Modelling Urban Growth Using Cellular Automata:
A case study of Sydney, Australia

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Modelling urban growth using cellular automata: A case study of Sydney, Australia

By

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Abstract

Urban sprawl is a global problem. Urban planning and policy making are the means to limit the impact but cities are complex systems and the consequences of policies are often unknown. Urban models have been used for testing policies but previous models have not been able to capture the realism of cities. During the past 15-20 years a new generation models have been developed, based on the assumption that an understanding of the details can explain the whole – i.e. a bottom-up approach. One of these models is cellular automata (CA). Cellular automata has been shown successful in capturing complexity with simple rules. However, there are many uncertainties with the technique and more research is required for adapting it better to an urban context. One of the most important parts in making CA more realistic is to find the transition rules which represent the real pushing and pulling forces. In this study, knowledge-driven methods were combined with data-driven methods with goal of relating micro factors to urban land use patterns. The modelling was done using the CA model Metronamica, developed by the Research Institute for Knowledge Systems (RIKS) in Maastricht, Netherlands. The study area was Sydney, Australia. The model was calibrated towards two recent land use maps validated using a long term prediction from 1956 until 2006. The model was then used for predicting the urban patterns during two scenarios of urban growth – planned and unplanned. The model was run until 2106 and the growth patterns were compared. The planned scenario resulted in more compact growth while the unplanned lead to sprawl along the transport links. The results were discussed from a perspective of planning. It was concluded that CA can be useful for exploring the future trends in development. However, perfect spatial accuracy is not achievable, e.g. due to the unpredictable location of new transport links.

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1. Introduction

Cities are known as complex systems. Only recently, scientists have been able to simulate some of this complexity. One of the simplest but yet successful techniques for doing this is cellular automata (CA).

However, one may ask – why is it desired to model complexity? How can this technique be helpful for other purposes than just the modelling as such?

This introduction chapter will try to give some answers to these questions – before leading over to the objectives of this thesis. The chapter follows the logic shown in figure 1.

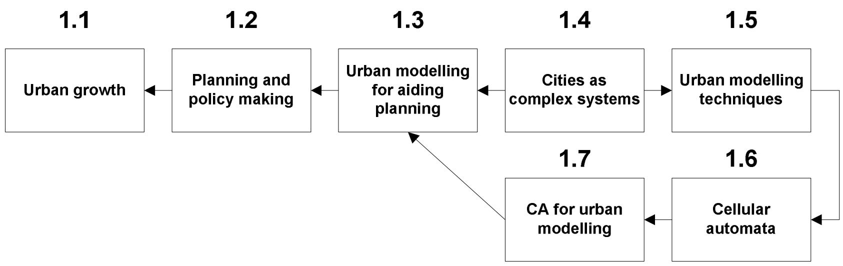


Figure 1. The contents of this chapter.

1.1. Urban growth

Urban growth is a management problem all over the world. In most big cities planning or policies are unable to control growth. This leads to uncontrolled, low-density expansion, characteristic for sprawl (Torrens, 2006). Although some positive impacts can be seen from sprawl (e.g. dispersal of pollution) the negative impacts are dominating. This is noticed internally as well as externally.

Internally, it can be seen as more congestions, longer transports, economic segregation, social disconnection, poor health, cost of infrastructure, and lately even as economic decline (Agency and Centre, 2006, Deal and Schunk, 2004, Sheehan *et al.*, 2001).

Externally, it can be seen in loss of farmland, open land, carbon sinks, biodiversity, pollution of ground water (e.g. due to infiltration through asphalt) and increased risk of flooding.

Seen from the view of some of today's and future's biggest issues: the overconsumption of food resources, loss of biodiversity and global warming – urban sprawl is clearly a major problem, also at a global scale.

1.1.1. Causes of sprawl

The causes of sprawl are typically connected to growth in population and economy, but also preferences in living (Batty *et al.*, 1999), changes in demography, price of land and cultural traditions (Agency and Centre, 2006).

Riddell (Riddell, 2004) mentions the British dislike of cities, which is shared by the former colonies such as Australia and America. Such attributes could have enforced the low-density settlements, and encouraged leap-frog (i.e. scattered) development.

Although planning is supposed to work against sprawl, it is sometimes counter-acting its own purpose. For example, by giving subventions for infrastructure in the urban fringe (Sheehan *et al.*, 2001) or unequal control between the fringe and within the main urban area (Torrens, 2006). Such and other counteracting measures may be unintentional, sometimes deriving from a lack of understanding of the complex systems which cities constitute.

It has been shown that the best way of limiting sprawl might not be to stop it totally, but to allow it within certain growth areas (Torrens, 2006). This is one of the elements of *smart growth* (Batty *et al.*, 1999).

1.2. Policy making and planning

In general terms, policy making is about reaching the preferred *state* of the city system (Engelen *et al.*, 2000a) (compare figure 2). This begins with policy making. Ittersum *et al.* (1998:310) identifies the following steps in policy making:

1. Problem definition
2. Agreement on the need for policy intervention
3. Identification of policy objectives
4. Identification of the means to realise these objectives

It is common that people have different perceptions in all of the four steps. Mostert (Mostert, 1998) finds three reasons for this: factual disagreements, conflicting goals or relational aspects.

Factual disagreements occur due to different understandings of reality. This could derive from poor communication or sharing of information, as well as lack of knowledge. Lack of knowledge forces the stakeholder to obtain information from personal intuition or other sources with low reliability (Mostert, 1998).

Conflicting goals can originate from different *interests* (e.g. biodiversity versus urban growth), *values* (e.g. the value of biodiversity), or different views of *basic needs* (e.g. food or water) (Mostert, 1998).

Relational aspects are connected to the relation between stakeholders, for example due to distrust in each other (Mostert, 1998).

Ittersum *et al.* (1998) notice the need for differing between preferences and information. While preferences are based on values, information is scientific (or *factual*, for using Mostert’s term). Land use models can help by informing the decisions. The medium for doing this is through scenarios.

1.2.1. Scenarios

Scenarios occur in many contexts and in many definitions. They are all connected to a systematic thinking about the future. Wollenberg *et al.* (2000) distinguish four types of scenarios (Wollenberg *et al.*, 2000):

- Vision
- Projection
- Pathway
- Alternatives

A *vision* represents the ideal or desired future, a *projection* is the anticipated future and *pathway* is the way for reaching the vision. *Alternatives* correspond to a comparison of any of the mentioned scenarios (Wollenberg *et al.*, 2000). However, a pathway can not be directly compared with a vision or a projection.

The formulation of a plan can be seen as a pathway scenario. This is where the policy objectives have to confront the reality. A vision can be seen as a reference scenario for comparing projections of alternative futures.

Engelen *et al.* (Engelen *et al.*, 2000a) use ‘scenario’ in a slightly different way. They differ between *external influences* (e.g. climate change) and policy *options*, where the former belongs to scenarios. Figure 2 shows the relation between the policy maker and the sub-systems which influence the policy maker’s decisions.

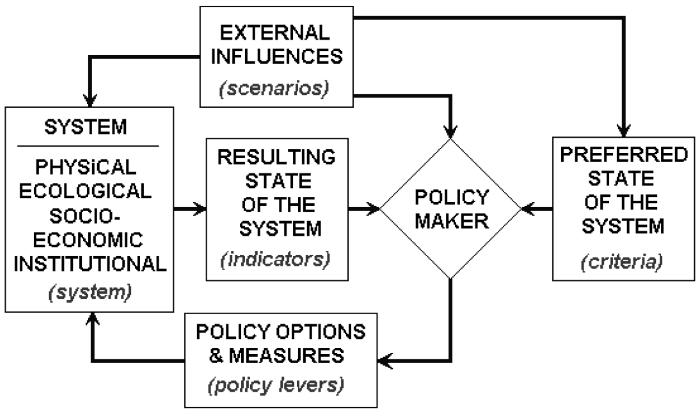


Figure 2. The connection between relevant parts for the policy maker, mentioned in the text (Engelen *et al.*, 2000a:19).

The figure is interpreted as the following. The policy-maker(s) comes up with *policy options*, which aims to reach the defined criteria for the *preferred state* of the system. Some decided policies are applied on the *system*, which in an urban context means the city with all its sub-components (e.g. the economic system). The outcome of the policies depends on the policy measures, *external influences* (scenarios) and the processes taking place within the system. The result is not perceived directly by the policy maker, but through *indicators*. Indicators could for example be fragmentation indices or estimations of remaining productive land versus food demand.

The problem for the decision maker(s) is to predict what will happen in future, both in terms of external influences (scenarios) and in terms of the results of the city system. This makes it almost impossible to formulate a policy (or plan) which can work without future modifications. A plan is therefore always an approximation which has to be adapted to unpredicted conditions (Kaiser *et al.*, 1995).

1.3. The use of urban land use models in planning

When the first urban land use models came in the 1950s and 60s, they were thought of as being able to *solve* planning problems. It was later understood that planning problems are not objective in the same way as many other problems. There is no objective *solution* to planning problems (Batty 2007). This was recognised in the 1970s when planning instead was assumed to reflect hidden political ideas (Klosterman 2001). Today, solutions are seen rather as the acceptable outcomes resulting from negotiations between stakeholders (Batty, 2007).

With the changes in planning, there has been a considerable change in the way that models are looked upon. Models are now thought of tools for facilitating thinking and discussion rather than substituting the policy-maker (Engelen *et al.*, 2000a).

The biggest potential use of land use models might be to show the consequences of policies. For example, in terms of risks and how well the policy will fulfil the objectives (Ittersum *et al.*, 1998). This can potentially aid communication between stakeholders and facilitate a common understanding or *consensus*.

Engelen *et al.* (1997) mentions the use of land use models for getting a holistic view of the city. A holistic view is necessary since policies taking place in one part of the city might have consequences in other parts of the city.

1.3.1. The level of causality

The diagram below (figure 3) shows how causalities captured by different forecasting methods can answer different questions. On the y-axis is causality and on the x-axis is uncertainty. Higher uncertainty could be coupled with a longer time horizon, and higher causality with a better understanding of the processes within the system. *Projections* are characterised by low causality and low uncertainty. Such models do not capture the causalities within the system, but rather the consequences of causalities.

Using longer forecasts, the projection becomes a *speculation* (less certainty). When a projection captures more causality within the system, it becomes a *prediction* (more certain) (e.g. (Pijanowski *et al.*, 2002). A prediction in the long time-horizon is not possible – or too uncertain – since stakeholders can decide to follow more than one path. Therefore, the term *exploration* is used. For both explorations and speculations, scenarios are used as a way of answering “what-if” questions (Ittersum *et al.*, 1998).

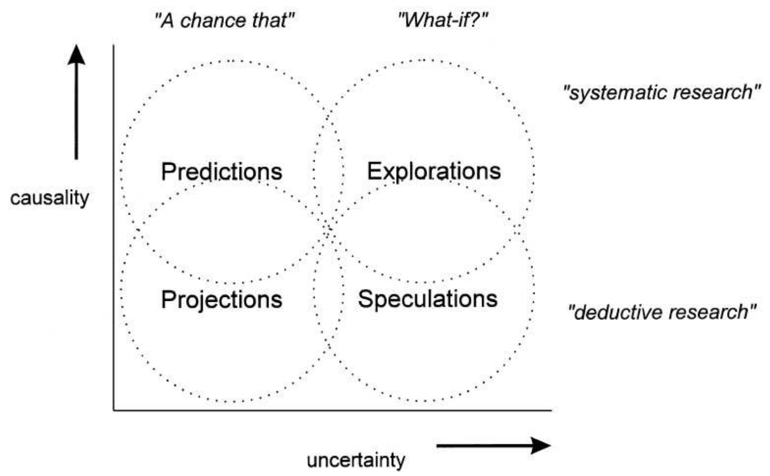


Figure 3. The diagram shows how different causality and uncertainty results in different types of forecasting, used for answering different questions (Ittersum *et al.* 1998:311)

In summary, land use models could contribute to achieve better planning and decision-making. They can contribute to easier reach consensus and better understanding of the city dynamics. They can potentially, show the consequences of policies.

Although these qualities of land use models are desirable they are not fully realised. One reason that past models have not succeeded is because cities are complex systems.

1.4. Cities as complex systems

Cities are examples of complex systems (Batty, 2005b). Since complexity has no precise definition (Parker *et al.*, 2003) many authors go ahead by mentioning the characteristics of complexity (e.g. (Barredo *et al.*, 2002)). Some of these are: non-linearity, emergence, path-dependence, self-similarity and self-organisation.

Self-organisation describes systems which are not following the second law of thermodynamics. This means, they do not evolve towards more and more disorder. Instead, they produce regular patterns. Cities produce fractal patterns, which per definition is an evidence of self-similarity (Barredo *et al.*, 2002). Fractal patterns resemble themselves, independent of scale. An example of this is shown in figure 4 produced by a cellular automata model (Batty, 2003).

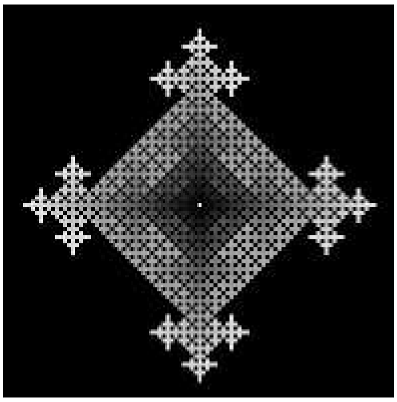


Figure 4. Fractal patterns produced by a CA model. As can be seen, the pattern repeats itself, independent of scale (Batty, 2003:12)

When the whole is something different than the parts which it consists of, it is described as *emergence*. As an example, water has different properties than the components it consists of (hydrogen and oxygen). Before complexity theory was formulated, emergence was used to describe phenomena that could not be reduced to more fundamental rules, as in the case of water (Smith and Stevens, 1996). The ordered attributes at the macro level of cities (e.g. fractal patterns) are believed to be the result of dynamics which occur at a higher scale, the micro level (Torrens, 2001). In emergent systems, what is seen at the macro level is the outcome of dynamics at the micro level. The results cannot be explained from the macro level or when the parts are studied separately.

1.5. Modelling urban growth

The first urban land use and transportation models were developed in the 1960s. They were based on the assumption that urban patterns are the result of changes in equilibrium within the city system, which could be understood from the macro level. These models are denoted “traditional” (Torrens, 2001) or “equation-based” (Parker *et al.*, 2003) models. An example of equilibrium change, is the simple relationship which can be found between urban density and distance to the central business district (CBD). It is true that densities are often higher as one comes closer to the city centre (Yeh and Li, 2002). However, for prediction purpose, these types of relationships are only valid as long as the city is in equilibrium. Cities are from equilibrium (Batty, 2005a).

According to Torrens (2001), traditional models have the following limitations (Torrens, 2001):

- A centralised structure
- Bad at handling dynamics
- Lack of detail
- Little usability, flexibility and realism

When a centralised structure is assumed *a priori* it cannot catch the transition from monocentric to polycentric cities which is common today (Kloosterman and Musterd, 2001, Torrens, 2001). A consequence of lack of detail is that a change in scale (e.g. from city to regional scale) might require a new model to explain the changed behaviour (Batty, 2000).

In summary, traditional models understand cities more from their aggregate (macro) attributes. This is resulting from an excluding *top-down* approach.

1.5.1. The new generation models

“*There is much less consensus about what represent the key ways in which cities evolve and grow than there was fifty years ago*” (Batty, 2007:5).

The new generation models, by Torrens (Torrens, 2001) termed “complexity models” or “geosimulation models”, try to model macro patterns by starting with the smallest entities – or the “atoms” of the system (Batty, 2005a:156). They begin modelling the dynamics at the micro level (Batty, 2005a) which is known as a *bottom-up* approach, as opposed to a *top-down* approach.

The understanding of social systems as complex systems, has also shifted the view of the purpose of urban models. Instead of being considered as prediction tools –

simulating the exact behaviour of system – they are increasingly understood as tools for thinking (Engelen *et al.*, 2000a, Engelen *et al.*, 1997). They can for example be used for finding how causes and effects are related in the system.

Among the new generation, based on a bottom-up approach, can be found cellular automata (CA) and agent or multi-agent based models.

Agent (and multi-agent) based models model the interactions between "agents". Agents typically represent humans (Arentze and Timmermans, 2003), animals (Ahearn and Smith, 2005) or any other type of entity which is not bound to a specific location.

In contrast to agent-based models, CA models are based on a defined neighbourhood. Every entity (in two dimensions represented by a cell) is interacting with the surrounding cells only. Thus, CA has been considered most suitable for processes where the immediate surroundings have an influence on the cell, such as diffusion processes. This includes processes of ecological dynamics (Parker *et al.*, 2003).

An agent-based approach is better at explaining details (what happens within a cell), as well as human interactions and action-at-distance (influences with origin far away, outside the CA neighbourhood). In the field of urban modelling, there are examples where combinations of the two approaches are utilised (e.g. (Torrens, 2001, Torrens and Nara, 2007b), (Batty, 2005b)). A combination might be able to compensate for the limitations of the approaches (Torrens, 2001).

1.6. Cellular automata

Cellular automata could conceptually be understood as a "cell-based" approach for modelling dynamic gravity processes at the micro level (Batty, 2005a). It has also been described as a diffusion approach (Almeida, 2003). Besides land use modelling, CA has been used for modelling deforestation (Menard and Marceau, 2007), forest fire (Karafyllidis and Thanailakis, 1997) and social phenomena (Smith and Stevens, 1996) to mention a few applications.

The main attraction of the method is that it shows complex behaviours from simple rules. This fits well with how complex systems work, where emergence (complexity from simplicity) is one of the characteristics (Torrens, 2001). The CA approach is also in line with bottom-up thinking and a decentralised understanding of processes

(Torrens and O'Sullivan, 2001). It can simulate any physical system (Silva, 2005). At least as long as it is allows to be reduced to the components of a CA.

The essential components of a CA is: a *lattice* (for 2-D CA this means a “raster”) consisting of *cells*, cell *states* (e.g. 1 and 0), a *neighbourhood* within which *transition rules* can apply, and a *temporal space* or *time-step interval* (Torrens, 2000c).

The simplest CA consists of a one-dimensional cell space. The change in cell state from time t=1 to t=2 depends on the formulated transition rule and neighbouring cells. These are formulated as if-else statements (see examples in (Torrens, 2000c)). For example, one could define a rule determining transition from state “0” to state “1” as one or more neighbouring cells required with state “1”. Transition rules can be formulated as complex as desired (Silva, 2005) but for realistic simulation they should capture reality.

1.7. Cellular automata and urban modelling

Wu (Wu, 2000) divides CA models into two general groups. One group has a broad, theoretical focus, while another group is focused on imitating real urban patterns. Models for decision-making belongs to the latter group.

Models for decision-making are usually, so called, “constrained” CA (Engelen *et al.*, 1997) p.4. In addition to the CA neighbourhood, these contain additional input, relevant for development. For example, steep slopes are less attractive for development while good accessibility is desired.

A stochastic (random) effect is often added to simulate unpredictable decisions, characteristic for humans (Barredo *et al.*, 2002). This are part of the transition rules.

Looking at the mentioned factors systematically, three components can be identified in the transition rules of a constrained CA (Barredo *et al.*, 2002):

- Suitability (intrinsic suitability)
- Spatial interaction (neighbourhood suitability)
- Stochasticity

Suitability can be visualised by figure 5. Suitability is here a function of zoning, accessibility and physical suitability. Where the big cube represents total available land, the small cube represents areas which are suitable for development. If changes occur in zoning, accessibility (e.g. a new road is built) or physical suitability, the areas suitable for development (and the form of the "cube") will also change.

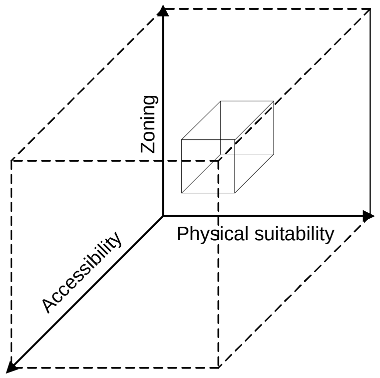


Figure 5. Intrinsic suitability determined by zoning, accessibility and physical suitability. The big cube represents available land, the small cube suitable areas. Adapted from (Barredo *et al.*, 2002:3)

Neighbourhood interactions ("pushes and pulls") determine the neighbourhood suitability could be added as a fourth dimension. This is calculated in the CA (or cell-space) model as shown in figure 6.

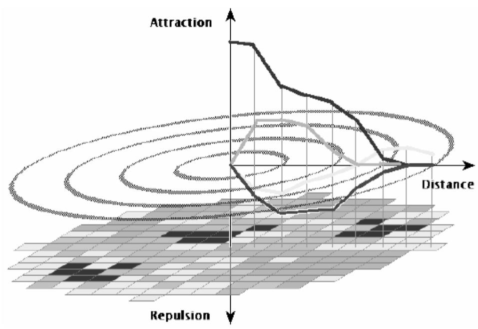


Figure 6. The "pushes and pulls" determining the neighbourhood suitability. (RIKS, 2006:14)

In figure 6 can be seen graphs displaying attraction and repulsion as a function of distance. The influence from neighbouring land uses is depending on how the graphs (neighbourhood functions) are defined.

In addition to the three mentioned components of the transition rule, a constrained urban CA model often includes a coupling between the macro and micro level. The amount of land uses distributed during each time-step (e.g. per year) can be constrained. This is shown in figure 7.

The potential for development is determined by the intrinsic suitability and neighbourhood suitability, as discussed earlier. All cells are then ranked in a descending manner according to their calculated suitability. The number of cells required during the time-step is then gathered from the macro model. This information could for example be derived from a dynamic model of population and economic trends. Cells are converted according to their calculated suitability, starting with the most suitable cells, until the macro model has distributed all cells required for that time-step.

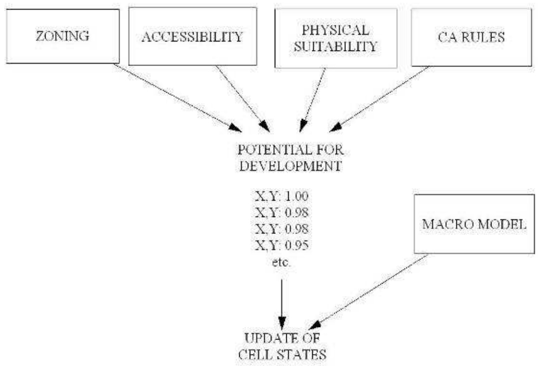


Figure 7. Components of a typical constrained CA model.

Models can only be simplifications of reality (Pidd, 2003) and CA is no exception. This means, some assumptions have to made regarding its parameters: cell size, transition rules, temporal resolution etc., to assure as realistic representation of reality as possible (Batty, 2003). These assumptions will now be discussed.

1.7.1. Transition rules and rule extraction methods

In conventional CA models, the transition rules can be defined arbitrarily. When applying CA in an urban context, the transition rules have to be extracted so that they are representative of reality. Rule extraction is also known as rule *elicitation*.

There are two main approaches for rule extraction, knowledge-driven and data-driven.

To the data-driven methods belong statistical methods (e.g. (Cheng, 2003)), neural networks (Guan *et al.*, 2005) or trial-and-error (White *et al.*, 1997). Trial-and-error is also used for visual calibration.

To the knowledge-driven methods can be mentioned different interviewing techniques. Jiao and Boerboom (2006) mention a few of these, such as document analysis and sorting.

The fundamental part in making CA more realistic, is to achieve a better connection between transition rules and reality (Torrens and O'Sullivan, 2001). The risk of using data-driven methods is that they can create a good output although the parameters are not representative of reality. However, data-driven methods are cheap (no interviews required) and the data is quantified while extracted. Even when using interview techniques aimed for quantitative extraction, there is a process of converting the words into numbers.

1.7.2. Cell size

Cell size is a concern in many, if not all, applications where a raster is used. The size of a cell should represent the smallest meaningful entity. Portugali et al. (1994) use a cell size corresponding to a residential lot.

1.7.3. Cell state

There are some examples on modelling with “continuous” cell states. For example, with application in land use density (Li and Yeh, 2000, Yeh and Li, 2002) and building height (Semboloni, 2000). In these models, each cell can have a value, e.g. 1-10, which is dependent on surrounding values (density or building height). These models use only one type of land use (urban) while they include different levels of density or building height.

1.7.4. Temporal resolution

In most CA all cells are updated synchronously, according to a pre-defined time-step length. During each time-step a number of cells change at once. Huberman & Glance (Huberman and Glance, 1993) have in an experiment showed that this is unrealistic when applying CA on natural social systems. In reality, decisions are taken at a continuous scale. A decision could affect the neighbour's decision, during a time interval which is shorter than the usual time step length (Silva, 2005). In order to come around this problem Huberman & Glance suggest to use a time-step length which allow at *maximum* one cell to change per time-step. What this implies for urban modelling time-step length is not clear.

1.7.5. Window size and form

The size and the form of the CA window defines the maximum distance of neighbourhood interactions. In the models of in the models created by the Research Institute of Knowledge Systems (RIKS) the neighbourhood consists of eight cells (as Euclidean distance) in each direction. Thereby, the distance of influence can be specified differently for different cell types (i.e. land uses). The problem is then not in the software (unless a longer distance then eight cells is required) but how to extract the transition rules. It has been suggested that these models should be called cell-space models instead of cellular automata models (Couclelis 1985).

CA cannot handle influences originating outside the CA window – a phenomenon called "action-at-distance" (Silva, 2005:99). On the other hand, the very principle of CA is that global order appears from local interaction (Almeida, 2003). One evidence of this is the fractal patterns, which are characteristic for CA and cities. These can be seen at all scales (per definition), even when using a window size which is much smaller than the larger patterns. White (White, 1998) suggests, this is not as surprising as the fact that the patterns are so realistic. He formulates the question whether action-at-distance is irrelevant for explaining the evolving land use patterns of cities.

There have been some attempts of combining CA with agents (Torrens, 2001) which can come around the problem of action-at-distance.

1.7.6. Calibration and validation

Data-driven methods for calibration and transition rule elicitation are, so far, most successful in predicting urban patterns (Almeida, 2003). These are for example based on neural networks (Li and Yeh, 2002a) (Li and Yeh, 2001a) or the automatic calibration methods used in RIKS's models. The problem of neural network based calibration is that the parameters are hidden and do not allow "what-if" experiments. According to what was mentioned about explorative models (chapter 1.3) prediction in the long term is not possible, but rather many different *explorations.* In this sense, the usability of neural network based models is limited.

Another problem with data-driven calibration methods is that they do not capture the actual processes of land use change (Almeida, 2003). A pattern could give a good fit with the real land use data, although based on unrealistic rules. This is sometimes known as “cheating with the model”.

1.7.7. Weaknesses of cellular automata in urban modelling

There are some limitations of CA which could affect the realism in urban modelling. One is that CA cannot handle top-down processes. This means, for example, changes that are enforced by policy-makers, such as zoning or locally applied incentives. However, most models have come around this by increasing the suitability or assigning zero suitability to those cells .

Parker *et al.* (2003) state that CA has been most successful in imitating ecological dynamics. However, processes where human decisions are involved have been less successful.

1.8. Research problem

As the introduction has tried to show, bottom-up modelling constitutes a new era of urban modelling. Cellular automata is just a tool for implementing this principle. As every model, CA bears on a framework which guides and limits the understanding of urban processes. The question is whether the framework is suitable for describing reality.

To find out, there clearly needs to be an understanding of what is meant by “good enough”. As discussed earlier, the primary use of a model would be for exploration of the future. This means, an understanding of the consequences of various options, maybe during different external influences.

Most research is based on the technical aspects of CA, while forgetting about what is needed to make it useful in planning. The technique has to be applied more on real management problems. This is the aim of this study.

1.9. Aim and objectives

1.9.1. Research aim

The aim of this research is contribute to the understanding of cellular automata and urban modelling for aiding policy-making and planning of growth.

1.9.2. Objective

The main objective of this study is to model urban growth through an understanding of the preferences in allocation of residential developments.

The second main objective is to model scenarios of urban expansion based on different planning options.

1.9.3. Research questions

The following research questions are to be answered in this study:

1. How can neighbourhood interactions, and inherent constraining and enhancing factors for urban development, be extracted and related to actual changes in land use patterns?

2. How can scenarios of planned and unplanned growth be created and used for evaluating policy options?

1.10. Research approach

Figure 8 shows the research approach for this study. Objective 1 covers the modelling part, while objective 2 covers the creation and interpretation of scenarios.

Observations and interpretation of reality leads to the creation of a conceptual model of growth. The conceptual model is translated into a computer model. This implies a quantification of the conceptual model. The computer model is then used for creating scenarios of growth, which are interpreted and compared.

Observations are never made isolated from the pre-assumptions. Similarly, the conceptual model is not independent from the framework of the computer model. This explains the two arrows between the conceptual model and rule extraction.

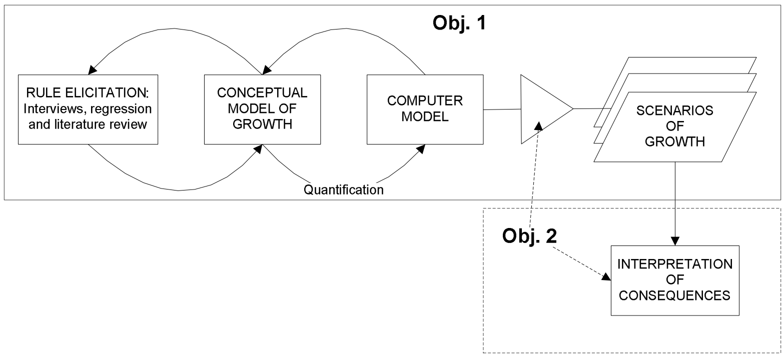


Figure 8. The research approach for this study.

2. Materials and methods

An overview of the methods and materials used for this thesis is described in figure 11.

2.1. Study area

The study area decided to use for this work was Sydney, Australia (figure 9). The study was limited to the metropolitan area of Sydney, seen in the figure below. Sydney is the most populated city in Australia and also the oldest. However, it was founded as late as at the end of the 18th century, after James Cook's first shipped here.

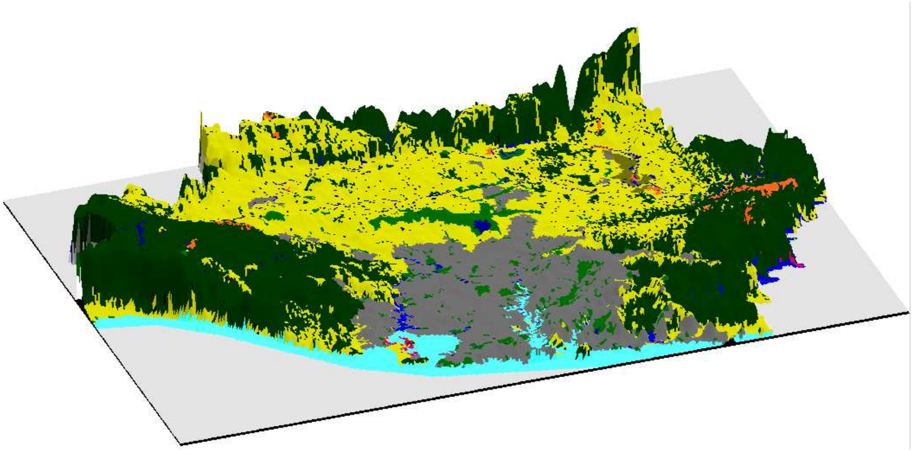


Figure 9. The study area in 3D, as visualised in Metronamica.

Because Sydney is a relatively young city, its growth has been much influenced by the car (Liu and Phinn, 2005). This can be seen in the sprawl-like patterns along the highways and railway lines.

Sydney has experienced a fast growth during the last decades. The expected growth of Sydney until 2031 is around 1 million people. In addition, the changes in demography will enforce the demand for new homes.

The Sydney Basin Bioregion (figure 10) has the fifth highest biodiversity in Australia out of 85 regions. At the same time, the agricultural production in the Sydney region represents 12 percent of the whole production in New South Wales' (NSW) (Department of planning, 2005). This means that there are many benefits of handling the growth in the right way.

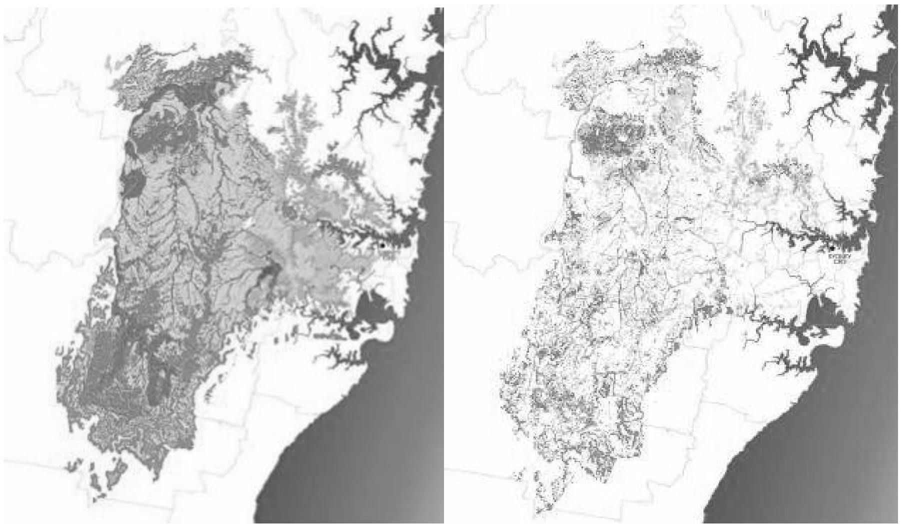


Figure 10. The vegetation before European settlement (lest) and today (right) (Department of Environment and Conservation, 2007).

2.1.1. The Metropolitan strategy

While urban expansion might not be possible to stop at once, it can be limited. For example, by allocating new buildings in existing urban areas and by building new urban areas with a higher density. These are two of the aims of the "Metropolitan strategy" for Sydney (Department of planning, 2005). The strategy aims to make Sydney into a more sustainable city, in terms of ecological, economical and social aspects.

One of the main challenges in managing Sydney's growth is to steer the growth into areas where it has less negative impact on extensive agriculture and remnant vegetation (Department of planning, 2005). The Metropolitan will allow growth within two growth zones, one in the southwest and one in the northwest of Sydney.

Another goal of the strategy is to decentralise the city. In addition to the central business district (CBD), another three centres will be formed – Paramatta, Penrith and Liverpool. One benefit of this, is that transports can be shortened. Local centres act as employment and commercial hubs. Decentralisation might also be a way of limiting sprawl (Torrens, 2006).

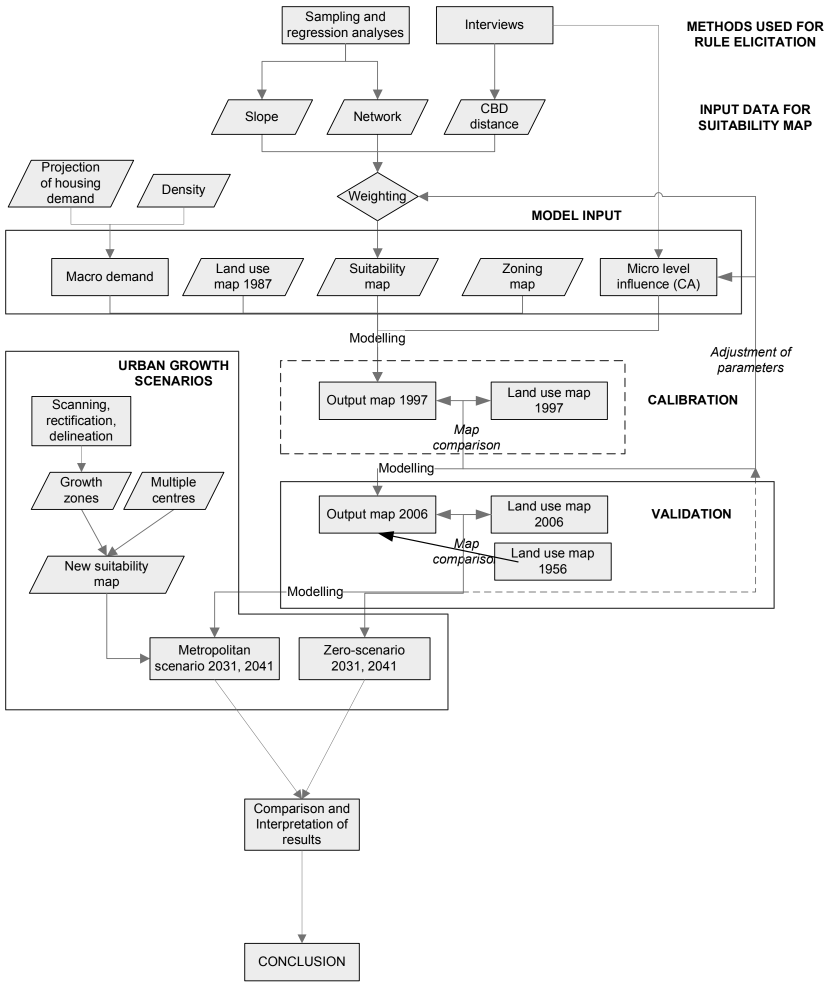


Figure 11. The flowchart shows the methods used in this thesis.

2.2. Description of Metronamica

The CA model used for the analyses is a model developed by RIKS (RIKS, 2008) in Netherlands, named Metronamica. This model was chosen since it allows for easy specification of the neighbourhood parameters. Metronamica is constrained CA model aimed to be used for policy-making and scenario modelling.

It has calibration methods in-built, as well as indicators for creating more meaningful information of the output data.

2.2.1. Input requirements

As a constrained CA model, Metronamica uses additional inputs to the CA core model. These are a suitability map, zoning map and a road network.

At minimum one land use map is required. Ideally at least three land use are used: one for the starting year, one calibration map and one validation map.

Cell states

Metronamica differs between three different land use and land cover types (from now on denoted *land classes*). *Function* and *vacant* are dynamic land classes, which means their amount and location can change. Functions are regulated by the macro model while the change in vacant land is entirely determined by the micro model. Functions are typically land *uses*, for example urban. Vacant land classes are typical land *cover* classes, for example forest.

Features are permanent land classes, for example airports and lakes. These cannot be affected by other land classes but they can affect other land classes (RIKS, 2006).

Neighbourhood influence

The neighbourhood influence is defined through “splines” (figure 12) (RIKS, 2006:67). These are defined as pushing or pulling forces (Engelen *et al.*, 1997). The spline is defined also at a zero distance, which represents the “inertia” (RIKS, 2006:14). The inertia could represent the cost of changing a land class. For example, although a cell with residential land use is more suitable for commercial land use, there is a resistance from the people living there to sell their house(s).

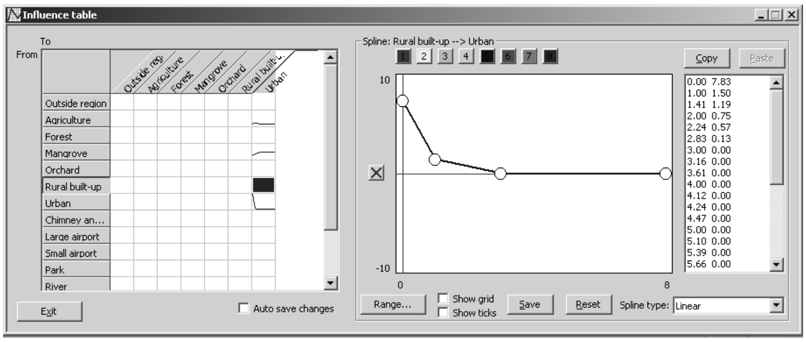


Figure 12. The splines where the neighbourhood influences are defined.

Splines can be defined for each land class and specified according to how it influences every other land class. For this study, only splines which affected the urban land class were defined. The distance (on x-axis) is given in cell units. Thus, if the cell size is larger, the influence range can be made longer.

Intensity denote the strength of the spline (i.e. changes in the y-range). *Range* is the distance at which a land class does not have any influence, which means where the spline reaches zero for the last time.

The macro model in Metronamica can be defined as a dynamic model or as a trend line function, similar to the splines.

2.3. Data and processing

The following data were used for processing (table 1).

Table 1. The data used for preparing the input. SU = Sydney university; CF = City Futures (CityFutures, 2007); MS = Metropolitan strategy (Department of planning, 2005), KRG = The council of Ku-ring-gai, Sydney

Used for	Data	Year	Format	Source
Land use map	Urban land of 1956, 1972, 1987, 1997, 2006		Vector	SU
	Rural houses	2006	Vector	SU

	Parks	2006	Vector	SU
	Forest, mangrove, orchards	2006	Vector	SU
	Water (lakes, rivers, wetlands etc.)	2006	Vector	SU
	Parishes and coastline	2006	Vector	SU
	Airports (small, large)	2006	Vector	SU
	Chimney's and mines	2006	Vector	SU
Suitability map	Elevation data	-	Isoline (10 m) vector	SU
	Transport network (roads and railway)	2007	Vector	CF
Zoning map	Prohibited areas	2006	Vector	SU
	National parks	2006	Vector	SU
Other	Local environment plan (LEP) of Ku-ring-gai	2007	Vector	KRG
External land	Detailed vegetation: core habitats, remnant vegetation	Approx. 2005	Scanned into raster (100m)	MS
	Extensive agricultural land	Approx. 2005	Scanned into raster (100m), delineated	MS
	Growth zones	2008<	Scanned into raster (100m), delineated	MS

Some of the data: a detailed vegetation map, a maps of extensive agricultural land and the planned growth zones, were derived from hard copy maps from (Department of planning, 2005).

2.3.1. Processing tools

For all the analyses, data preparation and modelling the following softwares were used:

- ArcGIS 9.2
- Erdas Imagine 9.1
- Microsoft Excel
- Geonamica (Metronamica)

All raster based maps were converted into a cell size of 250 m. The cell size was justified from the perception of the minimum size of new developments. It was assumed that houses are not built one by one, but in blocks as is shown in figure 13. Each cell should represent a whole block.

Figure 13. The cell size of 250 m corresponds to one block of developments (the image shows the urban fringe of Sydney. From Google Earth).

2.4. Conceptual model of residential allocation

Residential developers are the main actors of development in the fringe. They can be assumed to act according to a profit maximisation (Wu and Webster, 2000). Thus, the factors determining the allocation of new residential developments should identify the factors which influence the potential profit of the developer. This includes physical factors (e.g. slope, accessibility, quality of view) as well as policy measures for balancing negative externalities (pigovian taxes, zoning) (Wu and Webster, 2000).

The objective was to find the main factors which influence urban development in Sydney. The means for doing this were interviews and literature review.

2.4.1. Interviews

Three interviews were carried out with urban planners, where the interviewees were asked about the type of factors which influence the allocation of residential developments.

Based on the interviews, a Causal Loop Diagram (CLD) was created (appendix 5) representing the conceptual model. The factors perceived as most important were used for further analyses and quantification.

2.5. The suitability map

On the basis of the interviews and the literature it was decided to use accessibility, slope and distance to CBD, as layers for the suitability map. It is possible in Metronamica to use a pre-determined function for accessibility. However, in this study it was decided to use an empirically derived function, and therefore accessibility was included in the suitability map.

The influence from slope and the road network was derived through regression analyses.

2.6. Estimating the influence of the transport network

The regression analyses of the transport network aimed at the following:

- To reach a function which describes each networks' influence on new development (as a function of distance)
- An estimation of the *relative* influence between the link types

2.6.1. Distance from link type

Samples were taken within a statistical population, defined by the new growth areas of 1997-2006. All existing urban of 1997 was masked out during the analyses to reduce as much as possible of other influencing factors.

Railways and highways were grouped together as one link type. The reason for this was that their influence was overlapping. This implies that the influence was hard to distinguish when correlating with land use occurrence.

Conceptually, it could be more realistic to relate accessibility with entrances and railway stations. Despite this, most CA models use the accessibility lines (road and railway) for computing accessibility (e.g. (Clarke *et al.*, 1997, Engelen *et al.*, 1997)).

In Sydney, the distance between the railway stations is seldom longer than 1.8 km. The effect of making a buffer around stations and railway would therefore be almost the same as around the roads and railway. One should also take into consideration that new stations can be constructed. It could be more relevant to take stations (and maybe entrances) into consideration when modelling urban density. For example, the Metropolitan strategy aims to concentrate as much of the population as possible around railway stations (Department of planning, 2005).

For simplicity, the road buffer was used.

Main roads were used as a separate link type. Smaller roads where not used since they were covering existing land of 2007 with a high detail. Using these would lead to an *ad hoc* prediction of 2007s land use, because accessibility, and thus suitability, would already be present.

The distance from each sample point to the nearest link was calculated in ArcGIS. The points were grouped into intervals of 100 m and the frequency within each interval calculated. A trend line function was then created from the data and used for representing the influence of each link type on urban development (figure 14)

2.6.2. Relative influence of link type

The relative influence of the link types was estimated in accordance with the procedure described in appendix 1.

The method is based on a comparison between the influence as calculated from the graph and the influence as calculated from intersected growth. The expected growth as estimated from the graph, is compared with what is actually found. The resulting number will then be compared between the two link types, where a relative influence can be estimated. This can be summarised in the following ratio (figure 14).

$$\overbrace{\frac{\text{Intersected growth in interval A}}{\text{Total buffer area}} \Big/ \frac{\text{Integral of interval A}}{\text{Full integral}}}^{\textbf{Main roads}} : \overbrace{\frac{\text{Intersected growth in interval A}}{\text{Total buffer area}} \Big/ \frac{\text{Integral of interval A}}{\text{Full integral}}}^{\textbf{Railway and highway}}$$

Figure 14. A ratio of influence between main roads and railway and highway.

The method is based on the following pre-assumptions:

- The influence from other factors is irrelevant. If not – the effect from other factors is evenly distributed over the area
- The correlation between influence and actual intersected urban land must be equally represented between the link types

The latter condition could be expressed as the following:

$I_M \sim B_M = I_H \sim B_H$

Where:
I = Influence from main road within interval A
B = The percent area of urban land within interval A
$_M$ = Main road
$_H$ = Railway and highway

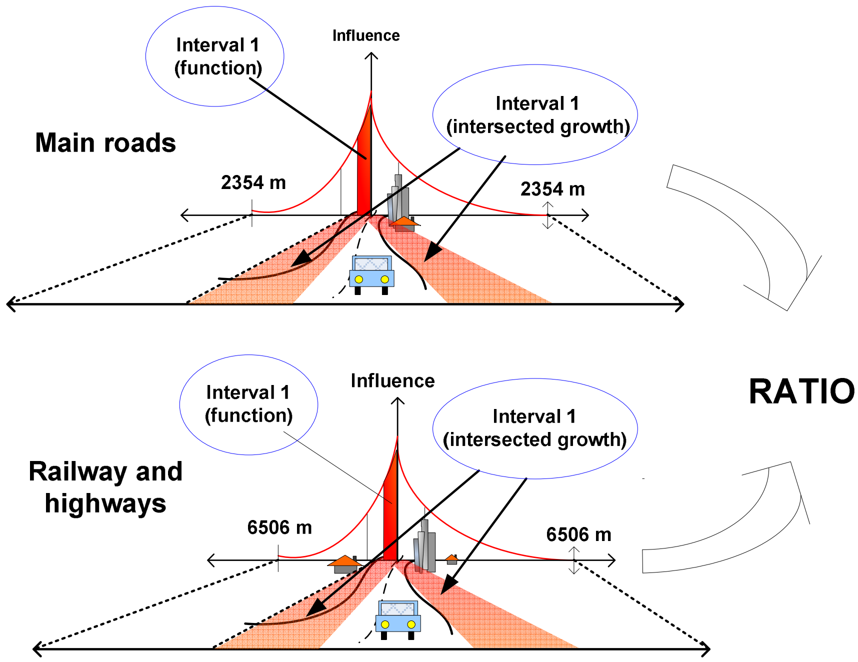


Figure 15. Schematic figure showing the method used for estimating the relative difference in influence between the link types.

Since the link types were evenly distributed across the area, it was assumed that they would have approximately the same prerequisites for stochastic (random) effects and external factors, which are not related to road influence.

2.6.3. Implementing the method

a) Intersected growth

In accordance with the flowchart (appendix 1), the two link types were buffered with a distance equal to the distance of zero impact for corresponding link type. The buffered areas where the two link types intersected each other were masked out to ensure that only one link type would have an influence on development. The buffer consisted of intervals of 500 m, each with an independent topology to facilitate overlaying. The buffer was intersected with urban growth of 1997-2006. In the resulting layer, each interval contained a fraction of growth, assumed to be explained by the presence of the transport link.

b) Integral of the influence function

The same interval used in the previous step (e.g. 500-1000 m), was used when calculating the influence from the influence function. This was achieved by calculating the integral of the road influence function. Thus, if the 500-1000 m interval was used in the previous step, the integral had to be calculated for x_1=500m and x_2=1000m, for corresponding link type.

c) Comparing link influence

The result from the intersection (step 1) was divided by the result from the calculated influence (step 2). The value for main roads was then divided by the value for railways and highways. Since the same calculation was done for many intervals, they could be compared to see if there were any discrepancies. The average value was used for the suitability map.

2.7. Estimating the influence of slope

Regression analyses were used to estimate the influence of slope as well. To avoid spatial auto-correlation random sampling was used.

Only looking at the slope for existing land would reflect the topography of the landscape more than the constraining effect of slope. Therefore, it was assumed that the distribution of urban land has to be calculated as a *percentage* of existing land. The expected relation between slope angle and urban land is shown in figure 15.

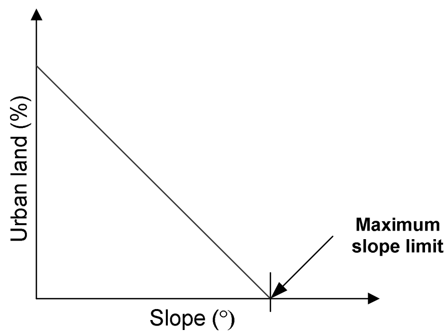


Figure 16. The expected relation between slope and urban land.

The first assumption of this method is that some areas are not developed because they are too steep. The second assumption is that increasing slope implies a higher building cost. With this assumption follows, that there should be a lower percentage of cells within higher slope intervals, compared to lower slope intervals.

On the other hand, in situations where the space is limited, the slope resistance could be lowered (Clarke *et al.*, 1997). This can explained as a balance between the potential profit for the residential developer and the demand for houses (figure 16). A house will be built only if the demand outweighs the cost of building a house. Note that a possible positive effect from slope – for improving the quality of view (Liu and Phinn, 2003) – is not taken into consideration here.

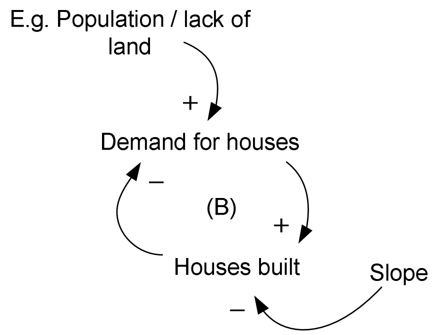


Figure 17. The influence of slope and demand on the amount of houses built. The plus and minus signs denote positive and negative correlation, respectively. The “(B)” denotes a balancing loop, as explained in Ford (1999).

The council district of Ku-ring-gai was used for the sampling (figure Ku-ring-gai). This region is comparably hilly and thereby assumed to give a good representation of the constraining effect of slope on urban development.

Ku-ring-gai is surrounded by national parks. It could be that these areas became national parks because there are steeper slopes in these areas. However, this is a speculation and a potential weakness of the sampling.

2.7.1. Implementing the method

The elevation map was interpolated using the Topo-to-raster tool in ArcGIS 9.2. This software tool is specifically made for creating a digital elevation model (DEM) from contour lines (ArcGIS 9.1 help section). A flowchart of the whole procedure can be seen in appendix 2.

Urban land within the region was delineated, as were the council boundaries. Two samples were taken within the council borders of Ku-ring-gai and urban land. Each sample consisted of 1000 random points.

The number of sample points was justified for allowing approximately 30-50 sample points within each interval (0.5 degrees).

The frequency of cells per slope interval was calculated. All intervals were then normalised according to the area difference between urban land and borders (appendix 2). Thereby, slope values derived from urban land could be calculated as a percentage of the whole area (appendix 2).

The data of land cover (in percent) were then used for creating a trend line function. The function was normalised to a scale of 0-10 and used for creating a slope influence map.

2.8. Suitability map

2.8.1. Multi-criteria evaluation

Multi-criteria evaluation (MCE) is a method for combining many layers or *criteria*. A criterion can be a *factor* or a *constraint* (Eastman, 1999).

Factors are mostly constructed as a fuzzy criterion, which means that there is a range of enhancing or detracting values. For example, slope and accessibility are typical *factors* for development. They enhance or detract the suitability (Eastman, 1999).

Constraints, on the other hand, are mostly made as either-or criteria (i.e. excluding or including). Areas prohibited for development could represent a typical constraint. The same could apply for slopes which are too steep to build on.

Eastman (Eastman, 1999) mentions three methods for combining criteria (layers):

- Boolean Intersection
- Weighted Linear Combination (MLC)
- Ordered Weighted Average (OWA)

Boolean Intersection (also known as “crisp” overlay) uses multiplication for combining layers. These must be classified into values of either 1 or 0.

In MLC each layer is weighted where after the layers are summed. The sum of the weights has to equal a value of 1. The summed layers are then multiplied by the constraints (Eastman, 1999).

The OWA method is similar to MLC, but adds another set of weights. The method is developed to allow a golden middle-way between risk-taking (similar to the AND operator) and risk-avoidance (similar to the OR operator).

The AND and OR operators can also be used for combining non-binary layers (i.e. fuzzy layers). These operators are then known as fuzzy AND and fuzzy OR. This is the same as using the minimum value from the input layers (fuzzy AND) or the maximum value (fuzzy OR).

2.8.2. Combining the link types

The resulting graphs describing the influence from each link type, were used for creating the influence graph. This was done by creating a multiple buffer around respective link type. Each buffer interval was assigned a value, corresponding to the integral of the influence graph (figure 17)

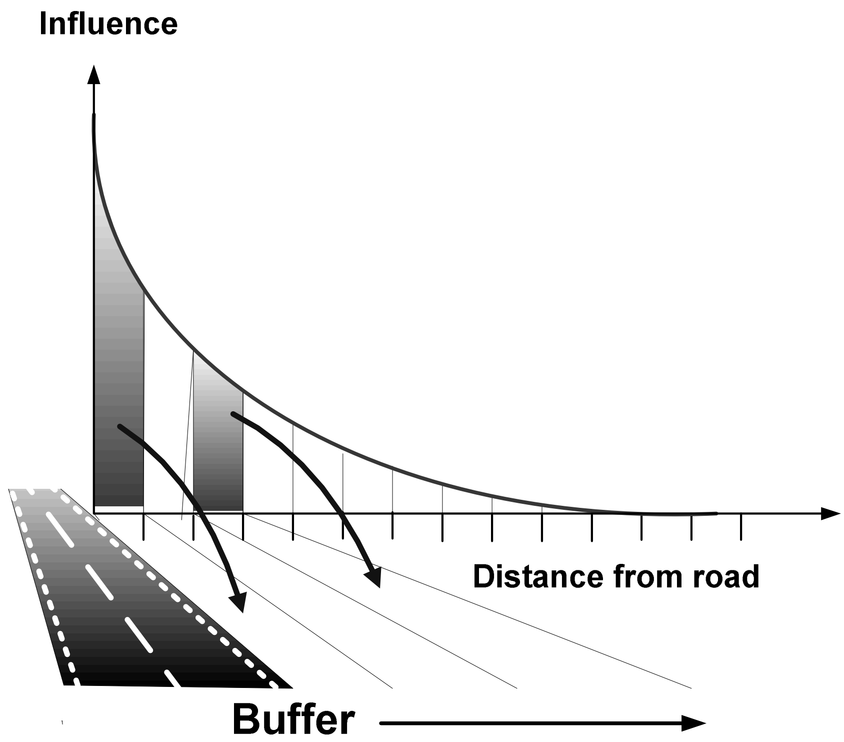


Figure 18. The area under the graph was measured and assigned to the corresponding buffer interval.

The resulting vector layers were then converted into raster layers of 250 m resolution.

When combining the link types it was assumed that two links which are close-by cannot add influence to each other. Instead it was assumed that the highest accessibility determine the total accessibility. Therefore, a fuzzy OR (i.e. maximum of inputs) was used for combining the two link types.

2.8.3. CBD influence

In the interview it was indicated that the land values decrease 30 minutes from the CBD (by train). However, an inspection of the map shows that most areas are already urban at this distance, which makes the CBD influence meaningless (unless land use density would be modelled).

In addition to slope and road influence, an additional layer was created, representing the influence from the central business district (CBD). This layer was created as a circle with one hour radius (estimated to 35 km) around the CBD, as derived using trial-and-error.

One hour was estimated as 35 km based on experience with train. Although cars do not have to stop at stations, as trains, they suffer from congestions and other forced stops.

2.8.4. Combining all layers

The suitability map created by combining the slope influence map, the combined road layer, and a CBD distance. A Weighted Linear Combination (MLC) was used, since it allows for weighting of the different layers in an uncomplicated way. The weighting of the layers were made from interpretation of interviews followed by a trial-and-error method. For example, the weight for CBD influence was lowered, which resulted in too much growth of satellite settlements (urban growth outside the core urban area). In the same way, too much weight on roads lead to more growth along the highways and railway tracks. Too little slope resulted in growth in areas with high slope and so on. The final weighting is shown in table 2.

After the layers had been summed, the result was multiplied by a constrain, representing areas of too high slope (i.e. where the slope influence map indicated 0-values). The layer used for the suitability map and corresponding weights internally and for the final overlay.

Table 2. The weights used for creating the suitability map.

Influence layer	Weight	Internal values
Slope	0.4	0-10
Network	0.4	1-10
CBD	0.2	10

2.9. Other maps and CA settings

A zoning map (in figure 20) was created by combining national parks and prohibited areas. They were set as prohibited for the whole modelling period.

Land use maps were created for the years 1956, 1972, 1987, 1997 and 2006. Only data of urban land was representative for the mentioned years, while other data (forest etc.) were taken from 2006 year's data. The land use classes with corresponding colour can be seen below (fig. 19). The urban land class is underlined which indicates a *function* class. All land uses above urban are *vacant* and classes below are *features*.

Figure 19. The land classes used in Metronamica.

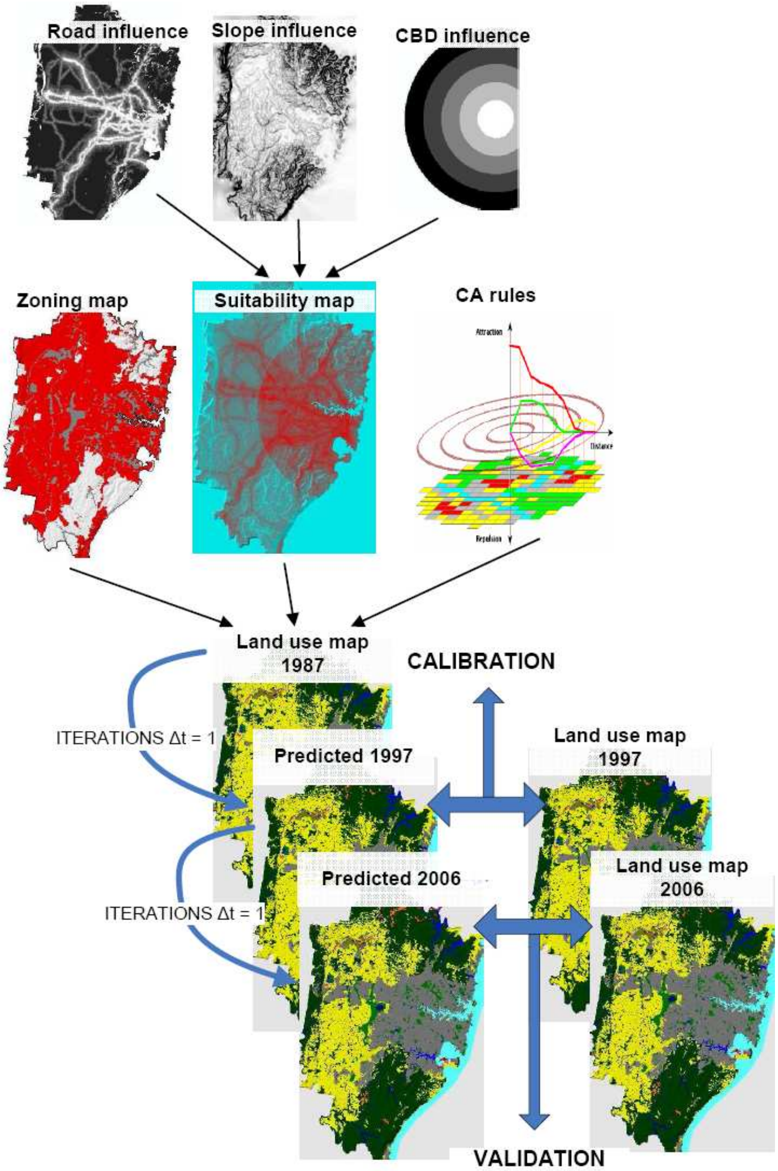


Figure 20. The input data used in the model and subsequent calibration and validation against land use maps of 1997 and 2006.

2.9.1. Macro model settings

In the macro model the demand for cells was specified. For calibration and validation, the demand for the years of 1987, 1997 and 2006 was derived from the maps.

For the future demand, it was calculated from the expected amount of dwellings in non-urban areas (Greenfield developments) and divided by the expected land use density in the new growth zones (15 dwellings / ha). The latter was given in one of the interviews (interview 1). The amount of land was then divided by 6.25 to convert from ha units to number of cells of 250 m resolution.

For demand until 2106 the trend was extrapolated based on the trend of 2007 to 2041.

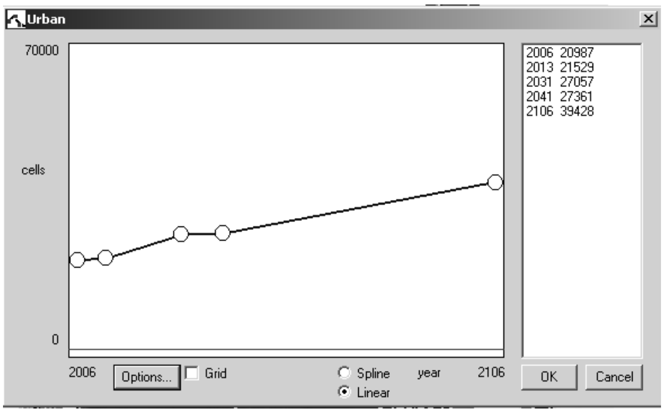


Figure 21. The specified land use demand from 2006 until 2106 (cell units).

2.9.2. Extracting and applying the neighbourhood rules

The neighbourhood rules were specified in accordance with the most important factors found from interviews and literature (Table influence_settings). It was attempted to use as few splines as possible, since a simple rule is better than a complex rule. This means, a linear graph is better than a polynomial function, and fewer splines are to prefer in front of many (RIKS, 2002c).

During all simulations the intensity of the urban spline was kept at 1. The inertia value was kept high enough so that all urban cells remained urban.

The model period was defined to 1987-2006. The land use map of 1987 was used as starting map, and land use maps of 1997 and 2006 were used for calibration and validation, respectively (figure 19). The calibration and validation were not strictly separated, however, as is otherwise a requisite. They were rather made used as two calibration maps. The reason for this was that it was easier to assess the process using both maps. Also, the accuracy assessment revealed inconsistency when comparing to 1997 and 2006 years' data. Although the calibration map indicated good results (using quantitative measurement), the validation gave poor results.

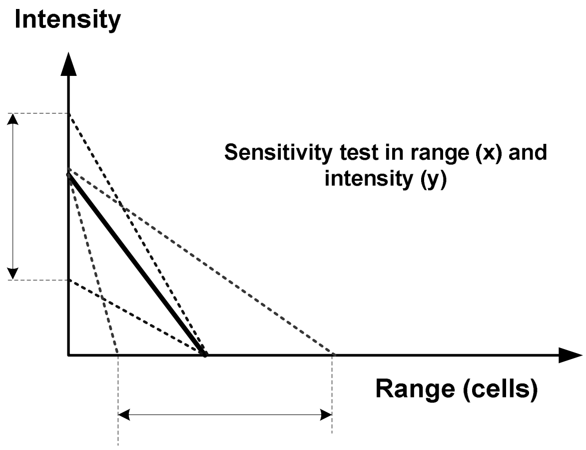


Figure 22. The principle according to which the sensitivity test was done. The test of range and intensity influence was done at separate occasions.

Before calibration, the variables were tested. This step is done in the same way as for calibration, but is more connected to rule extraction (White *et al.*, 1997). The splines were changed in intensity (y-axis) and range (x-axis), according to the principle shown in figure 21. The same method was used for calibration, but then only the intensity was changed.

The output was assessed using fuzzy kappa and visual interpretation. Fuzzy kappa is based on the kappa index, but allows slight discrepancies in the location of cells. The either-or assessment is replaced by a fuzzy limit so that cells can be fully distinct or fully identical (RIKS, 2006). The radius of the neighbourhood was set to 5 cells, the halving distance to 1, and the similarity matrix was set to unity. These were the default settings, and they were used consistent through the modelling.

2.10. Calibration

2.10.1. Trial-and-error

Visual methods for calibrating CA models have been shown useful (Cheng, 2003a, Clarke *et al.*, 1997, Ward *et al.*, 2000). This is because it involves assessment of processes (Cheng, 2003a). This means, not only the static patterns are assessed but also the dynamics. However, it might be valid to ask what attributes one should look for.

The following attributes are given in the user manual for the land use model Xplorah (RIKS, 2002c):

- Patterns
- Size and composition of patterns
- Amount of land in clusters
- Location of clusters

2.10.2. Automatic calibration

Metronamica has a built-in, automated process for calibration. Small changes are made to the splines, and the output is automatically verified against a predefined map. However, the results were not better than for manual calibration. Therefore the calibration was limited to visual interpretation and fuzzy kappa value assessment.

2.10.3. Validation

Although validation is not possible when modelling into future, the performance can be assessed from the capability of predicting land use data from the past.

The best neighbourhood settings from the calibration, were validated by running the model using a base map of 1956s land use. The predictions were compared with the land use maps of 1997 and 2006.

2.11. Scenarios

Two scenarios were created: one based on the Metropolitan strategy and one on a business-as-usual scenario. In addition, the demand for land was adjusted to investigate possible futures *if* the population projection goes beyond the expected.

The Metropolitan scenario was simulated by creating a new suitability map. All growth zones were used and assigned a maximum suitability. Instead of one centre, the influence of many centres was simulated. This was done by giving a higher suitability around the three centres of Paramatta, Penrith and Liverpool.

The business-as-usual scenario was simulated by keeping the existing suitability map.

The projected trend in growth from 2006 to 2041, was extrapolated into 2106. The scenarios were then compared for the years of 2031, 2051 and 2106.

If following the scenario definition used by Engelen *et al.* (2000a), the first two scenarios would be considered *options* under a scenario of growth.

3. Results

3.1. Conceptual model of growth from interviews and literature

From the interviews, it was found that distance to existing urban is the most important allocation factor for residential developments. This is also confirmed by literature (e.g. (Sheehan *et al.*, 2001)). The conceptual model explaining this is shown below (figure 22).

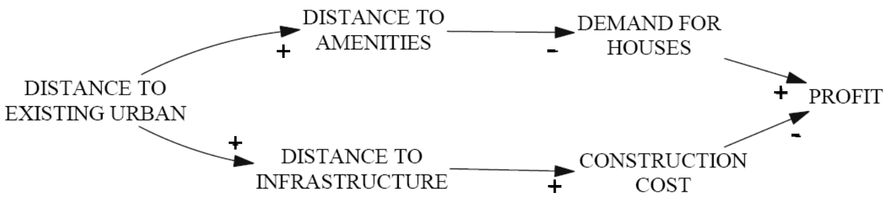


Figure 23. A CLD showing the causal relationship explaining why new settlement are more probable to be built near existing settlement. A plus sign indicates a positive relationship and minus indicates an inverse relationship, between two entities (as explained in (Ford, 1999)).

The potential profit is assumed to determine the location of a new residential developments. A low distance to urban land implies a lower distance to shops and other facilities which increase the demand for houses. A higher demand increases the potential profit for the developer.

A low distance to urban also means a shorter distance to infrastructure (e.g. sewage, electricity, water, roads). This implies a lower construction cost and thus a potentially higher profit.

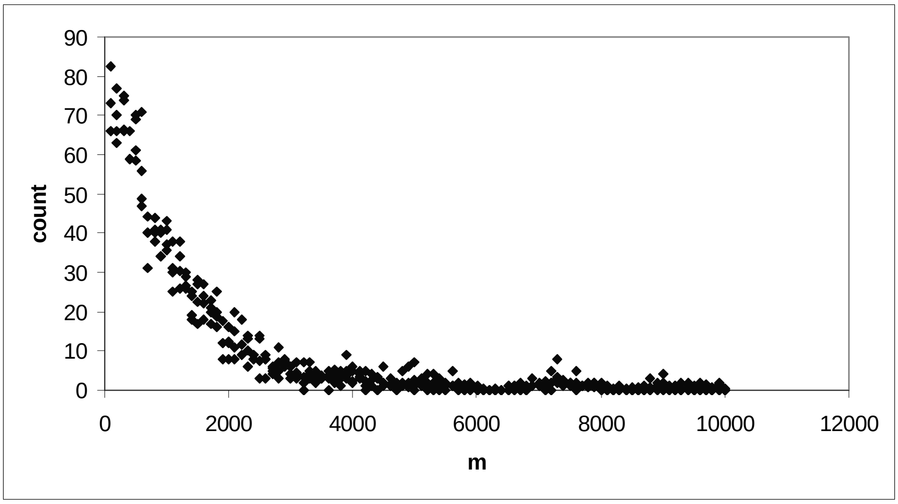
Quality of view was mentioned in one of the interviews (interview 3). Another interview (interview 1) mentioned the demand for living in the country-side, which could be related to quality of view.

It is well-known that sprawl is to some extent caused by preferences in living (Torrens, 2006). However, the exact causes and how it can be modelled in a CA framework is less obvious. It was noticed, however, that an attracting factor towards non-urban land was required to simulate leap-frog growth (scattered at the fringe) and satellite settlements (outside the fringe).

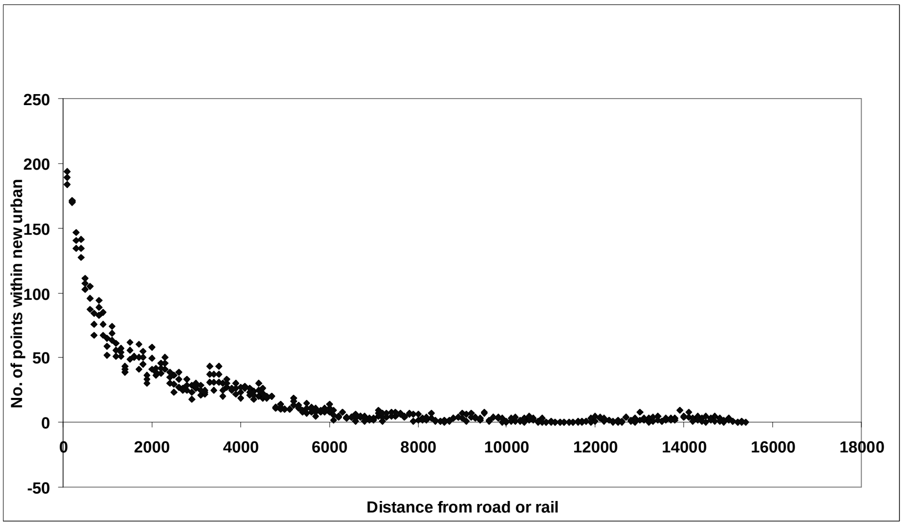
3.2. Suitability map

3.2.1. Transport network influence

The results from the sampling of main roads (figure A) and railway and highway (figure B) are shown below. The result was normalised to a range of 0-10 in figure 23.



Main roads



Highway and railway

Figure 24. The frequency of random points within new urban land (1997-2006) and distance from main roads (upper) and highway and railway lines (down).

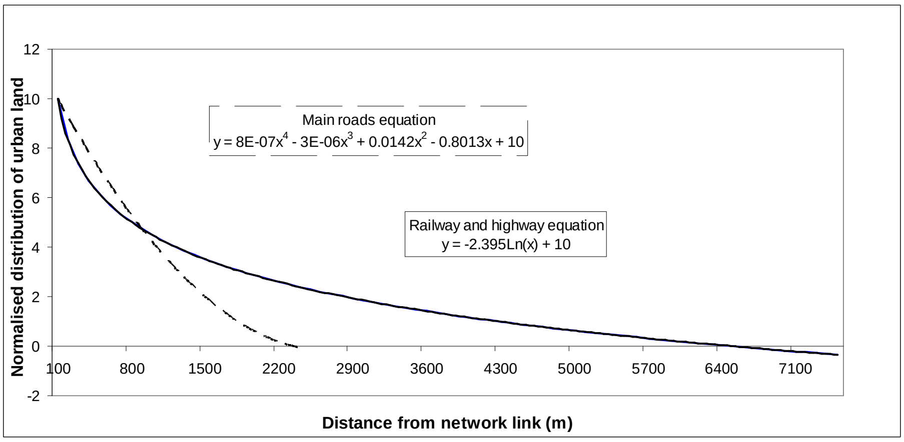


Figure 25. Average distribution of new urban land cover (1997-2005) as a function of distance from highway and railway (curve with long range), and main roads (short range). The values are normalised to an influence of 0-10.

The relative influence between the link types is given in table 3. This was calculated according to the function described in figure 14. The average value (bold) was used for the weighted overlay, for combining the roads.

Table 3. The relative influence of the link types

Interval (m)	Main roads	Railway-highway	Ratio
0 - 500	0.24	0.97	0.25
500 - 1000	0.26	0.87	0.29
1000 - 1500	0.31	0.77	0.40
1500 - 2000	0.48	0.75	0.64
Average	0.32	0.84	**0.38**

3.2.2. Slope influence

The estimated percentage of development within Ku-ring-gai can seen below. Figure 26 shows the results when using 100 m resolution and figure B for 250 m resolution. As can be seen the maximum slope for urban development decreases with larger cell size.

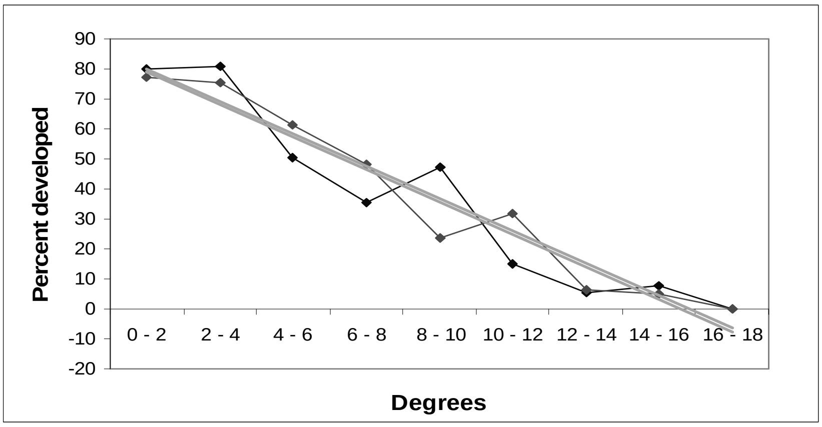


Figure 26. Sampled urban cells as a percentage of available land with 100 m resolution.

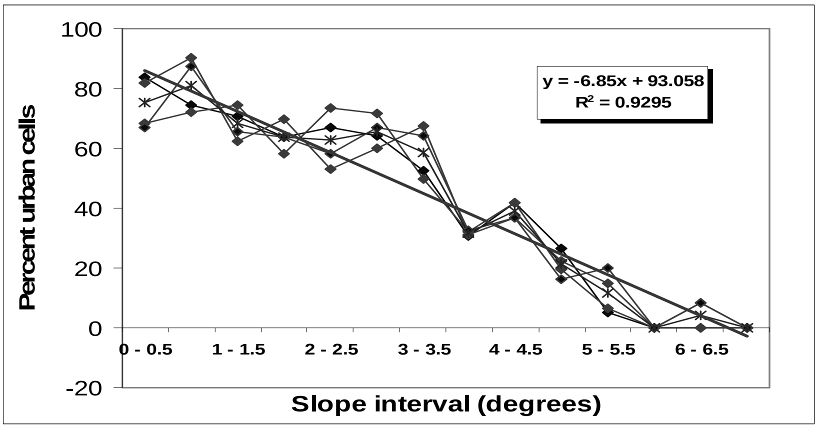


Figure 27. Sampled urban cells as a percentage of available land with 250 m resolution.

The equation in figure 250 m slope, was later normalised into a range of 0 to 10. This equation was then used to create an influence map of slope.

As can be seen in the diagrams, the maximum slope with urban was approximately 16° for the 100 m resolution, while only 6-6.5° for the 250 m resolution.

3.3. Neighbourhood influence

3.3.1. Results from trial-and-error

The results from the sensitivity testing of the urban spline showed that changes in intensity did not have any noticeable impact on the results. However, this was only if another spline was not defined.

Changes in range had more influence on the predictions (figure 28). Note that all accuracy assessment results below are given as fuzzy kappa (or fraction correct) of *all* cells.

Table 4. The results from map assessment for different ranges map 1997 and 2007. The intensity of the urban spline was equal to 1.

Range	1997 Fuzzy Kappa	Fraction correct	2006 Fuzzy Kappa	Fraction correct
1.41	0.92	0.963	0.881	0.945
2	0.923	0.965	0.879	0.944
3	0.923	0.964	0.881	0.945
4	0.923	0.964	0.883	0.946
5	0.923	0.964	0.884	0.946
6	0.922	0.964	0.883	0.946
7	0.922	0.964	0.881	0.945
8	0.922	0.964	0.879	0.944

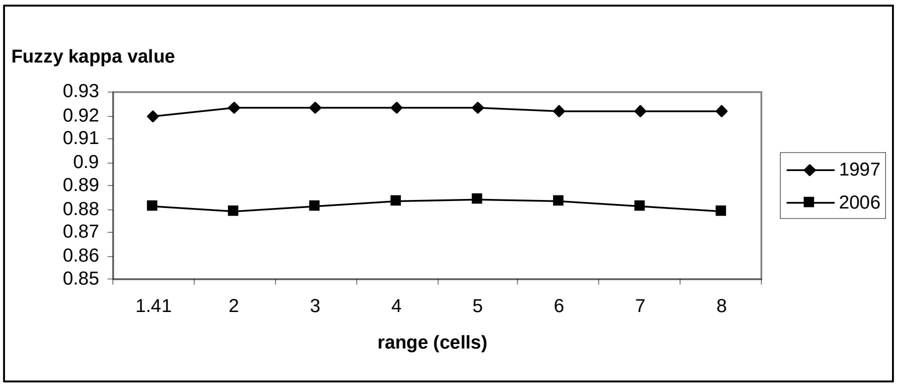


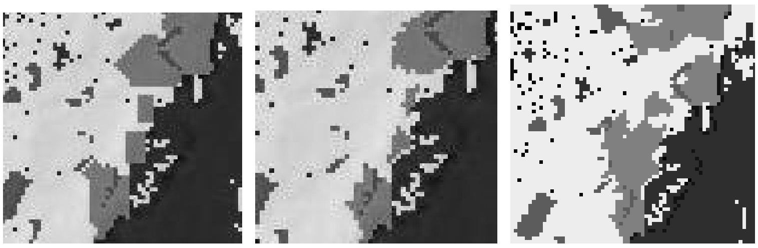
Figure 28. Fuzzy kappa of map comparison between predicted and actual land use (1997 and 2006). (Urban spline intensity = 1)

The fuzzy kappa was higher in the map of 2006 than 1997. This means, the error increases with time.

The best results for the 1997 prediction was achieved with the spline set to between 2 and 5 cells. For the year 2006, the best results are found in the range between 4 to 6 cells. A range of 1.41 resulted in the poorest results for the 1997 prediction, but one of the best results for 2006.

Visual assessment

A longer range resulted in more compact growth patterns and clusters without edges (figure B). Shorter ranges gave more diverging and variable growth. Only at a range of 1.41 clusters with distinct edges appeared (figure 29A). The thickness of new growth was found to increase with higher ranges.



A B C

Figure 29. The difference in output shapes using a range of 1.41 (A) and 8 (B). Figure C shows actual land use pattern of the same year (2006).

It was found that the growth patterns were more realistic with a very short range. As the iterations increased, the patterns from long ranges produced big round clusters, which did not resemble reality at all. However, this was more noticeable when the features had grown larger. This is because the features became smoother for each iteration.

Adding agriculture

With only one spline influencing urban development, the growth of satellite settlements could not be simulated. Therefore, a spline representing attraction to agricultural land was added. This was defined so that only neighbouring agricultural cells would contribute to a higher suitability, as shown in figure 30

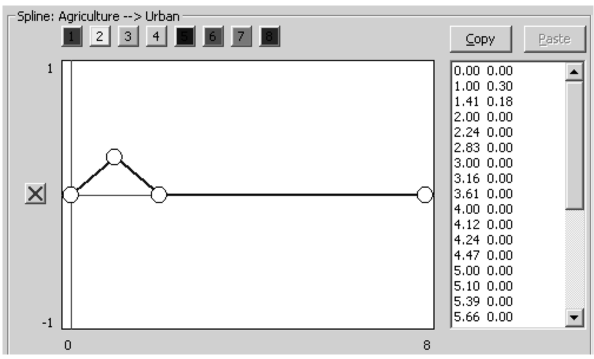


Figure 30. The spline for agriculture influence on urban development.

The same method used for the urban spline was used for the agriculture spline. For all results presented hereafter, the calibration was made with the urban spline intensity equal to 1.

The range of the agriculture spline affects the size of the clusters. A long range for agriculture resulted in larger clusters (figure 31(A)) than for short ranges (figure 31(B).

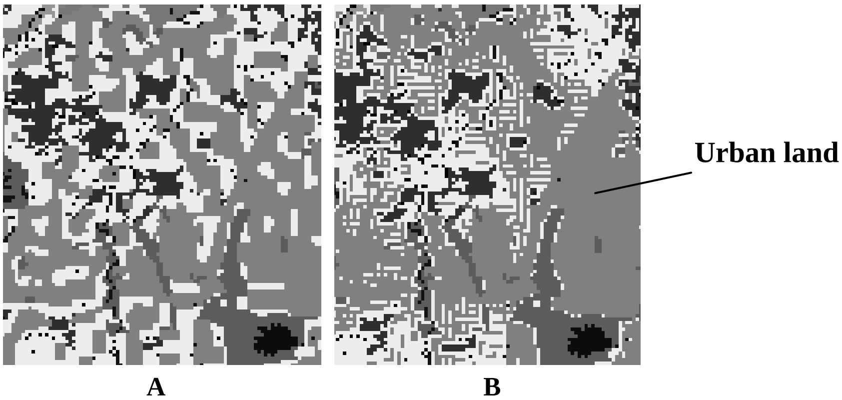


Figure 31. The patterns when using a long range for agriculture (A) and short (B).

The intensity of the agriculture spline controlled the degree of scattered growth. A high intensity resulted in more scattered urbanisation, while less intensity resulted in more compact growth. It was also noticed that a higher intensity in the agriculture spline lead to more urbanisation around transport links.

The results are shown as a diagram in figure 32.

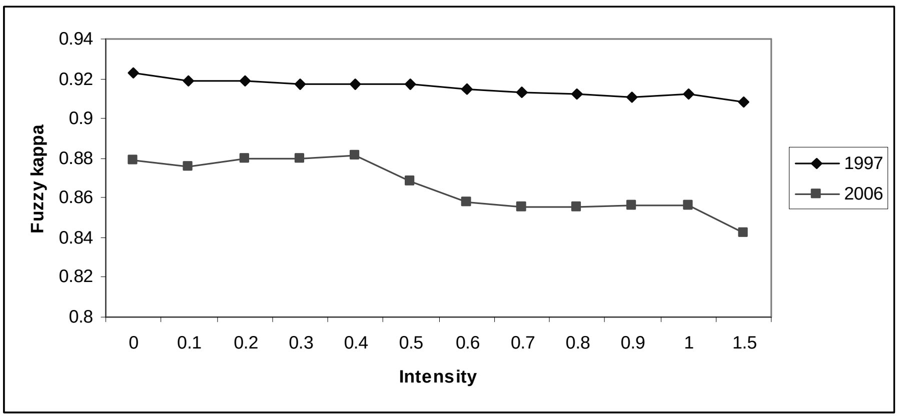


Figure 32. Fuzzy kappa for predictions using different intensities of the agriculture spline. Urban spline range = 2.

As can be seen in the figure above, the predictions deteriorates when the agriculture spline reaches above 0.4. It can also be noticed that the results for predictions of 2006 are more exaggerated.

The figure below shows the results with changes in agriculture spline intensity, but with an urban range of 1.41.

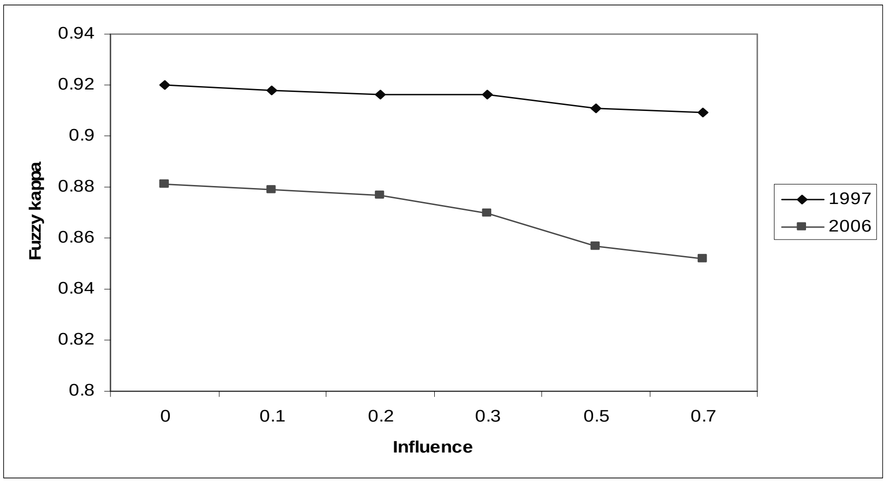
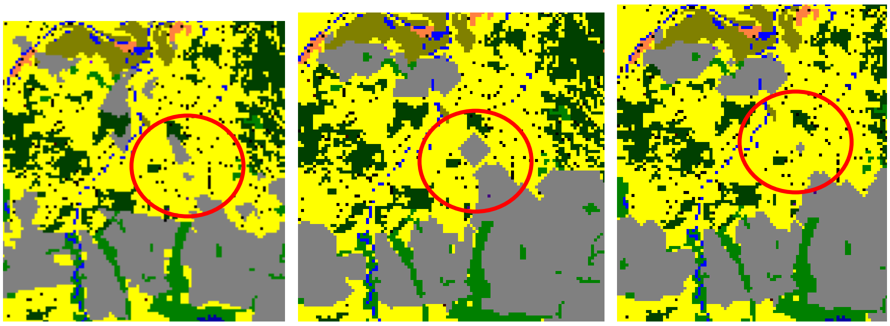


Figure 33. Fuzzy kappa values for predictions using different intensities of the agriculture spline. Urban spline range = 1.41.



Land use 2006 Prediction, intensity = 0.25 Prediction, intensity = 0.20

Figure 34. Actual land use 2006 and predicted using intensity of 0.20 and 0.25 for the agriculture spline. The red circle shows an evolving cluster along the railway line. Urban spline range = 1.41

Figure 34 shows the prediction using different intensity in the agriculture spline. As can be seen, higher intensity leads to more independent growth (no connection to existing urban land). The size of the cluster is more similar in the central image. However, the shape is not similar. This is because the road did not have enough effect in this area. The same applies for the two clusters in the upper left part of the images. These are round instead of following another road from north to south.

The figure below shows the importance of studying the process when calibrating. Urban land is stretching out, following the road. At a point in time (2003) a small cluster starts growing a bit away from the main urban land. It starts growing, and becomes gets edges. After some time (2008) the shape of the cluster changes and becomes more round. Later the cluster merges with the main urban land and follows the railway line towards the northwest.

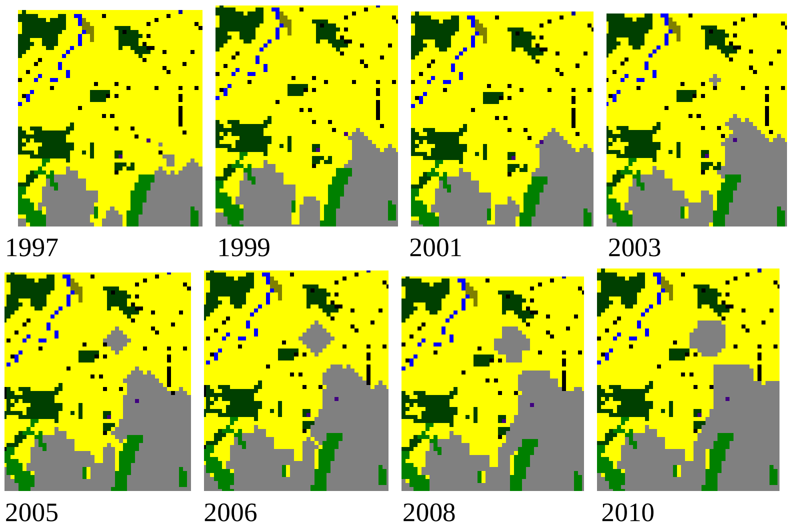


Figure 35. Growth of a cluster outside urban land. Urban spline range = 1.41.

With only an urban spline defined, the growth was compact and no clusters jumped out from the main land as shown in figure 35. This happened only when adding attraction to agriculture.

After fine-calibration it was decided to use a value of 0.23 for intensity in the agriculture spline (figure 36).

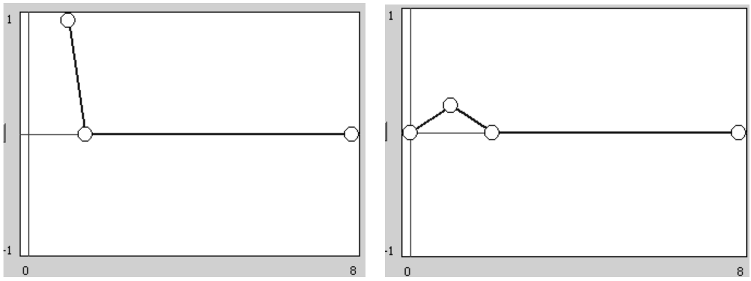


Figure 36. The splines as defined for urban (left) and agriculture (right) as used when modelling the scenarios**.**

3.3.2. Validation

The results from the prediction of 1997s and 2006s land use patterns can be seen below (37). The patterns were predicted starting with the land use of 1956 and applying the mentioned CA rules (figure 36).

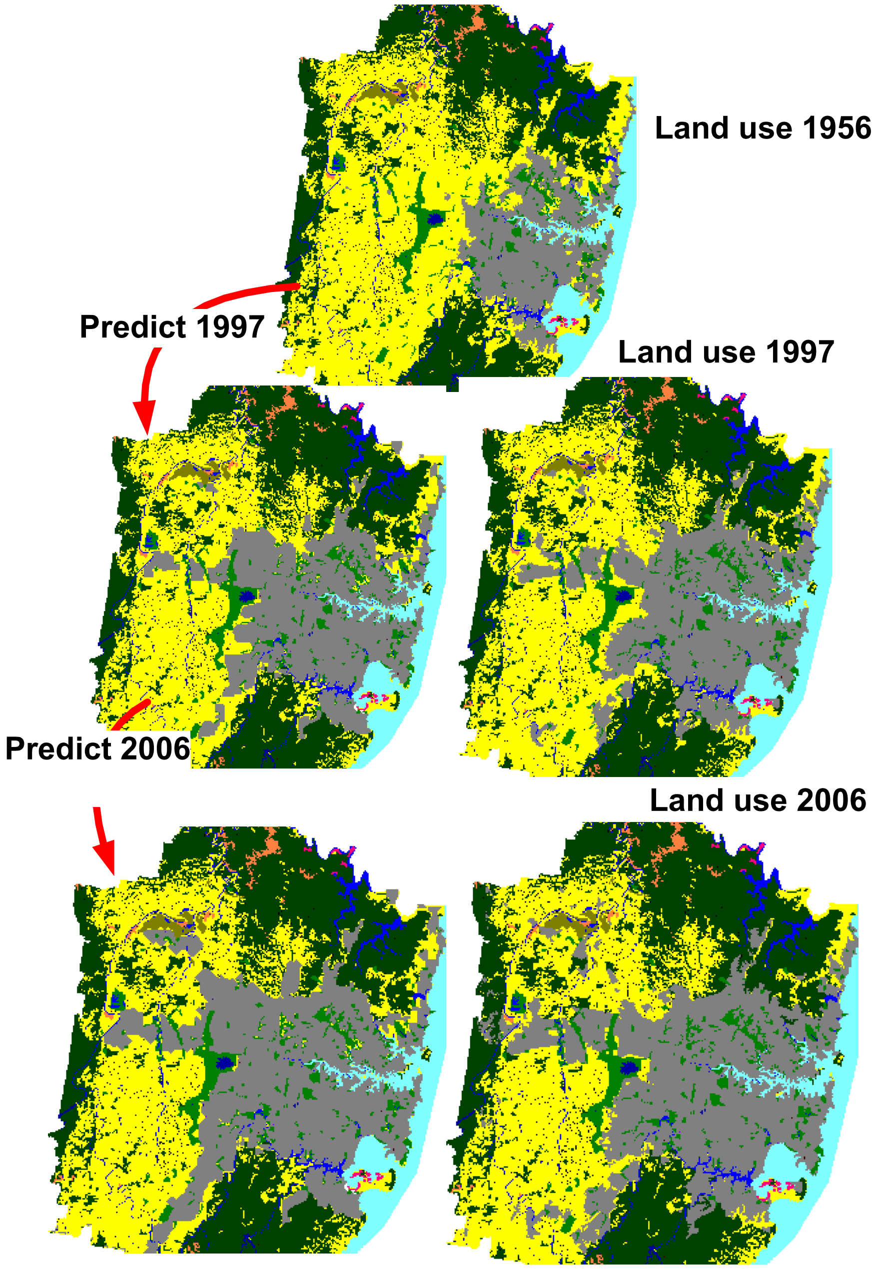


Figure 37. Prediction of the land use of 1997 and 2006, using the land use map of 1956. The actual land use map for corresponding year are shown to the right.

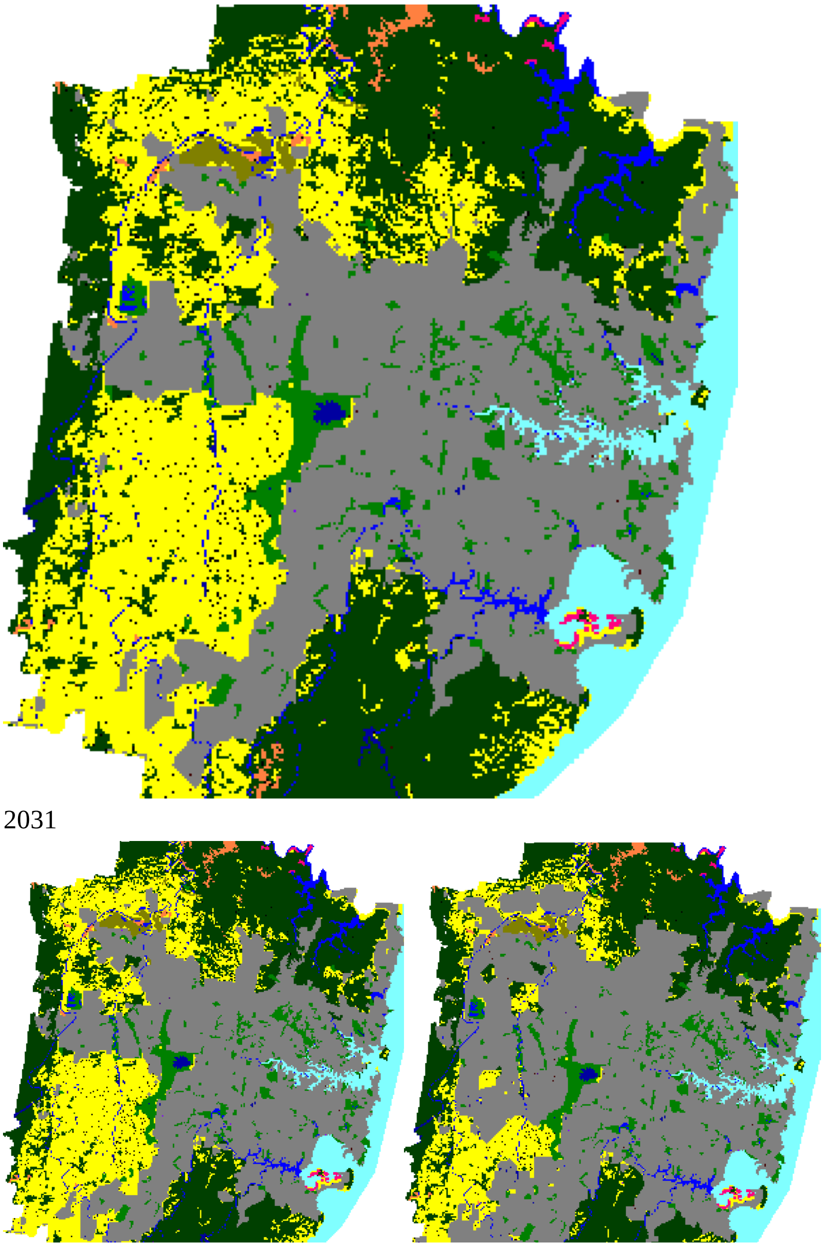
3.4. Results from the scenarios

The result of the growth following the Metropolitan scenario (figure 39) and the business-as-usual scenario (figure 38) are shown for the years 2031, 2051 and 2106.

As can be seen, the consequences of the business-as-usual scenario was extensive sprawl along the highways and railway lines. In the Metropolitan scenario, this was counteracted by allowing growth in the growth zones in the southwest and northwest.

The results from 2106 year’s prediction lead to a similar pattern for both scenarios. However, the Metropolitan scenario had more compact growth patterns than the zero-scenario, also at this time.

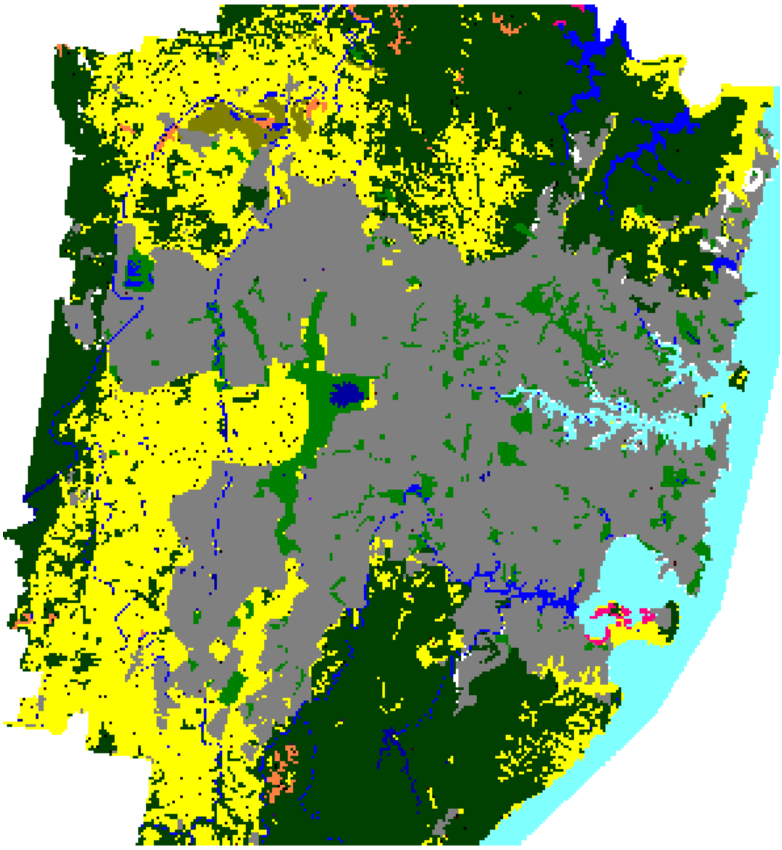
The expansion into the growth zones, in the Metropolitan strategy scenario, is far from natural. Instead of starting from the existing land, the urban land scatters within the zone, until it is full.



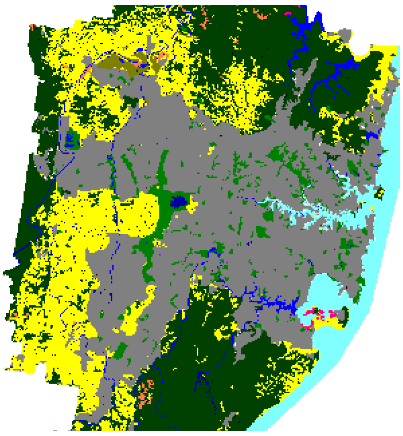
2031

2051 2106

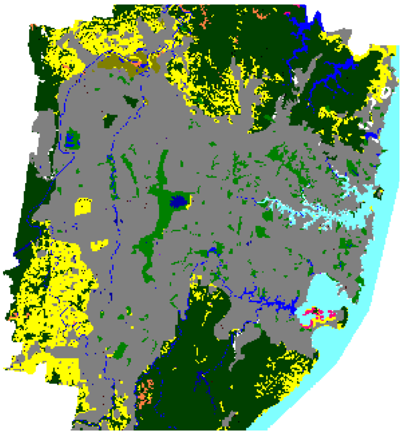
Figure 38. The business-as-usual scenario for the years of 2031, 2051 and 2106.



2031



2051



2106

Figure 39. The Metropolitan scenario for the years of 2031, 2051 and 2106.

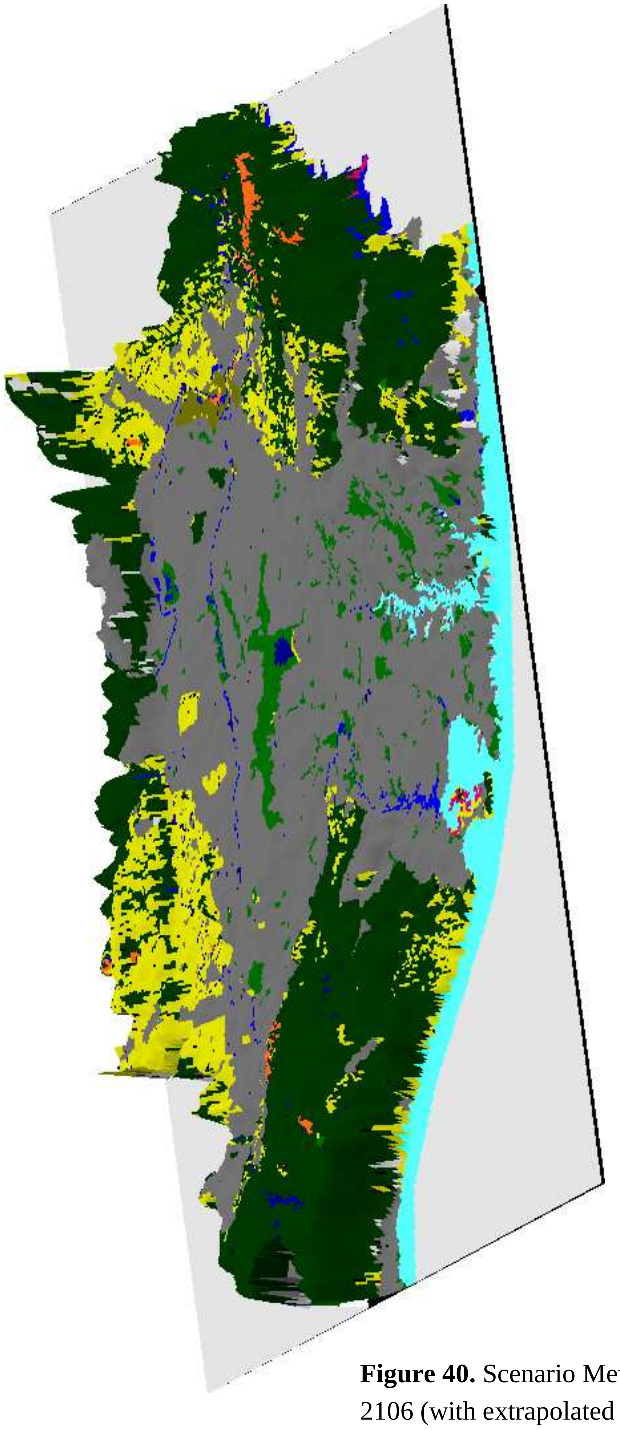


Figure 40. Scenario Metropolitan strategy 2106 (with extrapolated macro demand).

4. Discussion

4.1. The factors behind residential allocation

The results from the modelling confirm that urban has an attractive influence on new development. Cost and preferences from customers (in the case of residential urban land use) are the main reasons for this. The former can also be confirmed by examples where incentives have been used to limit the cost of infrastructure (e.g. roads, sewage, electricity, water pipes). This has enforced sprawl, because it makes it more profitable to build outside the fringe (Sheehan *et al.*, 2001).

The attraction towards agriculture is less obvious. It might be that agriculture itself is not the attraction, but rather the "quality of view" which is associated with open landscapes of agriculture. It is interesting that sprawl along roads is enforced when the attraction towards agriculture (or "quality of view") increases. This is realistic, since only accessibility by the means of car or train, can allow such living (Liu and Phinn, 2005).

From a modelling perspective, attraction towards agricultural both adds a pulling force, but also weakens the dependence of urban adjacency. Thereby it can allow satellite settlements to start.

In reality, the type of settlements which appear along roads are mostly commercial land use (Harvey and Clark, 1965). It is not likely that commercial land use depend upon "quality of view" as much as residential land use. The accessibility alone is an explanation good enough. Lower land values outside the city could possibly be a reason which could justify the attraction towards agriculture.

4.1.1. Fuzzy land use classes

This model did not take into consideration the different grades of urban land use. In reality, urban land use is not a distinct land use class, but rather includes a range of densities. This is particularly true in the urban fringe, where scattered, leap-frog patterns are common (Lessinger, 1962, Liu and Phinn, 2005).

For this reason, Liu and Phinn (Liu and Phinn, 2005) developed a land use model using “fuzzy” transition rules. These rules can handle different levels of urbanisation. A normal transition rule would define a change into urban when enough many urban cells are present in the neighbourhood. The fuzzy transition rule is based on the same rule, but the change only adds another step in the way towards a fully developed cells. Every step follows a logistic curve. A logistic curve is claimed to be more realistic in representing the urban development process, compared to conventional transition rules (Liu and Phinn, 2005).

4.2. Methods for creating the suitability map

4.2.1. Transport network influence

From the sampling it appeared that there is a strong relationship between distance to a link and the quantity of settlements.

There is one uncertainty. It is not known to what extent the urban-urban influence is present in the sampling. Once there is a seed (starting) settlement, new urban land is not increasing only because of the influence from the transport link. Existing urban land will also attract more urban land (figure 41). Thus, the influence from the accessibility graph might be exaggerated. Probably more further away from the road, since the seeds usually start where the accessibility is highest, which is near the road.

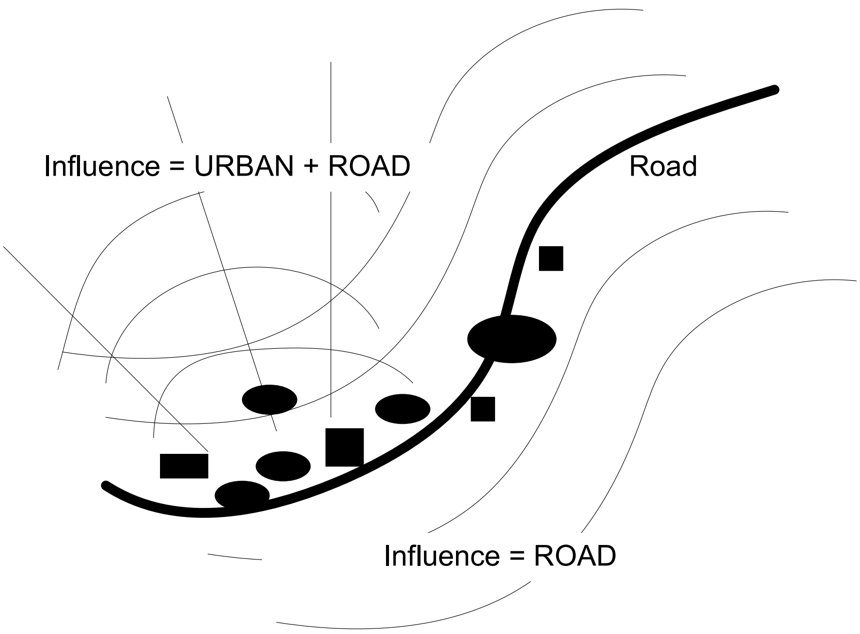


Figure 41. The road influence is “polluted” by existing urban settlements.

The second uncertainty, is that there might be an inverse relationship between settlements and transport links. That is, settlements which lead to the construction of a road. It is clear, however, that the transport links attract development along the western, north-western and south-western highway and railway. Since only new developments of 1997-2006 were sampled, this uncertainty was reduced.

4.2.2. Relative link influence

The method for finding the relative influence of the link type bears on the assumption that each link type is equally “saturated” with urban development. This means, that the accessibility is reflected in the urban patterns.

It was noticed that the trend in ratio between the buffer intervals was not consistent. The influence from main roads increased in relation to the highways and railway, as the distance increased. This could be explained by the effect previously discussed– the positive influence from urban land use on new developments. Since the influence from main roads is lower than for railways and highways, it means that the amount of land around main roads will be affected *relatively* more from the adjacency of urban land.

4.2.3. Slope

Deriving slope influence from the percentage of urban development is better than simply using the occurrence of land, as explained before.

Slope influence could possibly have been derived from interviews also. However, the results showed that different resolutions gave different maximum slopes. This means, if the maximum slope for development would be derived from interviews, it has to be adapted to the cell size which the model is using. From this point of view the mentioned statistical method is more suitable for deriving slope influence.

4.2.4. CBD

It was noticed that the CBD distance had an influence on limiting the growth of existing urban land outside the main urban land. Without a CBD the growth of these clusters was too quick. However, it is not easy to say what is a realistic CBD influence, in terms of intensity, intensity decay and range of influence. This was instead derived from trial-and-error.

A CBD influence is not congruent with a bottom-up approach. It would be more realistic to model, for example, the citizens dependence on distance to working places, shopping, leisure and so on. Such approaches are used in agent-based modelling (Torrens, 2001, Torrens, 2006).

4.2.5. Extraction of transition rules

The strength of data-driven methods for transition rule extraction is that they are congruent with the CA framework. The cell size of slope, for example, is defined with the same resolution as other data in the model.

When using interviews for extracting transition rules, the factors have to be quantified. More generally, it means that the conceptual model has to be translated to fit into the CA model.

The best alternative might be to combine data-driven and knowledge-driven approaches. The weaknesses of quantitative methods could be balanced by the strength of CA models, and vice versa. For example, interviews could be used get an understanding of the causes for allocation. These causes are then further derived using statistical analyses, trial-and-error methods and automatic calibration techniques. The found transition rule can then be validated against the perceived reality (e.g. interviews) according to figure 41.

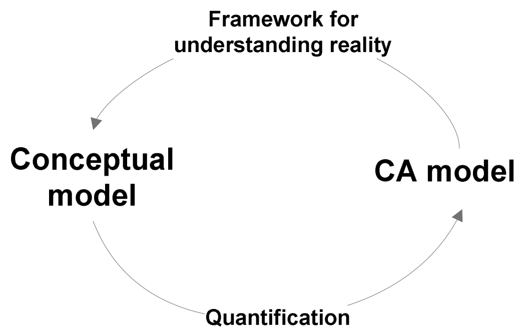


Figure 42. The relation between the CA model and the conceptual model.

4.3. Calibration

The most common methods for assessing maps are based on cell-by-cell comparisons, such as the fraction correct index. These methods are not fully appropriate when assessing outputs from CA models (White, 1998). A realistic prediction, assessed visually, could achieve bad values for kappa. This could be because urban forms are slightly displaced, for example.

Cell-by-cell comparison methods can also not assess the *processes* which lead to the patterns (Engelen *et al.*, 1997). Only measuring patterns means that one dimension is lost (figure 42).

Although, fuzzy kappa is not a strictly cell-by-cell based method it cannot capture patterns or processes good enough.

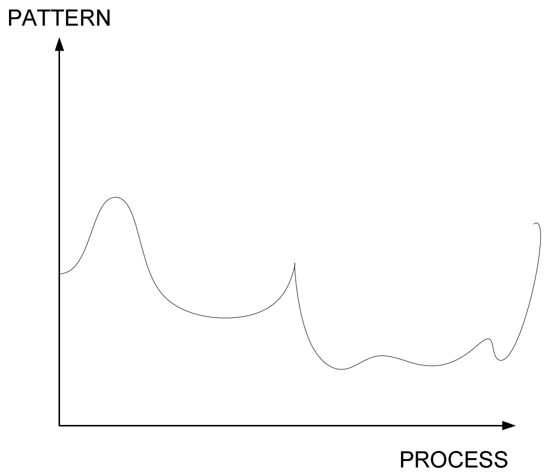


Figure 43. In calibration, pattern and process are two dimensions which have to be taken into consideration.

Automatic calibration also suffers from the problem of accuracy assessment. Calibration is dependent on a value for determining whether the settings (e.g. the spline) should be altered or not. Therefore, calibration without an acceptable way of measuring accuracy is pointless (Wu, 2002).

Assessment of performance is a problem for CA in general. White (White, 1998) suggests that the realism of CA is not limited by the models themselves, but of the methods for measuring realism.

4.3.1. Calibration results

The results indicated that it might be necessary to use longer intervals between the base map and the calibration map. The reason is that indications of fuzzy kappa could be low when comparing with the 1997 map, but high for the 2006 comparison. This might also be one reason for considering calibration towards many maps. Calibration towards many maps would also allow for better visual assessment of processes and patterns. When only a few maps are used it means that the trend in performance might not be captured (figure 43).

The results from the calibration confirms what was mentioned about static methods for assessing accuracy. They are not reliable for calibration. They might however, give an indication of performance which can be useful together with visual assessment. They could also be more useful when they are used with a short temporal distance.

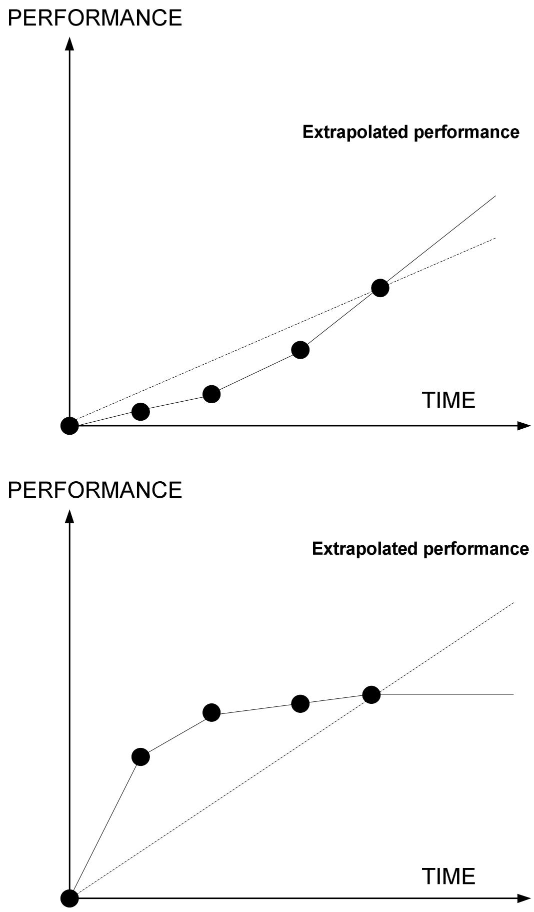


Figure 44
Extrapolation of performance based on two points could miss the trend in performance (dashed lines). When using many maps for comparison the trend can easier be seen (solid line).

4.4. Validation

It is often better to use a longer temporal distance between the base map and the latest map used for comparison. This is because the errors often increases with time. However, one should consider that longer modelling periods also means longer time for potential changes in the transition rules. For example, the dependence on the car have not always been the same (Sheehan *et al.*, 2001). This implies, the transportation network could have had a different importance, in different times.

The results from the prediction of recent land use patterns were, however, surprisingly good. Although some details were missing, the big patterns were captured fairly well. For example, it managed to capture the growth along the highways and railway and the local settlements in the northwest, outside the main urban land.

This could be a reason to think that the same accuracy is achievable 50 years into future. Unfortunately, an important reason for the good prediction is that the transportation network of 2007 was already present. Accessibility has been a quite important factor for the development in Sydney, particularly the latest 50 years (Liu and Phinn, 2005). This means, the prediction was made *ad hoc* – with some important knowledge about the future.

In reality, it is very hard to predict where and when new roads or railway lines will appear (White, 1998). Because accessibility is so influential on the urban patterns, it means that long-term predictions must always be *explorations* (Ittersum *et al.* 1998).

4.5. Unrealistic CA?

Cellular automata is often claimed to be realistic, particularly since it models from bottom-up. However, when applied on urban modelling, it is not unusual that the transition rules in CA are based on substitutes for real causes and effects. For example, the growth zones in Sydney are simulated by Liu & Phinn (2005) by faster growth inside than outside the growth zones.

The growth zones in this study, were based on similar approach as the one of Liu & Phinn. The growth zones were assigned a higher suitability. This means, the modeller is just telling the model where urban land should go.

The same applies for the attraction to the CBD or the regional centres. These are just areas with higher suitability, defined from top-down – *not* bottom-up.

Accessibility is mostly based on the distance to roads, with little consideration of how transportation is actually contributing to accessibility.

If applying these model on urban planning, the question should be – does it matter?

How complex is it required for the model to be to capture reality in a *satisfactory* way? The answer is of course depending on the purpose of the model. Thus, the question is, in what way the model is to be used.

4.6. Scenarios

"…simulation is clearly a tool which helps us not to know what will happen, but what can be made to happen" (Byrne, 1997:5)

Scenarios could make people think more creatively about future (Wollenberg *et al.*, 2000). For example, the scenarios created in this study could be used to visualise the consequences if the current growth continues 100 years into future. For this use, a perfect accuracy might not be necessary. The model is just a tool for conveying the big picture.

Ittersum *et al.* (1998:313) suggest that land use models could contribute in planning by handling the "science-driven" information. This means, creating scenarios from the information which is of a "technical" character (e.g. the neighbourhood interactions in a city). This is to be hold apart from value-driven *preferences* which are the subjective values in policy making.

This could also be seen in from the perspective of potential disagreements among stakeholdes (Mostert, 1998). Factual disagreements could be solved if stakeholders shared the same information.

Conflicting goals, however, could not be solved in the same way. These are "value-driven", to use the terminology of Ittersum *et al.* (1998:313).

Scenarios could contribute to a "operationalizing sustainable development" (Ittersum *et al.* 1998:312). This means, sustainable development which can involve all stakeholders, but still reach agreement (consensus) within the group – despite different *value-driven* goals (Ittersum *et al.*, 1998).

5. Conclusion and recommendations

5.1. Research question 1

The first research question of this study was: "How can neighbourhood interactions, and inherent constraining and enhancing factors for urban development, be extracted and related to actual changes in land use patterns?"

Four methods were identified and used for extracting the relevant factors for urban development:

- Interviews
- Literature review
- Regression analyses
- a trial-and-error method

It was found that the suitability of these methods differed depending on what was going to be extracted.

Interviews and literature review were identified as most suitable for finding the causes of urban development. However, their limitation lies in the quantification of the causes.

Regression analyses were identified as being most suitable for finding constraints in the form of intrinsic suitability. Distance dependent factors, such as accessibility, were also found possible to derive with regression analyses. Nevertheless, the accuracy could not be assessed, other than in the form of a model output, which makes this statement uncertain.

The trial-and-error method was found most effective for quantifying qualitative factors. It could potentially be used also for finding *causes* for development. However, the reliability is not so good and has to be confirmed by knowledge-driven methods. For example by interviews and literature review.

The framework for relating neighbourhood interactions and intrinsic factors was a CA model. The model could predict land use patterns from 50 years back, with a surprisingly good accuracy. However, the validation of this prediction was not reliable because of inherent suitability in the form of accessibility. Still it can be concluded that the simulation was successful within the scope of the modelling purpose – to relate extracted allocation factors to urban patterns.

5.2. Research question 2

The second research question was formulated as: "How can scenarios of planned and unplanned growth be created and used for evaluating policy options?"

It was found that the planned growth scenario could be created by changing the inherent suitability map. By adding more suitability in the growth zones, and around the regional centres, the growth was allocated mostly to these areas.

The unplanned scenario was used as a business-as-usual scenario. This means, no growth zones were delineated and only the existing intrinsic suitability map was used.

The results showed that the planned scenario had a more compact pattern than the unplanned scenario. The unplanned scenario lead to extensive sprawl along the main accessibility lines – to the west, southwest and the northwest of Sydney.

The validation gave promises of realistic simulation scenario simulations. However, this was only when taking into consideration the uncertainty of future road developments. It was assumed that the scenarios can give a general view of an optional future.

5.3. Recommendations for future research

Future research should study the techniques for finding the transition rules for CA. This is a crucial part of making CA more realistic. It is suggested that future research investigates a way of connecting data-driven methods with knowledge driven methods. The strong points of these methods can contribute for their respective weaknesses.

Another area of research, important for making CA more realistic, is to find new automatic calibration methods. Current methods are based on static measurements with no or little concern for spatial and temporal patterns.

A reliable automatic calibration method complemented with knowledge-based extraction methods, could make CA more widespread.

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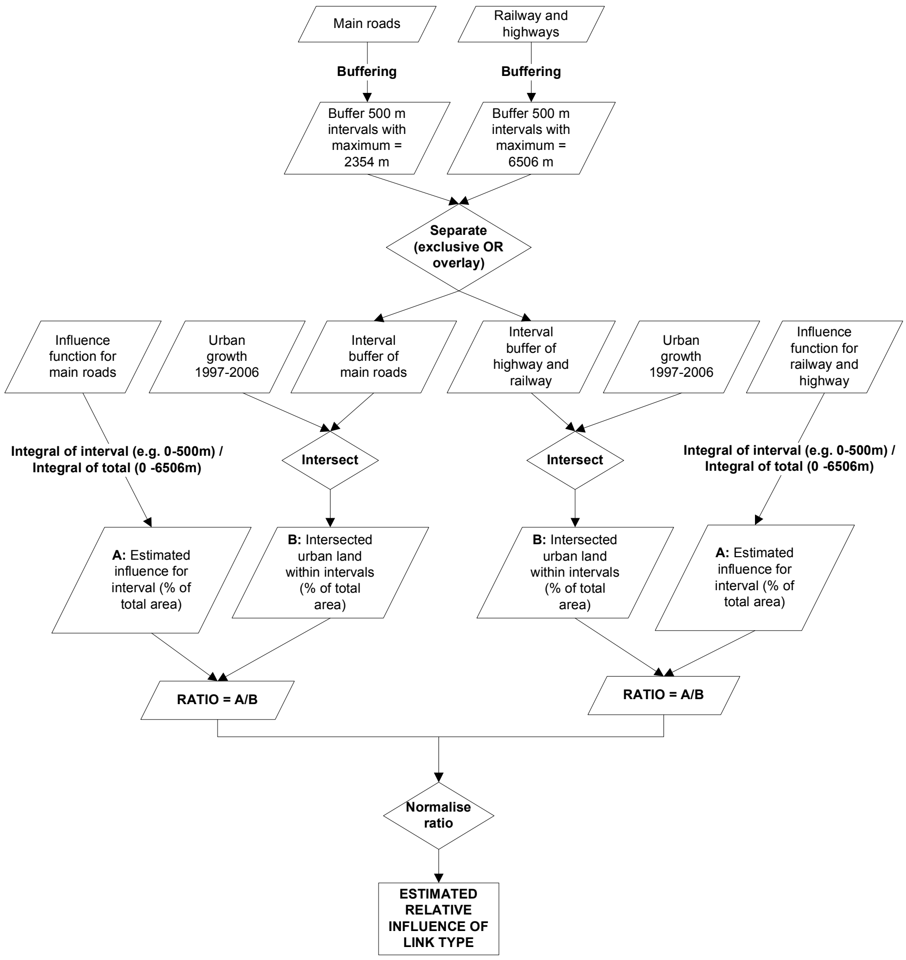
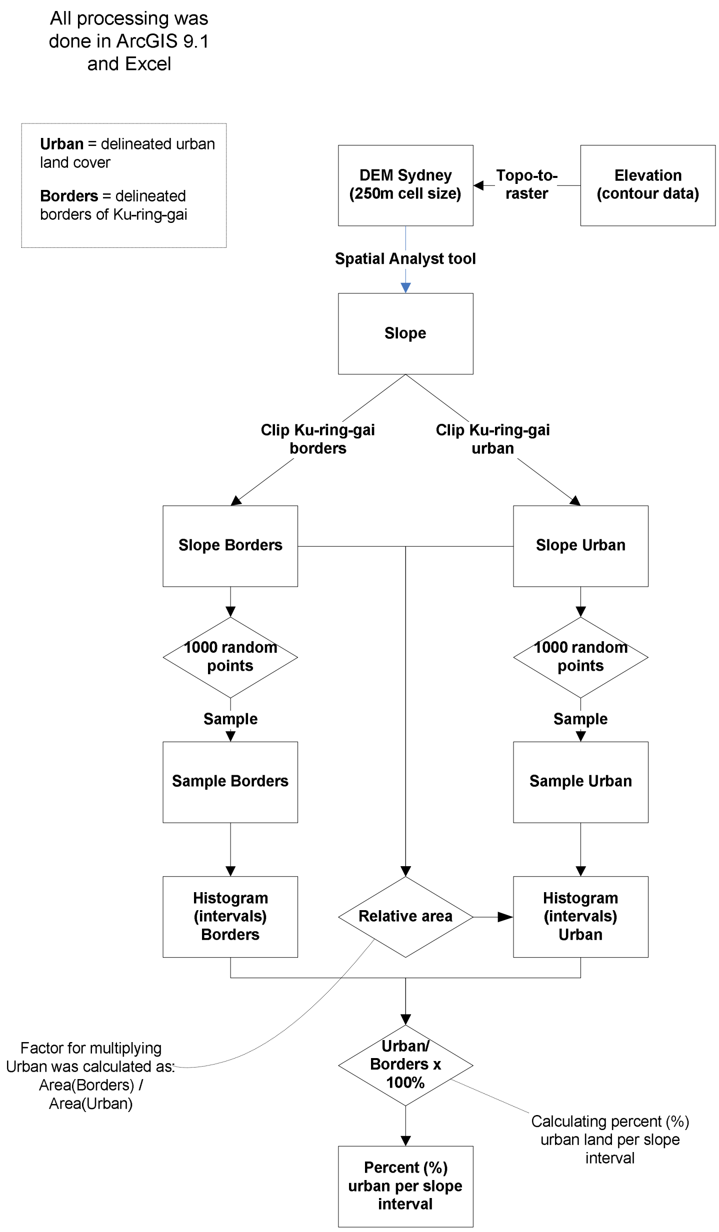
Appendices

Appendix 1.



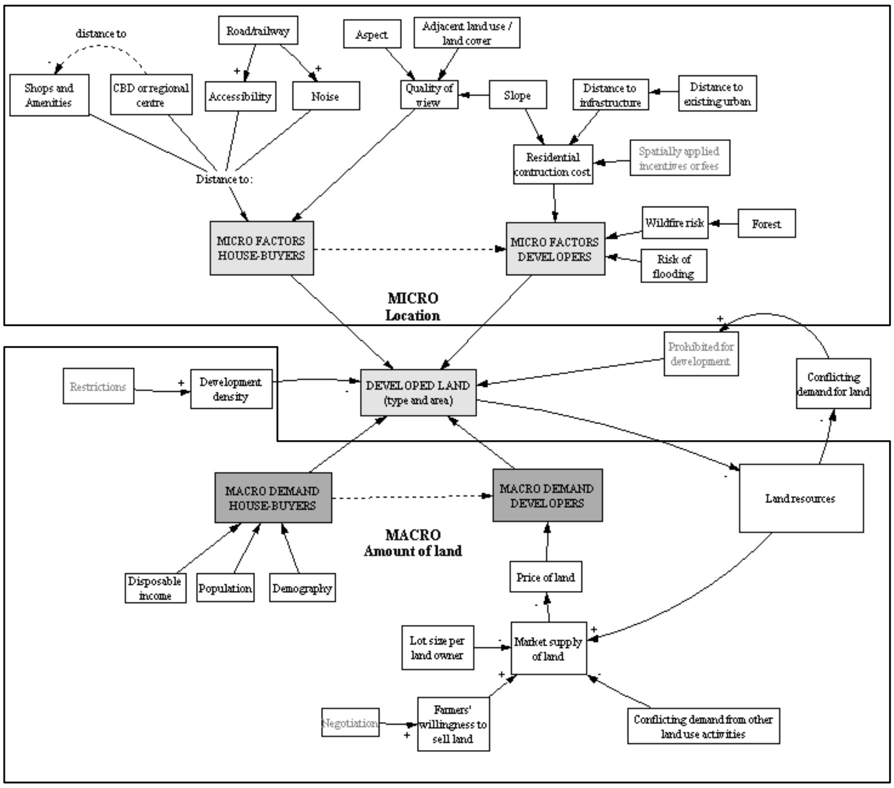
Appendix 2


All processing was done in ArcGIS 9.1 and Excel
Urban = delineated urban land cover
Borders = delineated borders of Ku-ring-gai
DEM Sydney (250m cell size)
Topo-to-raster
Elevation (contour data)
Spatial Analyst tool
Slope
Clip Ku-ring-gai borders
Clip Ku-ring-gai urban
Slope Borders
Slope Urban
1000 random points
1000 random points
Sample
Sample
Sample Borders
Sample Urban
Histogram (intervals) Borders
Relative area
Histogram (intervals) Urban
Factor for multiplying Urban was calculated as: Area(Borders) / Area(Urban)
Urban/ Borders x 100%
Calculating percent (%) urban land per slope interval
Percent (%) urban per slope interval

Appendix 3

	Urban spline range = 1.41		Urban spline range = 2	
Agriculture	**Fuzzy kappa 1996**	**Fuzzy kappa 2006**	**Fuzzy kappa 1997**	**Fuzzy kappa 2006**
0	0.92	0.881	0.923	0.879
0.1	0.918	0.879	0.919	0.876
0.2	0.916	0.877	0.919	0.88
0.3	0.916	0.87	0.917	0.88
0.4			0.917	0.881
0.5	0.911	0.857	0.917	0.868
0.6			0.915	0.858
0.7	0.909	0.852	0.913	0.855
0.8			0.912	0.855
0.9			0.911	0.856
1			0.912	0.856
1.5			0.908	0.842

Appendix 4


distance to
Shops and Amenities
CBD or regional centre
Road/railway
Accessibility
Noise
Aspect
Adjacent land use / land cover
Quality of view
Slope
Distance to infrastructure
Distance to existing urban
Residential contruction cost
Spatially applied incentives or fees
Distance to:
MICRO FACTORS HOUSE-BUYERS
MICRO FACTORS DEVELOPERS
Wildfire risk
Forest
Risk of flooding
MICRO Location
Prohibited for development
Conflicting demand for land
Restrictions
Development density
DEVELOPED LAND (type and area)
MACRO DEMAND HOUSE-BUYERS
MACRO DEMAND DEVELOPERS
Land resources
MACRO Amount of land
Disposable income
Population
Demography
Price of land
Lot size per land owner
Market supply of land
Negotiation
Farmers' willingness to sell land
Conflicting demand from other land use activities