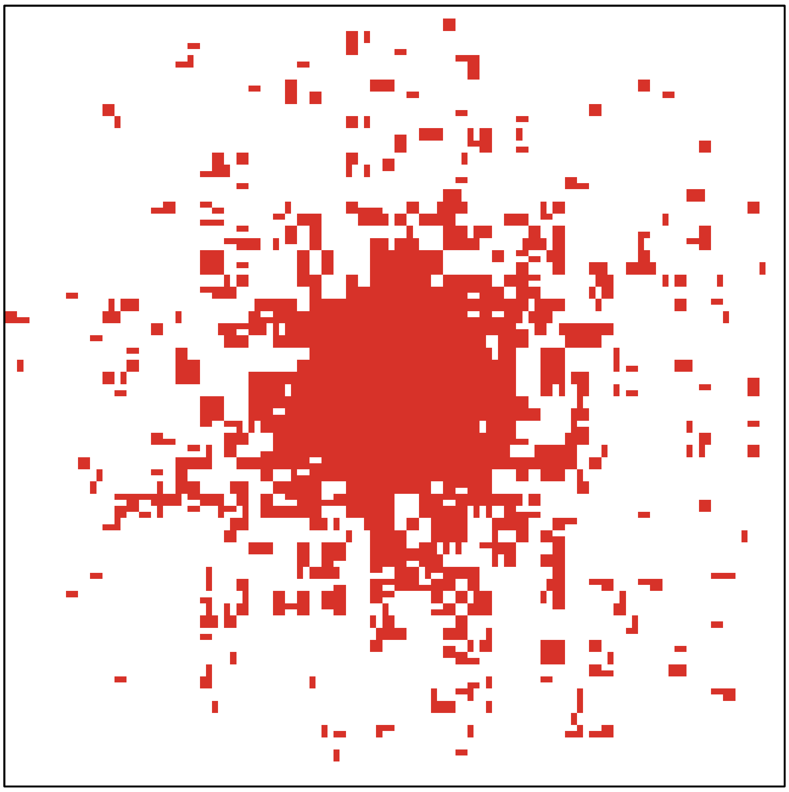

Figure 6.15: An example output from the model showing the binary ‘urban’ landscape

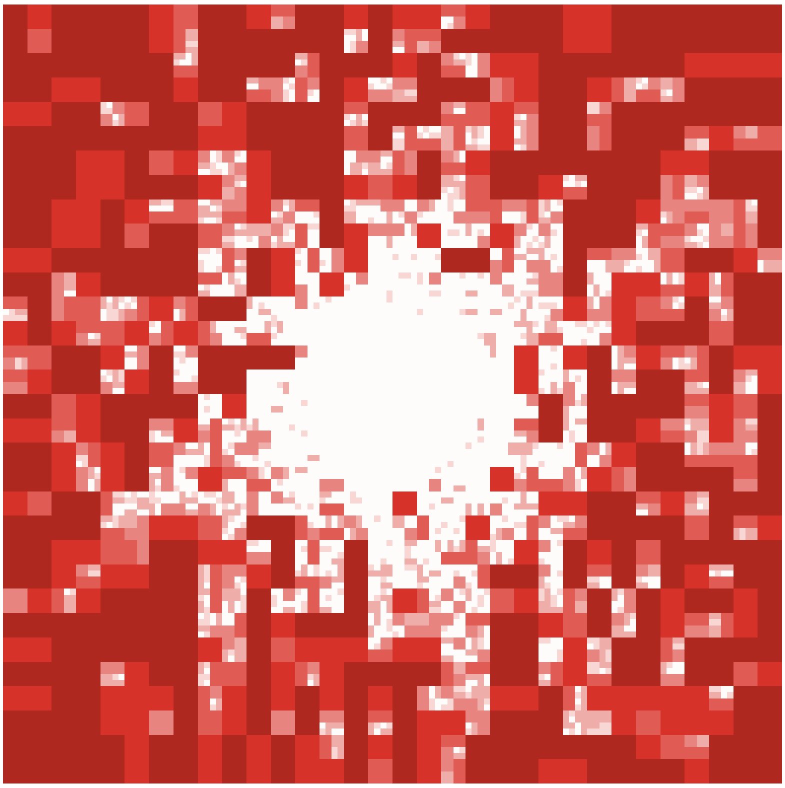

Figure 6.16: An example output from the model showing the parcel size (`LEVEL`) attribute

The **LEVEL** grid is a spatial representation of the LEVEL of all the parcels in the BSP landscape; as such the exported value for each raster cell is equal to the level of the cell's representative NODE and represents the size of the parcel. Figure 6.16 shows the output, with a graduated red colour scheme for increasing parcel size in the **LEVEL** grid.

The **URBAN** and **LEVEL** ASCII grids can be set to export the grids at any interval required by the user. In this research both grids are set to be captured at the start and end of the model as well as the end of each time step.

Portable network graphics (PNG) images for both results are exported for presentation purposes at the beginning and end of each model run. These images (as seen in Figures 6.15 and 6.16) are used to visualise the ASCII grids within the thesis.

In addition to the landscape statistics metrics, a number of aspatial metrics were exported from the model to a comma delimitated text file. These metrics (Table 6.1) record the changes in the underlying BSP tree structure for each time step.

Within Excel, the start and end metrics for each time step of the model were compared to provide a single 'change' value for each NetLogo based metric for each run. Dependent on the number of random seeds used in the experiment, each run had a number of 'identical' runs. These 'identical' runs were averaged together to remove any inherent trends based solely on the random seed value, to produce a value for each NetLogo metric that is representative of the input variables used in the models creation and execution. The range of model runs also enabled the variability of the dataset to be reported through the use of statistics such as the 95% confidence interval. Appendix B has a list of the random seeds used in both experiments for scientific repeatability.

Table 6.1: Aspatial metrics calculated internally within NetLogo each time step

Metrics	*Description*
Number of parcels	Count of all parcels
Number of urban parcels	Count of all parcels classed as urban (currently set to the three smallest parcel sizes through the `BASE-LEVEL` – 2 setting described on page 111)
Mean count of my-patches for parcels	Average number of cells associated with each parcel
Mean count of my-patches for urban parcels	Average number of cells associated with each urban parcel
Mean count of my-patches for non-urban parcels	Average number of cells associated with each non-urban parcel
distance-to-root	Average distance from each parcel to the root node.
Mean distance-to-root for urban parcels	Average distance from each urban parcel to the root node.
Mean distance-to-root for non-urban parcels	Average distance from each non-urban parcel to the root node

Landscape statistics

To analyse the changes the developer agents make to the cadastral landscape, a number of landscape metrics were calculated using the ASCII grid outputs from the model (Appendix C contains some examples).

Landscape metrics can be defined as quantitative indices to describe the structure and pattern of a heterogeneous landscape. Through the use of these metrics, the research aims to objectively describe the resulting cadastral landscapes, moving away from any subjective opinions created through their viewing. Landscape metrics have been widely used in the field of landscape ecology because of that discipline's emphasis on spatial patterns and ecological processes (Gergel and Turner 2002).

In this research, landscape metrics are used because the location and arrangement of the cadastral landscape is identical to the spatial configuration of land types within a landscape. In addition, the resulting complexity of the landscape means the underlying structure of development can be missed if only observed visually. The two outputs (**URBAN** and **LEVEL**) provide an understanding of how the urban area has developed over time. From this perspective, the **URBAN** output is intended to show the change in urban growth over time, while the **LEVEL** output is used to query the way in which urban form has changed over time.

While some metrics are classifiable and provide information about the landscape composition (such as proportion), other metrics focus on the internal configuration of the landscape and are dimensionless. These metrics require comparison between landscapes to discern trends in landscape change (e.g. contagion). The process for analysing these changes is well defined (Dunn et al. 1991), with numerous implementations investigating the growth and sprawl of urban areas (Herold et al. 2003, Herold et al. 2002, Ji et al. 2006). While the analysis of the **URBAN** model output follows a well-defined process, the use of cadastral parcel sizes (**LEVEL**) as a landscape class to be analysed appears to be unique in the literature.

The metrics used in this research are a subset of the numerous landscape metrics that have been developed. This subset is driven by three key reviews (Li and Reynolds 1994, McGarigal and Marks 1995, Riitters et al. 1995) which examined the suitability and success of the numerous metrics at characterising landscape patterns (Turner et al. 2001). Based on these three reviews a number of redundant and/or replicated metrics were not used. The subset of metrics used provides enough information to describe the changes in the landscape. The types of landscape metrics used in this research and a definition of how they are calculated can be found in Table 6.2. To highlight how the five landscape metrics (Contagion, Average Polygon Perimeter-Area Ratio, Edge Density, Aggregation Index and Total Polygons) respond to changes in the landscapes, four reference landscapes are provided below (Figure 6.17) with the associated metrics (Table 6.3).

Table 6.2: Landscape metrics used in analysis

Metrics	*Description*
Contagion (Li and Reynolds 1993)	One of the more useful metrics in defining the configuration of the landscape, contagion measures the extent to which the classes are clumped into polygons. The metric is landscape based so it combines the results into a single value for the entire landscape. The metric is calculated as follows: $1 + \frac{\sum_i \sum_j [(p_i * q_{i,j}) * ln(p_i * q_{i,j})]}{C_{max}}$ Where, p_i is the proportion of each class, $q_{i,j}$ is the adjacency probabilities between class i & j. C_{max} is the maximal value for a landscape with m classes (defined as $2\ ln(m)$)
Average Polygon Perimeter-Area Ratio (Dezonia and Mladenoff 2004)	Used as an indicator of average patch shape. Calculates the average perimeter to area ratio for all polygons present in the image. Calculated as: $\frac{Patch_{Perimeter}}{Patch_{Area}}$ It can be reported at both a landscape scale and at a class scale. In general, higher values indicate a greater patch shape complexity
Edge Density (McGarigal et al. 2002)	Calculates the total edge length divided by total image area for the given landscape or class: $\frac{Landscape/Class_{\ total\ edge\ length}}{Landscape/Class_{\ total\ area}}$ The metric uses the 'true' edge only (i.e., abutting patches of different classes including internal holes within the patches) so is a more accurate measure of the fractal nature of the class boundaries at both a class and landscape scale
Aggregation Index (He et al. 2000)	This metric measures the degree of aggregation of a particular class on the landscape by comparing the number of shared edges with the total possible number of shared edges. This results in a value between 0 and 1 where 1 equals the maximum number of shared edges and a completely aggregated class. It is calculated as follows: $AI_i = e_{i,i} / max\ e_{i,i}$ Where *e* represents the total shared edges of class *i* and *max_e* represents the total possible number of shared edges for class *i*.
Total Polygons	Using the **URBAN** and **LEVEL** outputs, count the total number polygons that represent a homogeneous landscape patch (i.e. multiple Class 15 parcels that adjoin combine into a patch)
Total Area	Total number of cells which are aligned with the coverage being measured. (i.e. total number of cells classed as urban cells)

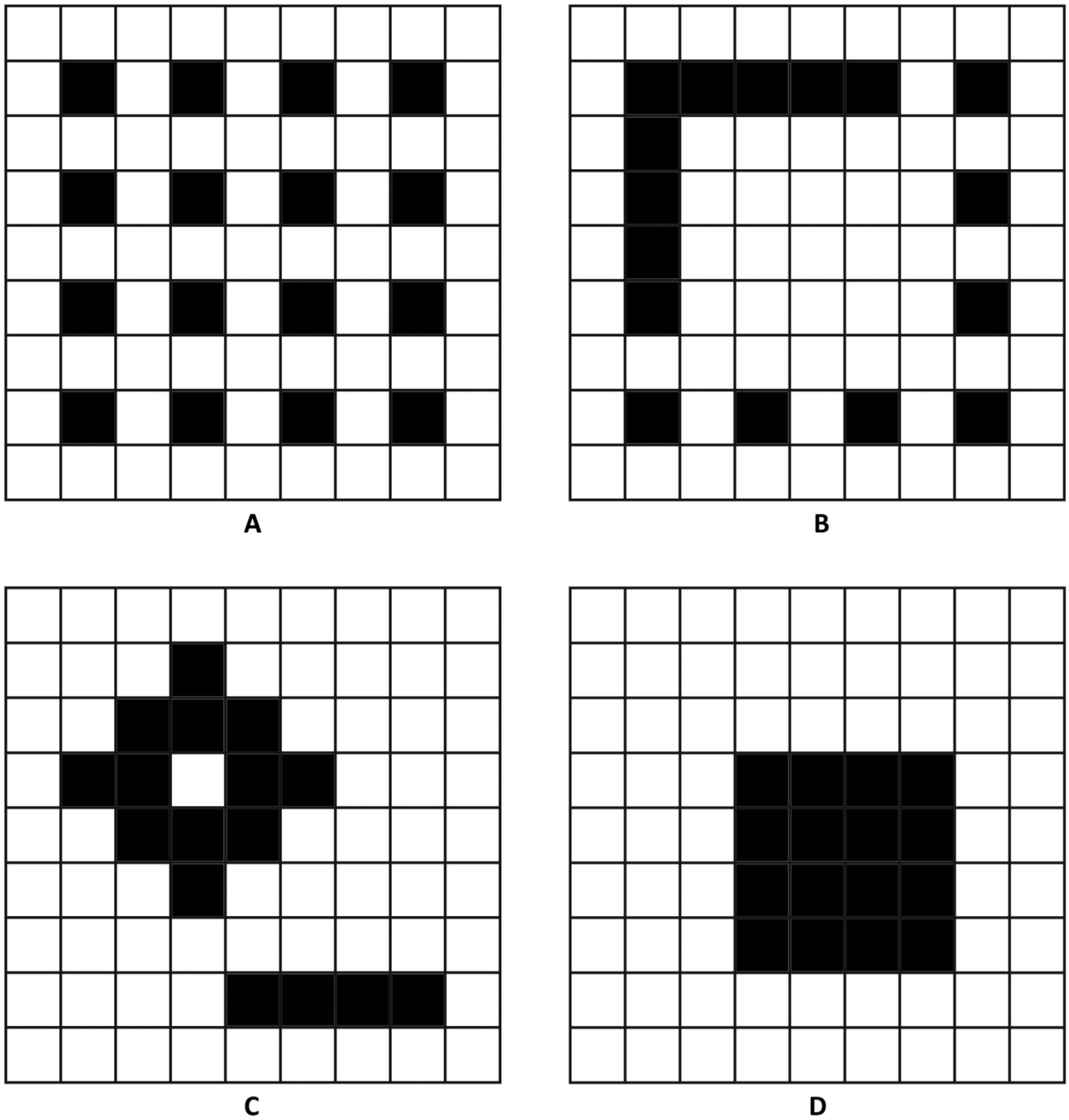

Figure 6.17: Four reference landscapes to examine the change in landscape metrics. Two classes are present in the image, the black and white classes

	Landscape (Both classes)				Black Class (i.e. Black cells only)			
	A	B	C	D	A	B	C	D
Aggregation Index	0.568	0.691	0.798	0.936	0	0.333	0.625	1
Avg. Poly Perim-Area ratio	3.855	3.502	2.383	0.9	4	3.778	2.25	1
Contagion	0.409	0.361	0.411	0.572	N/A	N/A	N/A	N/A
Edge Density	1.235	1.037	0.864	0.642	4	3	2.125	1
Total Polygons	17	9	4	2	16	8	2	1

Table 6.3: Landscape metrics for each of the reference landscapes

Additional spatial metrics, such as Moran's I and Geary's C, were not included because of the use of a range of fragmentation indices from the landscape statistics literature. These indices correlate well with both Moran's I and Geary's C. The research tradition of regional and patch based land-use change analysis supports this direction (Turner 1990, Turner and Gardner 1991, Turner et al. 2001).

The landscape metrics were calculated with a 4-cell neighbourhood definition using a raster image analysis program called IAN (Dezonia and Mladenoff 2004). IAN suited the raster nature of the model outputs through the ability to import the ASCII files directly. Because the ASCII files are the native format for IAN, the time taken to analyse each grid was trivial, allowing thousands of grids to be processed in rapid succession.

IAN creates a detailed report for each ASCII grid analysed (See Appendix C for a sample report). The numerous reports for each type of output were condensed into a single file using Python (Lutz 2001). The script stripped the state variables used in the creation of the model from the ASCII file name and appended them within the resulting comma delimitated text file. This conversion process enabled the import and analysis of the landscape statistics into Microsoft Excel and R.

As in the case of the NetLogo variables, the start and end metrics for each time step of the model were compared to provide a single 'change' value for each run. Dependent on the number of random seeds used in the experiment, each run had a number of 'identical' runs. These 'identical' runs were averaged together to remove any inherent trends based solely on the random seed value, to produce a value for each landscape metric that is representative of the input variables used in the models creation and execution. The range of model runs also enabled the variability of the dataset to be reported through the use of statistics such as the 95% confidence interval.

To analyse the change in landscape metrics, the core R statistical package (R Development Core Team 2009) was used alongside the ggplot2 (Wickham 2009) and BiplotGUI (la Grange et al. 2009) packages. Principal component analysis (PCA) were used where appropriate, to allow a multivariate examination into how specific ratios and behaviours changed the cadastral landscape. The resulting clusters were then compared either with the model's competition or with behavioural initialisation attributes to ascertain the type and severity of the change.

6.7 Conclusion

This chapter outlines the creation process, and the results of a binary space partitioning tree approach to create an abstract urban landscape. The approach is successful in its stated goal to create many similar and realistic urban spatial patterns. Controlling the structure of the resulting landscape can be done through either an equation or map-based approach.

From the perspective of its use with an agent-based model or residential developers, the linear distance-weighted equation produces realistic urban patterns with an urban core, as well as peripheral, exurban and greenfield areas. Spindles of development, common along transportation corridors, can also be seen within the pattern through the compounding iterative nature of the BSP process. The resulting patterns can be altered with changes to the distance-weighted equation, producing a more fractal monocentric pattern or a completely unfocused pattern with development randomly spread across the landscape. The substantial flexibility in the resulting urban structure belies the small number of parameters used to control the creation of the tree. However, based on the computational overhead in replicating a real-world number of parcels, the model will use the corner root node implementation. This reduction in size also allows a reduction in the numbers of developer agents, which further reduce processing time.

The secondary motivation for implementing a structured BSP tree approach was the development of a framework where developer agents would understand, analyse and could enact the mechanism of subdivision on the urban environment. Using the inherent partitioning process found in the BSP tree, this requirement has been met. Unintended additional benefits of the formalised node structure, such as the straightforward implementation of developer territoriality, neighbourhood attractiveness and spatial metrics, further reinforce the quality of the approach.

7 Developer competition and the resulting landscape in an agent-based model of urban development

> The popular views of development are either of a competitive industry or of one dominated by large powerful players. Both perspectives have some truth since the industry offers opportunities for many small players as well as advantages and opportunities for large and expanding firms
>
> (Coiacetto 2009, p. 132)

While how firms react to the level of competition within a marketplace is well understood from a general neoclassical perspective (such as Camerer et al. 2004, Katz and Shapiro 1985), a wider investigation into the resulting spatial decision making based upon the level of competition within the urban development market has not been reported. This chapter aims to capture the results of these spatial decisions by examining the selection and development of parcels in an agent-based model of urban development.

The discussion and analysis provided in the preceding five chapters have achieved the five objectives (detailed in the Chapter 1) that were highlighted as being required to examine the research goals. Consequently, the ability to undertake experimental runs using an agent-based model of developer behaviour *in silico* is now available. Therefore this chapter will focus on the first of the two research goals, namely:

- To examine how differing levels of property developer competition affect the urban landscape through an examination of the change in urban growth and form

This chapter is based around two parts. Part one, which is applicable to both this chapter and the subsequent one, begins with a discussion on the design of the competition experiment and then a review of some initial experiments undertaken to set the basic parameters of the wider model. Part two is focused on the results from experiments with a varying level of competition and the application of these results to developer competition and its effect on urban landscapes in the real world.

7.1 Parameterisation

A number of parameters were set in the process of designing these experiments. Some parameters were set based on the author's judgement while others were confirmed using results from some preliminary experimental runs. While not directly relevant to the aims of the thesis, these experiments were useful for a number of reasons;

- to provide an opportunity to optimise and validate the model and the modelling process;
- to understand the overall structure of the model and its effects on the experiments at the core of this research;
- to provide the basis for setting a variety of fixed model parameters;
- to provide the basis for defining the experimental range for the competition and behaviour experiments.

Each parameterisation experiment focused on an important aspect of the model's structure and examined how development patterns changed when the structure was altered. All of the parameters listed here affect the initialisation of either, the model or the BSP tree landscape on which the developers operate. For clarity, each of the parameters discussed here are separated into two sections, Model Initialisation and BSP Tree Initialisation.

BSP Tree Initialisation

Maximum and minimum parcel sizes

The maximum parcel size parameter was implemented to ensure that all parcels were of a small enough size to be realistic (see Figure 6.9 for reference), while also ensuring that most parcels were of a sufficient size and price to be developed by a developer in the model. As this parameter is closely linked to both the range of capital spread amongst the developers and the landscape itself, the parameter must be a compromise between these two aspects.

It is clear that this parameter is subjective, as land parcels in the real-world might be a variety of sizes some potentially more expensive than developers can afford without more external funding, something outside of the scope of this thesis. The model focuses on the shaping of urban development through developer competition and behaviour, not through the spatial arrangement of existing parcels of land too expensive to purchase. A number of options were tested based on the way capital was allocated. The value that fit both requirements was between a 256 cell and a 128 cell `max-parcel-size`. Based on the 400m^2 smallest parcel size, a `max-parcel-size` value of 128 cells (51,200m^2 or roughly 5 ha) was used in the final experiments. While some Greenfield type developments are substantially larger than this, this value is in line with the largest undeveloped land parcels that are currently zoned 'Residential' in the Auckland region (Gamble 2010).

A minimum parcel size was defined using the `Levels` attribute which halts the BSP tree at a set level. The smallest parcel available in the initial BSP landscape was set to a two cell parcel (i.e. one level above the smallest level available). This was done to provide a range of redevelopment opportunities within the existing urban core. This parameter causes the landscape to have a large number of two cell parcels (called Class 15 in the model). Based on the smallest parcel size (400m^2) defined above these two cell parcels equate to an 800m^2 parcel size. This value is in line (756 m^2) with the average residential parcel size in the Auckland region (Gamble 2010).

Root location

When evaluating these early experiments, the run length of the model was problematic. As seen in Chapter 6, the original BSP landscapes located the `root` node at the centre of the landscape and this in turn focuses the urban conurbation around the `root` node. While providing an aesthetically pleasing urban landscape, this approach was problematic. It was ascertained that the large number of parcels in the monocentric BSP landscape, combined with the associated range of parcels being assessed by each developer, produced run times that were not conducive to running multiple experiments within a reasonable time frame.

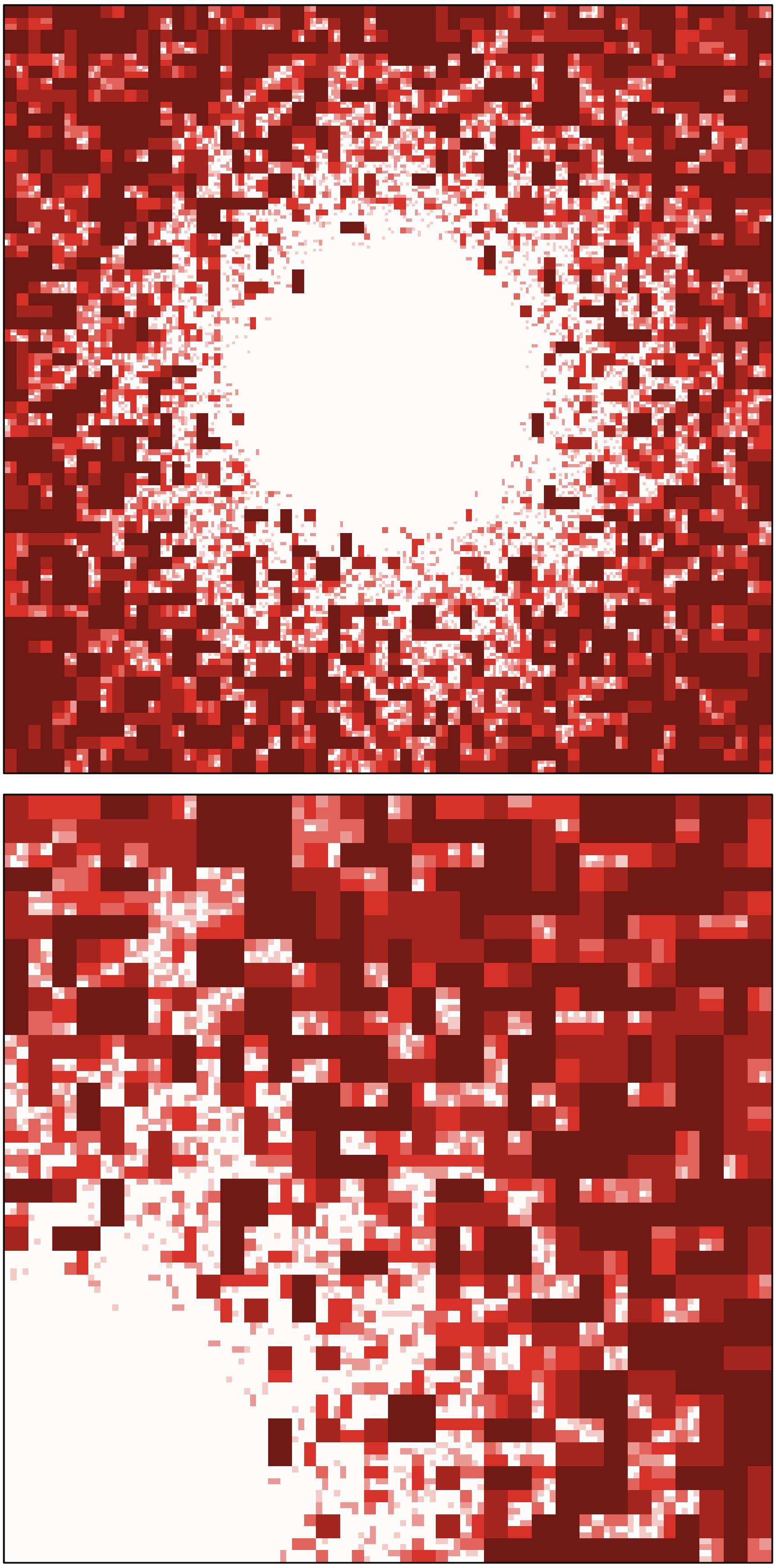

Figure 7.1: Comparison between an original and revised quarter landscapes (top image – root-node at centre / bottom image – root-node at bottom left corner)

The solution adopted in the final experiments was the `root-to-corner` implementation discussed in Chapter 6 (Figure 7.1). This `root-to-corner` approach renders an urban landscape which is an exact quarter of the original. With the move from a 512 x 512 to a 256 x 256 cell world, the approximate size of the landscape reduces from 10,485 to 2,621 hectares (when using 400m^2 as the smallest parcel size – discussed on page 73). It is important to note that while this approach reduced the number of parcels, it also reduces the number of developers required to effectively develop the landscape, further reducing the run time of the model. The smaller landscape, and the associated reduction in the number of developers, reduces the run time of the model at least twentyfold.

City size

The `city-size` experiment examined the role that the size of the existing city has on the resulting development, from both developer/development perspective and also through their spatial changes to the landscape. The `city-size` parameter was discussed in Chapter 6 (page 96), and relates to the creation of the BSP tree and the initial landscape on which the agent-based model acts. The application of this parameter is relatively straightforward, an increased `city-size` forces an area to be developed down to the number of levels defined in the setup stage. Using a set of developers to provide a range of developer competition, the experiment compared three sizes of the initial city (1.1, 1.2 and 1.3 – small through to large).

When examining the results it is apparent that altering the size of the initial city has an influence on the scale of development but the spatial configuration of the resulting development does not change. Table 7.1 shows the change in the number of urban parcels in the landscape. This table shows that the number of parcels developed significantly increases with an increase in `city-size`. When compared with the number of urban parcels in the initial landscape, the percentage increase in urban parcels is greatest in the lower `city-size` value. Table 7.1 also shows the lack of variation from a time-series perspective.

city-size	*Tick 0*	*Tick 20*	*Change in number of parcels*	*% increase in parcels*
1.1	2904 (±20)	3783 (±112)	879.58	30.29%
1.2	5640 (±28)	6701 (±112)	1060.75	18.81%
1.3	9304 (±36)	10627 (±122)	1324.53	14.24%

Table 7.1: Average change in the number of parcels based on city-size for 160 model runs (i.e. n=480) Values in brackets are the variation at a 95% confidence interval

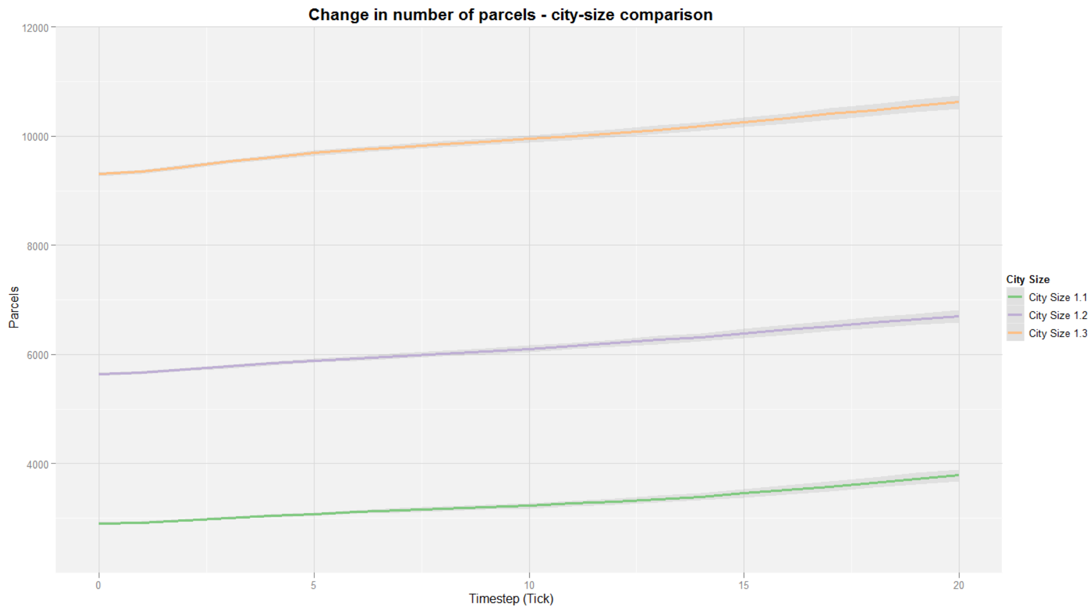

Figure 7.2: Average time-series examining the change in urban parcels based on city-size (160 iterations per `city-size` value, including 95% Confidence Intervals)

These patterns are mimicked when examining the average distance between all parcels and the root node of the binary tree landscape (Table 7.2). While the average distance between each parcel and the root node of the landscape decreased when `city-size` is increased, the change expressed as a percentage of the original landscape also decreased. Consequently the city grows at an increased rate when the initial `city-size` value is smaller.

city-size	*Tick 0*	*Tick 20*	*Change in parcels*	*% of original landscape*
1.1	46.94 (±0.18)	54.18 (±1.02)	7.24	15.42%
1.2	51.69 (±0.1)	58.04 (±0.55)	6.34	12.27%
1.3	59.63 (±0.07)	65.22 (±0.42)	5.59	9.37%

Table 7.2: Average distance between all parcels and the root node based on city-size (160 iterations per `city-size` value, ±=95% Confidence Interval)

While there is a difference in the scale of development, from a landscape metric point of view, the change in `city-size` has little to no effect on the resulting landscape when considered as a percentage of the initial landscape. Table 7.3 examines this result in more detail.

Metrics / `city-size`	*Tick 0*	*Tick 20*	*Average change in metric over run*	*Average % change in metric over run*
Contagion				
1.1	2.42 (±0.008)	2.58 (±0.009)	0.15	6.37%
1.2	2.22 (±0.006)	2.36 (±0.007)	0.14	6.39%
1.3	2.16 (±0.004)	2.29 (±0.006)	0.13	6.04%
Avg. Polygon Perimeter-Area ratio				
1.1	1.20 (±0.001)	1.39 (±0.001)	0.19	16.21%
1.2	1.24 (±0.001)	1.47 (±0.001)	0.22	18.04%
1.3	1.28 (±0.001)	1.53 (±0.001)	0.25	19.78%
Edge Density				
1.1	0.1466 (±0.001)	0.1519 (±0.001)	0.0053	3.62%
1.2	0.1645 (±0.001)	0.1717 (±0.001)	0.0072	4.39%
1.3	0.1734 (±0.001)	0.1829 (±0.001)	0.0095	5.49%

Table 7.3: Average change in parcel size landscape metrics based on `city-size` (160 iterations per `city-size` value, ±=95% Confidence Interval)

From a time-series perspective, the changes in landscape metrics are uniform and follow a similar pattern. Figure 7.3 shows the change in the urban contagion metric over twenty time steps of the model and highlights this similarity.

The initial results (Table 7.1) highlight the spatial constraints that the initial landscape can place on the agents when they follow the process of development. All developers are constrained by their finances when assessing parcel for development, although smaller developers appear to be more constrained with the lack of opportunities in a smaller initial city. Even so, the change is consistent with the starting `city-size` (Table 7.1). The landscape metrics also show that the way the urban landscape is changing is consistent with the starting city-size value (Table 7.3).

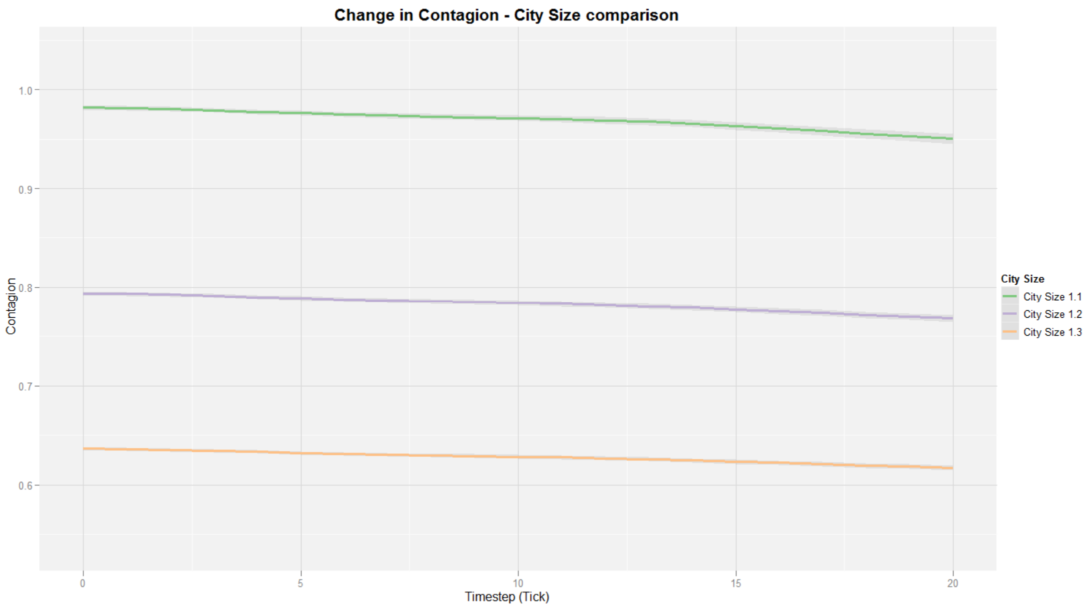

Figure 7.3: Time-series examining the change in urban landscape contagion metric based on a changing city-size value. (160 iterations per `city-size` value, including 95% Confidence Intervals)

It is clear that the size of the initial city does affect the way in which the city is developed and that the changes in landscape are consistent with the change in initial city-size. While the initial size of the city does have an effect, this is unsurprising. Based on these results and in conjunction with the change to a corner root node location and the `max-parcel-size` value, a `city-size` value of 1.15 was chosen to be used in the final experiments.

Model Initialisation

Duration

The duration of the model run was initially set to 20 ticks. This level was compared with both shorter and longer runs (ranging from 5, 10 and 50 ticks - Figure 7.4). Longer runs increased the chance of potential edge effects through the scale of development expanding out to the exterior edges of the landscape.

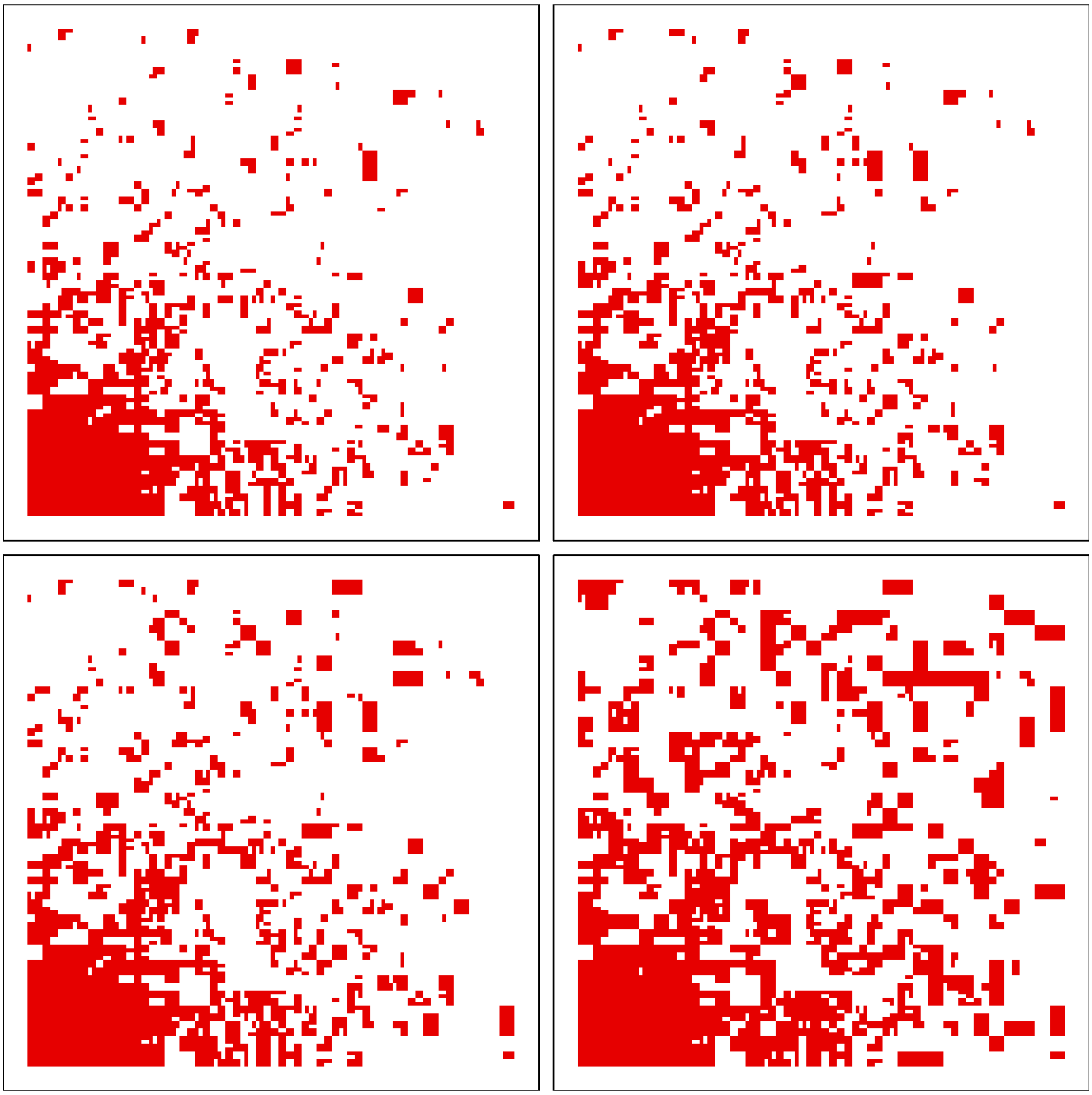

Figure 7.4: Comparison between model durations on the urban landscape.
Top left - 5 ticks, Top right - 10 ticks, Bottom left - 20 ticks, Bottom right - 50 ticks.

Shorter runs did not provide enough time for the developers to undertake a full range of developments. In most cases, the larger developers were under-represented in the shorter runs because of their use of land banking (page 55). In this situation, while the larger developers own the land they have not altered the landscape and development has not occurred. The use of 20 ticks as the duration of the model in the final experiment provided enough time for all developers to actively develop the landscape.

Percentage of parcels for sale per round

The percentage of parcels up for sale per round was defined in line with statistics from the Auckland region. Using the total number of dwellings in the Auckland metropolitan area for 2006 (Gamble 2010) and comparing that number with the total number of sales within the same geographic area and time frame (Real Estate Institute of New Zealand 2010) produced a total sales percentage of approximately 9% (35,730 sales / 388,863 dwellings = 9.18%). However, this is just the percentage of houses being sold rather than the total number of houses up for sale.

The Real Estate Institute of New Zealand do not capture the total number of new listings per month although one of Auckland's largest real estate agencies, Barfoot & Thompson, do publish the total number of new listings and house sales for the company on a monthly basis (Barfoot & Thompson 2010). Although their statistics on new listings do not date back past February 2008, Barfoot & Thompson are solely located in the Auckland region and therefore they provide statistics which are spatially comparable to the area. Based on the statistics published by Barfoot & Thompson (data listed in Appendix E) their ratio of new listings vs. houses sold between February 2008 and April 2010 is 2.09:1.

Using this ratio, the 9.18% of total sales in 2006 is converted into 19.2 % of houses up for sale. While this figure is higher than what would be expected the value can be explained. The total number of new listings provided by Barfoot & Thompson includes new apartments and houses as well as the normal resale of existing houses. The inclusion of these new apartment and houses in the new listings aligns well with the model. The new listings value also includes listings that are for sale by multiple agents which will inflate this value slightly. Even with these uncertainties, this was the best available information for the Auckland region to ascertain the percentage of houses that are put onto the market on a yearly basis. Therefore based on these values and the knowledge of how the agent-based model operates, the number of parcels that are randomly selected to be 'for sale' per round in the model was set at 20% of the total number of parcels in the landscape.

Market

Initially, the model had a dynamic market structure that rewarded and restricted developers based on their successes and failures. If a developer purchased a parcel, was incorrect in their assumption of the profitability of the parcel and it resulted in a loss, the developer would absorb this loss and then proceed to purchase a new parcel with their revised level of capital. The inverse was true if the developer was correct in their assumption. This approach results in a number of developers quickly 'dying', in that their available capital was below the price for the smallest parcel within the landscape. Once this occurred the developer is rendered impotent for any future development rounds.

The developers that failed were usually small in size, reinforcing MacLaran's (2003b) discussion on the timing and accuracy of development being particularly critical for smaller developers because of their lack of a financial cushion, should development be unsuccessful. From the reverse perspective, developers who were consistently successful began to skew the level of capital towards a few large developers. These two aspects resulted in a noticeable change in the level of competition which had an effect on the resulting level and shape of development. Since the structure of competition is a key aspect in this thesis, this dynamic reshaping of the level of competition needed to be controlled.

An approach where once a developer has 'died' that they are 'reborn' at the start of the next tick with the initially allocated allotment of capital was briefly explored. The approach was intended to mimic a new developer entering the market at the same capital level of the departing developer. Although this approach succeeded in reinforcing the bottom end of the developer market, it does not cap the runaway growth for the successful developers. Consequently the decision was made to fix the level of capital for all developers so that successes and failures do not affect the developer's available capital. From a conceptual perspective, it is assumed that smaller developers are replaced each round and larger developers are not reabsorbing any profit into their future development. Fixing the market structure provides the stability required to understand how competition plays a role in the development of the urban landscape. The property market in the model is unaffected by this change, the value of the parcels still increase and/or decrease based on the `market-future` variable at the end of each time step of the model. In addition instead of a stochastically derived market, a constant growth rate was used (see page 79 for more details).

Allocation of developer capital

When reviewing this and the subsequent chapter it is important to note that each developer's level of capital was initially defined through the use of a preferential attachment process using a Yule-Simon distribution (Simon 1955). This approach to the allocation of capital produced a different set of developers and competition based upon the initial random-seed value used, the total capital set for the experiment and a probability coefficient. Each set of developers is known as a 'developer set'. It was then intended to use the Herfindahl-Hirschman Index, or HHI, (Hirschman 1945) to plot the level of competition in the developer set against the change in urban development from both a spatial and aspatial perspective.

This approach created numerous issues which ultimately required an alternative approach. The difficulties were primarily in the reporting of the results. The HHI metric (explained in detail on page 80), while providing a value to quantify the level of competition, does not uniquely represent the number of, and variation in, levels of developer capital. A prime example of this can be seen in Table 7.4 which shows how an approach to allotting capital could end up with two HHI values which are close but the number of developers, and therefore the ability to apply this capital, is significantly different. This led to an evaluation of fixed developer sets which where pre-selected to provide a well understood range of developer competition (see Appendix D for details about the developer sets used in the final experiments). While not an ideal solution, these developer sets provide a straightforward way to describe the results from this thesis.

Developer Set 38 Developers Total Capital = 500 HHI = 0.0989		Developer Set 138 Developers Total Capital = 500 HHI = 0.0975					
100	2.5	150	5	2	1	1	1
70	2.5	10	5	2	1	1	1
50	2.5	10	5	2	1	1	1
50	2.5	10	5	2	1	1	1
40	2.5	10	5	2	1	1	1
40	2.5	10	5	2	1	1	1
25	2.5	10	5	1	1	1	1
25	2.5	10	2	1	1	1	1
5	2.5	10	2	1	1	1	
5	2.5	10	2	1	1	1	
5	2.5	10	2	1	1	1	
5	2.5	10	2	1	1	1	
5		10	2	1	1	1	
5		5	2	1	1	1	
5		5	2	1	1	1	
5		5	2	1	1	1	
5		5	2	1	1	1	
5		5	2	1	1	1	
2.5		5	2	1	1	1	
2.5		5	2	1	1	1	
2.5		5	2	1	1	1	
2.5		5	2	1	1	1	
2.5		5	2	1	1	1	
2.5		5	2	1	1	1	
2.5		5	2	1	1	1	
2.5		5	2	1	1	1	

Table 7.4: Developer set composition and the HHI

7.2 Experimental design

The competition experiment at the core of this chapter varied the ratio of capital allocated to developers. This enabled examination of how different levels of competition affect urban development from both a spatial and aspatial perspective. In the experiment, five developer sets (See Figure 7.5 and Table 7.5 for a graphical and tabular comparison of the five levels of developer competition or Appendix D for a more detailed review) were used to define five levels of competition, from a single large developer quickly falling away to a multitude of smaller developers (Developers Set 1) to multiple small developers (Developer Set 5). In all five levels of competition, the smallest developers are assigned a level of capital that is only sufficient to purchase small parcels.

One hundred random replicates were used in association with each developer set to provide a statistically relevant sample of cadastral landscapes to remove any bias that a single landscape might include. In addition, all developer behaviours discussed in Chapter 5 were included in this experiment. Consequently this experiment produced results for five hundred individual model runs which can be used to understand how developer competition affects urban development and the resulting landscape within a model of the urban development process. The results from this competition experiment are outlined and discussed below. For scientific repeatability, a list of all the parameters used in the model can be found in Appendix F.

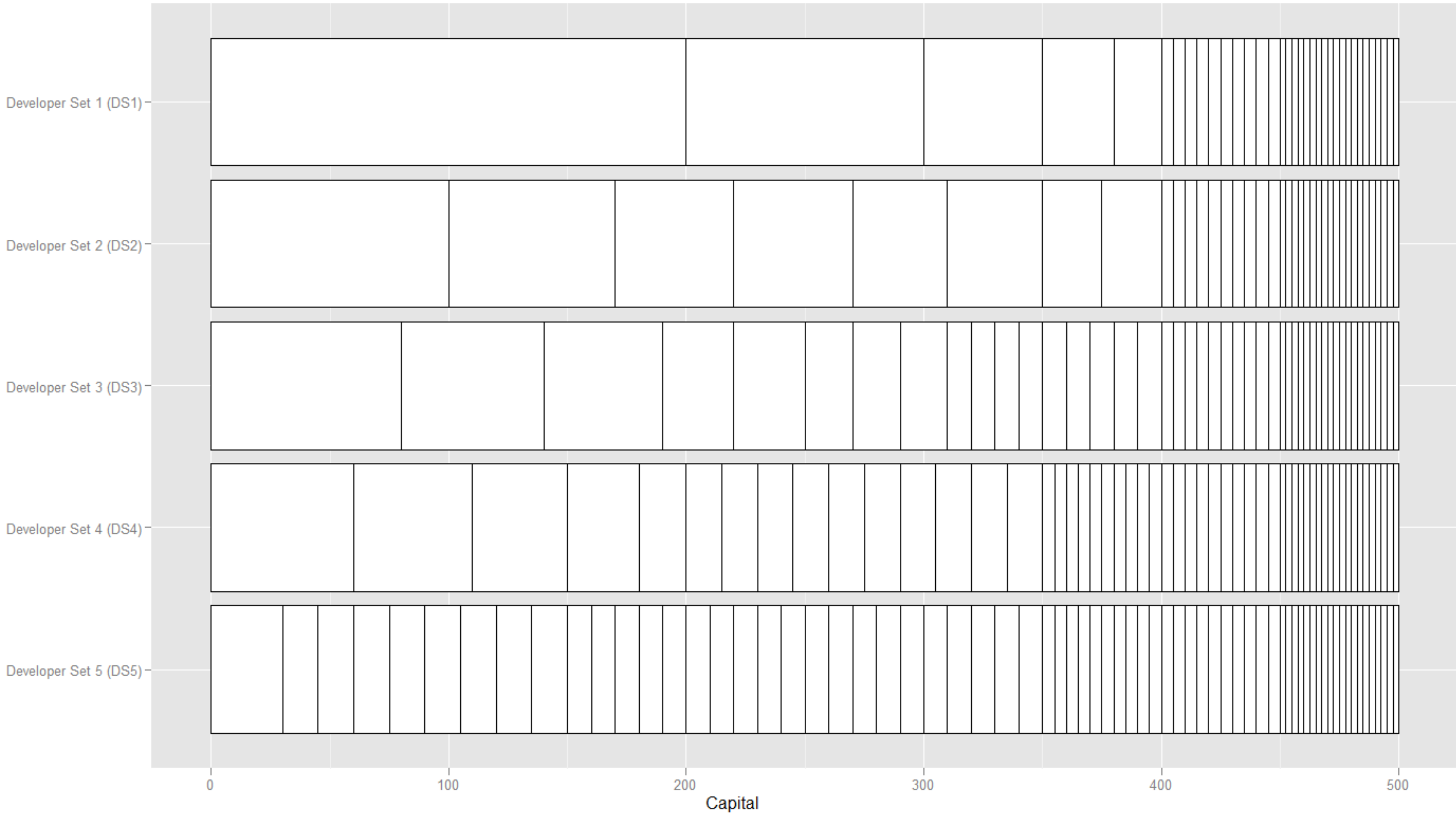

Figure 7.5: Graphical representation of the distribution of capital for each developer set

Level of Developer Competition	*Number of developers*	*Herfindahl-Hirschman Index (HHI)*
Developer Set 1 (DS1)	35	0.2167
Developer Set 2 (DS2)	38	0.0989
Developer Set 3 (DS3)	47	0.0671
Developer Set 4 (DS4)	55	0.0475
Developer Set 5 (DS5)	69	0.0213

Table 7.5: Tabular information for each of the fixed developer sets

7.3 Results

The results for this experiment will begin by examining the change in NetLogo reporters caused by the five levels of developer competition. These reporters recorded structural change in the landscape in terms of the change in the number of urban parcels, the average parcel size and the average distance from all parcels to the `root` node. This is followed by visualisation of the landscapes produced by a single random-seed showing the change in parcel sizes over the duration of the model.

In observing the detailed changes in the landscape a number of landscape statistics were calculated. Box plots are initially used to highlight the variation in the resulting landscape for each level of developer competition. Each of the landscape statistics is then examined in more detail through a selection of time-series graphs to observe how the landscape statistics change over the length of the model run. Finally a principal components analysis is used to investigate variability in the landscape statistics.

Overview results

Analysis of the role of competition in urban growth begins with an analysis of the basic descriptive statistics exported by the NetLogo model directly. Beginning with the change in the number of urban parcels and the change in mean parcel size for the landscape, these time-series graphs strongly suggest that the level of competition plays an important role in the scale of development that occurs over the duration of the model run. All time series graphs show the calculated mean value for each developer set at each time step. The dark gray ‘shadow’ around each of the developer set is the observed 95% confidence interval for each time series.

From an urban growth perspective, the change in the number of urban parcels is a clear indication that competition plays a role in the scale of development. Figure 7.6 shows the increase in urban parcels through the application of capital for each developer set. The developer set which has the least competition, Developer Set 1 (now abbreviated to DS1), has the smallest increase in the number of urban parcels. Conversely, the developer set which contains the most competition, Developer Set 5 (now abbreviated to DS5), has the greatest level of growth. This trend for more competition to equate to more development is reinforced with developer sets 2, 3 and 4 (abbreviated to DS2, DS3 and DS4 respectively) all recording levels of growth between the two outlying developer sets.

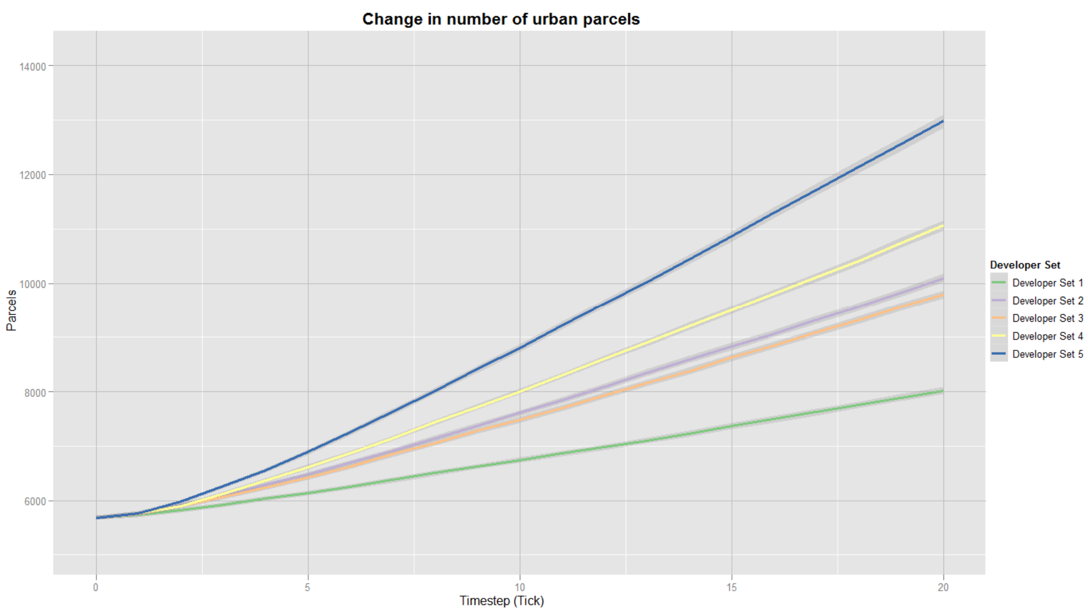

Figure 7.6: Time-series comparing the change in mean number of urban parcels for the five developer sets

Interestingly, DS2 has a slightly higher rate of growth than DS3 even though DS3 has more developers and an increased level of competition. It appears DS2 is in a ‘sweet spot’ with the general trend of more developers equating to more development being interrupted. DS2 appears to partially offset the lack of growth that developer sets with large developers entail. This result is repeated throughout most of the remaining results. It is important to note that the difference between DS2 and DS3 is within the margin of error, so a definitive conclusion cannot be drawn.

The mean urban parcel size (Figure 7.7) decreases with DS1 having the least impact on parcel size while DS5 again having the most effect. Developer sets 2, 3 and 4 all show the same trend where they occupy the middle of the DS1 and DS5 range. DS2 and 3 are almost identical and are well within each of their 95% confidence intervals shown on the time series graphs. The mean urban parcel size is theoretically limited to the smallest parcel size (a one cell parcel). The time series graph shows that the developers in DS5 are consuming the land which meets their financial requirements rapidly in the initial stages of the model with the trend line beginning to level off as it gets closer to the one cell level.

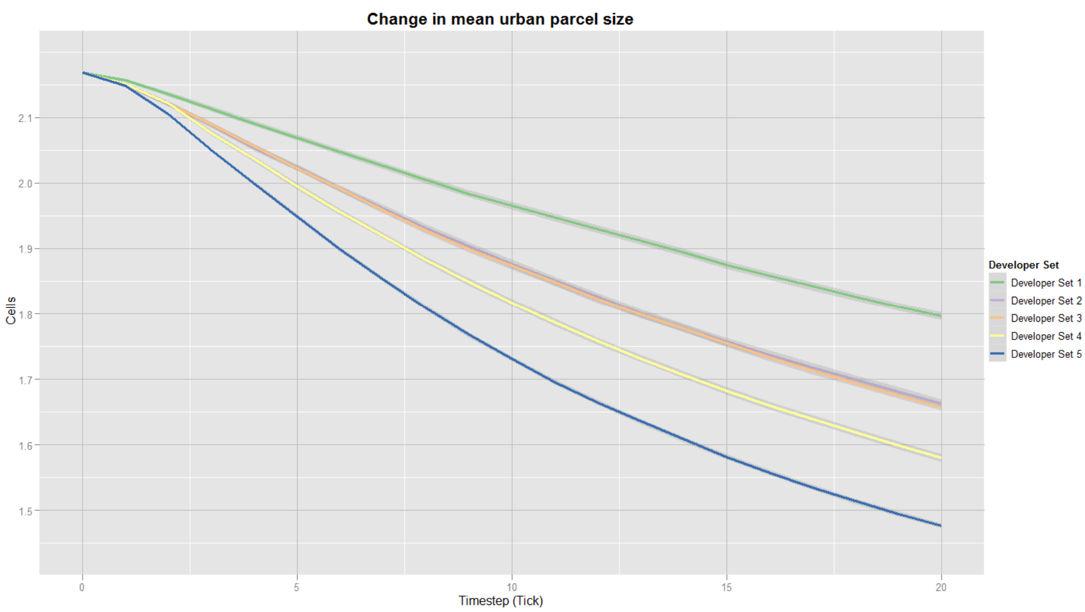

Figure 7.7: Time-series comparing the change in mean urban parcel size for the five developer sets

Gradually the supply of land which meets their financial requirements is exhausted and then the mean urban parcel size levels off. As seen later in this chapter, smaller developers' transition through a phase of developing more existing urban parcels (redevelopment) prior to the exhaustion of affordable non-urban parcels that have potential for development.

The final overview time-series results examine the spatial distribution of urban cells in the landscape and the saturation/fragmentation of urban cells throughout the landscape (Figure 7.8). While the common DS1/DS5 pattern is still in place, it is interesting to note that over the first few ticks of the model, the average distance to an urban cell for DS5 was decreasing in line with the DS1 level of competition.

For DS5 this means that early development was focused on the development of small urban fringe opportunities or the internal redevelopment of existing urban parcels. Once a proportion of these parcels have been consumed, the developer set moves further outward away from the urban core consuming larger non-urban parcels that fit their requirements. This disperses the urban parcels throughout the landscape, drastically reducing the distance between a non-urban cell and an urban cell.

The slow decrease in distance to an urban patch for DS1 is based on two factors; the lack of parcels being developed by this developer set; and the place-making approach to development undertaken by the larger developers in the developer set. The larger developers substitute the risk of development being geographically disparate compared to existing urban development by the investment in large parcels. Developer sets 2, 3 and 4 are unremarkable with the three developer sets reducing the distance to an urban parcel in line with DS5 but do not have the dramatic decrease between time steps 3 and 6 seen in DS5.

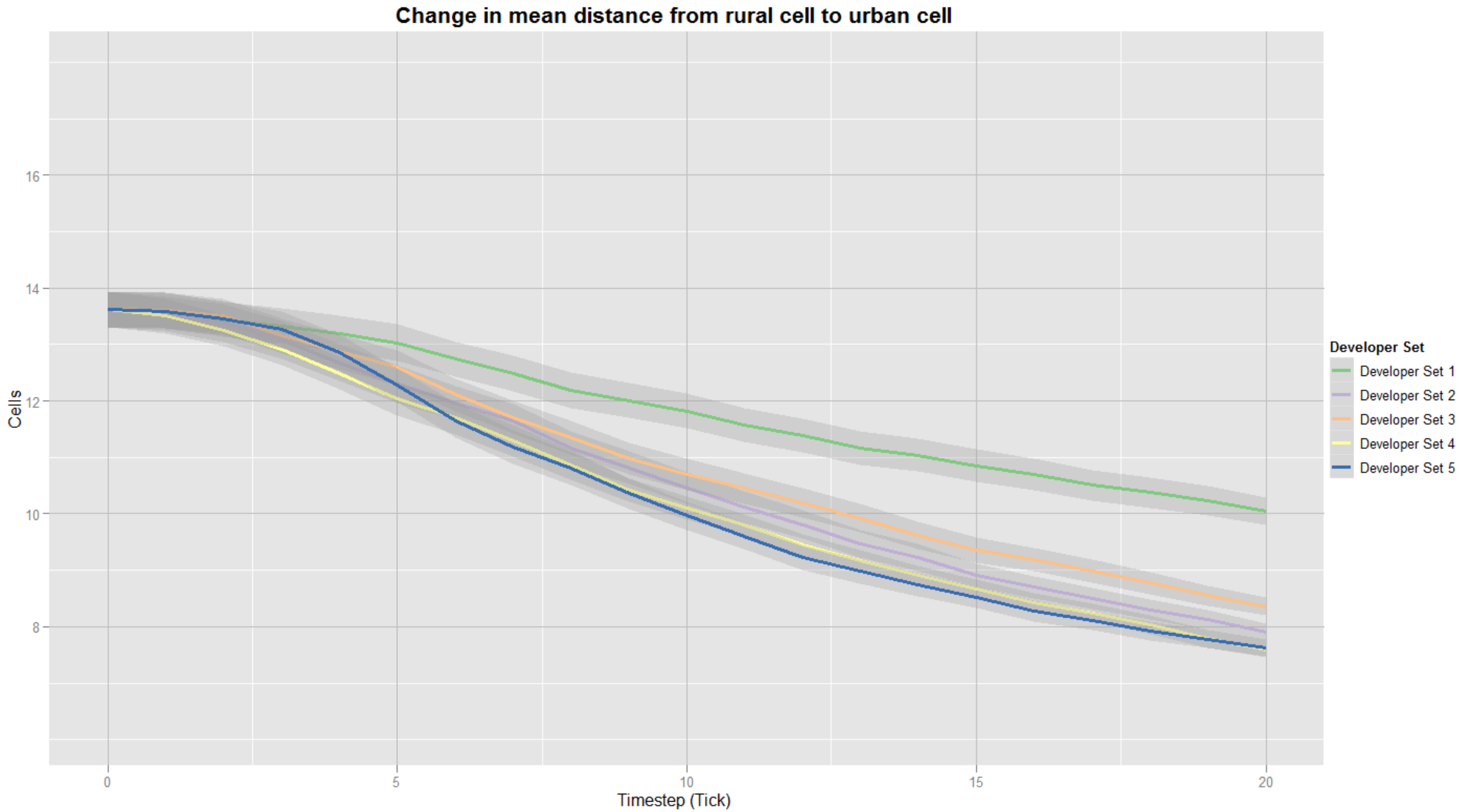

Figure 7.8: Time-series showing change in the mean distance from each rural to an urban cell

At this point the results will split into two sections; the first will examine the scale of urban growth seen through the differences in developer competition. This is performed through an examination of the change in size and shape of the urban area over the duration of the model. The second section examines the overall change in the spatial structure of urban form caused by developer competition through an examination of the change in the underlying parcel size (known as `Level` within the model).

Change in urban area

As has been discussed, the changes between the five levels of competition are hard to discern visually. To highlight these issues, a comparative image (Figure 7.9) is used to give the reader an idea of the changes occurring in urban landscape based on the variation in competition within the model. Please note that this image is only based on one of the 100 random seeds and so is not a representative sample, it is merely a way of highlighting the changes occurring. In addition, it is important to note that there is no control or guidelines for the location of development. The only aspect controlling the location of development is the way in which parcels are assessed by the developer (as such aspects around zoning are outside the boundaries of this thesis).

While the development in these images may appear to be randomly located, the figure shows that there is a clear increase in the amount of development undertaken with an increase in developer competition. Therefore the level of competition in the developer market does play a role in shaping the cadastral landscape. The reader should note that this is also only highlighting the change in the extent of the urban area. Developments which subdivide parcels that are already classified as an urban parcel are effectively ignored in this landscape and the image below (Figure 7.9).

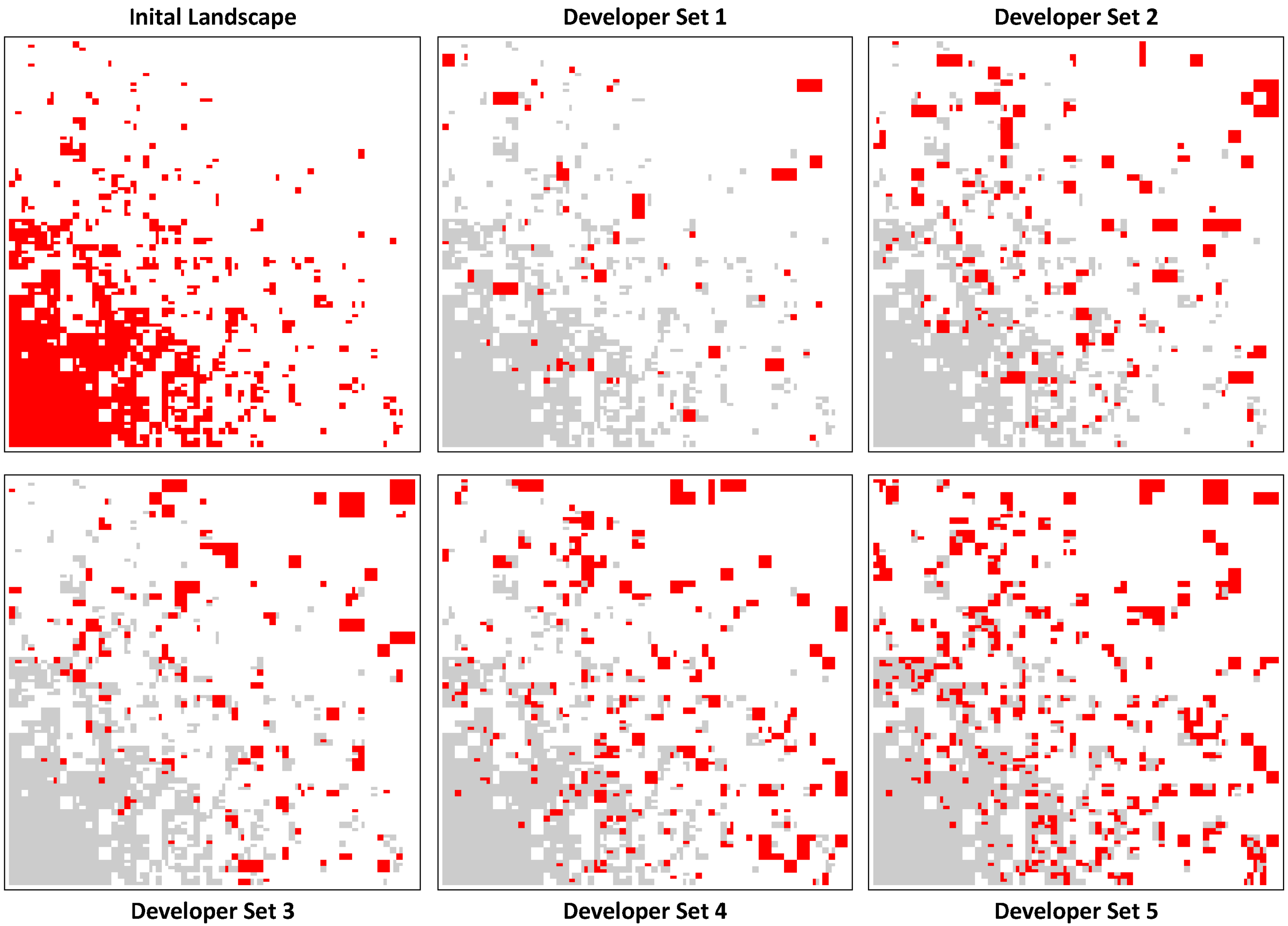

Figure 7.9: Comparison between the initial and resulting urban landscapes for the five levels of developer competition for a single random seed value. Note that these images do not highlight redevelopment undertaken within existing urban areas. Light gray areas signify the extent of the original landscape.

Using boxplots, the variation in the structure of the urban class caused by developer competition over the duration of the model can be observed. When comparing the urban class statistics between the various developer sets, boxplots are used to visually highlight the variation between all model runs, including the variation within developer sets. Each developer set boxplot consists of a box showing the median and 25th and 75th percentiles, with whiskers corresponding to the lowest and highest values within 1.5 times the interquartile range of the respective quartile. Outliers to these ranges are plotted as individual dots. Mean values for each developer set against each landscape metric, can be found in Table 7.6.

As was seen in the NetLogo reporters discussed above, an increase in the level of competition results in more development occurring. The shape and structure of the location of development in the urban landscape highlights a distinct pattern forming when there is more competition in the market.

The Average Polygon Perimeter-Area Ratio for the urban class (Figure 7.10) decreased as the level of competition within the developer market increases (with a marked drop in the metric for DS5). DS5 shows a strong trend towards a developments being clustered into more contiguous polygons, either through development in and around the core urban area or through external developments being more aggregated. DS1 shows a more dispersed urban class, not focused on developing parcels in or adjacent to the other urban parcels.

These results are reinforced when examining the Aggregation Index for each of the five levels of developer competition. The Aggregation Index, which is a measure of how contiguous a class is within the landscape, shows that the urban class becomes more contiguous with more competition (Figure 7.11). DS5 results in a urban class which has development occurring closer to the urban core or existing urban areas. DS1 results in the urban class being dispersed throughout the landscape, an approach that suggests a 'leapfrogging' approach to development. The increase in

Aggregation Index can also be explained through the substantial reduction in the total number of urban polygons in the landscape (Figure 7.12).

Based on these results, development in DS1 is more dispersed from the initial urban core, focusing on a place-making leapfrogging approach to developing a number of large non-urban parcels (as seen through the low Aggregation Index and high values for Total Polygons and Average Polygon Perimeter-Area Ratio). The many small developers in DS5 cannot afford such an approach, so they focus on smaller developments that are adjacent to existing urban parcel (increased Aggregation Index). The aggregated parcels to form polygons which are more linked to other urban polygons and the existing urban core (lower values for Total Polygons and Average Polygon Perimeter-Area Ratio). The final result shows that a more fractal urban development pattern is assumed when there is more competition (DS5), highlighting the less 'place-based' nature of development by developers with less capital. This result results in the edge of the urban class being more intermingled with the non-urban (and in this case rural) area.

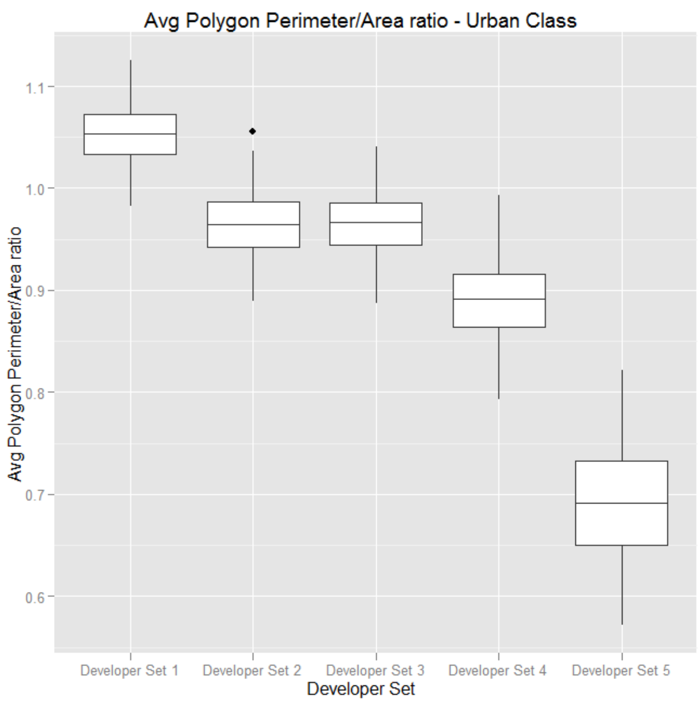

Figure 7.10: Change in Average Polygon Perimeter-Area Ratio for the urban class through developer competition

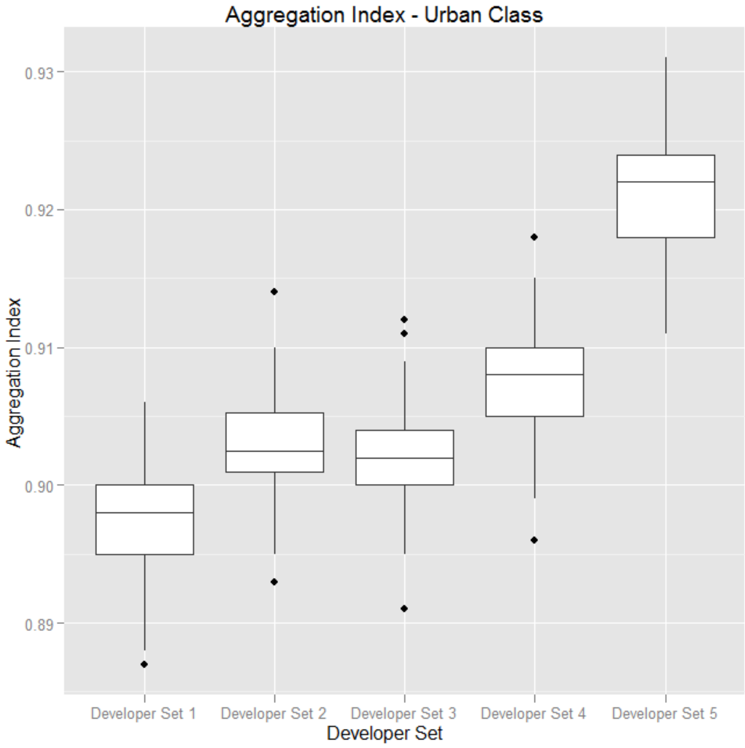

Figure 7.11: Change in Aggregation Index for the urban class through developer competition

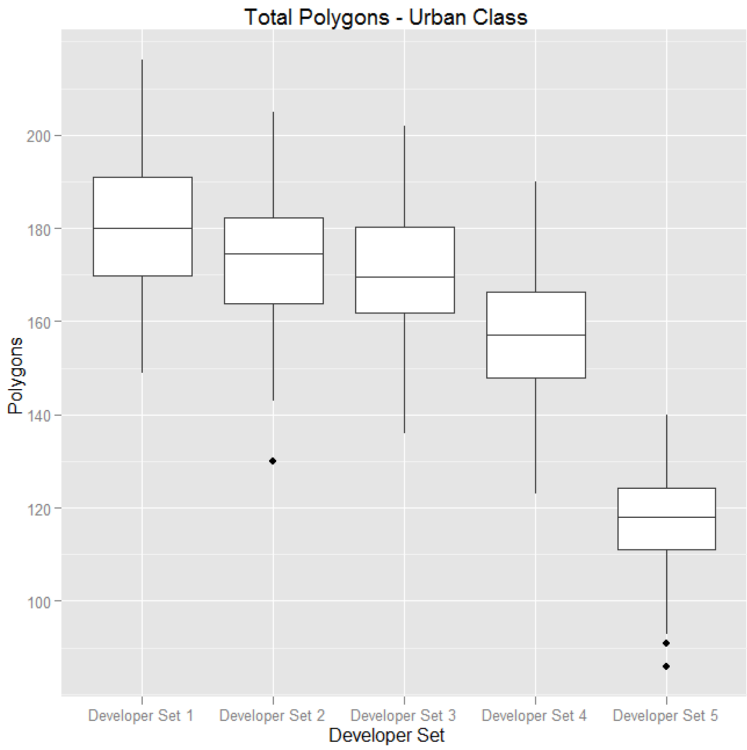

Figure 7.12: Change in Total Polygons for the urban class through developer competition

Metrics	*Dev Set 1*	*Dev Set 2*	*Dev Set 3*	*Dev Set 4*	*Dev Set 5*
Avg. Polygon Perimeter-Area ratio	1.0529 (±0.0059)	0.9639 (±0.0061)	0.9645 (±0.0062)	0.8919 (±0.0077)	0.6937 (±0.0112)
Aggregation Index	0.8975 (±0.0007)	0.9029 (±0.0007)	0.9024 (±0.0007)	0.9077 (±0.0008)	0.9212 (±0.0009)
Total Polygons	180.23 (±2.788)	172.85 (±2.7632)	170.63 (±2.5008)	170.63 (±2.5008)	117.19 (±2.231)

Table 7.6: Mean values of three landscape metrics examining the resulting urban/non-urban landscape by developer set (±=95% Confidence Interval)

Examining the changes over the length of the model, through time-series graphs, reinforce the patterns seen in the above boxplots. From an urban class perspective, more competition within the developer market results in more contiguous urban areas. This overall pattern can be seen in the linear reduction in the Average Polygon Perimeter-Area Ratio (Figure 7.13) and linear increase in Aggregation Index (Figure 7.14) metrics over the length of the model. This pattern is further reinforced when viewing the change in the number of urban polygons present in the landscape (Figure 7.15) which decreases markedly as the level of competition is increased.

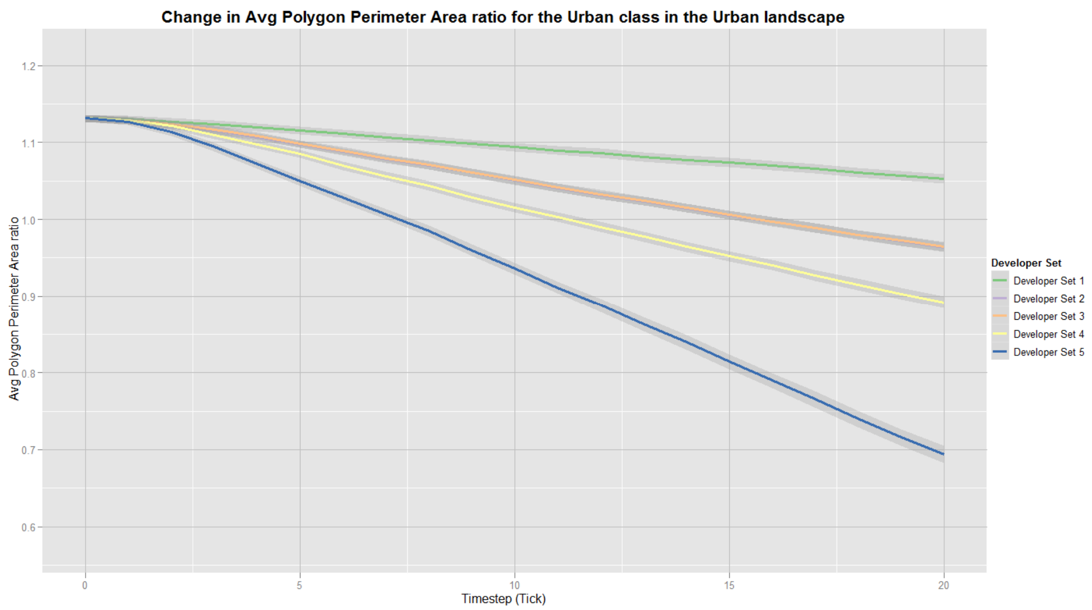

Figure 7.13: Time-series showing change in Average Polygon Perimeter-Area Ratio for the urban class through developer competition

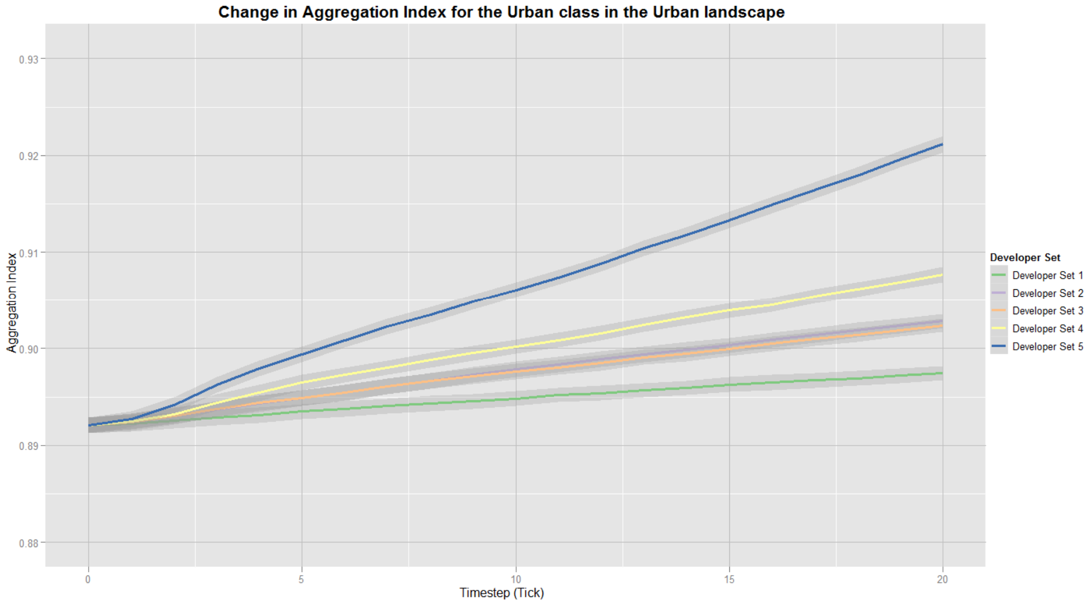

Figure 7.14: Time-series showing change in Aggregation Index for the urban class through developer competition

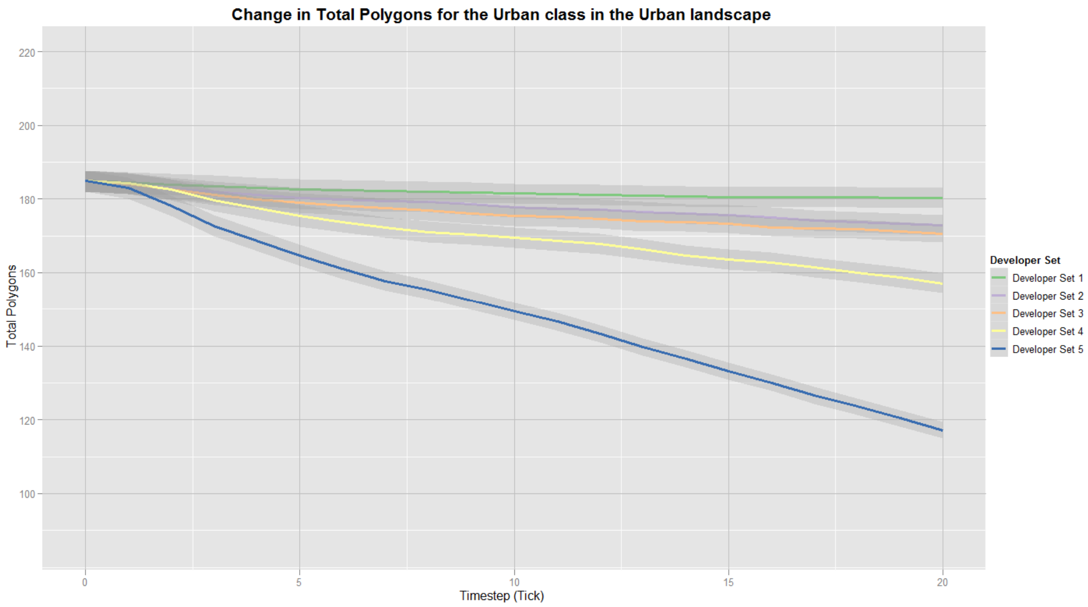

Figure 7.15: Time-series showing change in total urban polygons for the urban class through developer competition

To observe the multivariate response to developer competition, a principal components analysis was performed utilising urban class metrics from all 500 model runs. The results show a distinct grouping based on the level of competition that corresponds to the urban class metrics discussed above (Figure 7.16 along with supporting validation – Table 7.7). Developer Set 1 is aligned with a lower Aggregation Index and higher values for the Average Polygon Perimeter-Area Ratio and Total Urban Polygons when compared with the other levels of competition.

Developer Sets 2 and 3 overlap significantly and are located near the centre of the biplot, constituting landscapes that are slightly more aggregated than DS1 (higher Aggregation Index, Lower Average Polygon Perimeter-Area Ratio and Total Urban Polygons values). Developer Sets 4 and 5 continue this trend but the resulting cluster is more pronounced with DS5 a separate cluster with the highest Aggregation Index values and lowest Average Polygon Perimeter-Area Ratio and Total Urban Polygons values.

This biplot reinforces the results found in the previous results that, from an urban landscape perspective, an increase in competition results in a more clustered, contiguous landscape. In addition, with higher levels of competition the new urban development is more focused around existing urban development as seen through the decrease in the Average Polygon Perimeter-Area Ratio and Total Urban Polygon values.

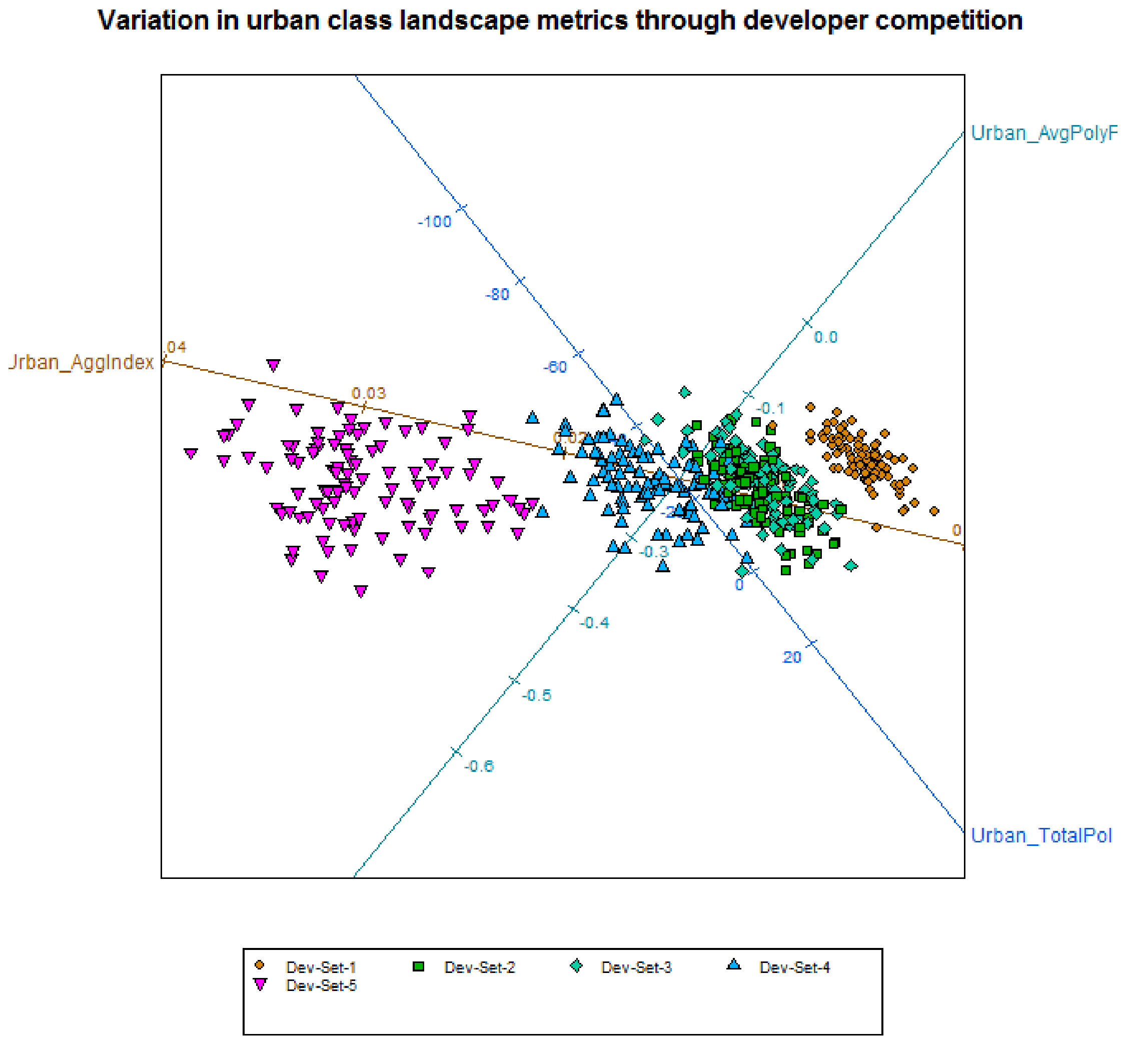

Figure 7.16: Principal components analysis of urban class landscape metrics based on developer competition

	Dimension 1	*Dimensions 1 and 2*
Aggregation Index	0.9742300	0.9761815
Avg Polygon Perimeter Area Ratio	0.9422356	0.9962148
Total Urban Polygons	0.9327166	0.9881009

% of variance explained in the two dimensions	*98.7%*

Table 7.7: Axis predictivities for and quality of the principal components analysis of urban class landscape metrics

Change in parcel size (`Level`)

While the urban/non-urban landscape is arguably more straightforward to decode, the use of the parcel size value (based on the landscape's `Level` variable) is more complex to understand. As in the analysis of the urban landscape, it is difficult to visually assess the changes based on the differing levels of competition. As a point of comparison, to understand what the resulting parcel size landscapes look like, Figure 7.17 shows a greyscale image that compares the initial landscape with the resulting parcel size landscape from the five levels of developer competition.

The severity of the changes seen in the five developer set landscapes have been made more pronounced through a numerical subtraction from the original landscape. Areas of the five developer set landscapes which are white, signify parcels that have had no development over the duration of the model (i.e. no change between the initial and the final landscapes). The severity of the change in the form of the landscape is signified by the increasing shades of gray used in the landscapes. The more intense the level of development when compared with the original parcel size, the darker the area in these developer set landscapes. For example the light gray areas in the bottom left corner of each landscape are existing two-cell urban parcels that were subdivided into 2 one-cell parcels. As in the urban landscape comparison, the image is based on a single random seed so results cannot be drawn from these images. It is merely a guide to enable the reader to visualise the changes that result in the parcel size landscapes.

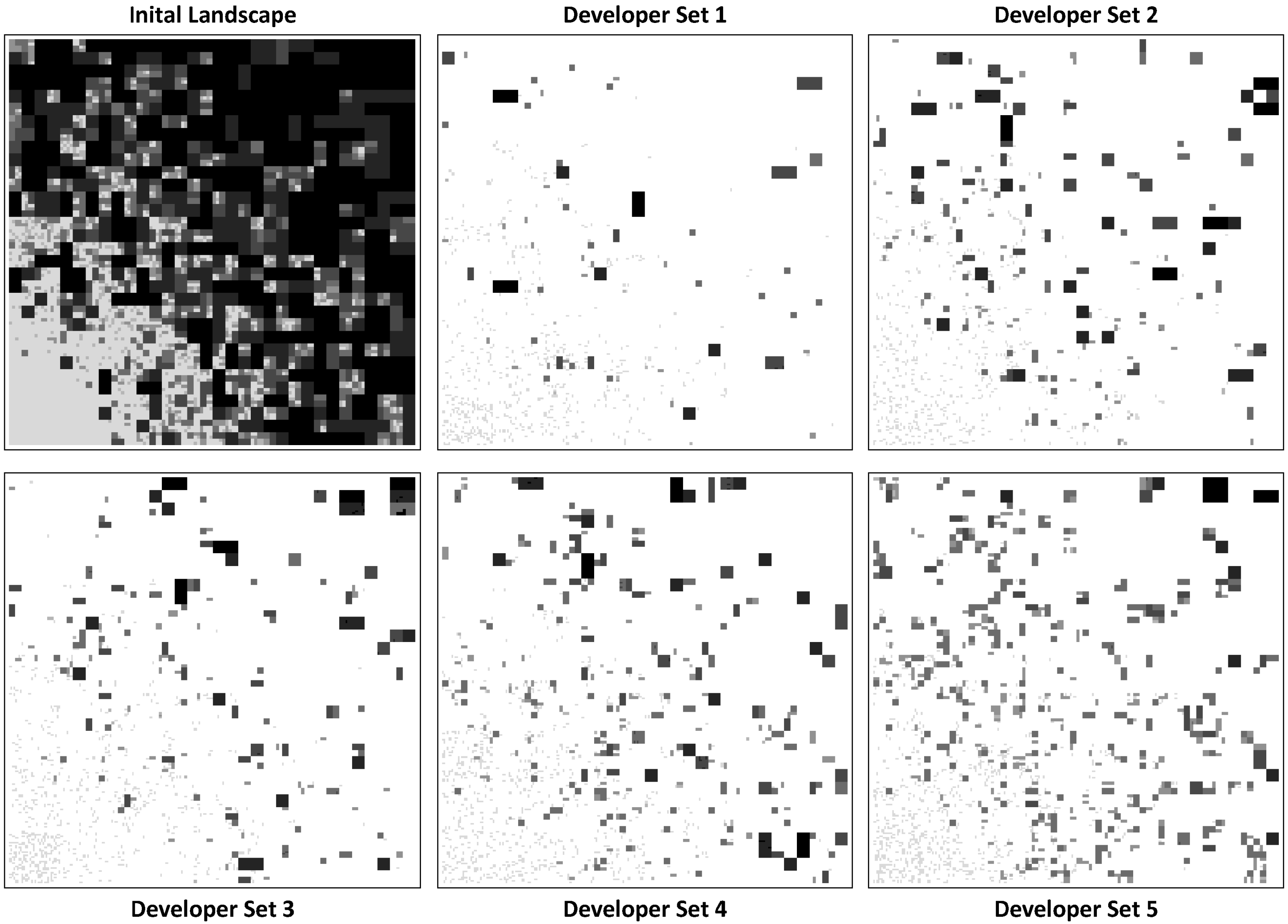

Figure 7.17: Comparison between the initial and resulting parcel size landscapes for the five levels of developer competition for a single random seed value

The dramatic increase in parcels being developed as competition increases can be seen in the comparative image. In addition to this, note the location and severity of development in the changes to the parcel size landscape. Developer Set 1 highlights the development of larger parcels closer to the urban core that are subdivided down to numerous small parcels. Developer Set 5 also has large drastic developments being undertaken but they are focused on the parcels well away from the urban core. Developer Set 5 highlights the combined power of small scale development.

As was the case in the urban landscape analysis, comparisons can be drawn based on a variety of other landscape-based metrics that can account for the intricacies of the numerous resulting landscapes. One of the more telling explanations of how the form of the landscape is altered by the various developer sets can be observed in a simple examination of the change in total area for each parcel size (Figure 7.18). The values are calculated by comparing the total area (in cells) for each parcel size (ranging from Class 9 – 128 cell parcels, down to Class 16 – 1 cell parcels) between the original and resulting landscapes for each random seed.

There are number of items to note about this graph. Initially, the growth of Class 16 is substantial because there were no Class 16 parcels in the original landscape. But more importantly the parcel sizes which are favoured by each developer set can be easily identified. DS1 draws mostly from Class 9 (the largest set of parcels that contain 128 cells) and follows a gradual decline through the rest of the parcel sizes until the smaller developers within the developer set contribute to the development of Class 15. With the smaller number of parcels being developed in this developer set, the overall scale of development is lower than the other developer sets (as seen in the small increase in area through Class 16).

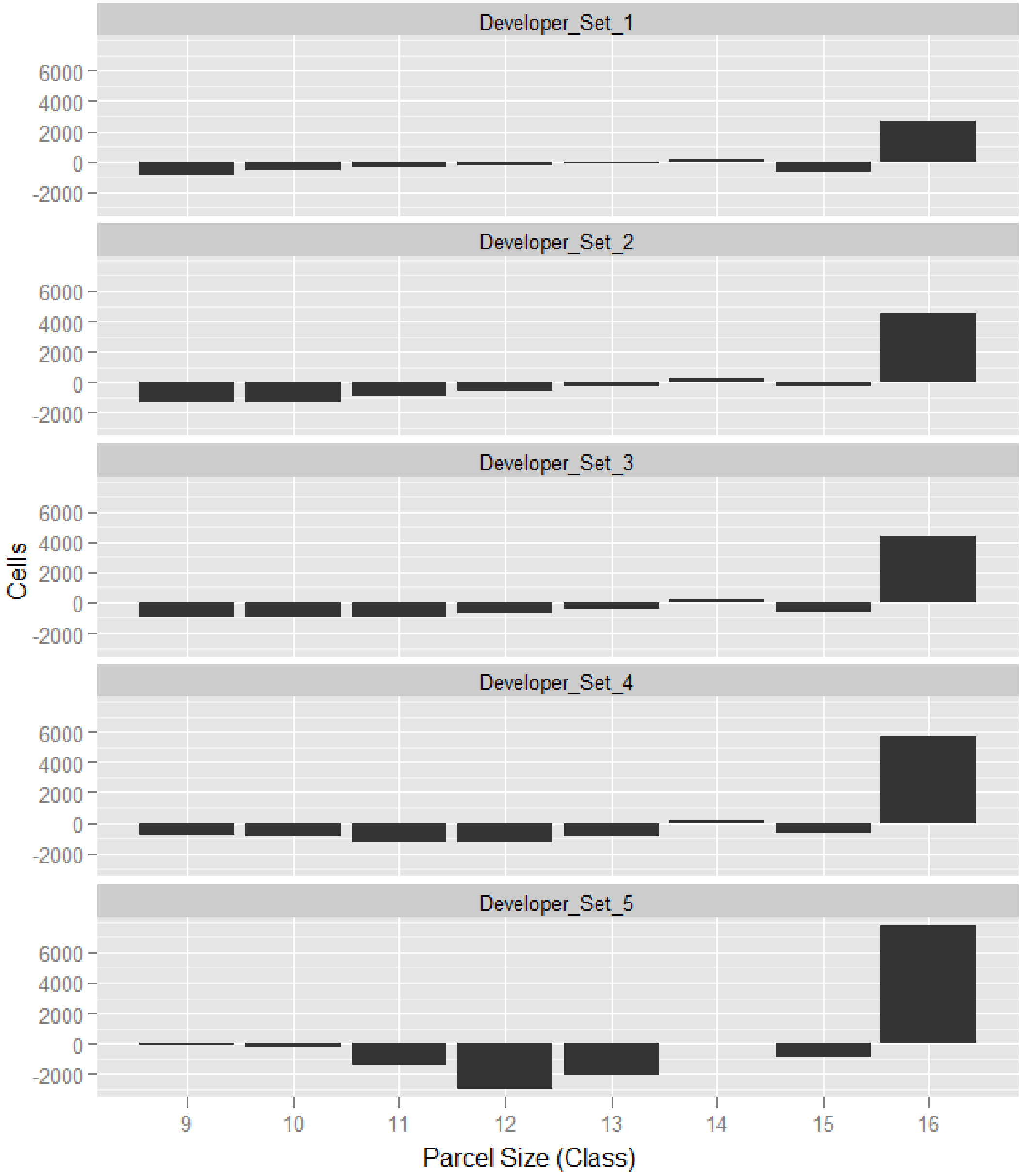

Figure 7.18: Change in parcel area based on parcel size classes caused by developer competition

When looking at DS2 there are two points to notice, development is primarily focused within Classes 9 and 10 at an increased level compared with DS1, and the resulting developments are at both the Class 16 but also Class 15 level. This development at the Class 15 level is seen through the comparatively small reduction in Class 15 when compared with the other developer sets. Class 15 is seen as both a source parcel size for development (by small developers) but also as a resulting parcel size through development (larger developers converting larger parcels). DS2's preference of Class 15 over the higher return Class 16 suggests a satisficing approach to development through the development of parcels which suit the surrounding area rather than maximising their return on investment.

DS 3 and 4, draw from across the spectrum of parcel sizes for their developments. DS4's higher level of competition is also seen in the higher level of parcels developed from the moderate parcel sizes (Classes 12 and 13).DS5 mainly draws from Classes 12 and 13 (and to an extent Classes 11 and 15) as the source for their developments and almost all of their new developments are at the smallest parcel size (Class 16). Because of the higher level of competition, the developer set also undertakes more internal redevelopment as seen in the slightly higher consumption of Class 15.

As in the case of the urban landscape, landscape metrics were calculated on the resulting parcel size landscapes for each combination of random seed and level of competition. These metrics were then plotted to produce a more representative analysis of change in the spatial location of parcel sizes caused through developer competition. The boxplots below were created in line with the boxplots in the urban class landscapes discussed above. Unlike the urban class boxplots, the parcel size landscapes consist of multiple classes (Class 9 through 16). To reduce complexity of these results, the metrics presented in this section are landscape metrics. Landscape metrics are calculated through averaging the metric for each class in the landscape. While this approach masks some of the class change, the overall trends are captured in this landscape-wide approach.

Unlike the urban landscape metrics examined earlier, the trend in these boxplots is the relative similarity between the different levels of competition. Where there is variation in the boxplots, the change is minor when compared to the scale of the boxplot (For example, the Average Polygon Perimeter-Area Ratio – Figure 7.19) or through the substantial overlap seen in the 25^{th} and 75^{th} percentiles (For example, Edge Density – Figure 7.20). Mean values for each developer set against each landscape metric for the parcel size landscape, can be found in Table 7.8.

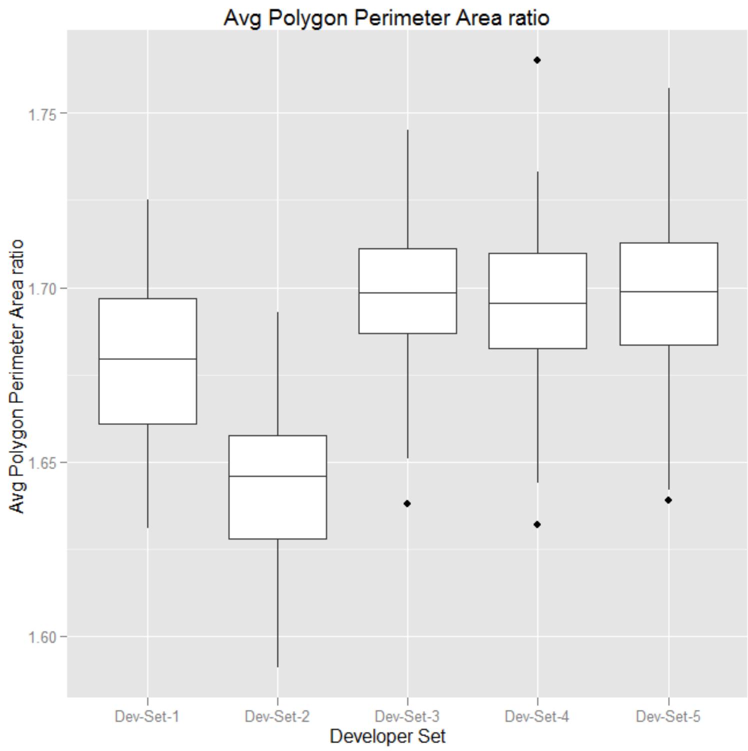

Figure 7.19: Change in Average Polygon Perimeter-Area Ratio for a parcel size landscape through developer competition

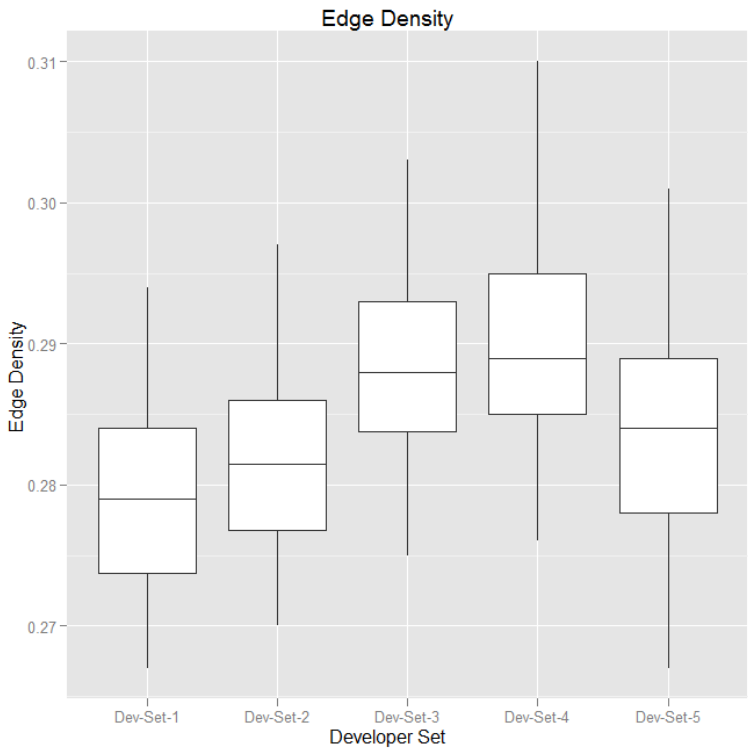

Figure 7.20: Change in Edge Density for a parcel size landscape through developer competition

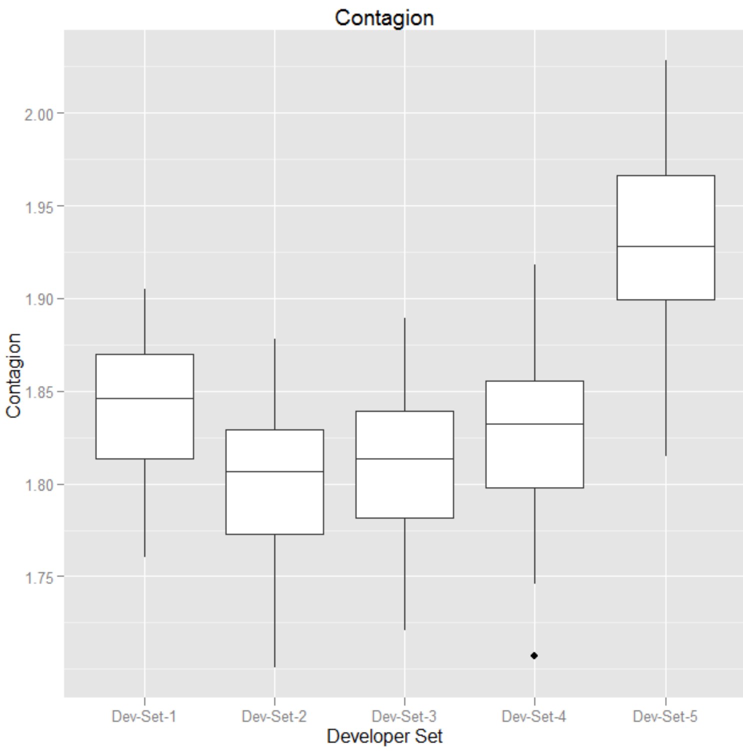

Figure 7.21: Change in Contagion for a parcel size landscape through developer competition

Metrics	*Dev Set 1*	*Dev Set 2*	*Dev Set 3*	*Dev Set 4*	*Dev Set 5*
Avg. Polygon Perimeter-Area ratio	1.6792 (±0.0041)	1.6435 (±0.004)	1.6989 (±0.0037)	1.6956 (±0.0042)	1.6984 (±0.0051)
Edge Density	0.2787 (±0.0013)	0.2815 (±0.0013)	0.2883 (±0.0013)	0.2899 (±0.0014)	0.2837 (±0.0015)
Contagion	1.8421 (±0.0067)	1.8021 (±0.0074)	1.8104 (±0.0071)	1.8271 (±0.0078)	1.9328 (±0.0093)

Table 7.8: Mean values of three landscape metrics examining the resulting parcel size landscape by developer set (±=95% Confidence Interval)

However, there are a few landscape metrics which highlight some subtle changes in the form of the parcel size landscape caused by developer competition. As seen in the Contagion boxplot (Figure 7.21), DS5 shows a trend towards increased values in Contagion based on the level of competition. When examining the parcel size landscape, Contagion relates how the parcel sizes within the landscape are formed into contiguous polygons with higher values signifying landscapes where the parcel sizes are arranged in a more contiguous fashion. Therefore this boxplot shows that the landscapes are more contiguous with more competition. As was the case when examining the urban landscape, when there is more competition the form of the urban landscape, through the spatial arrangement of parcel sizes, becomes more contiguous. One item to note, the slight increase in Contagion for DS1 (as seen in Figure 7.21) is because of the place-making nature of development that level of competition undertakes which in itself creates large urban polygons which are contiguous in nature.

When examining these landscape metrics from a time series perspective, only one metric shows a response which varies from a generally linear progression through to the end of the model, the Contagion metric (Figure 7.22). Within the time series graph, both Developer Set 4 and 5 shows an initial uniform decrease in Contagion until an inflection point where the metric initially levels out then increases. The inflection point occurs earlier based on the level of competition. As was seen in the Contagion boxplot (Figure 7.21), DS1 has the second highest value of contagion at the end of the model’s duration. Examining the time series graph highlights a downward trend for the DS1 Contagion metric. Comparing the slope of the DS1 metric with the general upswings seen for DS3 and 4 metrics show that over time DS1 would regress to one of the less contiguous landscapes.

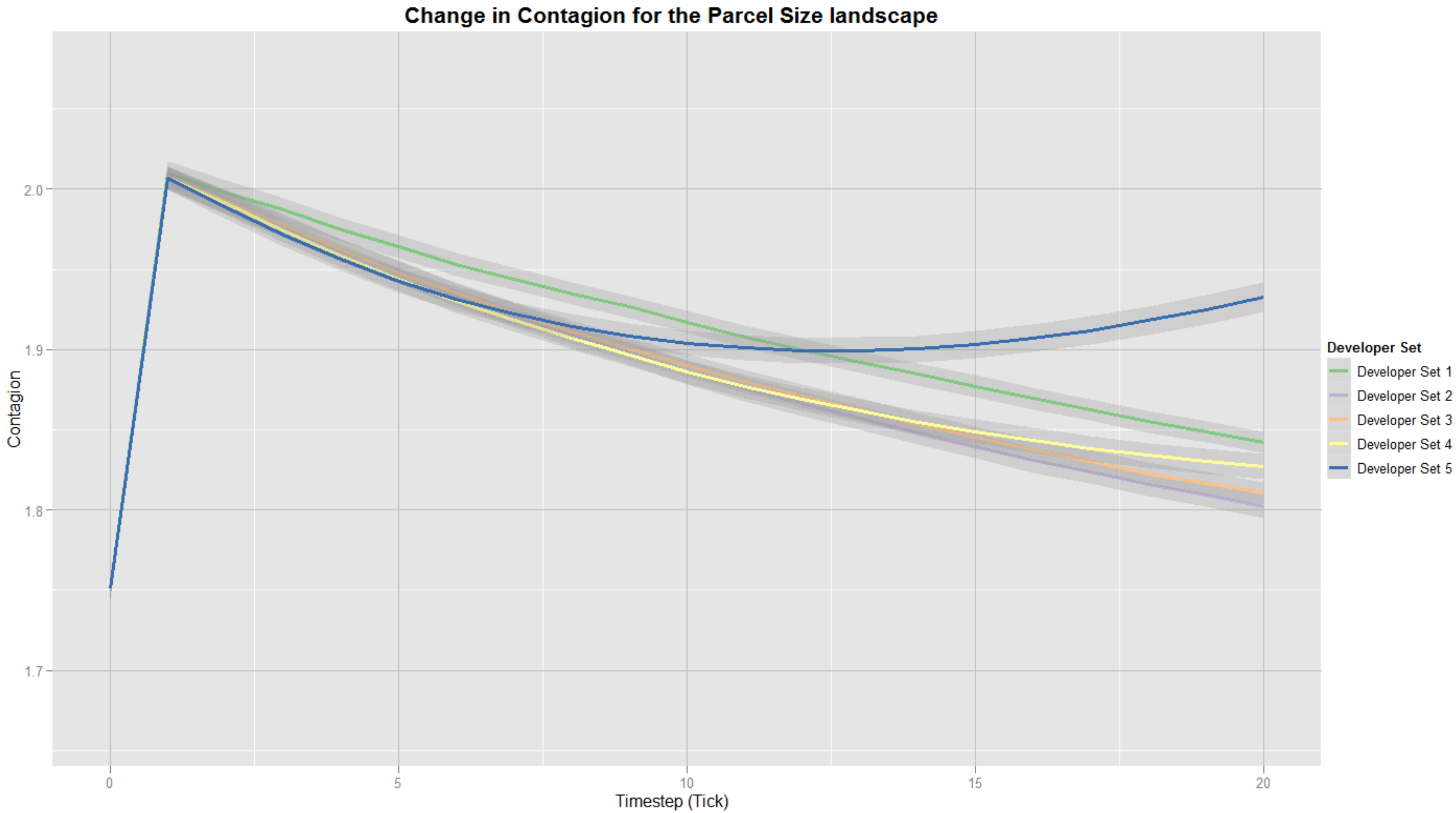

Figure 7.22: Time-series showing change in Contagion for the parcel size landscape

This increase in Contagion in the parcel size landscape for Developer Sets 4 and 5 shows that even from a parcel size landscape, more competition equates to a more contiguous urban form based on the distribution of parcel sizes throughout the landscape.

The inferred reason for these inflections is directly related to the distribution of capital amongst the developers in Developer Sets 4 and 5. Based on their assigned level of capital, larger developers in Developer Sets 4 and 5 are more likely to purchase parcels that are closer to the urban core. When subdivided, the new parcels are disparate from the surrounding parcel size landscape which decreases the Contagion metric. Because these parcels are usually located closer to the urban core, the range of smaller developers in these developer sets develops the middle ground. This process begins to link the parcels developed by large developers to the existing urban core, which increases the Contagion metric. Developer sets with more disparity in the spread of capital (DS1) do not see this reaction in the level of Contagion over time.

Note that the substantial increase from time step 0 to time step 1 is because of the increase in the number of classes over the time step. As discussed in Chapter 7 (page 123) the landscape created in the initialisation stage of the model does not have any single cell parcels. In the first time step a parcel is subdivided down to a single level parcel. For the Contagion metric the number of classes is used to define the max metric value and therefore the range of values.

As in the urban analysis, a principal components analysis (PCA) using a subset of the landscape statistics analysed for each model run was used to examine any multivariate variation in the dataset. The results (Figure 7.23 along with supporting validation – Table 7.9) again show a distinct grouping based on the level of competition which corresponds to one of the three parcel size landscape metrics (Contagion, Average Polygon Perimeter-Area Ratio and Edge Density) although the level of overlap between the metrics is greater than in the Urban PCA (Figure 7.16).

Like the PCA for the urban landscape, the PCA focuses only on the change in metrics caused by the level of developer competition. This is done by subtracting the metric value for the initial parcel size landscape from the final parcel size landscape for all 500 runs.

DS 3 & 4 shares the same space within the PCA, both being aligned at the higher end of the Edge Density axis. The data points for DS2 are tightly clustered at the low end of all three metrics used. In addition, the cluster of DS1 data points appears close to the DS2 cluster with only a slight increase in Contagion separating the two developer sets. Finally DS5 appears as a loosely clustered outlier, with a significant increase in Contagion and Average Polygon Perimeter-Area Ratio with the runs variable based on the change in Edge Density.

This biplot reinforces that the spatial arrangement of the parcel size landscape changes based on the level of competition. With lower levels of competition the parcel size landscape is more fragmented with the form of the urban landscape being haphazardly arranged. The Average Polygon Perimeter-Area Ratio, Edge Density and Contagion metrics for DS1 and 2 all signify these results. When the level of competition is increased (DS3 and 4), the level of Contagion in the landscape does not alter but the Average Polygon Perimeter-Area Ratio and Edge Density metrics increase, signifying an increase in the collocation of parcel sizes throughout the landscape. The co-location of these parcels form large polygons offset from the main urban conurbation (as seen in the low Contagion metric). With the highest level of competition (DS5), the landscape becomes substantially more contiguous as seen in the Contagion and Average Polygon Perimeter-Area Ratio metrics. This level of competition does see a slight reduction in the Edge Density (compared with DS 3 and 4) because of the increased level of urban redevelopment (Class 15 parcels being developed into two Class 16 parcels) occurring in certain landscapes.

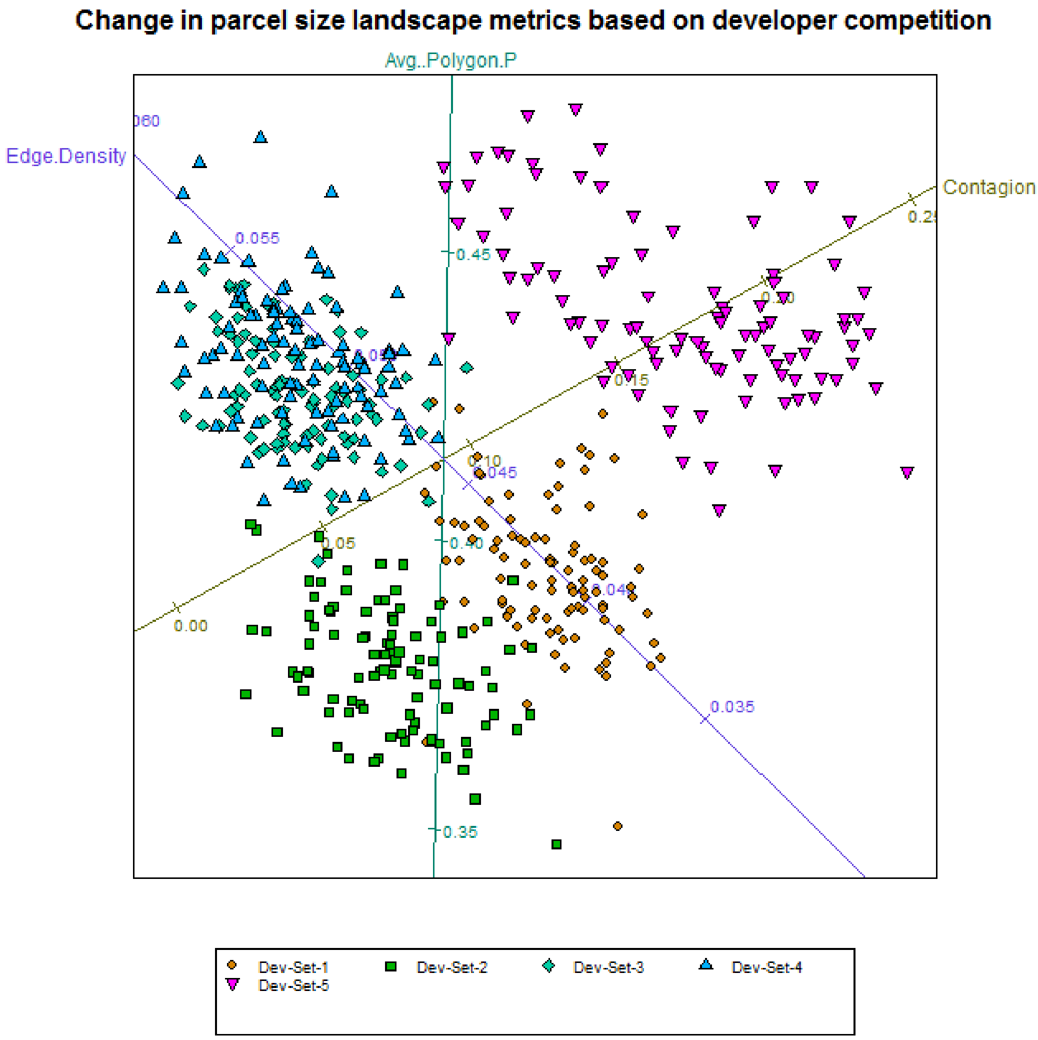

Figure 7.23: Principal components analysis of change in parcel size landscape metrics based on developer competition

	Dimension 1	*Dimensions 1 and 2*
Avg. Poly Perimeter-Area ratio	0.0004834	0.7559984
Contagion	0.7625358	0.9559523
Edge Density	0.5096161	0.9181237

% of variance explained in the two dimensions	*89.4%*

Table 7.9: Axis predictivities for and quality of the principal components analysis of parcel size landscape metrics

7.4 Developer and landscape responses to competition

Prior to the discussion, a brief review of the main results from the experiment is presented here. Increasing the level of competition (i.e. moving from Developer Set 1 through to Developer Set 5) resulted in;

- An increase in the number of parcels developed (Figure 7.6);
- A decrease in the mean urban parcel size (Figure 7.7);
- Urban class polygons that were more aggregated together (Figure 7.11), which resulted in less urban class polygons (Figure 7.12), and the resulting polygons were more compact (Figure 7.10)
- Parcel size landscapes that were more contiguous (Figure 7.21), and substantial differences in consumption and creation of the various parcel sizes (Figure 7.18).

One key result is apparent when explaining developer and landscape responses to the varying levels of competition - more competition leads to more parcels being developed. With more developers and more competition there are more 'eyes' evaluating parcels for development. While each developer within a more competitive market ultimately has a lower level of capital, with the increase in the number of developers assessing parcels – more parcels are ultimately selected by developers as being suitable for development and are developed into new parcels.

As seen in the results above, this level of competition also has an effect on the location of the new developments. The urban and parcel size landscapes from the model indicate that an increase in competition results in a more clumped contiguous urban landscape, where new developments are focused around the existing urban development creating a more homogeneous urban landscape while also promoting a more contiguous landscape where urban parcel sizes are more clustered together.

As might be expected, since developers aim to maximise their utility through the application of capital for development, the location of development is fundamentally driven by the developer's level of capital. Put simply, larger developers can afford larger parcels of land which meet their inherently larger financial capability. In line with real-world cities, these larger parcels of land are rarely found in an existing urban core of the abstract BSP tree landscapes, and are only slightly more common on the periphery of a city. Therefore even though large developers have more financial resources, they are more constrained in their locational decisions in regards to development.

Therefore the parcels purchased are usually located away from the existing urban core (also known as a leapfrog development) because the drive to maximise their financial utility is greater. While large developers may land-bank the parcel, even if the parcel is developed immediately after purchase, these large scale developments are places unto themselves mimicking the place-making approach discussed in Chapter 4 (page 51). While not built into this model, these types of developments in the real-world would negate any issues with the demand for the resulting product with the development being separated from the existing urban core. Larger developers focus on developing a parcel down to the smallest parcel size available to maximise their return on their investment (as seen in the general increase in area for Class 16 in Figure 7.18) but also retain the freedom to develop to a slightly larger parcel size to minimise the risk of developing further away from the urban conurbation.

Smaller developers are more financially constrained in the size of land parcel they can purchase but conversely have greater locational freedom and potentially more choice in the type of development that they can undertake. From the single level subdivision of single lot properties (i.e. subdividing a Class 15 parcel into two Class 16 parcels only) towards multi level subdivision of larger, cheaper parcels well outside of the urban core, smaller developers have a greater range of options.

While effecting such structural changes to the development market would be difficult, these results suggest that if large cadastral parcels were are able to be split up into smaller legal titles prior to large scale urban development (potentially by a regional governmental agency) this would encourage more smaller developers to work in this space. As seen in the results above, this approach might increase the level of development activity in the area and create a more uniform form of development.

Compare that approach with the existing single large parcel of land. Only a select few developers might be able to afford that parcel. If development is to go ahead, the larger developers will attempt to minimise their risk in one of two ways, cost or features. While the features of the resulting development (quality of the houses, etc) are outside the interest of this thesis, the resulting parcel size is a key feature because more land makes for a more desirable product to homeowners. In this case developers might choose to make a sub-optimal development choice in the resulting parcel size of the development. In addition, the larger developers might land bank the parcel for a longer period of time, which improves their profit but constrains growth until they develop.

Smaller developers buy smaller plots of land, and intensively develop them. They co-locate through selecting parcels for development around existing parcels of development closer to the urban core. They are unwilling to take on the financial risk involved in rural leapfrog development. The model does suggest that some smaller developers do undertake development away from the city core, in small exurban areas outside of the main core, because the existing level of development within these areas is large enough to support such development.

Larger developers focus more on the opportunities available to them regardless of the spatial location of the parcels and the level of development which surrounds the parcels selected for development. They are willing to take on an aspect of this locational risk because they will either; land bank the parcel and wait for development to get closer to the parcel; or will undertake a leapfrog type development (because their development is place-making in its approach) with large parcel sizes to offset the distance from the urban core.

7.5 Conclusion

As highlighted earlier, as land is currently developed to meet the demand of the city, the resulting land use can be seen as a fragmented patchwork of developed and undeveloped land. Issues surrounding sustainable development (such as congestion, air pollution and commuting times) can be viewed as a consequence of the pattern of growth rather than the amount of growth. Sustainable city initiatives need to be more focused on sustainable growth patterns, with a key focus on the more efficient use of existing land within the city's urban limits, with a particular focus on the structure of residential development.

As shown in the results above, changing the structure of the residential development market will encourage the development of a more sustainable form. When there is more competition and therefore more developers there are two key outcomes – more parcels are developed and the resulting development is more compact and homogeneous in both growth and form achieving the requirements of a more sustainable urban development.

8 Effects of homogeneity in developer behaviour on a agent-based model of urban development

> Important issues in the use of ABMs are how to appropriately represent the heterogeneity of agents and their environment as software objects in ways that accurately reflect the actual heterogeneity of "real-world" objects, and what effects heterogeneity has on the outcomes of the models.
>
> (Brown and Robinson 2006, p. 2)

As seen in Chapter 2, the high level of agent homogeneity found in the few agent-based models of urban growth that explicitly include developers is a considerable problem with the existing approach. Chapter 3 outlined the importance of developers within the process and Chapter 4 highlighted the way in which the heterogeneous nature of developer behaviour can shape the urban landscape through the urban development process.

Using the agent-based model of urban development, an experiment was conducted to examine how the homogeneous application of each of the developer's behavioural traits affects spatial investment decisions from both an urban growth and form perspective. This approach differs from the heterogeneous application of the traits used in the rest of this research.

This experiment is in line with the second research goal, outlined in Chapter 1;

- To examine the importance of property developer behaviour with a specific focus on how developer behavioural traits affect the resulting urban landscape.

The parameters used within the model are in line with the parameters decided on and defined in the previous chapter. In line with the results found in the previous experiment, the level of developer competition was purposefully assigned to a level which did not promote some of the extreme responses. Consequently, Developer Set

3 was used throughout the experiment to provide a balance in the level of competition within the model.

This chapter begins with the details of the experiment and approach used. The chapter then outlines the results of the experiments and then discusses these results and relates them to landscape and developer responses in the real world.

8.1 Experimental design

This experiment aims to compare the changes in landscape pattern when the five behavioural traits used by the developer agents are defined in both a heterogeneous and homogeneous way. The model inherently creates developer agents that are heterogeneous in the way they undertake the urban development process based on their level of capital. Using toggles in the initialisation stage of the model, each of the five behavioural traits are able to be individually switched 'off' and set to a state where the trait is applied the same across all developer agents, regardless of the level of capital the developer is assigned.

Using these toggles, a series of model runs were developed (Table 8.1) to explore the research goal. In addition to the five runs examining the landscape pattern changes caused by each trait being 'off', an 'all on' baseline was run that has all of the traits being set in a heterogeneous way. The 'all on' baseline was compared with the results of each trait when switched 'off' to observe the changes in the resulting landscape caused by how the trait was applied (heterogeneously – 'on' or homogeneously – 'off')

For reference, this experiment was also performed using an 'all off' baseline and turning each trait 'on' to see if this resulted in a substantial difference in the changes to the landscape. While there was a difference in the way the landscape was developed, my opinion is that the homogenisation of a certain trait should be applied alongside the other heterogeneous traits because the effects on the landscape would be more applicable to real-world developers. While the initial intention was to include some of the results of this approach in the discussion, the dissimilarity of the two sets of results and the more complex presentation prompted the decision to omit this approach from the results.

Run type	*Explanation*
'All on' Baseline	All behavioural traits 'on'
`Accuracy`	`Accuracy` 'off', all others 'on'
`Parcel Assessment`	`Parcel Assessment` 'off', all others 'on'
`Subdivision`	`Subdivision` 'off', all others 'on'
`Territoriality`	`Territoriality` 'off', all others 'on'
`Riskiness`	`Riskiness` 'off', all others 'on'

Table 8.1: Description of runs performed in behaviour trait experiment

The application of behavioural traits within the model is controlled through a range of Boolean settings set prior to the initialisation of the model. Table 8.1 outlines the runs undertaken for each random-seed. When 'off', the way in which the behavioural traits are applied is altered. For the `Accuracy`, `Territoriality` and `Riskiness` traits, the traits are applied in an explicitly homogeneous way. Because of the nature of the model and the fundamental process which the trait is linked to, the `Parcel Assessment` and `Subdivision` traits are applied differently. In both of these traits the factors used to make these decisions are reduced. This reduces the level of heterogeneity used in the decision but does not make all developers homogeneous. The removal of these factors makes the developers act in a profit maximiser way rather than the profit satisficer perspective inherent in the model. A detailed description of the way in which the traits are altered within this experiment is covered in Table 8.2.

Trait	*Detailed explanation*
`Accuracy`	`Accuracy` controls how the developer is assigned the 'accuracy' state variable. If 'on', the developer assigns the 'accuracy' variable in line with the level of capital resources to which the developer has access (i.e. larger developers are more accurate while smaller developers are less accurate). If 'off', all developers have the same 'accuracy' state variable. This does not mean that all developers calculate the same value for each parcel, but rather that the developers are all equal in the variability with which they estimate a parcel's value;
`Parcel Assessment`	`Parcel Assessment` controls the information inputs into the calculation of the desirability of a parcel for purchase. If the trait is 'on', the calculation is more detailed, with the overall trend of the market, the potential number of houses which could be developed on the parcel, the mean parcel size of the surrounding parcels, and the parcel's distance to an urban cell all being assessed. If the trait is 'off', then the developer only assesses the overall trend of the market (using the 'on' `Accuracy` trait), and if it is increasing the parcel is promoted for development;
`Subdivision`	`Subdivision` controls the decision to subdivide a developer owned parcel of land. If 'on', the assessment of profit is examined alongside the gap between the parcel's size and the mean surrounding parcel size, and a random stochastic element. If the variable is 'off', the assessment only examines the current profit margin, and bases its decision on the profitability of the parcel (that uses the 'on' `Accuracy` trait);
`Territoriality`	`Territoriality` controls the size of each developer's territory within which the majority of parcels are selected for assessment. If 'on', the developers are assigned a territory in line with their level of capital (large developers drawing from at least half, if not the whole of the landscape with smaller developers having small neighbourhood-sized territories). If 'off', all developers have the same territory which contains the entire landscape;
`Riskiness`	`Riskiness` controls the initialisation of the developer's attitude variable. If 'on', the attitude variable for each developer is stratified in association with their level of capital. Developers with a higher level of capital are more risk adverse, therefore more discerning when assessing parcels for purchase. Smaller developers are less risk adverse with an increased chance of selecting a more marginal development opportunity. If 'off', all developers are fixed at the initialised value with no differentiation in attitude across the developer set.

Table 8.2: Detailed description of how the traits are applied in both the 'on' and 'off' approaches

As was the case for the competition experiment, one hundred random seeds were used in association with the behavioural traits to provide a statistically relevant sample of landscapes to remove any bias that a single landscape might produce. Consequently this experiment examined one hundred individual model runs for each of the five traits and the 'all on' baseline. The numerical results for each of the one hundred trait-created landscapes are compared against the comparable value for the 'all on' baseline landscape that uses the same random-seed value. This produces a result which signifies the change in the landscape which is based solely on the change in the application of the trait. As outlined above the 'change' based results for each run are then averaged together to remove any unique landscape variation. Consequently the averaged 'change' based results examine how the application of the developer behavioural traits affects the resulting landscape. For scientific repeatability, a list of all the parameters used in the model can be found in Appendix F. The results from this experiment are outlined below.

8.2 Results

The results section of this chapter will follow the same general structure that was outlined in the previous chapter and will begin by examining the basic descriptive statistics captured through NetLogo. These statistics record the changes in the underlying structure of the binary tree caused by the individual behavioural traits. The changes in these statistics are recorded over the length of the model and are subsequently shown as time-series graphs.

The results then break into two sections, the first investigating the change in the urban/non-urban landscape caused by the behavioural traits and the second looking at the change in the underlying parcel size landscape. To observe the detailed changes in both landscapes a number of landscape statistics were calculated. A range of box plots is initially used to highlight the variation in the resulting landscape for each behavioural trait. Each of the landscape statistics is then examined in more detail through a selection of time-series graphs to observe how the landscape statistics change over the length of the model run.

For reference, each behavioural trait boxplot consists of a box showing the median and 25th and 75th percentiles, with whiskers corresponding to the lowest and highest values within 1.5 times the interquartile range of the respective quartile. Outliers to these ranges are plotted as individual dots. All time series graphs show the calculated mean value for each developer set at each time step. The dark gray 'shadow' around each of the developer set is the observed 95% confidence interval for each time series.

One important note, as outlined earlier in this chapter, this experiment is examining the changes caused by each of the behavioural traits when the trait is 'off'. The 'off' results for each of the behavioural traits are normalised against the 'all on' baseline results to quantify the change in the metric when the trait is 'off'. Consequently, the horizontal x axis of the boxplots and time-series graphs equate to the 'baseline' value for the experiment and the results are based on each trait's variation from the baseline values.

Overview results

The first result apparent in these overview time series graphs is that the `Parcel Assessment` trait produces a dramatic change in the level of development. When the `Parcel Assessment` trait is 'off' and an agent assesses parcels only using the direction of the market (i.e. when the three non-economic satisficing factors – the development potential of the parcel; the mean parcel size of the surrounding parcels; and the parcel's distance to an urban cell are excluded from the assessment) the reduction in the number of new (i.e. developed) parcels is substantial.

These changes can be seen in the change in both the number of urban parcels developed (Figure 8.1) and the mean urban parcel size (Figure 8.2). Both show a significant change when the `Parcel Assessment` behavioural trait is 'off', with a reduction of over 2500 urban parcels being developed and an increase in the mean urban parcel size. Consequently, the removal of the satisficing factors makes the developers more cautious, choosing fewer parcels to purchase which then results in less parcels developed.

Even though the structural changes for the other traits are not as substantial, there are indications in these overview results that most traits alter the way in which the landscape is developed and that the severity of their impact on the landscape varies significantly across traits. Figure 8.1 highlights the changes in the number of urban parcels when compared with the 'all on' baseline, with `Territoriality`, `Riskiness` showing an increase and `Subdivision` showing a decrease in the total number of urban parcels. In addition, turning 'off' the `Subdivision` trait produces an initial spike in the mean urban parcel size (Figure 8.2) which then trends back towards the baseline. The homogenisation of this trait, making the developers assess a parcel's best time to develop based purely on their assessment of the expected profit, appears to produce a lag in the amount of development through the tendency for developers to increase the length of time a parcel is land banked in waiting for a larger profit margin.

One of the more telling structural changes can be seen in the mean distance between each parcel and the root node time series graph (Figure 8.3). As was the case for the previous figures, the `Parcel Assessment` behavioural trait produces the most substantial variation away from the baseline. This is caused by the lack of development that occurs when this trait is disabled rather than any substantial alteration in the way the landscape is developed. The interesting aspect of this figure is the general increase in the metric for when the `Territoriality` trait is 'off'. This means that with a homogenous approach to developer territoriality (where developers draw on the same, very large, territory for their development opportunities) the resulting landscape is more diffuse and fragmented with more parcels being developed further away from the root node and presumably the urban core.

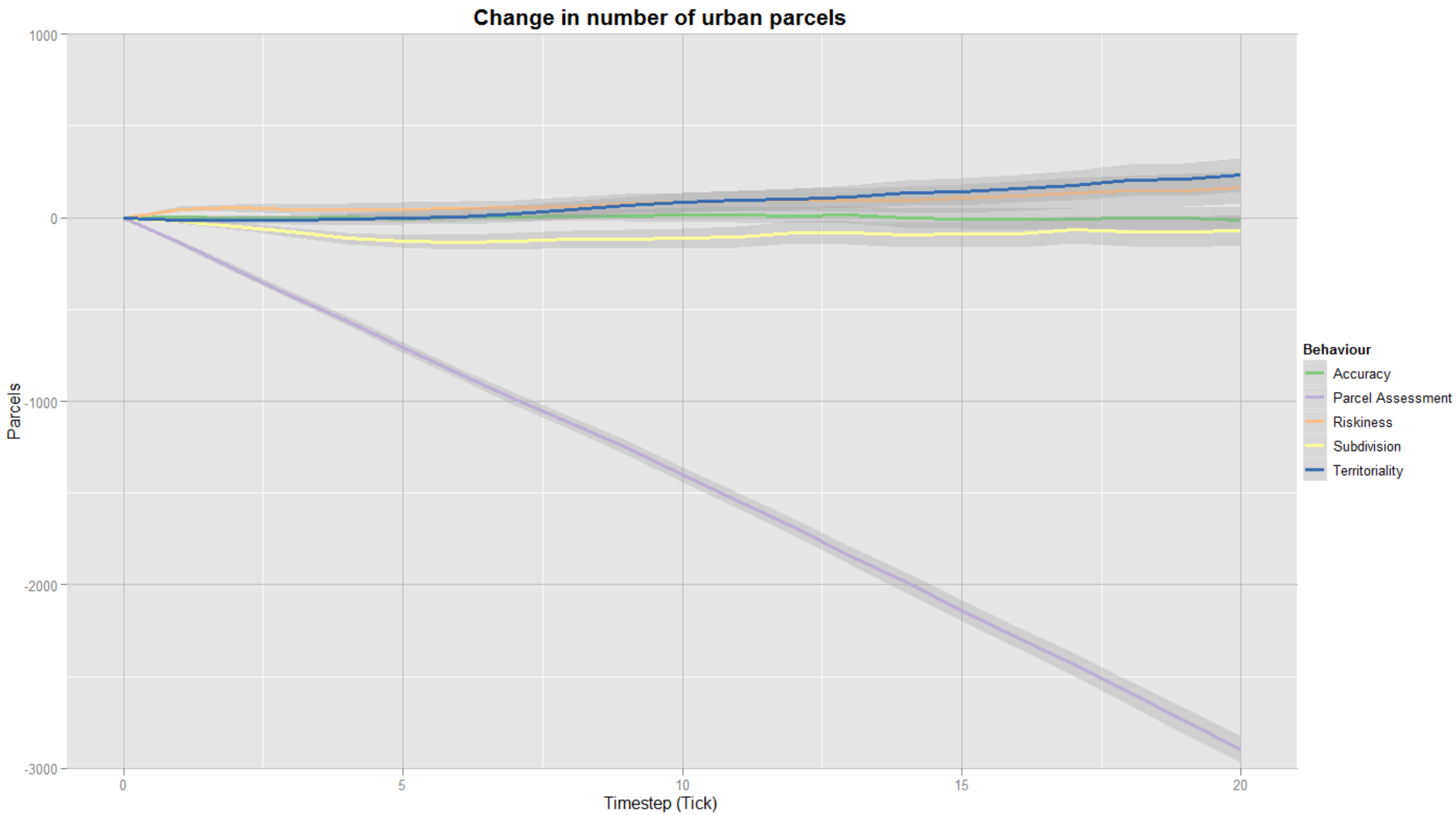

Figure 8.1: Time-series showing change in number of urban parcels

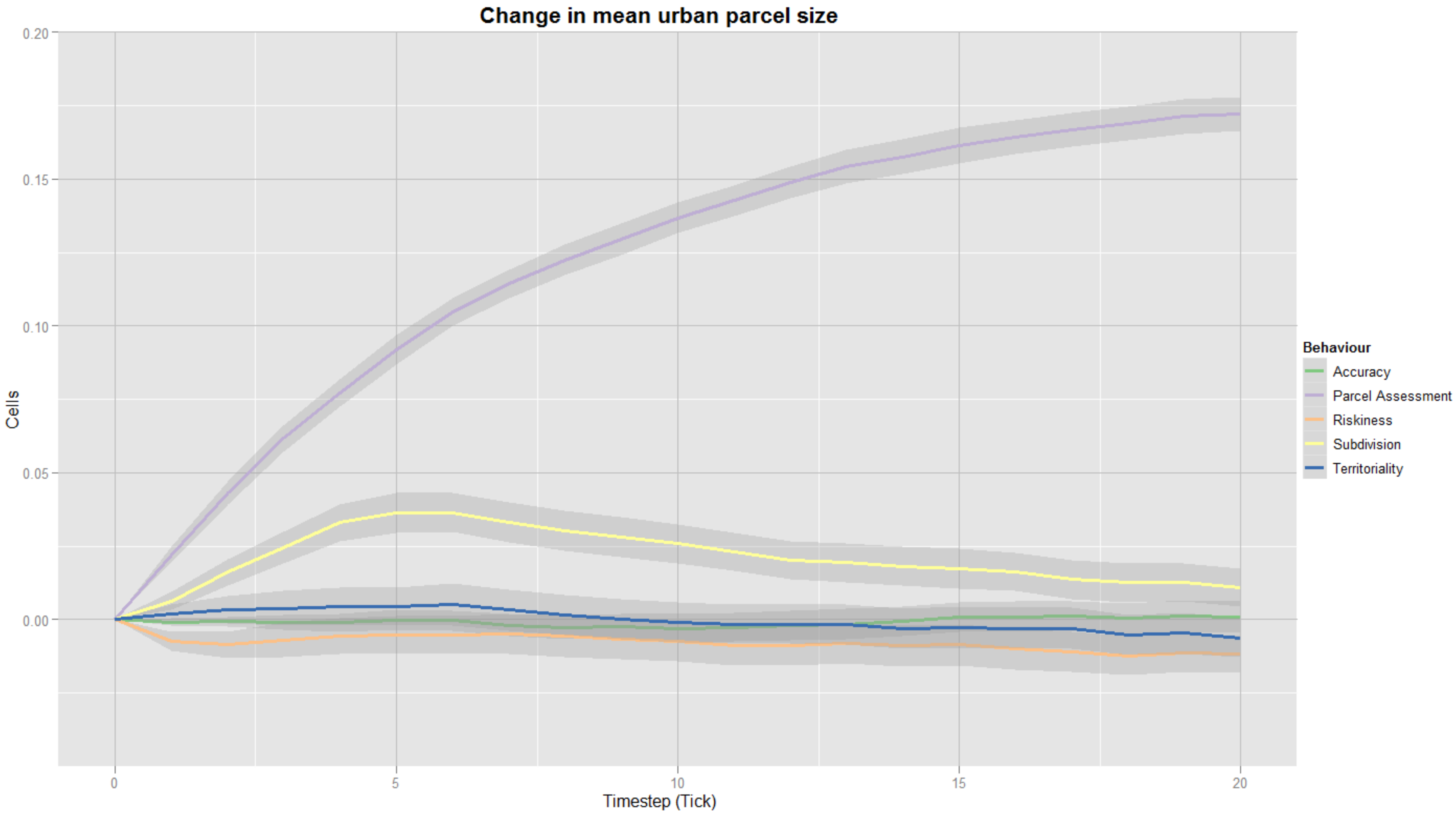

Figure 8.2: Time-series showing change in mean urban parcel size

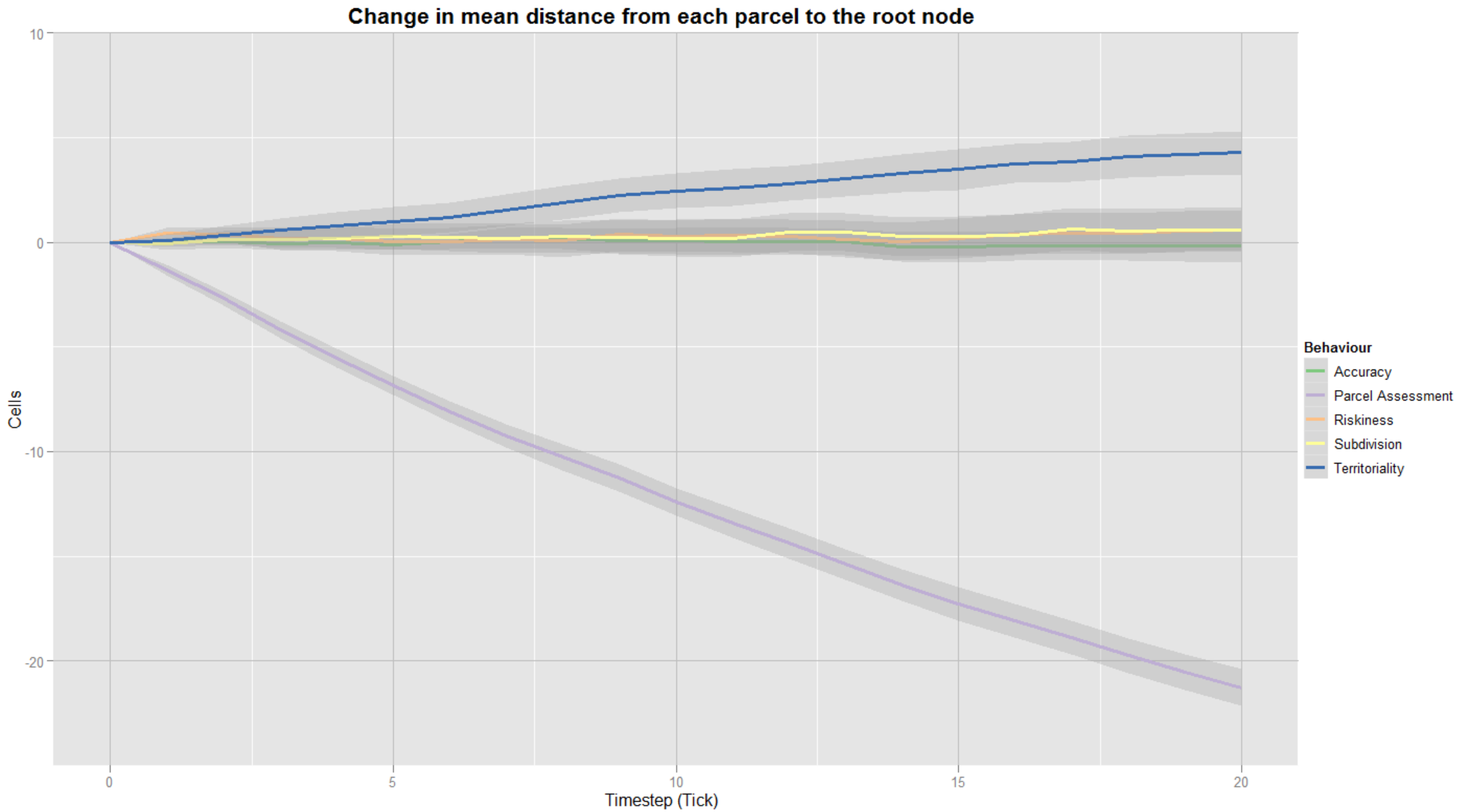

Figure 8.3: Time-series showing change in mean distance between all parcels and the root node

Parcel Assessment

Before moving onto the analysis of changes in landscape for this experiment, the `Parcel Assessment` behavioural trait will be discussed here in more detail.

The dramatic reduction in the level of development that occurs when the `Parcel Assessment` behavioural trait is 'off' poses a problem when comparing the spatial and structural changes caused by the five behavioural traits. Because of the common use of a profit maximising perspective in other urban models, and the constant growth rate built into this model (page 132), it was completely unexpected that there would be such a severe reduction in the amount of development.

It appears that when the `Parcel Assessment` behavioural trait is 'off', all developers are affected in the amount of development they would usually undertake. However, it is theorised that larger developers would be substantially more constrained because of their more risk averse position. Smaller developers should continue to develop but focus on the development of existing urban parcels through small-scale subdivision.

Two sets of results confirm this theory. Figure 8.4 shows the level of new urban parcels that are created for each step of the model. The time series shows that there is a constant amount of new urban parcels created per time step when the `Parcel Assessment` is 'off'. However this level of new development is substantially reduced when compared with the other traits and the 'all on' baseline.

When examining the consumption of non-urban parcels (Figure 8.5), it appears that the gap is caused by larger developers not developing as many non-urban parcels. On average, each time step results in approximately two non-urban parcels being converted into urban parcels when the `Parcel Assessment` behavioural trait is 'off'. When compared with the eight non-urban parcels being consumed each time step when all other traits are 'off' there is a substantial gap in the amount of new urban parcels being created from non-urban parcels. This reduction in the number of non-urban parcels being developed and the constant redevelopment of urban parcels can also be seen in the resulting urban and parcel size landscapes.

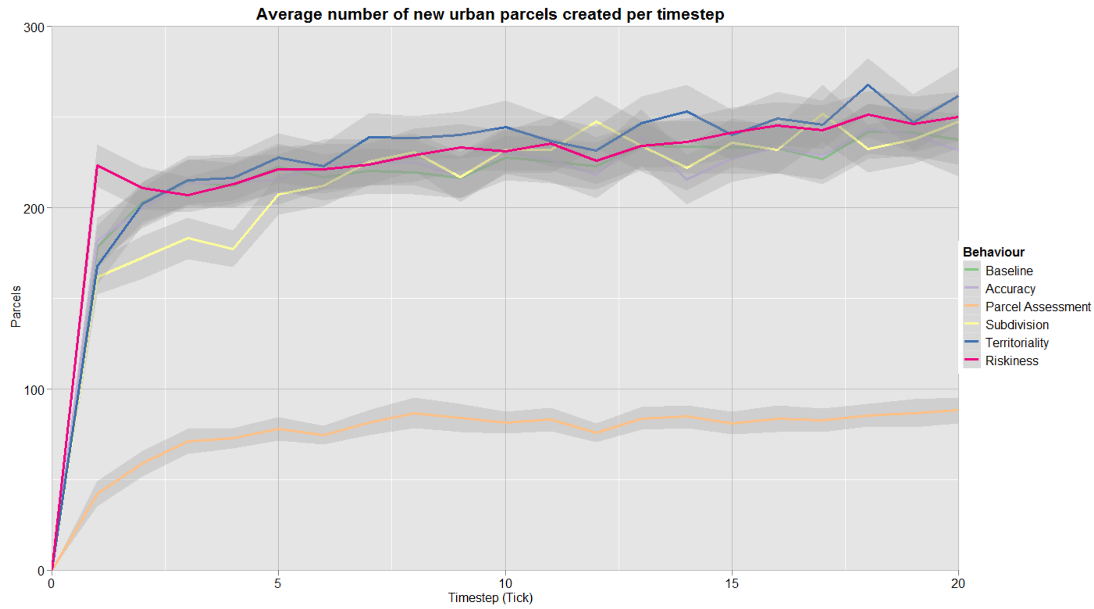

Figure 8.4: Average change in number of urban parcels for each trait

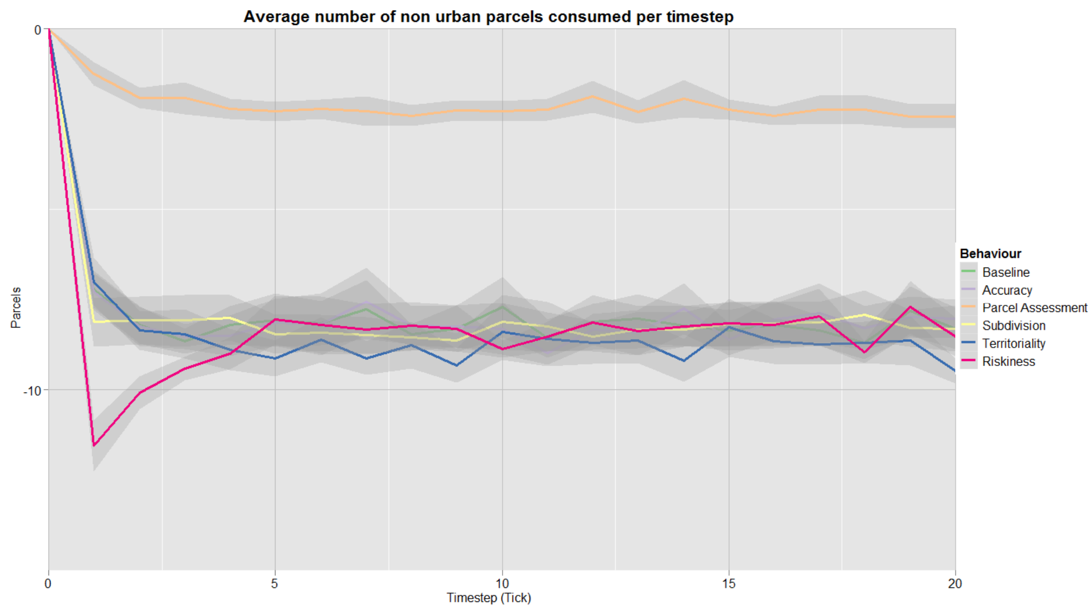

Figure 8.5: Average change in number of non-urban parcels for each trait

Using the comparative urban and parcel size landscapes these results are visible. The urban landscape (Figure 7.9) shows little to no development outside of the urban area, and the parcels that are developed outside the urban area are small and close to the existing urban area. The parcel size landscape (Figure 8.15) shows a substantial amount of development within the existing urban core that is comparative to other traits. It appears that the non-economic satisficing factors prompt larger developers to develop more economically marginal parcels. Without these non-economic satisficing factors, the larger developers either focus on smaller parcels which will return a greater profit, or choose not to develop at all. Based on these results and the variation in development, future research will need to investigate this issue in more detail.

The variation in the amount of development for this trait begins to suppress the changes in the other four traits. To be able to compare the results in this chapter, the `Parcel Assessment` trait will be removed from the remainder of the results. The trait will still be discussed in the conclusion section of this chapter and the two landscape comparison images will still include the trait for reference. To understand the spatial and structural changes in the four remaining traits, we now consider a landscape statistics analysis of the model.

Change in urban area

As we have seen in the previous chapter, the changes to the urban landscape caused by the change in behavioural traits are sometimes hard to discern from the landscape statistics. To highlight these issues, a comparative image (Figure 8.6) is used to give the reader an idea of the changes occurring in urban landscape based on the behavioural traits examined. This image is based on only one of the 100 random seeds and so is not a representative sample, it is merely a way of highlighting the changes occurring. In addition, it is important to note that there is no control or guidelines for the location of development. The only aspect controlling the location of development is the way in which parcels are assessed by the developer. For example there is no zoning, so development within these images may

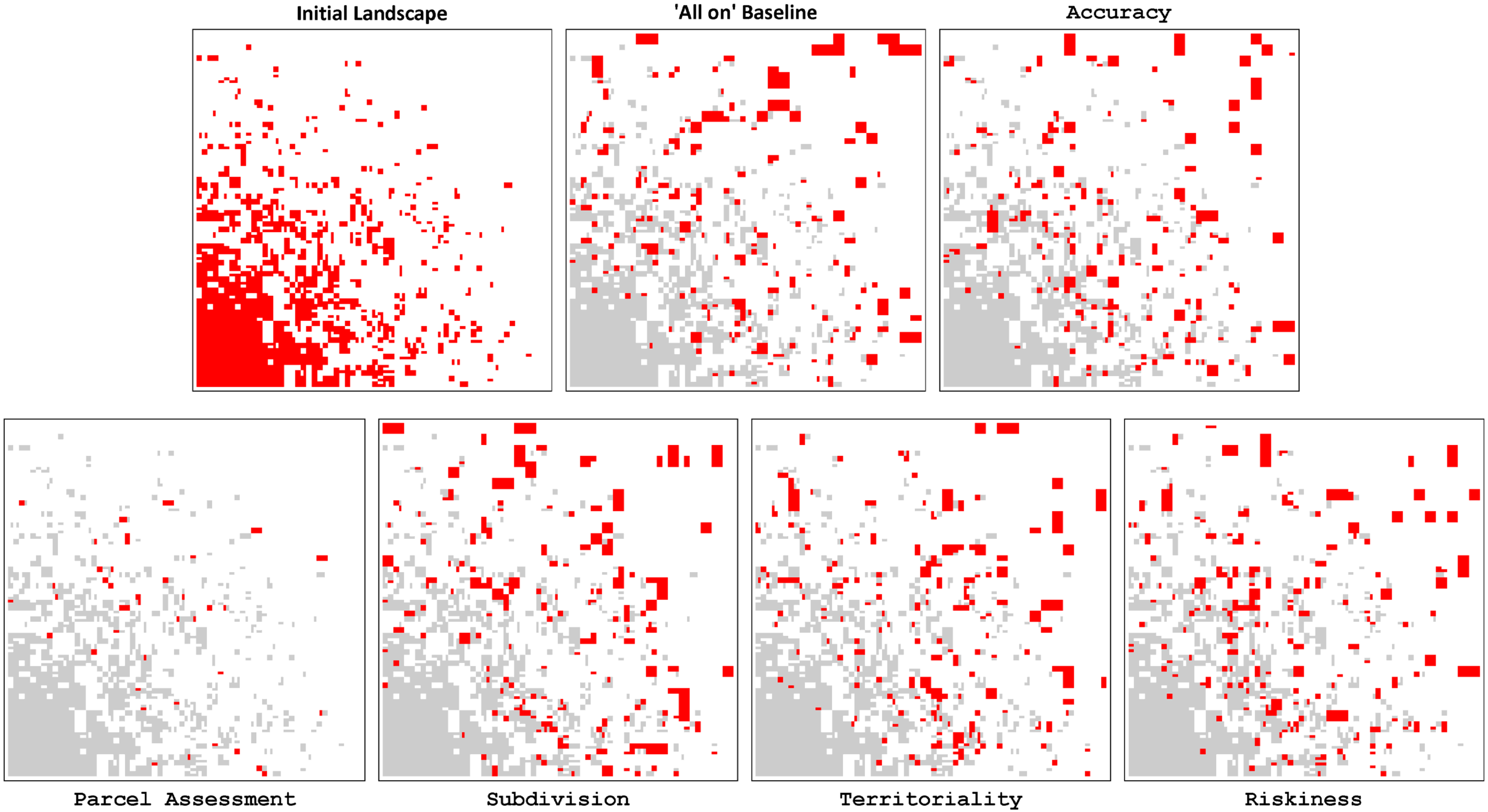

Figure 8.6: Comparison between the initial and resulting urban landscapes for the five behavioural traits and the ‘all on’ Baseline for a single random seed value. Note that these images do not highlight redevelopment undertaken within existing urban areas. Light gray areas signify the extent of the original landscape.

appear disorganised, however this is not the case and there is a clear trend in development for each behavioural trait which can be discerned from the landscape statistics.

When comparing the urban class statistics for each of the various developer traits, boxplots are used to visually highlight the variation between the traits, including the variation within the 100 runs for each trait. Each of the boxplots is focusing on the landscape changes occurring to the urban class rather than the entire landscape. As was the case in the previous chapter, mean values for each trait against each landscape metric, can be found in a summary table (Table 8.3.).

Looking at the boxplots for the three metrics, there is minimal variation for all four traits, from the 'all on' baseline. When 'off', the `Territoriality` trait decreases the Aggregation Index slightly, producing a slightly less aggregated urban class (Figure 8.7). This slight change can also be seen in the increase in the mean distance between each parcel and the root node (Figure 8.3). The other three traits (`Accuracy`, `Subdivision` and `Riskiness`) show little to no variation in the aggregation of the urban class.

The `Territoriality` trait also decreased slightly in comparison with the 'all on' baseline for the Average Polygon Perimeter-Area ratio of the urban class (Figure 8.8). This decrease indicates that development is more dispersed throughout the landscape, although the manner of this decrease in the metric is unclear. This decrease however could be because of an increase in the number of standalone urban polygons or the shape of the urban polygons being created.

Finally, the Edge Density metric (Figure 8.9) also shows a similar, but inverse, pattern with the `Territoriality` trait promoting slightly more edges between the urban/non-urban land covers, while the remaining three metrics result in little to no changes when compared with the 'all on' baseline comparison.

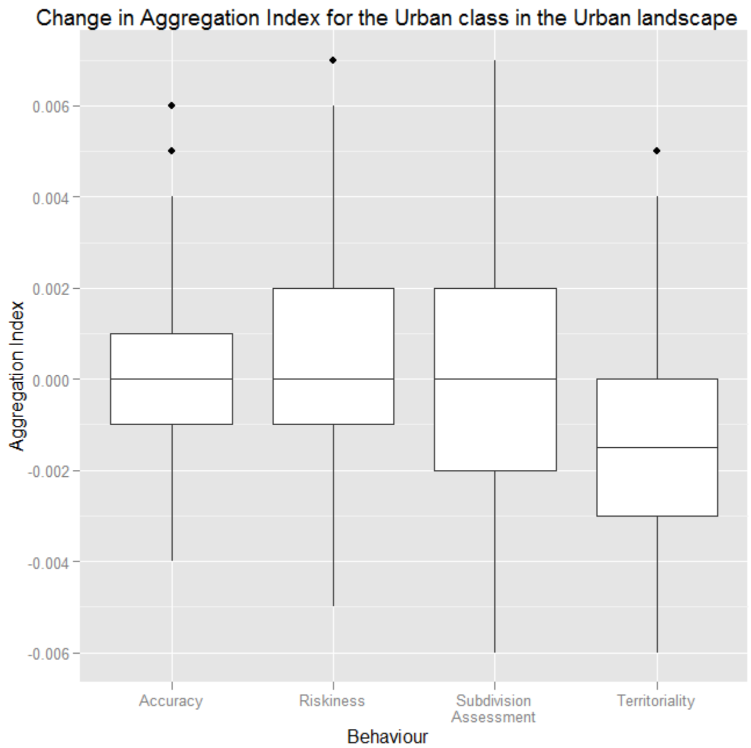

Figure 8.7: Change in Aggregation Index for an urban landscape through developer behaviour

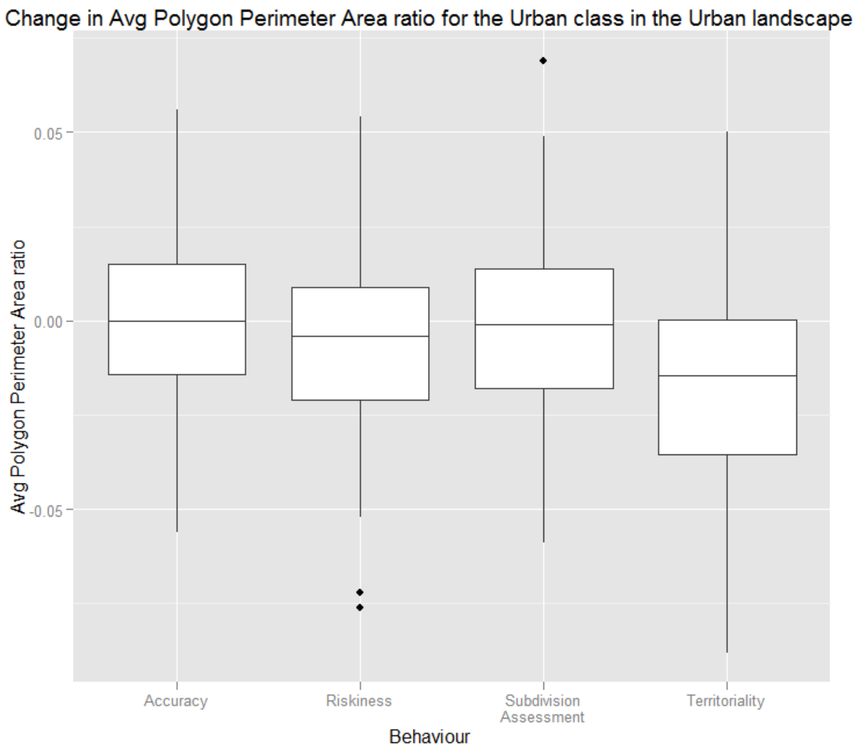

Figure 8.8: Change in Average Polygon Perimeter-Area ratio for an urban landscape through developer behaviour

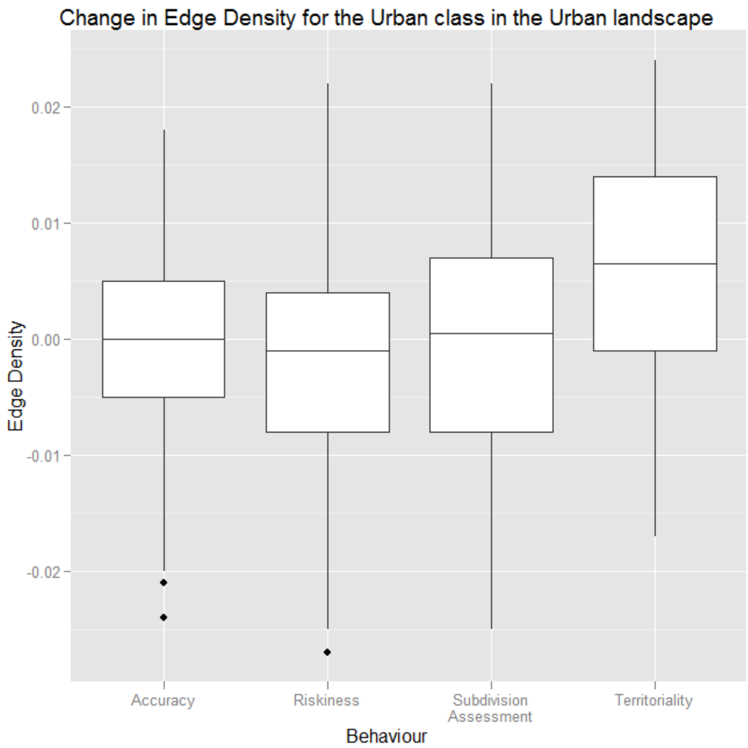

Figure 8.9: Change in Edge Density for an urban landscape through developer behaviour

Metrics	*Accuracy*	*Riskiness*	*Subdivision*	*Territoriality*
Aggregation Index (10^{-3})	0.23 (±0.4331)	0.54 (±0.4904)	-0.02 (±0.5284)	-1.55 (±0.4764)
Avg. Polygon Perimeter-Area ratio (10^{-3})	-0.28 (±3.9783)	-5.21 (±4.8607)	-1.39 (±5.1869)	-17.76 (±5.3963)
Edge Density (10^{-3})	-0.58 (±1.7009)	-2.07 (±1.9558)	0.14 (±2.0545)	6.21 (±1.902)

Table 8.3: Mean values of three landscape metrics examining the change in the resulting urban/non-urban landscape by behavioural trait. Each value is compared against the 'all on' baseline. Note that the changes in the first three metrics (and corresponding CI's) are shown at 10^{-3}.

While the urban class boxplots do not show much variation based on the developer behavioural traits, examining the changes over the length of the model does highlight some more significant patterns. In addition to the three metrics discussed above, two additional metrics, Total Urban Area and Total Polygons, have been included to examine some of the urban class changes in greater detail.

Aggregation Index (Figure 8.10) and Average Polygon Perimeter-Area ratio (Figure 8.12) decrease steadily over the length of the model, with the reverse pattern occurring for Edge Density (Figure 8.11). For all time-series graphs and as was seen in the above boxplots, there are negligible changes in the urban class when the `Attitude`, `Subdivision` and `Riskiness` traits are 'off' when compared with the 'all on' baseline.

The two additional time-series graphs also highlight the lack of variation in the other three traits. Both Figure 8.13 (the Total number of urban polygons) and Figure 8.14 (total urban area) show an increase when the `Territoriality` trait is 'off', both of which point to a more fragmented approach to development when the trait is applied in a more homogeneous fashion. Figure 8.14 also shows a significant increase in the total urban area when the `Riskiness` trait is 'off'. This corresponds to the rise in urban parcels for the trait which was seen in Figure 8.1.

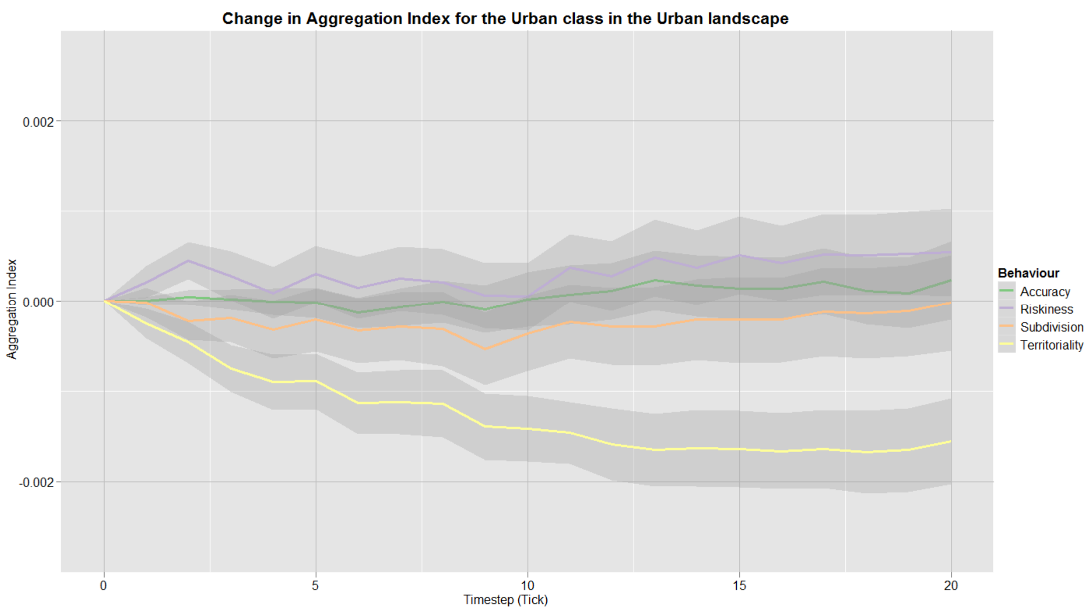

Figure 8.10: Time-series showing change in Aggregation Index for the urban class through developer agent homogenisation of behavioural traits

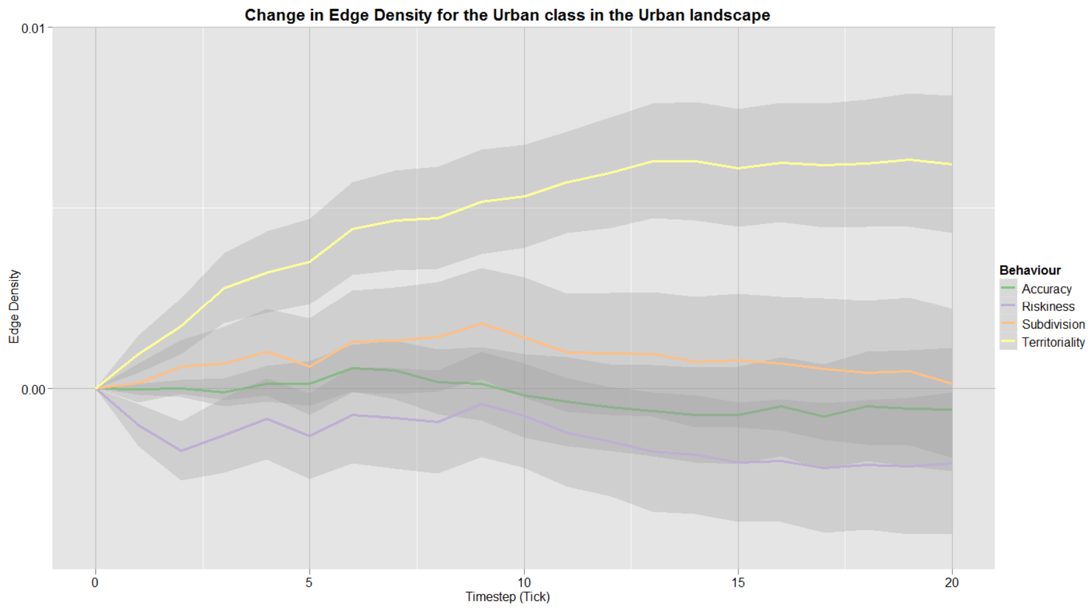

Figure 8.11: Time-series showing change in Edge Density for the urban class through developer agent homogenisation of behavioural traits

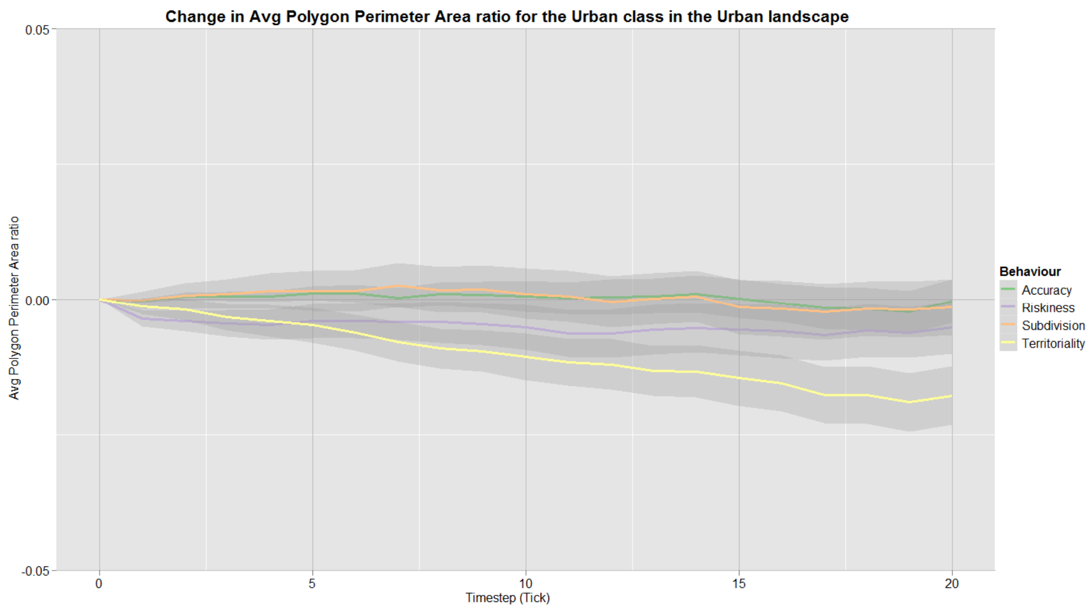

Figure 8.12: Time-series showing change in Average Polygon Perimeter-Area ratio for the urban class through developer agent homogenisation of behavioural traits

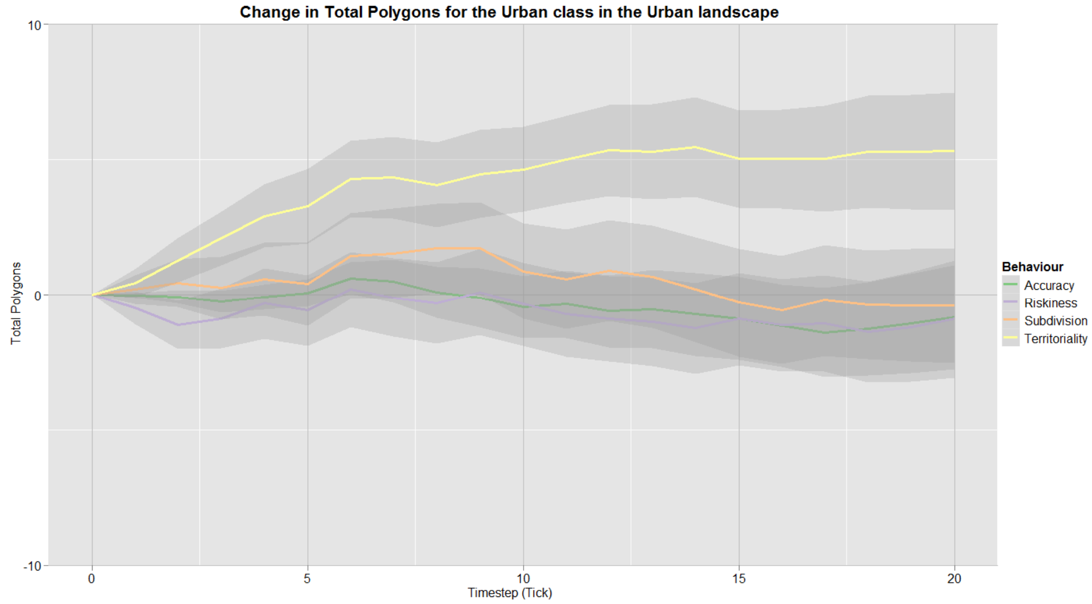

Figure 8.13: Time-series showing change in Total Urban Polygons for the urban class through developer agent homogenisation of behavioural traits

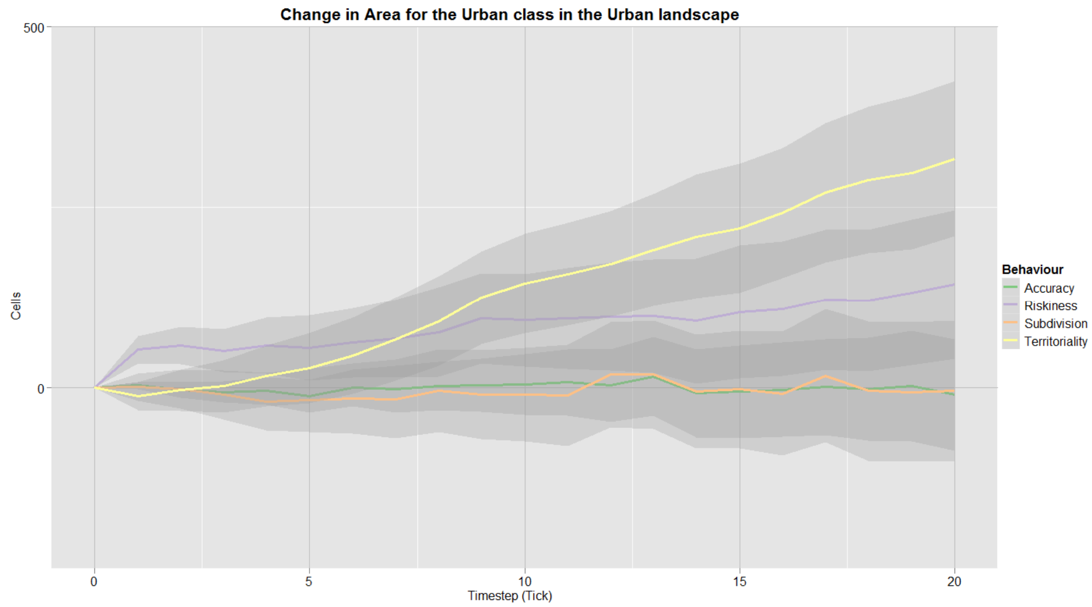

Figure 8.14: Time-series showing change in Total Urban Area for the urban class through developer agent homogenisation of behavioural traits

Change in parcel size (`Level`)

As was discussed previously, the way in which developer behavioural traits shape the landscape is hard to discern visually. While the urban/non-urban landscape is arguably more straightforward to decode, the use of the parcel size value (based on the landscape's `Level` variable) and the additional classes (moving from two in the urban/non-urban landscape to eight) makes this landscape even more complicated to understand and analyse visually.

As a point of comparison, to understand what the resulting parcel size landscape looks like, Figure 8.15 shows a greyscale image that compares the initial landscape with the resulting parcel size landscape from the five behavioural traits and the 'all on' baseline. As noted earlier in this chapter this image is based on only one of the 100 random seeds and so is not a representative sample, it is merely a way of highlighting the changes occurring.

The severity of the changes for the five behavioural trait landscapes have been made more pronounced through a numerical subtraction from the original landscape. Areas of the five developer set landscapes which are white, signify parcels that have had no development over the duration of the model (i.e. no change between the initial and the final landscapes). The severity of the change in the form of the landscape is signified by the increasing shades of gray used in the landscapes. The more intense the level of development when compared with the original parcel size, the darker the area in these developer set landscapes. For example the light gray areas in the bottom left corner of each landscape are existing two-cell urban parcels that were subdivided into 2 one-cell parcels.

As was the case in the urban landscape analysis, comparisons can be drawn based on a variety of other landscape statistics that can account for the changes in the landscape caused by the numerous behavioural traits. Unlike the straightforward nature of the urban landscape, the parcel size landscapes show some interesting results in how the form of the landscape is shaped by the various behavioural traits.

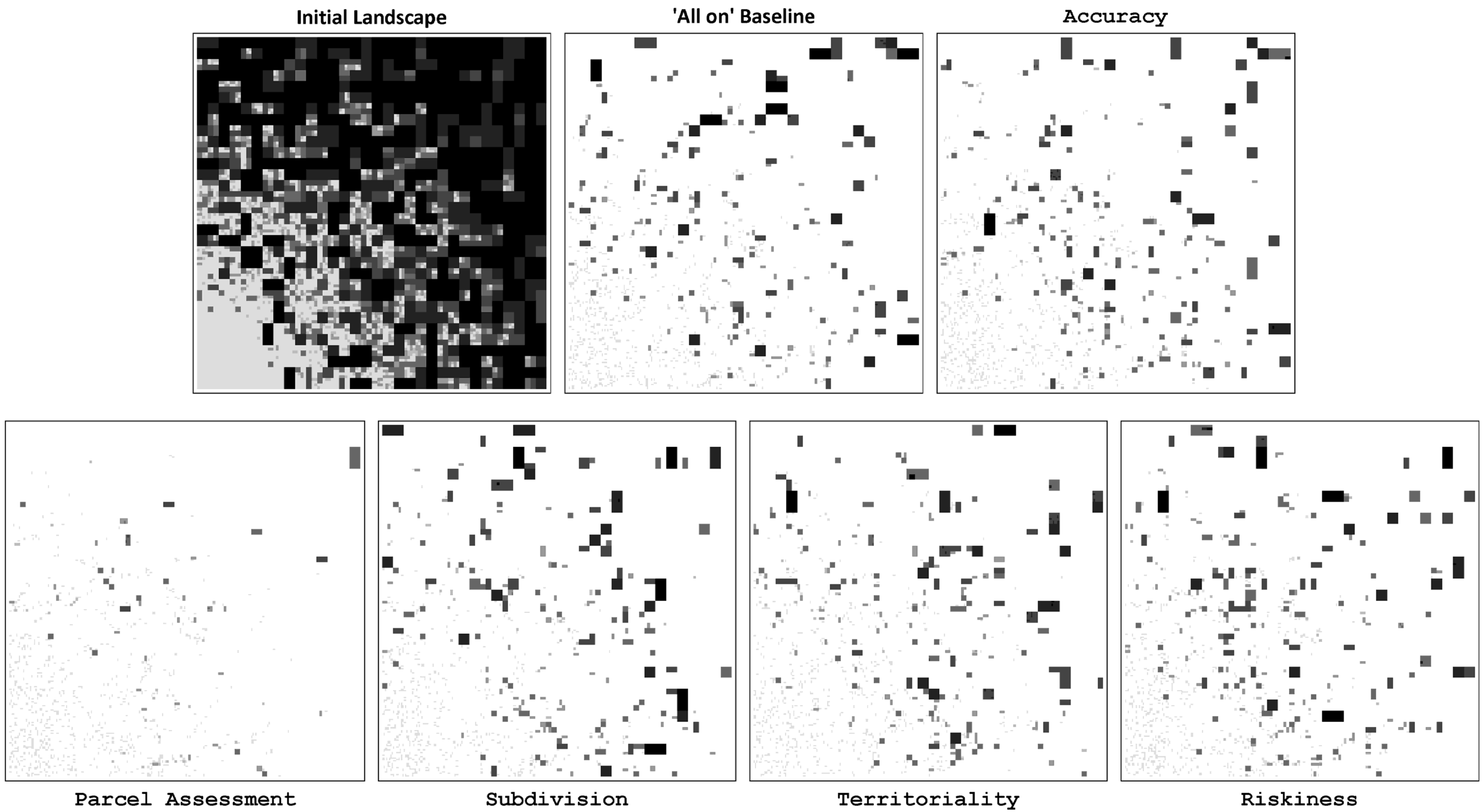

Figure 8.15: Comparison between the initial and resulting parcel size landscapes for the five behavioural traits and the 'all on' Baseline for a single random seed value

The Contagion metric (Figure 8.16) shows some variation from the baseline for both the `Subdivision` and `Territoriality` traits. Turning 'off' the `Subdivision` trait induces a slightly more aggregated parcel size landscape. This creates a more clustered urban form which is also signified in the reduction of the total number of parcel size polygons in the landscape (Figure 8.17).

Examining the changes in total polygons at a parcel size level highlights the significant reduction in the number of Class 14, 15 and 16 parcels (the three smallest parcel sizes). With the amount of new urban parcels for the `Subdivision` trait being approximately the same as the 'all on' baseline (Figure 8.1), this means that the urban parcels are being collocated in a more clustered manner.

When the trait is 'off' it restricts the level of satisficing factors used to make a decision about when to develop a parcel that is currently owned. Consequently, the removal of the satisficing factors in the `Subdivision` trait makes developers more selective about when the parcels that they own are developed, holding onto them longer, which increases the chances that they are similar to the surrounding parcel sizes, leading to a substantial reduction in the total number of polygons and a rise in Contagion.

When the `Territoriality` trait is 'off', the Contagion in the landscape slightly decreases compared with the 'all on' baseline. As seen in the urban landscape discussion above, this decrease is because of the selection and development of parcels throughout the landscape, promoting a more dispersed urban landscape. This outcome is also visible in the parcel size landscape (Figure 8.17) through the rise in the total number of polygons for the urban parcel sizes. When examined further the rise in total polygons is occurring through a substantial increase in the number of Class 16 parcel (Figure 8.18).

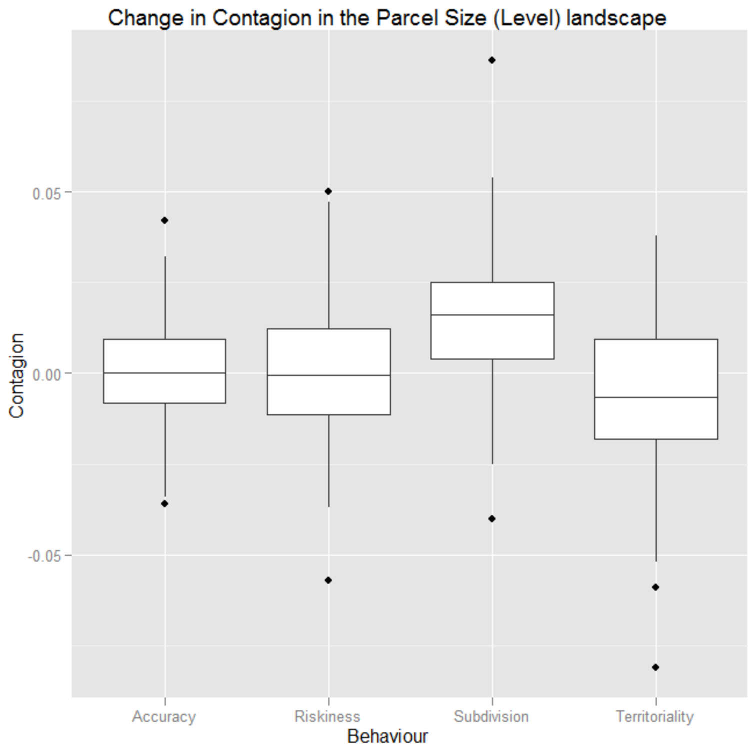

Figure 8.16: Change in Contagion for an parcel size landscape through developer behaviour

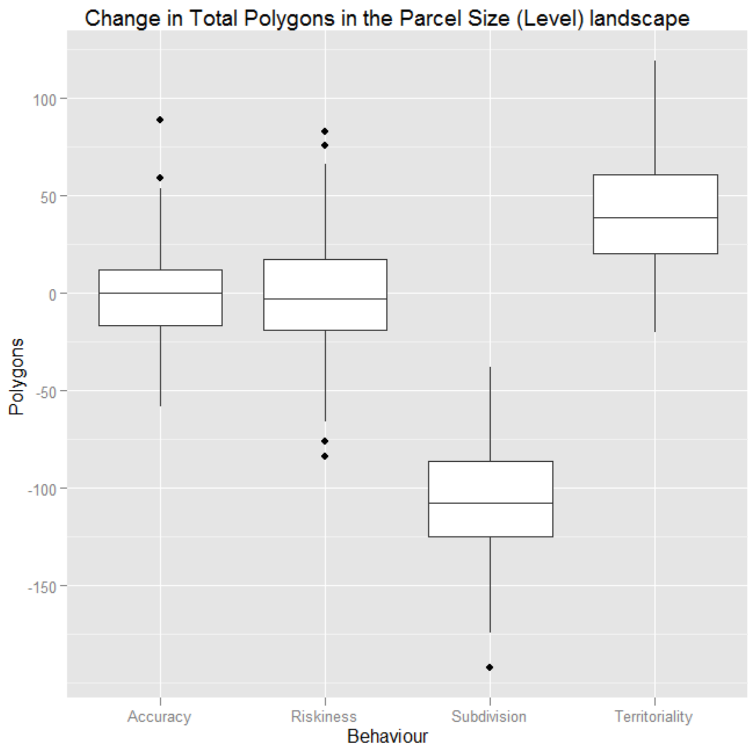

Figure 8.17: Change in Total Polygons for an parcel size landscape through developer behaviour

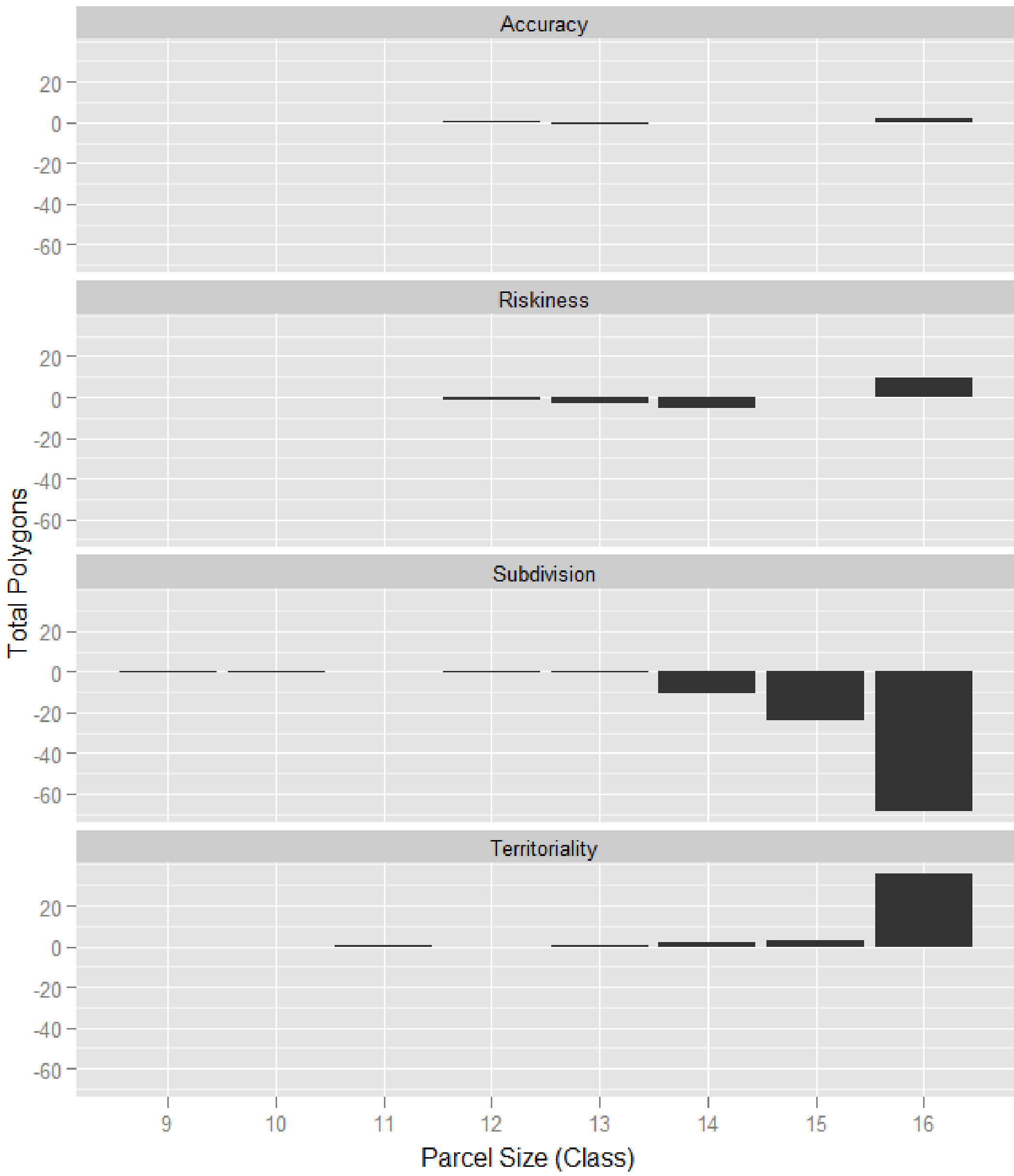

Figure 8.18: Change in Total Polygons based on parcel size classes caused by developer behaviour

For the Edge Density landscape metric (Figure 8.19), the same two traits show a deviation when compared against the baseline. The `Territoriality` trait shows a slight increase in the number of edges in the resulting landscape, further reinforcing the fragmented nature that occurs when `Territoriality` is 'off' and all developers examine development options from the entire landscape. The substantial decrease in the number of edges when the `Subdivision` trait is 'off' is because of the developers deciding to land bank parcels for longer so that when they do develop, and the developer is selecting the form of the resulting development, the development is usually surrounded by smaller parcels which encourages developers to mimic these surrounding developments.

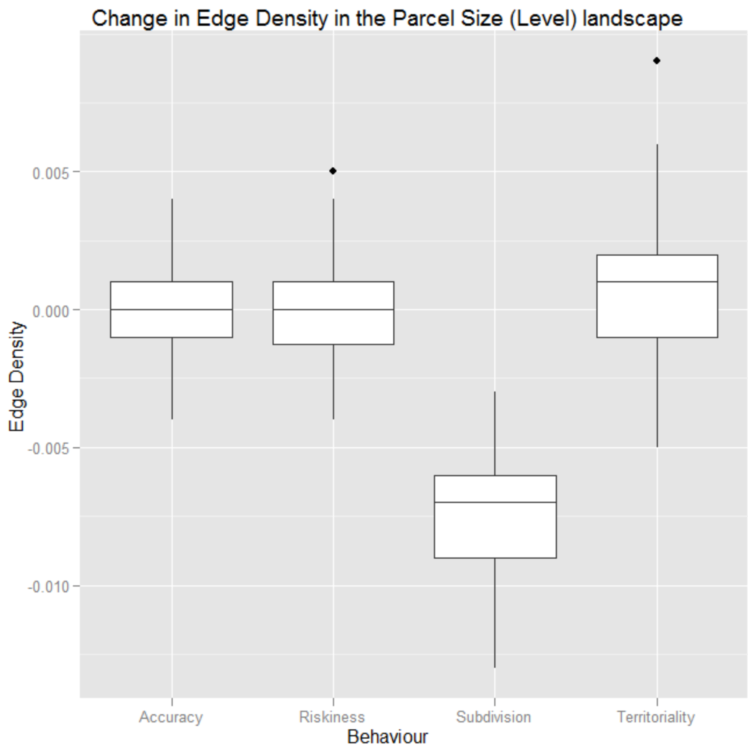

Figure 8.19: Change in Edge Density for an parcel size landscape through developer behaviour

At a landscape level, the Average Polygon Perimeter-Area ratio reinforces the changes outlined in the previous two boxplots (Figure 8.20). Turning 'off' the `Subdivision` trait promotes a smaller ratio which signifies larger, more rounded, polygons where as turning 'off' the `Territoriality` trait promotes a higher ratio which signifies a more fragmented landscape with parcel sizes being distributed throughout the landscape. A table consisting of the means for the three metrics for each trait when compared to the deviation against the 'all on' baseline is provided in Table 8.4.

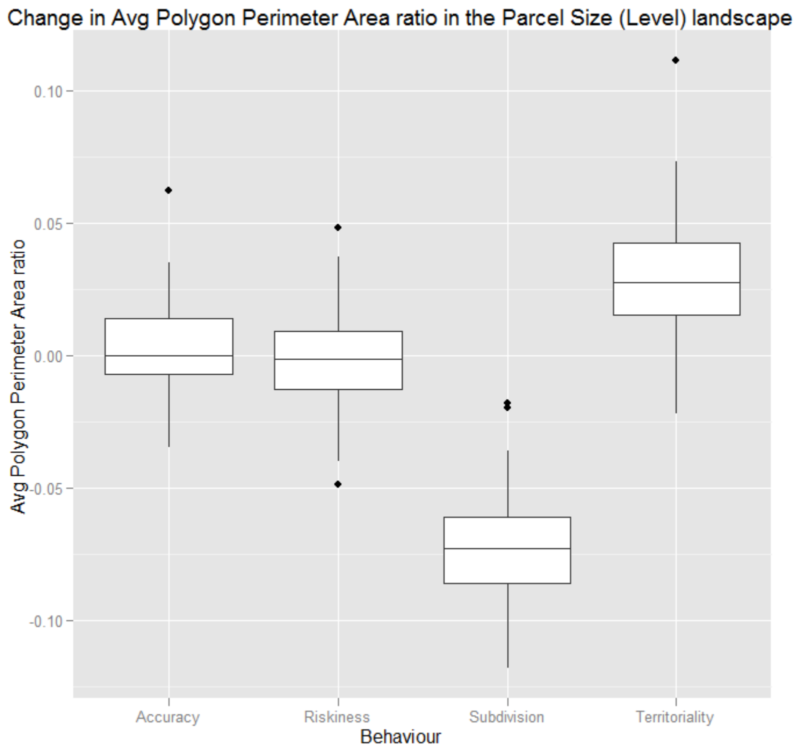

Figure 8.20: Change in Average Polygon Perimeter-Area ratio for an parcel size landscape through developer behaviour

Metrics	*Accuracy*	*Subdivision*	*Territoriality*	*Riskiness*
Aggregation Index (10^{-3})	-0.1 (±2.9161)	14.58 (±3.7991)	-5.62 (±4.1102)	1.08 (±3.7572)
Avg. Polygon Perimeter-Area ratio (10^{-3})	2.65 (±3.2468)	-72.1 (±3.6583)	29.59 (±4.0714)	-2.28 (±3.7598)
Edge Density (10^{-3})	-0.01 (±0.3517)	-7.36 (±0.4401)	0.9 (±0.5017)	0 (±0.4387)
Total Polygons	0.33 (±4.7499)	-105.24 (±5.5328)	39.95 (±5.5232)	-1.21 (±6.4155)

Table 8.4: Mean values of four landscape metrics examining the change in the resulting parcel size landscape for each behavioural trait. Each value is compared against the 'all on' baseline. Note that the changes in the first three metrics (and corresponding CI's) are shown at 10^{-3}.

When the results from the boxplots are transferred into a time-series to examine how the metric developed over time, there are some trends to highlight. Looking at Contagion (Figure 8.21), `Riskiness` and `Accuracy` are stable and are primarily in line with the baseline which is along the horizontal x axis. The `Territoriality` trait produces a slight linear decrease which signifies the more fragmented landscape seen in the above boxplots.

The `Subdivision` trait is arguably the most interesting. The trait produces an initial spike in the metric when compared against the baseline value (suggesting that the development being undertaken has created a more contiguous parcel size landscape). When the `Subdivision` trait is ‘on’, each developer investigates the current profit made since purchase, the development level of the local landscape, and a random stochastic value. When ‘off’ the developer only undertakes an assessment of profitability. Based only on the Contagion result, the lack of satisficing factors appears to make developers more cautious to develop in the initial stages of the model.

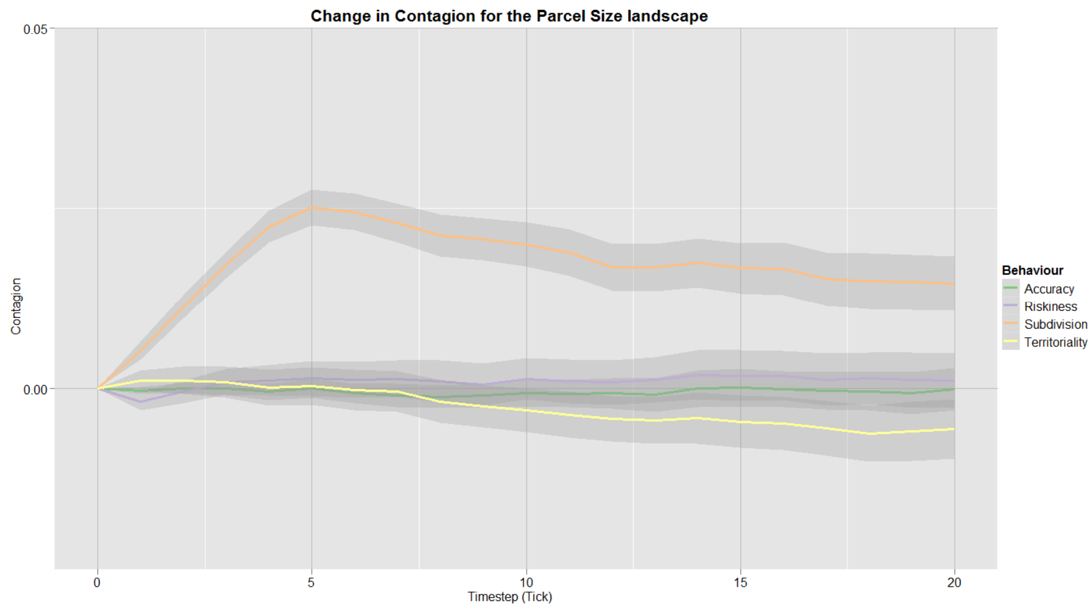

Figure 8.21: Time-series showing change in Contagion for the parcel size landscape

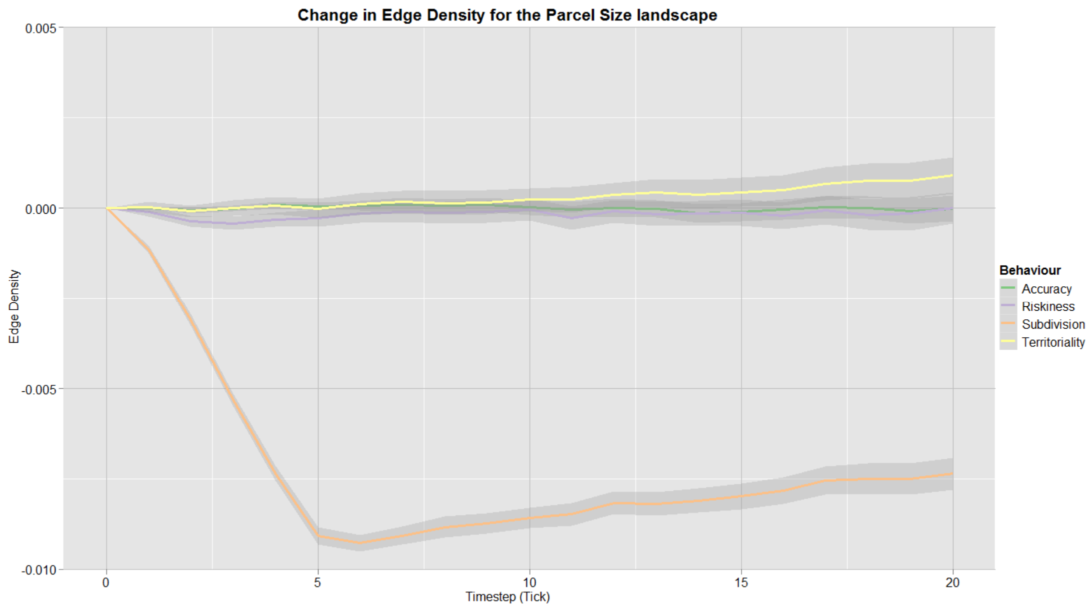

Figure 8.22: Time-series showing change in Edge Density for the parcel size landscape

As discussed in Chapter 5 (page 86) there is a 'soft' limit to the number of parcels each developer can 'own' at a time. This is done though the gradual reduction in each developer's threshold for subdivision when the developer owns more than five parcels. While this limit is rarely enforced within the model (because each developer can only purchase a single parcel per round) it does occur with frequency when the `Subdivision` trait is 'off' because developers' land bank parcels for significantly longer. Also, after the initial enforcement of the limit (which can be seen in all four time-series graphs) development continues normally from this point onwards, with most metrics tending back towards the baseline.

This spike in the `Subdivision` trait is also apparent in the Edge Density (Figure 8.22) and Average Polygon Perimeter-Area ratio (Figure 8.23) time-series graphs. Apart from the spike these graphs show the same trends as outlined in the above boxplots. The `Territoriality` trait shows an increase in both Edge Density and the Average Polygon Perimeter-Area ratio. This trend signifies that the resulting parcel size landscape contains parcel size polygons which are more distributed throughout the landscape (the increase in Edge Density). These polygons are also elongated or highly irregular in shape (increasing Average Polygon Perimeter-Area ratio).

As in the urban landscape discussion above, a time-series graph of the total number of parcel size polygons (Figure 8.24) is used to show the change in form of the development, in particular an increase in leapfrog type development. As was the case in the urban landscape results, the `Territoriality` trait shows a significant increase in the number of polygons that constitute a different parcel size. With the trait turned 'off', so that developers can assess parcels for purchase from across the landscape, developers are more likely to purchase and develop a parcel away from the existing urban core, promoting a fractured and distributed urban form.

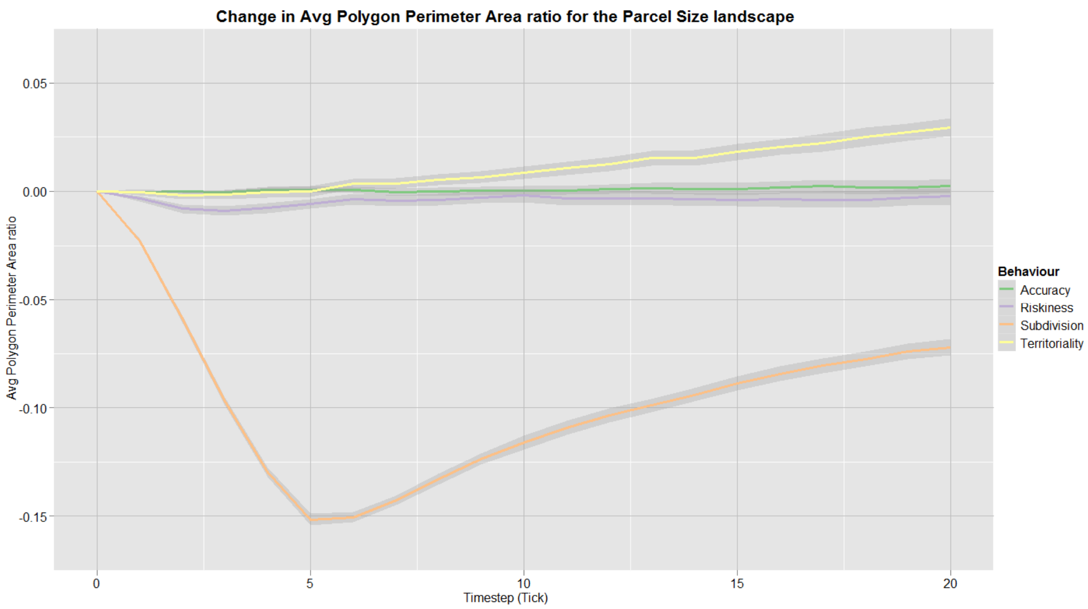

Figure 8.23: Time-series showing change in Average Polygon Perimeter-Area ratio for the urban landscape

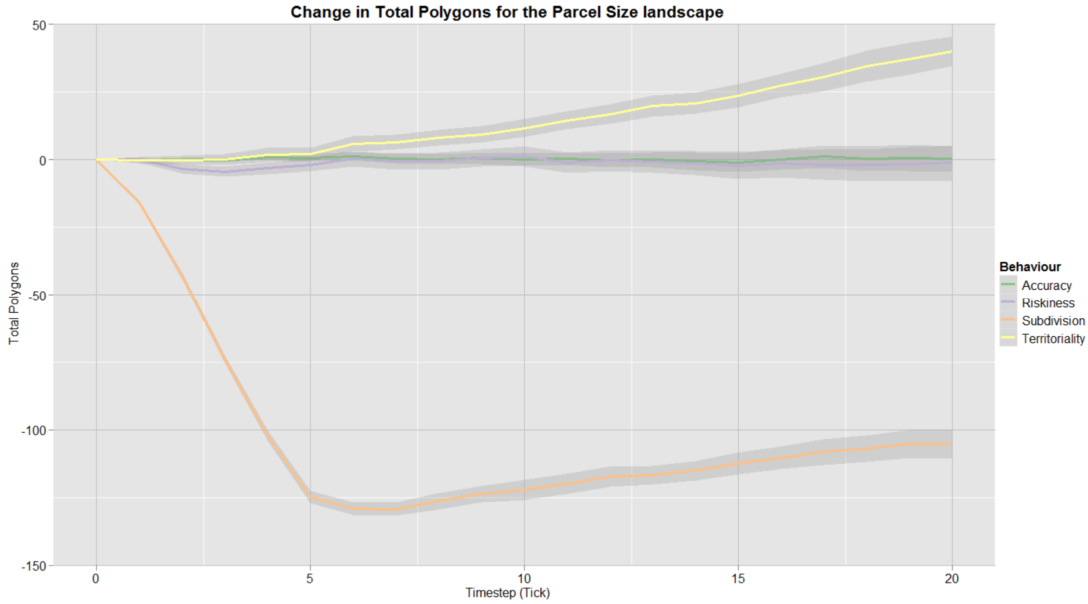

Figure 8.24: Time-series showing change in Total Polygons for the parcel size landscape

Based on these results, the next section will reiterate the results that each trait causes and align the changes in landscape statistics with the changes in urban growth and form that these results indicate.

8.3 Developer and landscape responses

As seen in the above results, each behavioural trait when applied in a more homogeneous fashion produces a noticeable effect in the underlying BSP tree structure, or landscape changes in either the urban/non-urban landscape or parcel size landscape. Some of these changes are pronounced, others more subtle, with one trait (`Accuracy`) causing little to no change in the resulting landscape from all three perspectives. This is itself a result, based on the previously assumed importance of the trait. Linking the landscape changes with the altered application of the development traits and understanding how homogenisation of behaviour effects development is where this section begins.

Parcel Assessment

It is apparent from the results above that the selection of land is the most important constraint in defining the extent of development within a landscape. Once the Parcel Assessment trait was constrained (through the removal of all satisficing factors and concentrating on a profit perspective) the developers became more cautious about the landscape and the potential opportunities that the landscape offered for development. The level of development which occurred was severely reduced (as seen in Figure 8.1). The lack of development when the Parcel Assessment trait was 'off' caused substantial variation in both the urban and parcel size landscape metrics. Because of this, the trait was removed from all analysis within both the urban and parcel size landscape analysis.

Even with its removal from the landscape analysis sections of this chapter, this trait was one of the more important results from the experiment. The variation in application of the developer's Parcel Assessment trait emphasises the role that satisficing factors have within the selection of parcels for purchase. When included, a range of factors are available for assessment by each developer. Decreasing the number of factors used in the assessment of parcels for purchase alters the landscape, resulting in a dramatic reduction in the number of parcels developed. While the reduction in the number of parcels developed is applicable to all developers, the lack of development by developers with a larger level of capital is an interesting point. The literature on developer behaviour (Chapter 4) outlines that larger developers are more financially focused, shunning non-economic satisficing factors for the 'cold hard facts' of market forecasting and detailed parcel economics. It appears that all developers use satisficing factors, and that combined information is critical to the parcel selection stage of the urban development process.

Subdivision

The Subdivision trait also highlights the importance of satisficing factors in the urban development process. Unlike the Parcel Assessment trait, the resulting number of urban parcels was nearly identical to the 'all on' baseline (Figure 8.1). From an urban landscape perspective, the landscape is converted in a similar fashion to the baseline, leading to little to no change in shape of urban growth caused by the trait.

However, there were significant changes to the form of the landscape through changes to the parcel size landscape when compared with the 'All on' baseline. Turning the `Subdivision` trait 'off' results in a reduction in Total Polygons, Average Polygon Perimeter-Area ratio and Edge Density, all pointing to a more contiguous parcel size landscape. While the amount of development undertaken was similar to the 'All on' baseline (Figure 8.1), removing the satisficing factors from the developer's assessment of the best time to develop a parcel, to one based purely on their assessment of the expected profit, produces what appears to be a lag in the execution of development activities by developers (seen as a 'spike' in Figures 8.21, 8.22, 8.23 and 8.24 for the trait).

Investigating these results in more detail, the spikes appeared to be caused by developers being more discerning about when the parcels that they own are developed (and consequently a rise in land banking occurring). Further investigation signifies that while there is more land banking occurring, the spikes seen are primarily caused by large developers holding back on development over the initial time steps of the model.

This position is inferred from the knowledge of how larger developers undertake development within the model gained in the previous chapter. Large developers aim to utilise their financial resources to undertake large scale developments. Parcels that meet their criteria are usually found further away from the existing urban core. When larger developers develop these parcels, metrics such as Average Polygon Perimeter-Area ratio and Total Polygons would increase because the parcel is developed away from parcels of a similar size.

The parcel size landscape metrics here are showing substantial decreases in Edge Density (Figure 8.22), the Average Polygon Perimeter-Area ratio (Figure 8.23) and the total number of polygons (Figure 8.24), changes that would occur if development was occurring in and around the urban core. This is a location that smaller developers are more likely to develop based on the smaller parcel sizes found there and their reduced level of capital.

Consequently it appears that the smaller developers, who usually selects smaller parcels closer to the city centre (most commonly Class 14 and 15), are developing as normal throughout the initial stages of the model. This means that even with their inherent variability in the accuracy of the expected profit, smaller developers appear to rely less on the surrounding parcel size satisficing factor than larger developers. Larger developers seem to be more cautious with the removal of the surrounding parcel size satisficing factor. This results in the larger developers holding onto parcels for longer until the 'soft' limit built into the model causes one or more parcels to be developed. These developments by larger developers begin to decrease the parcel size metrics as seen in the trait trending back towards the baseline.

As discussed in the `Parcel Assessment` section above, the role that satisficing factors have within the selection of parcels for development is an interesting finding. Decreasing the satisficing factors here affects the development pattern but only through limiting the amount of development undertaken by large developers. Small developers continue to develop even with the satisficing factors removed. This trend suggests that smaller developers are more constrained by the structure of urban development (can only afford smaller parcels and these parcels are usually spatially constrained), larger developers have a greater degree of agency in their development decisions.

Territoriality

Applying the `Territoriality` trait in a more homogeneous way was always expected to stimulate changes in the way that development occurs. The very nature of applying the trait in a more homogeneous way fundamentally shifted the focus, direction and range of development options for each developer. The mean distance between each parcel and the root node time series graph (Figure 8.3) provided early confirmation of the expected effects. The increase in distance underscores that more parcels are being developed further away than the mean distance within the baseline landscape. This implies that a more disparate and fragmented development pattern occurs when the `Territoriality` trait is applied in a homogeneous fashion.

From an urban perspective, analysis of the landscape statistics showed slight decreases in both the Aggregation Index (Figure 8.7) and Average Polygon Perimeter-Area ratio metrics (Figure 8.8). The indications from these metrics confirm the more disparate and fragmented development pattern discussed above. The manner of these changes are confirmed through the recorded decrease in the total number of urban polygons (Figure 8.13) and the mean distance between each parcel and the root node time series graph (Figure 8.3). Both results show that the trait encourages the development of numerous urban parcels away from the established urban core.

Moving to the parcel size landscape, both the Contagion (Figure 8.16) and Average Polygon Perimeter-Area ratio (Figure 8.20) metrics show a decrease while the Edge Density of the landscape is increased (Figure 8.19). All of these changes point to a more fractured and disparate urban form. The fragmented nature of the resulting parcel size landscape is also visible in the rise in the total number of polygons for the parcel sizes (Figure 8.18 – In particular classes 14, 15 and 16). This trend signifies that the resulting parcel size landscape contains parcel size polygons which are more fragmented and distributed throughout the landscape (the increase in Edge Density). The resulting polygons are also elongated or highly irregular in shape (increasing Average Polygon Perimeter-Area ratio). Consequently even from the parcel size perspective, the move to a more homogeneous application of the `Territoriality` trait produces a fragmented and distributed urban form.

Riskiness

Assigning all developers the same attitude level in the model, rather than a more diverse approach which makes smaller developers more risk-taking and larger developers more risk-averse in their parcel purchase and development decisions, has only a minor effect on the resulting landscape.

The initial structural metrics do show a slight variation away from the ‘all on’ baseline through a slight increase in parcels developed (Figure 8.1) and a reduction in the mean size for urban parcels (Figure 8.2). The most telling is the change in total urban area (Figure 8.14) that shows an immediate increase in the total urban area when compared against the baseline figure.

These structural changes indicate that the trait makes developers initially prefer more small non-urban parcels for development. This preference is found in the rise in non-urban parcel size. The conversion of small non-urban parcels to urban parcels increases the mean non-urban parcel size. As the time-series for the non-urban parcel size shows, once these types of parcels are developed, the parcel size levels out at a high level compared to the baseline. From the perspective of the urban and parcel size landscape metrics, the `Riskiness` trait causes little to no discernible variation from the ‘all on’ baseline.

Accuracy

The most interesting aspect about a more heterogeneous application of the `Accuracy` trait is that there is no discernible difference in the structural metrics across the board. While the parcels selected by the developers are different (See for Figure 8.6 an example) the urban and parcel size landscapes do not deviate from the ‘all on’ baseline. In addition, the more structural metrics (such as the number of urban parcels developed) do not record any variation either.

While the `Accuracy` trait seems to make no difference whatsoever to either the Structure, Urban or Parcel Size landscapes, this was not expected when the behavioural trait was defined. It appears that the variation of `Accuracy` trait within developers plays a minor role in the resultant path of the model and that the satisficing factors, used in the developer assessment of parcel profit and market direction, plays a more significant role than originally thought.

8.4 Conclusion

The homogenisation of developer behavioural traits produces a variety of responses. At a structural level, the `Parcel Assessment` trait shows a significant reduction in the amount of development, underpinning the importance of non-economic satisficing factors when deciding on the suitability of a parcel for purchase. For the urban landscapes the homogenisation of behavioural traits only has a minor effect, with `Territoriality` showing a slightly more dispersed and fragmented urban landscape. For the parcel size landscape there was a greater response to the homogenisation of the behavioural traits. Both the `Territoriality` and `Riskiness` traits produced some significant variation when the trait was turned 'off'.

Understanding how the homogenisation of a behavioural trait affects the resulting landscape, helps to define the critical aspects of the urban development process. While it is unrealistic to expect that the homogenisation of these traits is possible within the wider developer community, the understanding of how developers might respond to economic and or policy changes is critical to a more complete understanding of the urban development process.

An example of this can be found in the proposed dissolution of the local and regional governments within the Auckland region. The seven city councils which each had their own approaches to residential development are being dissolved together to create a single council. The new organisation will create a more standardised approach to the development of land, compared to the fractured and sometimes even competing situation previously. As outlined in the Chapter 4, residential developers are territorial; locating development projects in areas they know; and in areas where they are familiar with the development rules and regulations. Understanding how residential developers might respond to the homogenisation of development rules and regulations is an area where this thesis can contribute.

9 Conclusions and future research directions

> humans not only construct and manage landscapes, they also look at them, and they make decisions based upon what they see (and know, and feel)
>
> (Nassauer 1995, p. 230)

This thesis explored the integration of agency and process within a model of urban development, in order to gain understanding of the role that residential property developers have in shaping urban growth and form. This was done through the development of an agent-based model of developer behaviour that was consistent with the urban development process. The research then explored two questions surrounding developers, the level of competition amongst developers and the application of behaviour, to ascertain how the two aspects shape and affect urban growth and form through residential property development. The agent-based approach allowed the two questions to be explored in detail, enhancing our understanding of the role of residential property developers while also contributing to the core urban modelling literature.

The direction of this thesis was outlined in the Chapter 1; it consisted of a number of issues that arose in relation to the literature that needed to be resolved prior to the development of an agent-based model and answering the two research goals. The outcomes of these issues will be briefly reviewed here to provide a framework on which the research outcomes of the thesis can be compared against.

The first issue was that existing spatial urban models currently under-represented both the processes which drive urban growth and the actors that enact it. Chapter 2 undertook a review of existing mathematical- and equilibrium-type spatial urban models and came to the conclusion that these types of models focused on the growth and structure of the city structure but were unable to explain the processes that caused it. Subsequent critiques of urban modelling highlighted the lack of vision in how the system is viewed. It was concluded that examining the detailed ‘process’ of urban development enabled a move away from the ‘black box’ mathematical formalism that formed the basis of early urban models. This move would allow a greater understanding of the way in which cities grow, through a detailed understanding of the various components that make up the process. The rise of computational tools, such as agent-based models, allowed the integration of a variety of agents and their behaviour in urban models. In addition the approach enables the creation of an explicit process that can be altered to mimic how the process unfolds in the real world. Even with the rise of these tools, detailed investigations into the role of the actors in shaping their environment were largely ignored. On the rare occasions that behavioural attributes were included in the models, the heterogeneity in their behaviour was either ignored or superficial. Finally the common representations of space within urban models were found to restrict the process of urban development through the inability to allow actions, such as subdivision, to be performed on the landscape.

The second issue that was reviewed was combining an understanding of the urban development process with the unique role of residential property developers. This was done to understand and highlight the importance of the process while acknowledging the substantial work done in this domain. This was undertaken in Chapter 3 which began with a review of the conceptual models and theories regarding the urban development process developed in the property and planning literature. The review focused on the links between the conceptual theories of structure and agency in urban development and also in the variety of conceptual models that have been developed. One type of conceptual model, Agency, focused on the role that key agents had within the process while also acknowledging the detailed process surrounding the agent’s behaviour and choices. An obvious link can be drawn between the agency conceptual model and the methodological approach of agent-based modelling. In addition, it was concluded that using an agency conceptual model of the urban development process provides a detailed pathway for implementation within an agent-based model.

The third issue was the analysis and development of a typology of developer behaviour. This was undertaken because of the existing narrow academic view of developer behaviour and was carried out through the analysis of the sparse empirical studies of residential property developers. While developers were widely seen as a central part of the process of urban development, existing research mainly focused on their role and the types of tasks undertaken. Research into developer types, strategies and behaviours was limited with Coiacetto (2000) stating that property and planning literature tends to treat residential property developers as an "undifferentiated whole, as if all developers were the same" (p. 353). Interestingly, this statement can also be said about the lack of variation seen in any of the existing urban models that explicitly include property developers. With the move towards implementing an agent-based model that followed the property and planning literature's agency conceptual model, a detailed typology of their behaviour was required.

The resulting typology, developed for this thesis (Chapter 4), found that the application of numerous behavioural traits is closely linked to the level of available capital. This size-based stratification of developer behaviour led to a number of behaviours being developed for inclusion in the resulting model. Underlying these behaviours was the philosophical decision to implement the developer agents as profit satisficers, moving away from widely-held perspective that developers acted as explicit profit maximisers. This decision was based on both the behaviours reviewed (in particular the way developers manage their risk position) and the rise in behavioural economics and bounded rationality as both a way to understand behavioural responses but to also model them. At the end of the chapter there was a clear link between developer behaviour and how the resulting land-use patterns could be effected though an alteration in that behaviour.

The fourth and fifth issues were the integration of developer agency within a spatial model of the urban development process and the creation of a spatial representation that allows developer agents to understand and enact the process of development on the landscape. At this stage the thesis moved away from the synthesis of the theoretical framework and justification, towards the model's implementation and then onto the results and discussion from the experiments that were undertaken to complete the goals of this research. While the implementation and experimental results will not be reviewed here directly, the implications for urban modelling based on the methodological approach and the two experiments will now be discussed.

9.1 Methodological implications for urban modelling

Using both the typology of developer behaviour and an understanding of the urban development process, developer agency was integrated into a spatial agent-based model of the urban development process. To undertake this from a methodological standpoint three unique approaches were required; a representation of space where the agents can understand and enact development; the detailed integration of the urban development process within an agent-based model; and realistic developer agents.

The representation of space used in this research, a binary space partitioning tree approach, is unique within the literature. Such an approach was required because the commonly used cellular representation restricts the process of urban development. A spatial representation that allowed developer agents to understand and enact the process of development while also providing an abstract urban cadastral structure was required to meet the goals of this research.

The BSP tree approach met both of these requirements through; enabling a developer agent to quantify and enact the action of subdivision; and the creation of a range of cadastral landscapes through a bounded stochastic process. While the resulting landscape lacks the spatial accuracy of a real-world cadastral pattern, the inherent qualities of the BSP tree results in an abstract but realistic representation of urban areas that is suitable for the requirements of this research.

The underlying features of a BSP tree were used extensively throughout the development of the model and the developer agent behaviour. These underlying features enabled developer agents to understand, analyse and enact the mechanism of subdivision on the urban environment while also providing the straightforward implementation of developer territoriality, neighbourhood attractiveness, the delineation of the urban area, and a range of spatial metrics through the formalised node structure.

This BSP tree implementation allows developers to ‘understand’ the landscape and enact subdivision. Most abstract agent-based urban models do not use a landscape that allows such a process to be performed, agents ‘develop’ a single cell from an undeveloped to developed state rather than implement the structural process of subdivision that this landscape allows. Consequently this BSP approach provides a unique and useful landscape and is recommended to urban modellers who are considering the more common cellular approach.

While an agent-based model investigating urban growth is hardly unique, the inclusion of a detailed real-world process within the agent based model (in this case the urban development process) is a unique feature of this research. This approach was taken as existing models were lacking in transparency, providing answers about the amount of growth but unable to explain the processes that caused it. This move towards a detailed process provides transparency to the model by moving away from the ‘black box’ mathematical formalism that was the basis of early urban models. The resulting model allows for a greater understanding of the system as a whole and the importance of the decisions made by the agents in the model.

From a wider perspective, this thesis questioned the role of detailed processes in agent-based models. Based on the results from this research, the inclusion of the process provides an insight which is missing from 'black box' models. This insight ranges from the ability to implement behavioural traits to the ability to analyse how and why individual developers made certain decisions. This research does not advocate the use of such an approach for all models. As with most models, the modeller needs to clearly decide what aspect of the system they are trying to model. In this case the combination of agents and the research questions being asked meant that such an approach was suitable but in another approach the detailed process would be overly complex.

The inclusion of developer agents within the model provides another 'viewpoint' into the role of agents within urban modelling. This enables a move from the more common demand-focused application of existing agents (such as homeowners) to an examination of the system that supplies residential housing for the homeowners. A demand-focused application of agents within urban models would be valid if the developers who supply the housing were profit maximisers. Based on the synthesis of information developed in the literature review, it was concluded that developers are not profit maximisers. Rather they aim to satisfice in their development decisions, weighing a variety of factors when making their purchase and subdivision decisions. Integrating this shift in perspective into future urban models is important to capture a realistic representation of urban development.

9.2 Developer implications for urban modelling

In most urban agent-based models, the actions of developers are subsumed within the inner workings of the model. When the agents are not integrated within the model, the developer agents are unrealistically defined in both their attributes (such as their allocation of capital) and their behaviour (Benguigui et al. 2001a, b, Semboloni et al. 2004). Based on the results from both experiments, urban modellers need to realise and account for the important role of the developer in the urban development process, and the effect that the assigned attributes and behaviours have on development.

Competition

When looking at the implications of developer competition on urban modelling, one key result is apparent - more competition leads to more parcels being developed. As outlined in Chapter 7, with more developers and more competition there are more 'eyes' evaluating parcels for development. While each developer within a more competitive market ultimately has a lower level of capital, more parcels are ultimately selected by developers as being suitable for development and are developed into new parcels. This change in the communal ability to purchase parcels also affects the location of the new developments. The landscape statistics show that for the urban landscapes, an increase in competition results in a more clumped contiguous urban landscape. Landscape statistics for the parcel size landscapes also show a similar pattern, a more contiguous landscape where urban parcel sizes are more clustered together.

What implications do these results have for the future of urban modelling and in particular urban agent-based models? The primary message is that developers are variable in the way in which they undertake development. Models that aim to capture the urban development process need to take into account a heterogeneous developer market. This research has shown that the structure of the urban development process (aspects such as parcel prices, level of capital) constrains smaller developers into developing smaller parcels closer to the existing urban core. Larger developers have more agency in their decisions based on the financial ability to select and develop parcels throughout the landscape. If developers are defined as a singular type with a common level of capital, as they have been in the few urban models that explicitly include developers, the resulting development caused by the developers will not be realistic.

The second message to be taken from this research is that developers play a major role in the urban development process. The role of the developer does not appear to have the same appeal within the urban modelling field when compared to other agents within the process such as homeowners and their locational preference. From a conceptual perspective, property and planning theory has long acknowledged the importance of developers as a central agent. Hopefully this research will promote developers as a key agent within urban models that will lead to their inclusion in more urban models and more relevant outcomes for urban modelling.

Behaviour

Based on the results from both experiments there are a number of behavioural implications for urban modelling. The primary implication for urban modelling was also raised in the earlier section on methodological implications. Based on the evidence found in the literature review, the developer agents were implemented as profit satisficers rather than the more common profit maximiser approach. This approach produced agents which aimed to find a parcel which met their requirements rather than finding the most economically advantageous parcel for development. This approach was valid, enabling other non-economic satisficing factors to be included when parcel decisions are made. In addition, the behaviour experiment showed that the satisficing factors used in these satisficing decisions is very important for developers.

The removal of non-economic satisficing factors when assessing parcels for development (`Parcel Assessment`) significantly altered the way in which the landscape was developed. It appears that the non-economic satisficing factors prompt larger developers to develop more economically marginal parcels. Non-economic satisficing factors were also removed from the subdivision timing decision (`Subdivision`) meant that developers held onto parcels for longer before subdividing which produced a landscape which was more clustered, and from a parcel size perspective, more uniform.

The three remaining traits all produced interesting responses. The homogeneous application of the developers risk position (`Riskiness`) and assessment of accuracy (`Accuracy`) producing little to no effect on the level and form of development, contrary to the expected importance of the traits. Both of these traits appear to be constrained by the structure of the urban development process. An example of this is a developer's level of capital limits the developer to purchase small set of parcel sizes. Based on this constraint, the importance of the `Accuracy` and `Riskiness` traits are diminished for smaller developers.

The application of a developer's territory (`Territoriality`) produced one of the more substantial responses in the landscape. When compared with a heterogeneous application, the homogeneous application of a developer's territory produced an urban and parcel size landscape that was more dispersed and fragmented. Development was unconstrained in its spatial location leading to developers examining a range of parcels from across the landscape for development.

The experiments in this research have shown that behaviour is important for agent-based models. In addition they have also shown that how the behaviour is applied to the agents does affect the resulting urban development pattern. Based on these findings, behaviour should be applied in a heterogeneous way, mimicking how the real developers differ in how they undertake these decisions. It is assumed that this recommendation could extend to other agents in the process.

9.3 Implications for other disciplines

While not directly intended, this research also has wider implications than just in the urban modelling discipline. As discussed in the introduction chapter, this research has touched upon a range of other disciplines, property and planning, behavioural theory, behavioural economics, spatial economics, and sociology.

The model and the results from the two experiments have reinforced the conceptual models of the urban development process. In particular they have validated the importance of developers within the process and the placing of them at the 'nexus' between all other actors. The importance of satisficing information in economic decisions has also been highlighted through the substantial change in the level of development between maximising and satisficing behaviours. This shift needs to be explored in more detail (see future directions below) but it shows the power of satisficing factors in decision making and the fallacy of the near-universal use of profit maximisation in economically focused urban models.

While used extensively, the HHI index does not provide a stable index to compare competition in the form described here. The lack of normalisation based on the number of agents in the marketplace means that while providing a value to quantify the level of competition, it does not uniquely represent the diversity amongst the agents in the marketplace. This is especially apparent for markets with a large number of small players.

9.4 Future research directions

There are three clear directions that this research could follow, the first focusing on the existing landscape upon which the developer agent enact the process of subdivision; structural changes to the model of the urban development process such as additional agent types; and further exploration of behavioural traits associated with residential property developers. These three avenues for future research will be discussed in more detail below.

Landscape

While an abstract representation of space was suitable for use within this research, applying this research to further cases will require a more realistic representation of space to enable a more spatially accurate visualisation of the resulting property developments. A move to a vector representation that could accurately account for real-world cadastral parcel sizes while integrating the flexibility offered through the underlying BSP tree structure would produce a suitable alternative. Such an approach would allow for a more realistic variety of cadastral parcel sizes and shapes.

Rules based on council zoning could be integrated to ensure any development undertaken by the agents is in-line with any statutory requirements.

An issue would arise in the spatial organisation of the new subdivision. How would a developer agent decide how a parcel should be subdivided and potentially link any transportation infrastructure between the existing development and the new subdivision? Recent work in this area has begun to computationally generate realistic development patterns for cadastral parcels based on a pre-defined set of parameters (Vanegas et al. 2009). In the case of this research, the parameters that would define the automatic generation of the subdivision pattern would be decided by the developer agents, who would act in line with their behavioural traits. Integrating this parameterised generation of subdivision patterns on a vector landscape that incorporates aspects of the BSP tree approach, would enable a wider audience to understand and appreciate the outcomes of the model.

Another future approach for the research would be to implement a vertical dimension to allow developers to develop multi unit housing which is built up (such as apartment blocks) alongside the single unit options that are currently available to them in the landscape. Such an approach would more accurately represent the cadastral landscape of a real-world city.

Model

The model was designed as a heuristic learning device to understand the role developers have within the urban development process. The model and the experiments undertaken for this research have acknowledged the benefits of modelling the individualistic behaviour of developers in understanding urban growth. The model itself has a number of future avenues for research.

The primary avenue would be to include additional agents found in the urban development process and to model their role in the shaping of urban development.

The agents currently considered are councils (in particular their interactions with developers to shape the structured growth of the city) and homeowners (examining the questions around the wider supply and demand structure in the urban development process). Both of these agents are known to play a role in the structure of urban development, and while homeowners have been investigated (Brown and Robinson 2006), the role of local government and their spatial response to pressures from both homeowners and developers has not been investigated. As outlined above, the introduction of homeowners into any future iteration of the model developed for this research would be used to explore the role and importance of these two agents in driving urban development.

The secondary avenue of research would be more applied. The current design of the model has embedded most of the developer behaviour and actions within the wider code base. In its current state the experience gained through the development of this model could be 'lost' if left in such a platform. Consequently the intent is to develop a developer 'module', through which developer agents could be easily implemented within other models and in particular larger scale models of land-use/land-cover change where these actors are still overlooked. Exporting the process based implementation and the detailed behavioural approach that was implemented in this model could enable a more holistic perspective to agent-based modelling which will facilitate the move away from the 'black box' perspective that is problematic in current models.

Experiments

Using the model as it currently stands, a range of additional experiments could be undertaken to further analyse and explain the role of developers and their behaviour in shaping urban development. Initial experiments could explore some of the questions that arose in the course of this research, such as the role of information sources in developer decisions. The experiments detailed in this research showed that restricting the amount of information that developers have when making decisions played a major role in the amount and location of development.

Understanding how the types of information sources alter the decision making process would be valuable to research, not just within the area of urban modelling but also to explore the wider economic concept of satisficing.

Additional experiments would be around investigating the role of the market in shaping urban growth patterns. With the well rounded developer agents developed for this research actively scanning a landscape for opportunities the importance of local and regional market factors would be substantial. Currently the model has a dynamic but simplistic approach to the market. How would localised feedbacks from new development, redevelopment and even gentrification at a neighbourhood scale change the way in which a city develops? With a more comprehensive market embedded in the model, and the ability to structurally change the way in which the market develops, it would be possible to carry out a detailed investigation into the role of the market in catering for or suppressing development.

From a behavioural perspective, additional experiments could investigate certain traits in more detail rather than the multi-faceted investigation that was undertaken in this research. Based on the results from this research, further examination of the role of territoriality in developer decision making is an avenue of interest and in particular the role that developer/council interaction plays to define a developer's territory. Councils try to shape territoriality in developers (through zoning) and developers usually align their territory with the boundaries of a particular council based on the knowledge of how the council operates. Based on the current move to a single council for the entire Auckland region (from an original seven local and one regional councils), this model could explore questions about how such a move will affect the spatial distribution of development in the region.

Finally, since this research has examined and begun to understand the role of developers and the system and process of urban development, other experiments could aim to rerun the model with more real world data particularly through aligning the number and diversity of developers and their capital to real locations such as

Auckland. These experiments would use the real world BSP tree implementation discussed in Chapter 6 (page 109) to provide a landscape representing the area of interest. In effect, this approach would be a 'ground-truthing' of the model, moving away from the *in silico* approach used in this research.

9.5 Conclusions

This investigation focused on the residential developer as the key decision maker in the urban development process and whose decisions affect the spatial distribution of residential housing. As outlined earlier in this thesis, this was undertaken because urban modellers have previously not represented developers in their models, instead adopting an abstracted 'black box' approach to urban development processes. In addition most urban models either under represent or inaccurately represent developers and the way in which they operate.

The preceding chapters suggested and then implemented a range of novel approaches aimed at capturing and investigating this aspect of urban growth which has been overlooked in existing urban models. The resulting model was designed to be a heuristic learning device, one that will advance our knowledge of how, where, and why developments occur with a broader aim to understand the factors required for more sustainable growth of urban areas. At this stage, the two research goals could be answered through a detailed examination of how differing levels of property developer competition affect the urban landscape and examining how the application of behavioural traits affects the resulting urban landscape.

This research could have produced an agent-based model that had an applied focus, using real world developer numbers and dispersion of capital which reflect the current state of developers in Auckland. Putting aside the substantial investment required to capture such empirical data, at the end of such an approach could the applied model answer structural questions about the role of developers in the process of urban development? I would be inclined to say no, as the range of applied inputs into the model could result in a high level of path dependence in the results.

The approach used in this research begins to answer some of these structural questions, in particular the ones outlined in the introduction chapter, but there are still many more questions to be answered. Hopefully the answers found in this research, alongside the novel methodological approaches developed, will enable ongoing improvement in the quality of urban models and modelling.

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Appendices

Appendices A through F can be found on the supplied CD.

Appendix A

Model initialisation variables

Outlines the initialisation variables for the model.

Appendix B

Model code and random seeds used in the experiments

This appendix includes the raw code for the agent-based model of residential developers and also includes the code for the BSP tree implementation. Finally, a list of the one hundred random seeds used in the developer competition and developer behaviour experiments is stored here for scientific repeatability.

Appendix C

Urban and level landscape sample files

This appendix shows the initial and analysed results for both the exported "Urban" and "Level" (otherwise known as 'parcel size') landscapes. From the original ASCII and png files, the repackaged landscape for IAN analysis, and finally the corresponding landscape statistics report.

Appendix D

Investigation of competition levels

Compares the five developer sets and reports on a variety of statistics which show the range of capital for each developer set.

Appendix E

Barfoot and Thompson - Sales vs. New listings

Compares the monthly sales and new listings figures published by Barfoot and Thompson for the Auckland region between February 2008 and April 2010.

Appendix F

Experiment model parameters

This appendix outlines the model parameters that were used in both the competition and behaviour experiments for scientific repeatability.