# Improving Urban Growth Forecasting with Cellular Automata: a Case Study for Hervey Bay

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**Abstract:** This paper investigates approaches for predicting patterns of urban growth within land use planning scenarios. Planning scenarios for a coastal area in Australia use demographic (socio-economic) and land use (physical and environmental) to assess the impacts of growth. The paper describes two different approaches for defining the spatial pattern of growth: i) based upon a supply and demand for land uses, and ii) historical growth patterns modelled using cellular automata. Predicting patterns of growth is important in spatial planning to assess impacts of future growth pressure.

***Keywords:*** *Urban; Simulation; GIS; Cellular Automata; Modelling*

## 1. INTRODUCTION

The paper describes a method to predict future patterns of land use based upon influencing factors that operate at regional and landscape scales. Predictions are made within planning scenarios to allow users to place different values on their environment and to impose development controls. This offers new perspectives on land use planning in which professionals and the public alike explore planning alternatives through computer simulations and visual displays illustrating the consequences of their actions (Brail and Klosterman, 2001).

Previous work focused on urban growth issues for a coastal Queensland city and surrounding areas (approx. 2,340 km$^2$) comprising the Shire of Hervey Bay. See Figure 1. Hervey Bay is the gateway to North Fraser Island, which is a World Heritage listed area. Modelled land uses included: residential (4 classes of parkland, low, medium, and rural), industrial (2 classes of general and light), commercial (2 classes of retail-office and social infrastructure), preservation (open space, wetlands, etc), and local (shopping). Socio-economic characteristics of Hervey Bay include strong population growth, high levels of unemployment and an economy dependant upon the tourism industry and settlement driven by retirees. The city is experiencing classic signs of growth and decline; referred to as the attractiveness principle (Forester, 1975). The city attracts population due to a strong market in tourism and service provision, and its popularity due to its naturally attractive coastal shoreline. However, it is located regionally in an area that is experiencing decline in manufacturing and other industries so there is a large net movement of people to Hervey Bay. The inflowing workforce is not well suited to the specialist industries in Hervey Bay, and this is creating unemployment and other social problems. In addition, rapid settlement growth is generating concerns for the environment and maintaining the character of the area with its traditional rural setting.

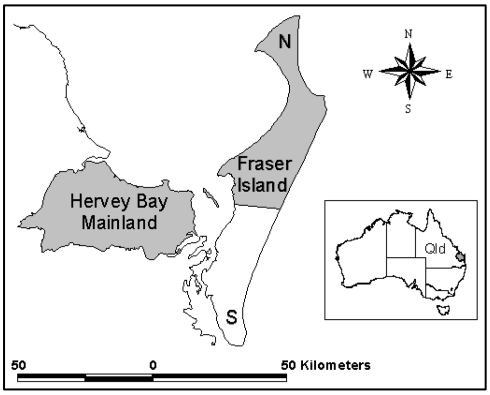


**Figure 1.** Shire of Hervey Bay Locality Diagram.

Three different urban growth scenarios were explored to understand land use dynamics for the area up to the year 2021 (Pettit et al., 2002). The three scenarios were: i) 'business as usual' based upon growth trends, ii) 'improved wealth' as indicated by land values, and iii) achieving an integrated set of objectives for 'sustainable development'. All three scenarios used the same socio-economic projections, but very different methods of analysis. The 'business as usual' scenario provided a good comparison to see what would happen if growth patterns followed the same planning regime. It analysed growth trends and applied these in a straightforward manner. The ‘improved wealth’ scenario aimed to define a preferred land use mix and to optimise this to maximise the land values (or rates base for the area). It included a large number of constraints in developing an optimised solution. The ‘sustainable development’ scenario provided a more comprehensive analysis of land suitability inclusive of the communities aspirations to find a balanced resolve between the environment and the well being of society. This is expressed in strategic plans and it is hoped that reformed land use planning will lead to progressive actions (UNEP, 1996). Model simulations predicted land use patterns up to the year 2021. The simulation results (Pettit et al., 2002) were then compared with policy objectives and planning goals to identify conflicts. The benefits of the study were in: i) demonstrating potential land use conflicts over time, ii) developing an explicit set of land use requirements from a wide range of policy documents and strategic goals, and iii) identifying possible environmental and social impacts.

One aspect of the analysis where improvement could be made was in the rules for allocating future land use growth. Assumptions made on how and where this growth occurred could not be readily validated. Growth rules describe the way urban expansion spreads out from city centres, propagates along roads, or springs up at new locations. It is important growth rules fit to constraints and opportunities afforded by existing settlements, transport corridors and landscape conditions. The best opportunity for estimating growth rules is from observed conditions and behaviour. The purpose of ongoing work is to:

i) improve the growth simulations with more comprehensive growth rules, and
ii) attune and validate these growth rules from historical land use data.

The outline for the paper is a follows. The next section reviews current research on land use growth models. Section three discusses a macro-level model for land use supply and demand, and a micro-level model to better describe spatial patterns of growth. Section four describes the implementation of the models in a modelling simulation framework. The complete model is decomposed as a coupled set of modules. Finally we conclude with a discussion of progress on the project with creation of datasets for Hervey Bay.

## 2. MODELLING BACKGROUND

There is a huge body of work on quantitative methods for forecasting and evaluating urban growth, land-use change and transportation land-use interactions. Comprehensive reviews and assessments of models include Wegener and Fürst (1999), and Brail and Klosterman (2001). A good conceptual framework for understanding models is presented in Figure 2 as macro-level and micro-level modelling.

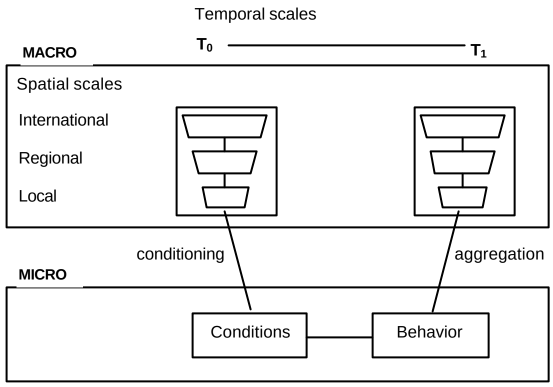


**Figure 2.** Conceptual framework for urban growth modelling (Source: Coleman, 1990).

Macro-level models are deterministic models to describe the way the world works based upon conceptualised or observed relationships for the behaviour of a system. No spatial analysis unit is assumed, although land use / transportation zones are the most commonly analysed spatial unit in planning and local government control (Wegener and Fürst, 1999). Micro-level modelling attempts to analyse patterns of land use change as the aggregate outcome of many disparate individual land use decisions across space. In this case space may be represented as networks or cellular automata (White and Egelen, 2000). The advantage of micro-level modelling is that it provides sufficient resolution to represent land use decisions (by agents or individuals) in terms of discrete choices of land usage and location selection (Schotten et al., 2001). The difficulty is that there are potentially an explosive number of actors and interactions needed to account for any land use decision. The inter-play between the two levels reveals an interesting and complex relationship: macro-level patterns emerge from micro-level processes and behaviours which are highly controlled by macro-level constraints.

Research on urban growth and land use change may be broadly divided on whether the purpose is to develop a better understanding of urban dynamics (Allen, 1997) or to provide better decision support for urban planning (Brail and Klosterman, 2001). Our focus is on the later, where model integration at a landscape scale is an active research topic. Integration covers the key components of an urban system such as land uses, transport, biophysical environment, ecosystems, and spatial economy (White and Engelen, 2000)

(Irwin and Geoghegan, 2001). The most promising models operate at a spatially explicit scale (at the fold of the macro-micro levels) to have sufficient resolution to model natural-human processes and to enable effective spatial planning.

Previous work focussed on developing urban growth scenarios for a rapidly expanding coastal town (see Sect. 3.1) using macro-level modelling at a local spatial scale. The ability to disaggregate regional socio-economic projections to a local spatial scale is important for evaluating and identifying land use conflicts between predicted growth and preferred land uses specified by regional policies and planning instruments. It was possible to validate overall associations between socio-economic indicators and land uses, but there was no rigorous way to assign land uses across space. Without historical data describing spatial patterns of growth we could only apply generic rules for allocating growth; namely by assigning land uses on the basis of suitability and proximity to urban centres and transport corridors. Obviously the spatial allocation of land uses has important implications for spatial planning and impact assessment. It is important to validate predictions on the amount and location of land use change. The next section will briefly review two urban growth models: a land use supply-demand model and a morphological growth model. The aim is to improve the spatial allocations for the former model with growth rules ascertained from the later model.

## 3. URBAN GROWTH MODELS

This section will review two models. The first is a macro-level model that uses socio-economic drivers and land use requirements to predict land use change. The second is a micro-level model that models spatial behaviour using cellular automata. A subsequent section will describe a modelling framework and work in progress to build an improved urban growth model using a combination of these models.

### 3.1. Supply-demand urban growth model

Supply and demand is a basic theory in economics. In land use modelling the area of land (in hectares) used for a particular land use serves as an appropriate currency for balancing supply and demand. Supply reflects the availability of land and its suitability for changing to a more valued land use, and demand reflects the needs for specified land uses.

With regard to supply, a lot of factors influence land needs and regulate its transformation. Based upon the principles of maximum utility one would expect that land uses can change from lower to higher market values. For instance, low intensity agriculture or under-utilised vacant land is vulnerable to change to residential land. The determination of future land use supply is the main distinguishing characteristic between the three scenarios for Hervey Bay; namely: i) ‘business as usual’ scenario based future supply on the appropriation of land use among existing sectors, ii) the ‘improved wealth’ scenario based future supply on achieving the maximum net market value of land within a broad set of constraints and conditions, and iii) the ‘sustainable development’ scenario based future supply on having desirable land uses to achieve goals for a sustainable future as defined by policy and strategic plans. A standard scoring procedure (Malczewski, 1999) is used to derive land use suitability. Most of this analysis is done in a GIS with geoprocessing and tabular operations.

The demand is largely controlled by regional trends as determined by economic models or transport-land use models. Our work used the results of economic analysis for long-term industry employment and population projections for a period of 20 years. Population and household projections were produced by the Queensland Department of Local Government and Planning (DLGP, 2001), and projected employment growth extrapolated from the Monash University forecasts (Centre of Policy Studies, 2002). A shift-share ratio is used to disaggregate employment forecasts to appropriate industry mixes within the study area (Pettit, 2003). These regional socio-economic figures are converted to land use areas defined by planning schemes (HBCC, 1996). A distinction is made between residential zones and employment zones in input data. Residential zones are derived from household projections on the basis of housing density, size of housing footprints, and infill percentage. The calculations allow sub-categories for different intensity land uses, i.e. low, medium and high. Employment zones for various land use categories are related to industry sectors by an associative table. Areas are derived from employment, workforce density, and infill percentage. Again, the calculations allow sub-categories for different intensity land uses, i.e. retail, office, etc. Land use conversion parameters are derived by relating present land uses to current regional economic demands. GIS proved to be a good geocomputational tool for this task.

As with economic theory, supply and demand are equalized. Land use modelling approaches to balance supply and demand include: i) equilibrium models in economic geography, or ii) discrete choice models (Schotten et al., 2001). We use the later where individual land uses are allocated based upon suitability (supply) to satisfy a land area objective (demand) and growth rules. Growth rules specify allowable land use transitions and preferred growth patterns such as intensifying city neighbourhoods, spreading at the urban-rural fringe or propagating along transport corridors. Growth rules ideally require historical data to derive growth estimates, but even then spatial growth patterns are complex and it is very difficult to discern simple explanatory rules. The allocation procedure used in Hervey Bay assigned land uses to the highest ranked scores and resolved: i) over demand by using land use transitions rules from lower valued land uses, i.e. undeveloped land to residential, and ii) deadlocks (areas with equal suitability scores) by using a growth rule pattern that said expansion is most likely to occur close to urban centres. Again GIS proved to be a suitable tool for performing these calculations.

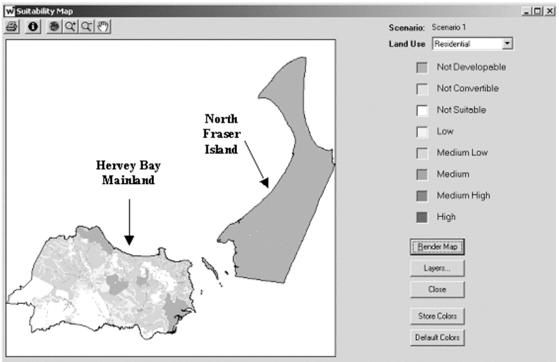


**Figure 3.** What if? Residential Land Suitability Map for Hervey Bay.

Two of the scenarios for Hervey Bay were programmed in ArcView GIS. The third scenario for 'sustainable development' used the 'What If?' program (Klosterman, 1999) as it provided support for setting suitability scores, computing land use conversions, and defining allocation procedures. Figure 3 shows an example screen shot from 'What If?' for setting land suitability maps. As a planning support tool, it also entertained a number of planning instruments in the model. For instance, minimum land parcel sizes set in accordance to planning schemes (HBCC, 1996), infrastructure plans relating to sewer, water and roads, and development controls that define permissible future development according to strategic plans.

### 3.2. Morphological urban growth model

Morphological growth models define urban change in terms of land use form and spatial structure. Land use is viewed almost in an organic sense where structural dependencies and interactions define growth patterns. Growth patterns are considered to be a mix of macro-level influences (economics, transport, communication, social, environmental, etc.) and micro-level influences (society and individual choice). The later is seen as being non-deterministic in nature, but spatial patterns of growth do emerge from the aggregate behaviour of human decisions and interactions (Allen, 1997). Observed patterns of land use change include: spreading, clustering, networks, and random dispersal. The main tool used for describing these patterns is cellular automata (CA). CA assumes a regular partitioning of space and program logic to define an output spatial pattern from simple rules matched to combinations of input spatial data. It is possible to build a rich scientific theory based upon discrete spatial structures and computations on cells (Wolfran, 2002).

To deal with the nondeterministic behaviour of urban spaces it is necessary to formulate some general growth rules and to customise the way they are applied. A good example of research in this area is the SLEUTH system (Clarke and Gaydos, 1998; Candau et al., 2002). SLEUTH models urban growth using four rules: spontaneous growth, spreading centres, edge growth, and road gravity growth. Coefficients control the effect of each rule, and these may be calibrated based upon observed growth patterns for a particular region. The data requirements include GIS layers for terrain characteristics, land use, excluded areas, and transport over several time periods. Land use change is modelled as a probability with various heuristics used to change land use for a cell or its neighbours. Land use change is forecast using a Monte Carlo simulation. SLEUTH has been applied in several case studies with many program improvements and data refinements over time.

The next section will describe an open modelling framework used to develop urban growth simulations. It is a very flexible environment for programming the above urban models.

## 4. WORK IN PROGRESS

Current work is focussed on improving the growth rules with validated coefficients in the model. Two key activities are being undertaken: i) application of SLEUTH to derive validated growth rules, and ii) implementation using a modelling framework to enable specification of custom rules.

The SLEUTH program requires historical GIS data layers for land use, slope, excluded areas, urban extent, transportation corridors, and hill shading. Historic data on land use is the most difficult to acquire, and typically requires mapping from remote sensed images. Complete Landsat TM/ETM image scenes have been acquired for the dates 1991, 1996, and 2001 over Hervey Bay. These are currently being mapped using photo-interpretation from the image scenes and auxiliary information from land zoning maps.

The model has been implemented in the SimuMap modelling framework (Pullar, 2003). SimuMap is a modular simulator that controls the scheduled execution of models, simulation timing, and data exchanges between modules. It has been developed to allow integration of different types of software components using Microsoft .NET architecture. Components are tools used to write modules. Currently SimuMap supports components for Excel, a GIS map algebra modelling language called MapScript (Pullar, 2001), and user interface controls programmed in Visual Studio. A visual programming interface is used to build a model in SimuMap.

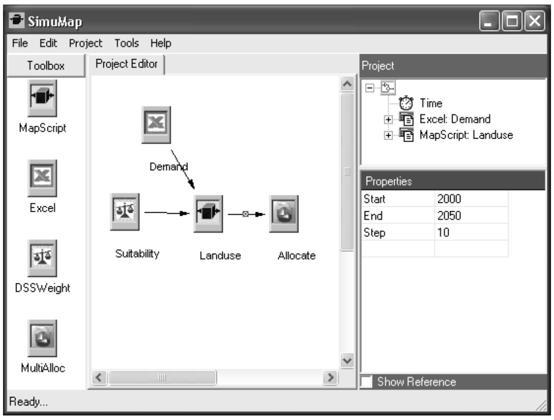


**Figure 5.** Visual programming interface for SimuMap.

A model (see Figure 5) is being developed for Hervey Bay from the following modules:

i) Suitability module implemented as a special user control component in Visual Studio. It computes the weighted linear combination (WLC) of several weighted criteria (GIS layers) with high scores indicating high suitability for a particular land use (see Figure 6 for example of user control to set factors and define weights)

ii) Demand modules implemented as an Excel component with spreadsheet data and calculations to convert economic figures to land use areas

iii) Land use module implemented in MapScript to integrate and rank the land use layers as a pre-processing step before allocation

iv) Allocation module implemented using the multi-objective allocation program in IDRISI GIS (Eastman, 1995) where each particular land use defines an objective and the allocation computes trade-offs based upon weightings and constraints on total land available.

Once growth rules have been obtained these will be added to the land use module and a more prescriptive allocation weighting will be used.

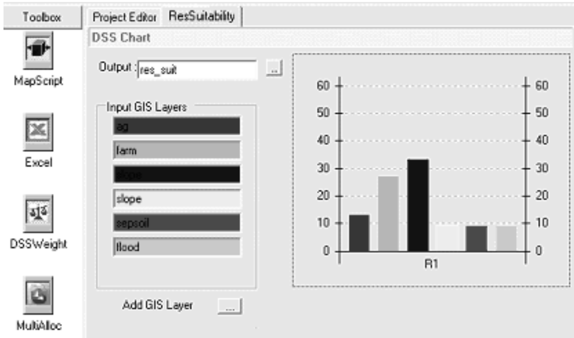


**Figure 6.** Suitability module implemented using a decision support weighting component.

## 5. CONCLUSIONS

The paper has described an urban growth case study for a coastal region facing rapid population growth and compounding environmental and social issues. Past work focused on land use scenarios that satisfied strategic policy options for improved local wealth and sustainable development. Results are published in Pettit et al. (2002). A challenge for that study was to show how regional socio-economic indicators on population and employment growth to the year 2021 could be evaluated in relation to land uses. The final result made predictions of future land uses taking into consideration the land use conditions and growth behaviours. Scenarios for land use maps up to the year 2021 were cross-tabulated with areas of land deemed as supporting future sustainable functions, and conflicts were identified Pettit et al., 2002). However in the course of the study assumptions were made on the nature of urban growth within the region. These assumptions could not be validated as it required further modelling of growth patterns based upon past conditions and growth behaviours. The final result identified land use conflicts spatially. Therefore, gaining a better understanding of factors that influence spatial growth patterns was important to improve the rigor of the final result. It was also important from a spatial planning perspective because it now opens the possibility to explore other options within scenarios. For instance, modifying human activities in relation to land use transport interactions (Wegener and

Furst, 2001) and natural values on land (Schotten et al., 2001) could be incorporated in a demand and supply model. Another important enhancement would be to use a time horizon of 50 years as part of a more complete systems analysis (Soroczynski, 2002).

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