THE USE OF A CELLULAR AUTOMATION LAND USE MODEL AS A TOOL FOR URBAN PLANNING

JOAQUIM MANUEL MOCITO AGOSTINHO

THE USE OF A CELLULAR AUTOMATON LAND USE MODEL AS A TOOL FOR URBAN PLANNING

by

© Joaquim Manuel Mocito Agostinho

A thesis submitted to the

School of Graduate Studies

in partial fulfilment of the

requirements for the degree of

Master of Arts

Department of Geography / School of Graduate Studies / Faculty of Arts

Memorial University of Newfoundland

November 2007

St. John's Newfoundland and Labrador

Abstract

A constrained Cellular Automata (CA) based model of the land use dynamics of Dublin, Ireland, is used as a platform to evaluate planning strategies at both metropolitan and regional scales. In particular, the New Urbanism movement advocates a variety of strategies from zoning to urban growth boundaries in order to reduce sprawl, increase densities, and encourage mixed use development. These strategies are implemented in the CA land use dynamics model and the resulting land use patterns are evaluated and compared with results in the absence of planning constraints, using spatial metrics such as Total Urban Edge and fractal dimensions. Some apparently powerful planning measures such as the imposition of an urban growth boundary are found to have a limited effect.

Acknowledgments

I'd like to thank, above all, Roger White for all his support and patience. I am also very grateful to the MOLAND project and Research Institute for Knowledge Systems (RIKS) for making the model available to me.; the Social Science and Humanities Research Council of Canada (SSHRC) for the financial support; Chris Sharpe for the inspiration to always ask the "So what?" question; all the loving staff in the Department of Geography at Memorial University, as well as all the graduate students from the class of 2001-2003 for the friendship and fun times. I also thank Clara Espírito Santo, for triggering the great Canadian adventure; my family for all the love and support; Alistair Bath and all the Bath family for making me feel at home; all my friends in Portugal for staying in touch; and . finally, Tânia and Daniela, who gave me the needed strength and motivation to finish the thesis. I would also like to dedicate this thesis to my dear grandfather - my hero.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

TOD – Transit-Oriented Development

CA – Cellular Automaton / Cellular Automata

UGB – Urban Growth Boundary

NU – New Urbanism

TE – Total Edge

PAFRAC – Perimeter-Area Fractal Measurement

MURBANDY – Monitoring Urban Dynamics

MOLAND – Monitoring Land Use Changes

List of Appendices

Chapter 1. Introduction

Increasingly, in urban regions land is too scarce a commodity to allow it to be taken up in unplanned growth. However, any action–or lack of it–to influence land use has significant consequences both for the people, businesses, and organizations in the area, and, more generally, for the urban morphology itself. Foreseeing the effectiveness as well as the indirect consequences of policies are two main focal points of planning studies. Tools capable of producing insights about the possible consequences of decisions made by planners are, hence, of some importance to planners. This thesis will demonstrate the value of a cellular automaton-based land use model as a tool for urban planning. The focus will be on the kinds of insights such a framework is capable of producing, and their usefulness to the urban planner in the creation of efficient land use plans.

Can modelling provide genuine insights into land use structure and behaviour? Can it help to identify potentially deleterious forms of urban growth? Can it be used to test alternative scenarios of growth and the efficiency of policies to control growth? These questions are tackled using a modelling framework working at two different spatial scales with Dublin, Ireland serving as the test location. The theoretical grounds for the creation of alternative scenarios are two of the three main New Urbanism proposals advanced by Peter Calthorpe (Calthorpe and Fulton 2001) – imposition of growth boundaries and the encouragement of transit. The third, mixed-use development was impossible to model at the resolution of the available land use data.

New Urbanism (NU) developed as a response to urban sprawl – characterized by low density and single-use developments with a high level of car dependency. NU is a planning trend that falls under the sustainable practices umbrella. Together with other planning trends, such as smart growth or sustainable development, its aim is to create liveable communities. This is accomplished by going back to a focus on the human scale as a factor in making new plans. New Urbanism has been around since the early 1980s, and has been mostly applied in the American context, the most famous example, from 1981, being the town of Seaside, Florida. It has, however, crossed borders, acquiring international scope with master planning in cities such as the Dutch city of Rotterdam and Sidoarjo, in Indonesia. The approach has been expanding since its creation, partially supported by the increasingly important concept of sustainability with which it shares some strong theoretical grounds. New Urbanism's proposed cure for the urban illness of sprawl is multi-dimensional. Rather than creating an entirely novel approach, the theoretical approach reworks existing concepts of place making instead. In a nutshell, it is based on walkability, transit encouragement, mixed-use activities and sensitivity to the aesthetic and comfort qualities.

The choice of using New Urbanism guidelines in this thesis is based on it being a fairly recent, and apparently growing, planning practice, with a highly proscriptive methodology. Not only is it easier to translate its guidelines into modeling parameters through the use of zoning maps, but also it allows for the testing of a planning practice with such traits. One would think that it would be difficult for a specific activity to locate somewhere else than on the spot for which it was planned. However, cities do share the characteristic of being dynamic entities, with self-organization capabilities. It is believed that such capabilities can be used as allies in diverting urban expansion towards a desired goal. The fully-fledged implementation of New Urbanism guidelines may generate an urban pattern wished by planners, but it may be working contrary to the organic development of the city. To prevent this, planning guidelines must be tested for their actual effects on the urban fabric. The ultimate test of such effectiveness is observed at its best in real cities. But can we afford to try out a strategy that could produce disastrous results? The answer to this problem is to test proposed planning policies in a virtual environment, which allows for the envisioning of alternate futures of growth and the generation of results which can be analyzed in terms of policy effectiveness before growth occurs.

All new planning theories, and most importantly, the current ones, should be targeted for such testing, including New Urbanism and other recent sustainable practices. The recent creation of workable and validated high-resolution land use models allows for the testing of such practices in a fast, affordable and safe way. In the particular case of New Urbanism, testing the implementation of its guidelines on a European city could help to assess its effectiveness in a different context than the one for which it was initially defined. Such an evaluation, however, rather than constituting a criticism of the NU practice, is intended to serve as a contribution to research on the topic by providing some insights from a cellular automata (CA) land use modeling perspective.

In this study the test area of Dublin, Ireland, is modelled at two different scales: at the regional scale, land use in the nine counties of the Dublin Area is modelled at a resolution of 200m ; while at the metropolitan scale, the Dublin urbanised area and a small peripheral area are modelled at 100m resolution. The metropolitan scale, with its finer resolution, will be used to investigate issues pertaining to changes in land use patterns and scattered, discontinuous development, or "leapfrogging". The effects of general preference for transit use and its effects on land use patterns are tested at the regional scale.

A baseline simulation - the "Business as Usual" scenario - is made for both scales. Here, the focus is on how the model is able to yield important information about the land use datasets by allowing the extraction of different types of measurements. After preliminary analysis, the effects of "leapfrogging" prevention are tested, at the metropolitan scale, through the creation of two different types of growth boundaries following Calthorpe's guidelines – the imposition of growth boundaries and the use of greenbelts. Two variants of the growth boundaries are tested, only differing in the amount of vacant land made available for the expected growth. The aim is to determine whether the constraint of growth via these planning instruments induces significant changes in the underlying structure of land use. The results indicate that not all the imposed constraints deliver the expected outcome.

Chapter 2. Related research

2.1. Why model?

Models, by definition, are "a simplification of some reality which involves distilling the essence of that reality to some lesser degree" (Batty and Torrens 2001). It follows that models can never portray reality exactly. So, why do we consistently create them? One of the reasons put forward is because "by studying idealized models and their implications we can sharpen our analytical tools and broaden our range of insights for real world applications" (Abler et al. 1971 p. 233). It is, thus, part of a parsimonious process towards a better understanding of the world we live in. But while keeping this main goal in sight, models can be used differently depending on their purpose. The case of urban modelling is no exception.

According to Simmonds (1986), "modelling may be descriptive, predictive, explorative, or normative" (Simmonds 1986 p. 76). Normative modelling is used as a means to find an optimum level for a given set of constraints. By focusing on the final result, normative models prove themselves useful for the production of "the best" solution to specific location problems. Their application is, however, somewhat limited as they disregard the actual processes of urban morphogenesis. This focus is used in the development of descriptive models and this is why the latter are used as the basis for explorative and predictive modelling. Explorative modelling is speculative, providing insights into other realities, and tends to produce theoretical models. Predictive modelling, on the other hand, aims for an integration of available understanding of the system by creating a solid test tool for "what if" scenarios. The kinds of models resulting from this approach are more pragmatic in their application and are known as operational models.

2.2. Early urban modelling efforts

Early models of urban systems, such as the ones devised by Von Thünen (1966), Christaller (1966), Lösch (1954) or Alonso (1964), fit into the group of descriptive models. They remained, however, as theoretical descriptions of the urban system. The resulting theories were static and timeless, reflecting the prevailing scientific thinking at that time, but were at odds with perceived reality. However, these theories of urban structure endured through time, being continuously replicated in textbooks, although planners never used them in their practice.

With the advent of computers a whole new dimension in model building opened up, allowing the field of science to go beyond human cognitive limitations. Models could now also work as an extension of the human mind, performing endless complex calculations. For planners and scholars of urban studies, this rush for technology greatly influenced early modeling efforts. At the same time, there was a growing awareness of the complex features of cities, expressed most notably in works such as Lynch (1960), Jacobs (1961), and Alexander (1965a, 1965b). This view acknowledged that cities were composed of multiple forces in constant interaction in a complex mesh of systems. This was, however, not seen as a problem, because the complexity of cities could now be understood through the use of these newly devised tools. Due to generalized post-World War II optimism, all efforts were oriented to the creation of computerized urban models hoping that this technology would reveal the truth behind urban complexity.

The most lively time in this early modelling period was, undoubtedly, the 1960s, when the climate of economic prosperity allowed large amounts of money to be allocated to the development of extremely ambitious computer-based models. Examples of early models include the Lowry model (1964), using a gravity model to predict activity locations; Chapin (1965); Chapin and Weiss' (1968) probabilistic models for residential growth, and Herbert and Stevens' (1960) attempt to model Alonso's (1964) theory of urban land markets. The focus was mainly on land use and transportation features of metropolitan areas, acknowledging their interrelation, and this was justified by the kind of urban growth characterizing the post-war period, which later came to be characterized as urban sprawl – car dependence and large tracts of single-use zoned land – which still persists today.

By the early 1970s, in spite of such a lively environment, modelling efforts seemed to end in failure, with Lee's requiem (1973) as the epitaph. Early models were caught in their own trap of attempting to replicate the behaviour of entire complex systems. The models were too complex to be useful to planners. And by being just computerized versions of pre-conceived urban systems theories, the results of models generated by Lee's "sins" of mechanistic wrong-headedness were often at odds with reality. They focused on refining the predictive accuracy of such theories rather than being used as innovative insightgenerative tools. So, once again models fell out of favour for planners, who regarded them as very cumbersome and resource-consuming tools for the perceived advantages.

Conversely, the interest in GIS as a good supportive tool for planning practice increased. GIS allowed the management of huge amounts of data, which were still being used as the basis for the creation of new plans, more quickly and effectively. But in spite of growing popularity, they were not predictive tools. The use of models to generate insights about the structures and dynamic processes of cities persisted, as well as the continued refinement of calibration procedures and modelling techniques. For modellers, hope lay in the fact that computer use was becoming commonplace in government agencies, and data systems were becoming more effective and more integrated (Wilson 1974). This allowed the parallel development of model-based planning systems, and, allied with the increasing interest in the academic field, would make modelling a worthwhile approach for the study of urban settlements.

2.3. Steady progress and new insights

As the field was becoming established, a significant number of publications started to appear as a reaction to Lee's article (Batty 1994). Along the way, problems were identified and addressed with the aim of making more integrated, workable and reliable models. Issues of time and process were deemed crucial, as the equilibrium approach did not seem to suit all the observed phenomena. Additionally, the "aggregation problem", acknowledging the difficulty of linking new insights about micro-scale phenomena to comprehensive theory, was also addressed (Wilson 1974). Practical issues of modelling techniques and calibration procedures were also addressed with dedicated monographs (e.g. Batty 1976), focusing on model building and calibration techniques.

Modelling efforts were reviewed a decade later, with Hutchinson and Batty's compilation (1986). This work recognized the main achievements of recent modelling efforts in the optimization of models towards a unification of predictive and prescriptive models. Unlike the status of the field in its early days, the main problem then became an abundance of theoretical work and a dearth of practical applications. In spite of Wilson's (1974) alarm about the use of existing urban models, a decade went by without an application of the models developed to practical case studies. Special attention started to be paid to dynamics and dynamicized versions of the static models, in the works of White (1977, 1978), Allen (1981) and Allen and Sanglier (1983) on dynamic central place theory, which acknowledged the importance of multi-agent behaviour and economic characteristics in shaping the form and structure of the central place system.

The exponential rate of technological advances allowed for the construction of better tools leading to new insights into the dynamics of complex systems. Simple deterministic systems, thought to be in equilibrium and thus fully predictable, showed in fact chaotic behaviour under certain conditions. Reality, in all of its facets, did not always show a linear progression of events but rather evolved to some points where, all of a sudden, drastic changes occurred. Examples of this include economic, social, and natural changes such as a stock market crash, the outbreak of war, or an avalanche. Moreover, the randomness so far considered by classical science as "noise" was found to be vital for successful evolutionary behaviour. These views of system dynamics evolved into the 1980s' theories of chaos and fractals, order, diversity, self-organization, spontaneity, evolution, cooperative behaviour, and increasing returns (Batty 1994) characterizing real world phenomena. Such discoveries then were used in urban systems theory (Wilson 1981) and the production of models. The framework that would grow to be the most efficient for modelling such complex behaviours to date had, however, already been created in the 1950s: cellular automata (CA).

2.4. Cellular automata

2.4.1. First CA: a generic framework

The first CA is attributed to the mathematician John Von Neumann, in the early 1950s, when he pursued the logic of self-reproducing machines. A generic CA is defined by:

(1) An *array* of cells, which interact with one another;

(2) A set of possible *states*;

(3) A *neighbourhood*, around each cell;

(4) A set of transition *rules*;

(5) *Discrete time steps*.

The *array* may assume many forms ranging from a 1-dimensional string of cells to a 2-D grid or a 3-D solid. The variable each cell can assume is called a *state*. This can be either a number or a property and may range from two states (e.g. on or off), to several ones (e.g. land uses, population densities, real estate prices). Each cell directly interacts with its counterparts constituting the cell's *neighbourhood*. In a grid these are normally the cells physically closest to the cell in question and their number may vary, according to the needs of the model. The way the cells interact among themselves is defined in the set of transition *rules*. *Time steps are discrete* and at each step each cell computes its new state from that of its close neighbours. Thus, at any given time we can assess the next state of each cell. A CA can also be a fully deterministic or a stochastic system. These features can be modified in order to better suit the model's use and still preserve its integrity.

2.4.2. Conway's Game of Life

CA enjoyed a boost in popularity twenty years later, with an article by Martin Gardner (1970) on Conway's Game of Life. John Conway used Von Neumann's framework to create a game capable of complex behaviour resulting from simple rules. Conway's Game of Life became famous by showing how a few simple deterministic rules could engender a surprisingly complex world displaying a wide assortment of interesting events and patterns, most of them bearing random-looking behaviours: indeed, a small universe comprising elements of life, birth, growth, evolution, and death. Although Conway did not seek out these behaviours, they were the inevitable result of the application of the rules. A myriad of objects started to appear, some being more natural than others, in a

Darwinian fashion (Poundstone and Wainwright 1985). CA challenged classical science by creating a different perspective about random events. Previously random seeming behaviours were now seen to be an unveiled order; and "chaotic" patterns, earlier thought of as "noise", could indeed be clouding the really important results. CA soon became a focus of interest in different fields of science, especially where modelling of spatial dynamics is of the most importance, establishing as important "conceptual and practical models of spatially-distributed dynamical systems" (Toffoli and Margolus 1987 p. 11).

2.4.3. CA applications to geography

The application of CA to geographical issues was pioneered by Tobler (1970) using a demonstration model of demographic growth in an attempt to provide intuitive insights about the dynamics of urban growth. He later formalized his definition of cellular geography (Tobler 1979) focusing on the creation of a generic geographical model for land use change. Tobler argues for a generic CA model composed of a homogeneous rectilinear cell space and ubiquitous transition rules. The contrast with real-world phenomena is, however, acknowledged where heterogeneous neighbourhoods and context-dependent transition rules may occur. The potential interest CA has for geographers is stressed by Couclelis (1985). She argues for the metaphoric use of CA for urban studies, contextualizing CA methodology in bifurcation theory, and for cognitive science modeling of individual decision and behaviour; and she addresses issues of complex spatial dynamics and chaotic behaviour and the formation of complex structures resulting from individual interactions through the use of CA frameworks (Couclelis 1988, Couclelis 1989). This work is followed by Phipps (Phipps 1989, 1992) focusing on neighbourhood properties, exploring their influence on the self-organizing and self-maintaining behaviour of patterns with critical values. The use of CA to explore general principles of self-organization was also developed by Portugali et al. (1997, 2000), and Portugali and Benenson (1995). Batty (1991) explored the morphological characteristics of urban settlements through the use of diffusion-limited aggregation (DLA) and dielectic breakdown models (DBM) and also suggested how cellular models could be used to simulate a wide variety of urban growth and form (Batty and Xie 1994).

The link from studies of artificial life and evolving systems to cities and urban systems is made by White et al (White and Engelen 1994), on urban and regional scales. They show how cities, in order to evolve, need to keep their inner structure in a delicate balance between order and chaos. Further research has been done on possible urban structures and possible urban forms which such structures are able to generate (Batty 1997) and on the dynamics of urban morphology (Benguigui et al. 2001). The recent morphological pattern of polynucleated urban landscapes has also been approached by Batty (2001) and Wu (1998a).

2.4.4. Advantages of the CA framework

The attractiveness of CA to model real-world phenomena is manifold, and is highly connected to their characteristics. They are simple, although not simplistic, and highly adaptable and intuitive in their making. They are capable of producing highly complex, realistic dynamics, with properties such as phase transitions, bifurcation points and fractal structures found only in continuous dynamic systems—merely through the effects of individual decisions. CA's capability of universal computation (Wolfram 1984) grants them the ability to virtually model any type of spatial dynamics. They are thus useful in the creation of experimental agent-based worlds, allowing for the testing of theoretical systems (Semboloni 1997), and creating a bridge between abstract theories and empirical tools (Portugali and Benenson 1995 p. 1664). By being intrinsically spatial, CA stand out as being particularly attractive to geographers and planners and can thus constitute powerful tools for spatial analysis and territorial planning.

2.4.5. CA and fractals

Another important feature of CA is the capability of generating fractal structures. Since Mandelbrot's early work (Mandelbrot 1967), fractal theory has been found to be applicable to several areas of study. Mandelbrot starts from nothing more than stating the obvious – that we do not live in a Euclidean world. However, we tend to measure the world with the simplified models Euclid devised more than a millennium ago. And although such simple geometry proves useful in day-to-day living for the majority of human needs, we still lack a gauge for a more knowledgeable study of real phenomena and things. Fractal theory provides the needed metrics for measuring irregular (*fractus*, in Latin) shapes. In short, fractals constitute a way to quantify complex patterns through a new set of measurements, allowing a more complete description of those patterns. Moreover, it has been found that all evolutionary systems display fractal properties, which means that fractal theory is applied at its best on the edge between "order and chaos" - the ever-changing boundary of biological and sociological systems.

The initial use of fractals for urban modelling aimed to develop models capable of generating fractal structures. Frankhauser (1988) was the first to suggest the application of fractals to the study of urban structures, using radial, grid and correlation fractal dimensions (Frankhauser and Sadler 1991) for the measurement of a number of cities on several continents (Frankhauser 1994). Batty and Longley's (1994) work focussed on area-perimeter relations and the fractility and complexity of the urban boundary. White used the radial dimension and cluster size frequency on real cities (White and Engelen 1993). The new fractal dimensions were used as additional parameters of a good fit in the calibration and validation processes of models. As the focus shifted to models capable of producing fractal structures, the interest in fractals faded. Nevertheless, the study of fractals unveiled a new dimension of urban structure and the use of fractal theory in conjunction with CA modelling has already produced new insights into the multifractility of cities and their evolution in time and space (Benguigui et al. 2000, Benguigui and Daoud 1991, White et al. 2001, White and Engelen 1993, White and Engelen 1994). It is believed that research in the area was dropped prematurely and that there is still more to be discovered (White et al. 2001).

The idea of using CA to pursue this research is based on the notion that a modelling laboratory to research urban morphogenetic properties can only be useful if it is capable of recreating the same fractility observed in real-world settlements. The CA framework stands out as the preferred tool not only because it is capable of doing so but also because this capability does not compromise its simplicity.

2.5. CA as predictive tools

2.5.1. Increasing realism

The use of classical CA has already produced important insights into urban dynamics. These insights are, however, of an abstract kind, and the inability to establish direct links to real-life processes of urban growth limited their use to a metaphoric one. In order for CA to evolve into predictive tools the degree of realism needed to be improved.

This improvement is accomplished in practice through the introduction of relaxations as a way to circumvent some of the limitations of classical CA and still preserve the properties of CA space. Homogeneous cell space, short-range neighbourhood effects and space- and time-invariant deterministic transition rules are some of the features of classic CA targeted for relaxation as they do not apply directly to real urban dynamics. The introduction of relaxations is, however, two pronged. If used too freely, they may compromise the formal integrity of the original CA framework as well as lead to Lee's trap of model complicatedness (Couclelis 1997) and at the same time divert the modelling efforts from their theoretical basis. Examples of successful CA with relaxed definitions include the work of Clarke et al. (1997), using non-stationary transition rules, and the constrained CA land use model of White et al. (1997), and White and Engelen (1994), working with inhomogeneous cell space, controlled cell demand and a partially randomized individual decision level.

CA integration with other systems has also proven fruitful. CA capabilities are enhanced and some limitations overcome when integrated with other systems that perform better in other areas. One example is the integration of CA and GIS, where CA's powerful modeling potential has been joined to GIS' data management and analysis capabilities. This linkage with GIS helped move CA-based urban and regional models from the realm of instructive metaphors to that of potentially useful qualitative forecasting tools (Couclelis 1997). This was possible because of the natural affinity with the data structures of raster GIS, allowing the use of processed GIS data as inputs to the CA model, and is also regarded as the best solution, considering the problems present when one approach replaces the other.

Integration thus provides "a mechanism to allow each component to perform those functions at which it excels" (Wagner 1997p. 229) and although the importance of CA integration with GIS has already been acknowledged with works such as Clarke and Gaydos' (1998) San Francisco and Washington/Baltimore models; Li and Yeh's (2001) model for zoning agricultural land; Wu's (1998) land conversion simulator; and Engelen et al. (1997) constrained urban CA. Other types of integrative modelling have also been tested. (Engelen et al. 1997, Engelen et al. 2002, White et al. 1997, White et al. 1999, White and Engelen 1993, White and Engelen 1997, White and Engelen 2000). A CA-based urban land use model integrates a CA structure with economic and demographic models. This integration allows the introduction of other forces akin to urban dynamics but operating at large-scale or non-spatial levels. This is the case for commerce, where commercial activity clusters in different areas of the city, competing for customers at the scale of the entire urban area; or for overall economic growth of the entire region, which will affect, in turn, the demand for each urban activity. The result is improved realism in the simulations and, hence, a more reliable set of results for the end-user, making it easier for the planner or urban scholar to quickly identify the immediate outcomes of urban morphological dynamics.

2.5.2. The limits of prediction

The fact that simulation results are becoming increasingly realistic does not mean, however, that we are capable of producing more accurate hard predictions. In fact, with the development of these new modeling techniques, new issues about their predictive capability begin to emerge in the modeling arena.

Batty and Torrens (2001) address some of the issues pertaining to the limits of prediction. One is the issue of complexity, which deals with the incapacity of complex systems models to comply with the principle of parsimony, or requisite variety. The richness of interrelations of complex systems hinders attempts to narrow down the explanation of the same phenomena with fewer intellectual constructs. In some cases of CA-like models, "there are so many assumptions about the representation of space and the nature of transition rules that are used to determine development that it is not possible to definitely use such a model to make predictions we can act upon" (Batty and Torrens 2001 p. 15). The issue of emergence turns up when it is taken into account that research on global order coming from local action, although understood, is still new, whereas "models that generate growth poles where none existed before are important in that although we might know the generic reasons for such growth, the precise conditions for their emergence may not be known" (Batty and Torrens 2001 p. 15). The quality of prediction is thus affected by such "precise conditions" remaining unknown.

The introduction of controlled amounts of random perturbations into the simulations helps modellers to increase the level of realism of model outputs but it also blurs the perception of the meaning of actual simulations when they can vary from run to run. In other words, there are no means to differentiate simulations from each other, thus making unviable the selection of a single limiting case. This is also a concern at the calibration and validation stages where a quantified measure for the degree of similarity of categorical map comparison is needed (Torrens and O'Sullivan 2001, White et al. 1997). Research on automated pattern recognition applied to map comparison is ongoing although still infant. Efforts are being made to devise a method capable of mimicking the human facility for pattern recognition and comparison, to provide a detailed assessment of similarity. Techniques based on fuzzy set theory have already been used for model calibration (see Hagen 2003).

The models' predictive capabilities may also differ depending on the temporal and spatial scales. Predictive accuracy decreases with an increase of resolution and time horizon.

Conversely, stronger forecasts are attained for shorter time periods at rougher resolution values. In short, the more we know about complex systems the more we are aware of their Popperian "openness" and that we cannot predict the future precisely. Modelling efforts have mirrored this notion in a way that the bases for model validation have also changed, with plausibility of results often favoured to the detriment of accurate results.

The idea of using models as crystal balls driven to a large extent by a blind faith in technology – is fading, giving way to a more moderate notion of models as tools with which to think and debate. Models are thus being developed to help planning, as scenario-generating tools, rather than as a failsafe basis for planning. This perspective is not new to land-use planners, who have been using scenarios as a means of depicting the future for decades (Xiang and Clarke 2003). What is new is that the observed future scenarios are not a direct product of the planner's assumptions of what implications the proposed policies will have, but rather the outcomes of dynamic play at the agent level – too complex to be calculated without tools. If a valid model is used, unpredictable events are more likely to appear and hence, to contribute, to debates about the effectiveness of planning policies.

Planning practice itself also faces the hindrances of uncertainty. Rather than being simply a problem with data, uncertainty is regarded as "an inherent characteristic of the decision making process itself" (Eastman 2001 p. 1). This is also expressed by the fact that, in planning, there are no optimal solutions, but rather more or less satisfactory answers. The answers are more realistic when the model's incapacity for embracing to the fullest the uncountable dimensions of a specific problem is acknowledged. A more enlightened group of users, aware that uncertainty needs to be understood and accommodated, has emerged, engaging in policy discussions using qualitative forms of modelling which are slowly permeating into the development of Decision Support Systems (see e.g. Engelen et al. 1997). The CA model used in the current thesis is an example of recent efforts to apply new theoretical insights and technological advances to improve the efficiency of these types of systems.

2.6. New Urbanism

In the last twenty years, the field of urban planning theory has seen the emergence of new planning ideas as a reaction to post-World War II suburbia with the development of a counter-proposal for the design of better neighbourhoods and communities. Most of the criticism is directed towards low density and single use zoning as well as a car oriented street network as the main factors responsible for problems cities face everywhere such as "increasing traffic congestion and worsening air pollution, the continuing loss of open space, the need for costly improvements to roads and public services, the inequitable distribution of economic resources, and the loss of a sense of community" (Corbett and Velasquez 1994). This set of ideas was given the name of New Urbanism (NU), and is also known as "neotraditional town planning" or "traditional neighbourhood design". The proposal was formalized in a document known as the "Ahwahnee Principles" which set out the movement's directives. The document was named after the lodge in Yosemite National Park where leading neotraditionalists met in 1991. Among them Andres Duany, Elizabeth Plater-Zyberk and Peter Calthorpe are the most notable practitioners. Their projects— Seaside (Florida) and Kentlands (Maryland) by Duany and Plater-Zyberk, and Laguna West (Sacramento) by Calthorpe—although attacked by many critics, still prevail as good examples of the new doctrine in practice.

The rise of New Urbanism follows a cultural evolution (Talen 2005). Many of Jacobs' (1961) critical points were transformed into a list of principles that should guide planning practice. The new doctrine is also heavily influenced by the previous movements of City Beautiful and Garden Cities. It claims, however, an up-to-date reinterpretation of early 20^{th} century planning, rather than just being nostalgic. It is above all, "about the way we conceive a community and how we form a region" (Katz et al. 1994 p. xvi) In short, according to the Ahwahnee document "all planning should be in the form of complete and integrated communities containing housing, shops, work places, schools, parks and civic facilities essential to the daily life of the residents" (Corbett and Velasquez 1994). It follows that such activities should be located within easy walking distance from each other and transit stops. At a regional scale, land use planning should be integrated within a larger transportation network built around transit rather than freeways, and regional institutions and services should be located in the urban core. Environmental concerns are represented with the creation of continuous greenbelt/wildlife corridors to be determined by natural conditions, and the reduction of car-dependency with the encouragement of pedestrian and bicycle use by street and connecting-paths design.

In 1993, the Congress for the New Urbanism (CNU) was created to actively promote neotraditional ideals. Since then CNU has sponsored annual Congresses, providing CNU's diverse members the opportunity to converse and to teach one another how to develop better cities and towns. Each of the first three Congresses focused on the principles expressed in the Ahwahnee document with respect to a specific scale of action. The principles for working on each of these scales were then compiled into the Charter of the New Urbanism, the defining document of the NU movement (CNU 1998). The movement has flourished in the past decade. While at the beginning the advocates of NU were a handful of architects and other design professionals, today at least 2,300 members, from various fields of expertise in 20 countries and 49 states, are registered in the CNU database (2002a).

Most of the movement's successful developments, such as the Walt Disney's Co. community of Celebration, have been counter-proposals to standard urban design. Opened in 1994, Celebration heavily promoted the new urbanist principles, showing how certain values defended by the NU ideology are, in fact, marketable, such as high density residential areas and mixed use projects. Defying standard practice in many aspects, Celebration generated one of the most heated discussions around NU. It has, nevertheless, and despite some criticism, proven that people are sometimes willing to relinquish some private gain in favour of more interesting and usable public spaces.

As the millennium ended, however, a second generation of new urbanists started applying the principles of traditional town planning to a wider range of projects – including ones in the inner city and third-world countries (Dunlop 1997). Rather than creating the "ideal new urbanist town" from scratch, recent interventions dealt mostly with fixing places that went wrong. One of the main advantages for this second wave of professionals is that they could "afford to be less rigid, less reflective and more pragmatic" (Correa in Dunlop 1997) than the founders of the movement, who had to be the standard-bearers. Thus, the focus became suburban development and infill development as strategies to prevent disinvestments and sprawl, and to promote equity and affordable housing (Harmon 2002).

Other critics of NU point out that this kind of success is, however, limited to suburban development itself. Although a broader scale of action is present in the new urbanist principles, little or nothing has been proved about its effectiveness in a regional context. On this aspect of NU, Peter Calthorpe has been leading the way. His books, *The Next American Metropolis* (Calthorpe 1993) and *The Regional City* (Calthorpe and Fulton 2001) present guidelines within which regional urban development should take place. In the latter, the cities of Portland, Seattle and Salt Lake City are analysed in terms of their success and failure when using NU guidelines to steer future growth. Nonetheless, although presenting an encouraging view for a new model of metropolitan development as an alternative to the post-World War II suburbs, the proposed framework is still looked upon with a certain scepticism (Wheeler 2001). The fact is that New Urbanism is growing in importance. As public policies and as both civil and governmental bodies at all scales start to question the kind of cities post-modernist planning principles yielded, New Urbanism begins to become adopted and looked at as a possible alternative.

Societal needs and ideological and technological evolution have always stood as pillars of new planning movements. NU should not be considered an exception. Although it reclaims older values from before the modernist movement, recent discoveries about the functioning of human systems and tools which have been developed and made available for the new urbanist should also be taken into consideration . Furthermore, because NU is still a new practice, it is thought that much more is yet to be uncovered about its real effects on the morphology of cities. The evolution of NU practice should be followed closely in terms of its effectiveness from several different perspectives, especially in its early years and experiments, before there is hasty acceptance of NU as the dominant way of doing planning. The present thesis proposal provides one possible perspective in the evaluation of NU. This evaluation, rather than constituting a full-fledged criticism of the NU practice, is intended to serve as a contribution to research on the topic of smart growth, by providing some insights from a CA land use modeling perspective.

Chapter 3. The modelling framework

3.1. The MOLAND project

The model used in the current thesis is defined as a constrained CA-based land use model. It is an improved version of the ongoing research by White et al. (1997), White and Engelen (1993, 1994, 1997) on the development of land-use CA, and is one of the components of the European project MOLAND. The MOLAND project is being carried out at the Institute for Environment and Sustainability of the Joint Research Center (JRC) of the European Commission with the aim of providing a spatial planning tool that can be used for assessing, monitoring and modeling the development of urban and regional environments (2002b). This tool is intended to support the preparation, definition and implementation of European Union (EU) policies and legislation (2002b). MOLAND is strongly connected to the European Spatial Development Perspective (ESDP), because it adopted ESDP guidelines in its development strategy, and currently is the "only project able to immediately provide the basic tools needed to implement the ESDP at urban and regional scales at the appropriate administrative levels" (2002b), presenting a methodology capable of assisting in the development of planning policies by providing the means to monitor, understand and evaluate the spatial dimension of their applicability.

The development of these kinds of tools is contextualized with the maturation of a holistic view of an environment composed of a mixed interactive landscape made up of built and natural features. In order to assure a kind of "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development 1987:43), a series of sustainability policies for urban and regional development is needed. The spatial dimension of sustainability policies is formally acknowledged with the creation of the European Spatial Development Perspective (ESDP) the aim of which is to work towards a balanced and sustainable development of the territory of the European Union (European Commission 1999).

The project initially started as MURBANDY (Monitoring Urban Dynamics) launched by the Centre for Earth Observation (CEO) programme in 1998 to provide a "measure of the extent of urban areas, as well as of their progress towards sustainability, through the creation of land use databases for various cities" (Lavalle et al. 2002:32), but its success justified an extension of its scope and areas of study. The project was hence integrated into the MOLAND project now comprising 25 areas of study. Results acknowledging the regional component of metropolitan growth led to an enlargement of the scale of study so that a wider area could be embraced. The contribution of MURBANDY to the MOLAND project is that its framework provides much more detail about urban land uses by extending the standard CORINE land use classification.

The project is structured into three interlinked components. The CHANGE component deals with the creation of a reference land use database of urban and peri-urban areas over a period of approximately 40 years for the areas of study. UNDERSTAND focuses on the development of a number of urban and environmental indicators that make clear the observed dynamics and environmental impact of urban land uses. FORECAST is dedicated to developing scenarios of sustainable urban and regional development using socio-economic and spatial data. The scenarios are carried out using a computerized dynamic urban model – a constrained CA-based land use model.

3.2. Description of the CA Dublin model

The model in question is an adaptation of previous models of urban and regional systems (Engelen et al. 1997, White et al. 1997, White and Engelen 1997, 2000), adapted to reproduce the observed dynamics of the region of Dublin, Ireland, and can be defined as a constrained CA-based land use model. Two versions of the model are used, one operating at the metropolitan level and the other comprising the Greater Dublin Area, which includes the surrounding counties. What follows is a description of both versions, based on Engelen et al. (2002).

3.2.1. The metropolitan model

The modelling framework is composed of two interlinked sub-models operating at different geographical scales. Macroscale dynamics are determined by the use of a cell demand file for the entire area. Contrary to the generic CA framework, growth is determined exogenously to the cellular model, representing the land use needs related to the rate of urban expansion and governmentally imposed growth constraints. Other methods could have been used to determine growth demands (e.g. White and Engelen

1997, White and Engelen 2000) but added complexity would not necessarily yield better overall results for the metropolitan area at the present cellular resolution (Engelen et al. 2002). Microscale spatial interactions are modeled using the potentialities of the CA framework.

3.2.1.1. *The cell space*

The cellular space is defined by a rectilinear grid of cells 100m on the side, with 348 rows by 343 columns. The use of this resolution is tied to the resolution of the source land use datasets for the modeled area (Engelen et al. 2002). In this case, an increase in the level of detail would not necessarily increase the quality of the predictions (Engelen et al. 2002 Part I, pgs 5 & 6). Out of a total of 119364 cells, 69165 are within the modelled area, which is the area of investigation as defined by the MURBANDY project.

"The area of investigation was selected on the basis of the contiguous artificial surface – core area – of the city centers, plus a periurban buffer zone. The former usually corresponds to the 'artificial surface' class of the Corine land cover map and equals an area (A). The buffer zone was calculated as follows:

Buffer zone width = $0.25 \times \sqrt{A}$

This extends the area by approximately double the basic core area" (Lavalle et al. 2002 p. 41).

3.2.1.2. Neighbourhood

Each cell reacts to a nearby neighbourhood defined as the circular region around the cell out to a radius of 8 cells. A neighbourhood of 196 cells is thus used, accounting for a radius of 800m. This distance delimits an area that is similar to what residents and entrepreneurs commonly perceive to be their neighbourhood. For each land-use function, the transition rule is a weighted sum of distance functions calculated relative to all other land use functions and features. Attractive and repulsive forces are generated between land uses which will in turn be reflected in the resulting patterns (Figure 1).

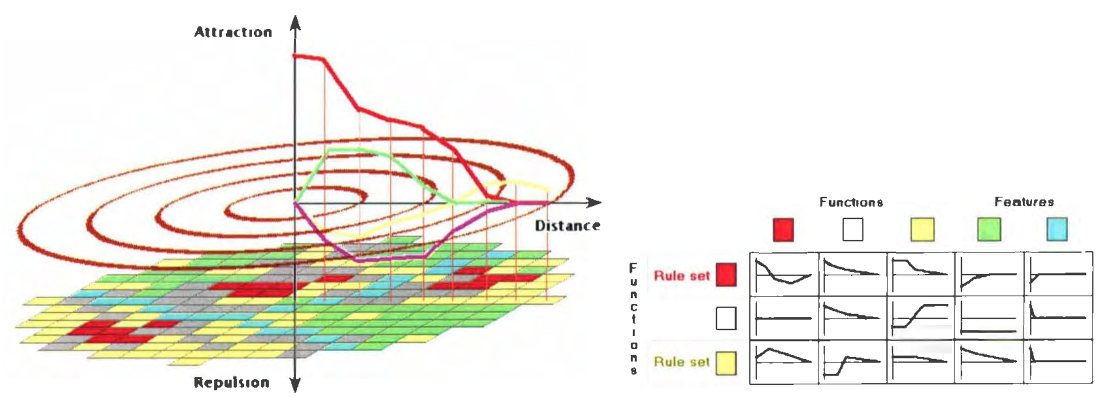


Figure 1 Circular neighbourhood with a radius of 8 cells (left). For each function, the transition rule is a weighted sum of distance functions calculated relative to all other land use functions and features (right) (in Engelen et al. 2002).

3.2.1.3. *Cell states*

At each iteration, each cell can assume one of a set of different states expressing the dominant land-use for that cell. An extended version of the Corine land cover legend is used to define the different states each cell can assume. For modelling purposes, a distinction is made between dynamic and static states. These are called land-use functions and land use features, respectively. While land use functions represent the states to which cells can be converted throughout the simulation, land use features are unresponsive to the micro-dynamics at play. They will, however, influence to some extent the location of land use functions. Also within the category of land use functions, some can be considered as "passive" functions since their number varies in response to the land being taken by the "active" functions.

Table 1 Land use functions and land use features used in the metropolitan version of the model.

Land use functions		**Land use features**
Active Functions	*Passive Functions*	
Residential continuous dense urban fabric	Arable land	Road and rail networks and associated land
Residential continuous medium dense urban fabric	Permanent crops	Airport
Residential discontinuous urban fabric	Pastures	Mineral extraction sites
Residential discontinuous sparse urban fabric	Heterogeneous agricultural areas	Dump sites
Industrial areas	Forests	Artificial non-agricultural vegetated areas
Commercial areas	Shrub and/or herbaceous vegetation associations	Water bodies

Public and private services	Sparsely vegetated areas	Outside metropolitan area
Port areas	Wetlands	
	Construction sites	
	Abandoned area	

3.2.1.4. Neighbourhood effect

The effect of the surrounding neighbourhood is applied simultaneously to every cell and varies with a distance-decay relation. The closer the neighbourhood cell is to the central cell, the stronger its weight will be, and vice-versa. The neighbourhood effect is calculated as:

$$^{t}R_{K,x,y} = \sum_{c}\sum_{l} w_{K,L,c} \cdot {}^{t}I_{c,l}$$ **Equation 3.1**

with:

$^{t}R_{K,x,y}$ Contribution of the CA-transition rules in the calculation of the transition potential of cell (x,y) for land use *K* at time *t*;

$^{t}I_{c,l}$ the Kronecker delta function: $^{t}I_{c,l}$=1 if cell *l* at a distance (the concentric ring) *c* is in the state L, otherwise $^{t}I_{c,l}$=0;

$w_{K,L,c}$ weighting parameter expressing the strength of the interaction between a cell with land use *K* and a cell with land use *L* at a distance *c* in the CA-neighbourhood.

3.2.1.5. Transition rules

In order to apply the transition rule to the cell space, a vector of transition potentials is calculated for each cell. The transition rule is to change each cell to the state for which it has the highest potential. The purpose of adding the potential vector to a cell is to define a method of ranking all cells by their highest potential, following cell transitions starting from the highest ranked cell down. However, not all cells end up changed to the land use for which they have the highest potential. When a sufficient number of cells for a particular land use has been attained, the potentials for that land use are subsequently ignored in determining cell transitions. This is because the number of new cells for a given land use is determined exogenously to the cell space – with the macro-scale model. The propagation of land uses is thus constrained by a higher order mechanism. This also happens in real cities, where activities do not propagate freely as a mere response to local geographical circumstances but are driven by the regional, national and global role of the city. Additionally, the deterministic value obtained for the potential vector is stochastically disturbed, so that most values are changed very little but a few are changed significantly:

$$ {}^{t}P_{K,x,y} = {}^{t}v \, . \left({}^{t}R_{K,x,y} \right) $$ **Equation 3.2**

where

$$ {}^{t}v = 1 + \left(-\ln[rand] \right)^{\alpha} $$ **Equation 3.3**

with:

$0 < rand < 1$ is a uniform random function;

${}^{t}P_{K,x,y}$ CA transition potential of cell (x,y) for land use K at time t;

${}^{t}v$ scalable stochastic perturbation term;

α stochastic noise factor.

The level of random perturbation is obtained through a calibration process. Realism of results is also very attached to the calibration of this value, when increasing or decreasing it would significantly alter the final outcomes, generating non-realistic results, such as highly sparse or cluttered urban patterns, respectively. In this case, the random perturbation value is set to generate patterns with the same radial (fractal) dimension of the urbanised area measured for the actual land use map. In this case it is also fine tuned, to generate a sufficient number of new "seed" cells of various land uses in new locations, e.g. rural areas, which will subsequently grow into, for example, new industrial, commercial, or residential areas (Engelen et al. 2002 part 1 pg 20).

3.2.1.6. Inhomogeneous cell space

The cell space in a generic CA is homogeneous, with all cells having an equal potential to be developed. If one wants to approach realistic dynamics, however, an inhomogeneous cell space must be assumed. This type of cell space can be accomplished by characterizing each cell with several vectors - in this case, through the application of three attributes.

First, to each cell a value is given accordingly to its **suitability** to support a specific land use. The suitability of each cell "is defined as a weighted sum or product of a series of physical, environmental and institutional factors characterising each cell" (Engelen et al. 2002 Part I, pg. 15). The factors are normalised to values between 0 and 1 and are constant throughout the entire simulation unless edited manually by the user. Second, **zoning** maps are used, representing conscious institutional acts upon the territory. The maps vary in their land uses and for various periods in the simulation. Finally, an **accessibility** vector is added to each cell representing the importance of access to the transportation networks for the various land uses. The higher the value, the more accessible a land use on that particular cell is to the transportation network. Accessibility is calculated as a function of distance from the cell to the nearest point in the network as represented in the equation:

$$^{t}A_{K,x,y} = \frac{1}{1+\frac{D}{a_K}}$$

Equation 3.4

with:

${}^{t}A_{K,x,y}$ Accessibility of cell *(x,y)* for land use K at time t; [-]

D Distance between cell *(x,y)* and the nearest cell *(x',y')* on the transportation network; a_K Distance decay accessibility coefficient expressing the importance of good access to infrastructure element r for land use K.

The combination of suitability, zoning and accessibility makes possible a differentiated cell space, with each cell unique for the establishment of different land use activities. And it is this same richness of cell space that allows for increased realism when urban dynamics unfold. Consequently, Equation 3.2 and Equation 3.3, used to calculate the transition potential for each cell, need to account for these cell space inhomogeneities and should read as follows:

$$ {}^{t}P_{K,x,y} = {}^{t}v \, . \left(S_{K,x,y}\right)^{\sigma 1_K} . \left({}^{t}Z_{K,x,y}\right)^{\sigma 2_K} . \left({}^{t}A_{K,x,y}\right)^{\sigma 3_K} . \left({}^{t}R_{K,x,y}\right)^{\sigma 4_K} $$

with:

$S_{K,x,y}$ Suitability of cell (x,y) for land use K;

${}^{t}Z_{K,x,y}$ Zoning of cell (x,y) for land use K at time t;

${}^{t}A_{K,x,y}$ Accessibility of cell (x,y) for land use K at time t;

$\sigma 1_k, \sigma 2_k, \sigma 3_k$ Exponents determining whether the effects of Suitability, Zoning, Accessibility and the CA-transition rules are (=1) or are not (=0) taken into consideration in the calculation of the CA-transition potential. They work, therefore, as ON and OFF switches.

3.2.1.7. Land use demands

In generic CA the observed patterns at iteration *t+1* are calculated exclusively based on the patterns at iteration *t*. In urban CA, however, a constraint needs to be introduced, accounting for other aspatial forces shaping the city. One way to achieve this is with the use of aspatial models able to estimate cell demands for a particular setting. The regional version of this model uses an integrated ensemble of models to generate the estimates of activity levels. These are then converted via productivity or density relations into demands for the cell space. For the metropolitan version, however, cell demands are read from a file at each iteration since the application of the previous method would not substantially improve the metropolitan land use forecasts (Engelen et al. 2002 p. 18). The cell demands for each land use function can thus be set using a simple table tool built into the simulation software.

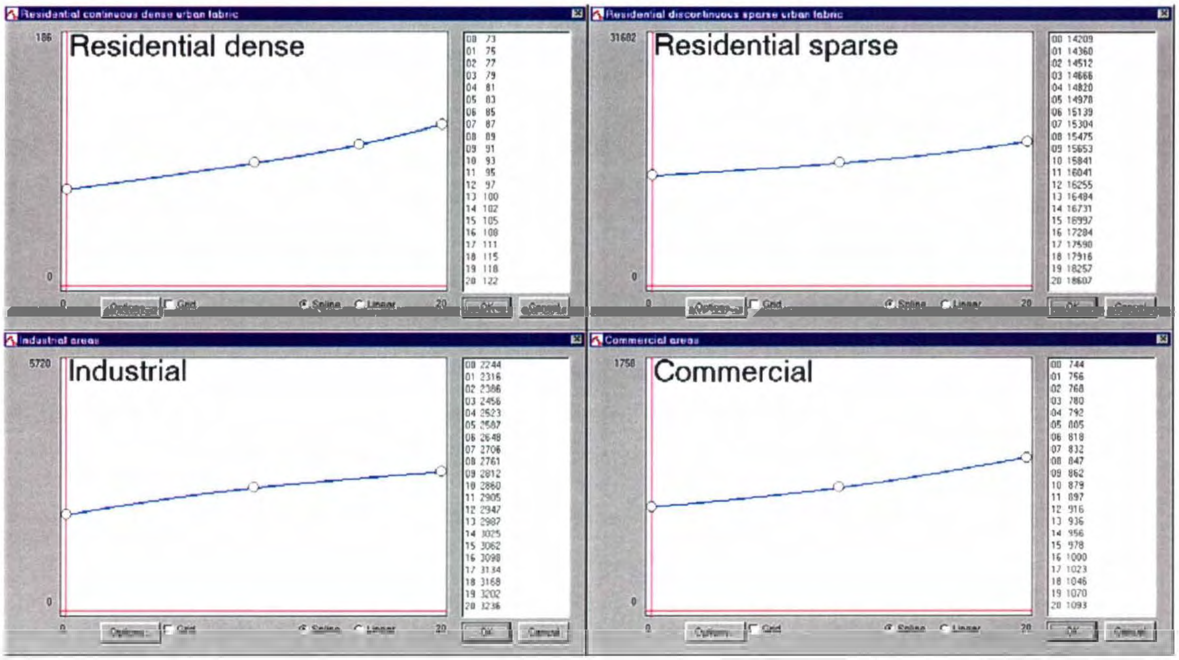
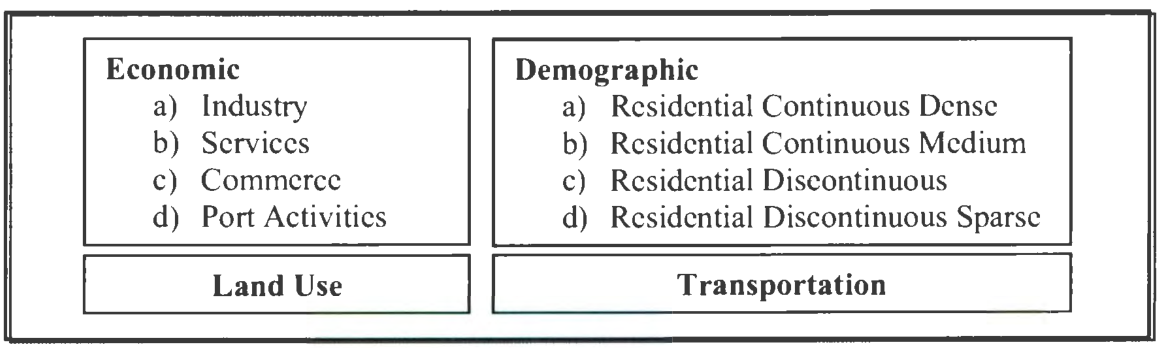


Figure 2 Dublin: total cell demands for four urban land uses, yearly from 1988 to 2008 (in Engelen et al. 2002).

3.2.2. The regional model

The same base is used for the development of an integrated land use regional model for the Greater Dublin Metropolitan region. This version comprises not only the entire Dublin County but the surrounding counties as well. There are 9 counties in total: Dublin, Kildare, Laois, Longford, Lough, Meath, Offaly, West Meath, and Wicklow. The working scale of this version induces a stratification of the spatial processes into three hierarchical geographical levels: Global, for the whole area covering the 9 counties; Regional, for each county; and Local, at the cell level. The macro-model of the metropolitan version is represented here by the first two levels - Global and Regional - while the Local level corresponds to the model's micro-level CA processes.

The overall model is therefore made up of different sub-models, each representing sub-systems affecting spatial dynamics. Some of these are then aggregated into sub-categories so that the allocation of activities can be easily transposed to the cellular level. This way, we have 4 sub-models: Economic; Demographic; Land Use; and Transportation. The economic sectors are aggregated into four main categories: industry, services, commerce, and port activities; and the demographic assigned to four different residential categories: residential continuous dense, residential continuous medium, residential discontinuous, and residential discontinuous sparse.



MODEL

Figure 3 The model's sub-systems and respective sub-categories.

The choice of the sectors, at the Global and Regional level, and the partition of the economic and demographic into additional sub-categories, with strong links to the land use classification system, is justified by the distinct spatial requirements and specific spatial behaviour, as well as by the quality, match, and availability of data at the three geographical levels of the model (Engelen et al. 2002p. 24).

3.2.2.1. Inter-operatibility between scales

Although the model is divided into three different levels with each playing a different role, they are intimately intertwined. First, global figures of growth or decline are derived and entered into the model as trend lines. These are estimated considering economic and demographic growth scenarios for the study area in the Irish context and the world beyond. The trend lines are then forwarded as input data to the Regional level.

Next, at the Regional level, a dynamic spatial interaction based model provides the allocation of Global growth as well as estimates of interregional migration of activities and residences based on the relative attractiveness of the counties. The attractiveness of a specific county is measured considering "its importance as a centre of economic activity and housing, its position relative to other counties, and its position in public and private transportation. (…) The mechanism driving the interregional exchanges of people and activities is based on the *relative potential calculation*" (Engelen et al. 2002p. 24).

The macro-scale dynamics are calculated regionally by 4 sub-models in conjunction.

A *Regional economic module* calculates the employment for each economic activity, its location and relocation among the regions.

A *Regional demographic module* deals with the demand for housing, its location and relocation among the regions.

A *Transportation module* calculates the migration of people and businesses between the different regions. The position of the regions relative to one another and the quality of the roads connecting them play an important role in this.

A *land-claim module* translates the Regional growth numbers into spatial claims. The latter are passed on to the model at the Local (cellular) level for a detailed allocation. Two principles are applied at this level: claim for land is fixed and passed on as a "hard constraint", representing the application of policies directly controlling the spread of particular activities. This principle is here applied to the *Port* activities, although this constraint can be extended to other types of land use, such as natural land, recreational land and some agricultural activities (Engelen et al. 2002p. 24).

The CA is used at the Local level, allocating economic activities and people on a high-resolution grid. The cell space in this version of the model differs from the metropolitan one. There is a larger cell space area, comprising a mosaic of 362000 cells of 4ha each (200 on the side). There are also some slight differences regarding the land use classification system, although the 8 most important land uses – the dynamic land uses – are maintained. Additionally, there are 7 vacant land uses and 9 land use features, as mentioned in Table .

Table 2 Land use functions and land use features used in the regional version of the model.

Land Use Functions	Vacant Land Use	Land Use Features
Residential Continuous Dense Urban Fabric	Arable Land	Construction Sites
Residential Continuous Medium Dense Urban Fabric	Pastures	Road and Rail Networks and Associated Land
Residential Discontinuous Urban Fabric	Heterogeneous Agricultural Areas	Airport
Residential Discontinuous Sparse Urban Fabric	Forests	Mineral Extraction Sites
Industrial Areas	Semi-Natural Areas	Dump Sites
Commercial Areas	Wetlands	Artificial Non-Agricultural Vegetated Areas
Public and Private Services	Abandoned	Restricted Access Areas
Port Areas		Water Bodies
		Outside Area

The constraints imposed by the Global and Regional levels acquire their spatial expression through the use of four map types: (1) a suitability map, (2) a zoning map, (3) an accessibility map, calculated in function of the communication routes, and (4) the land use map at each time step for each cell, within a radius of 8 cells. For each time step, calculations of the transition potential are made for each cell and function. As long as the regional demands have not been reached the cells will change into the land use function for which they have the highest potential. It may happen that a cell is not converted into the land use function for which it has the highest potential, though. This is possible if the demands for a particular activity have been satisfied.

So far, we have been describing the simulation in a way that may lead the reader erroneously to think that modelling processes take a top-down approach. In fact, the influence each level has on its counterparts is mutual. So far, we have seen that growth figures are calculated globally and are imposed on the regional models. Next, these figures are distributed and allocated to the 9 counties which will in turn impose the regional totals at the cellular level. The CA capabilities of the model will then use the introduced constraints and the transition potentials to map growth at a finer resolution. The process does not stop here, however, as the output of the cellular model informs the regional model of the availability and quality of space for further expansion of each type of economic or residential activity. This input may have a decisive impact on the relative attractiveness of the individual regions, especially if the system is experiencing a phase transition.

3.3. MOLAND as an Integrated Spatial Planning tool

This model can be useful as an integrated spatial planning tool as it allows the simulation of a myriad of scenarios at a very detailed scale. The output generated at the Regional and Local levels can be used for strategic planning in the assessment of critical limits or the emergence of new types of urban expansion. The potential and land use maps are particularly useful: the potential maps can be used to assess the pressures exerted on the land by urban growth, and land use maps generated in a large number of runs can be used to calculate probability maps showing the likelihood of some regions getting developed or not in a specific context.

The model also allows for the extraction of data useful for the development of quality of space indicators pertaining to different levels of sustainable growth. In the current version of the models, these indicators need to be calculated externally to the model via the use of GIS tools, but such calculations could become an integral part of the model in future versions (Engelen et al. 2002).

In order to be useful, the model also must be easy to use, as the target users are mostly planners and professionals at the decision-making levels. The model's complexity should not lead to a complicated model. To accomplish this, a graphical user interface allows access to all the variables, parameters and maps used at every level of detail. This way, the user is free to devise customized scenarios for growth and observe how the system reacts to the introduced constraints.

Finally, the model is also a powerful tool for communication. A picture can be worth a thousand words, and through the presentation of maps instead of numbers to characterize a specific geographical reality, discussion can be stimulated about a given problem or solution, and thus facilitate collaboration and consultation among the different planning institutions and departments. The same principle also applies to the general public, who can more easily grasp the outcomes of a proposed action by watching them in a movie-like fashion, instead of looking at charts and graphs and listening to endless talks by bureaucrats.

3.4. Why Dublin?

The reason for using Dublin's land use datasets in the model is connected with the availability of data as well as its accuracy. Of all the cities and regions considered by the MOLAND project, it was Dublin's metropolitan and regional area that displayed the best match between observed and mapped urban land uses. This choice was not, however, made by the author. Land use information comes with the modelling framework and is therefore used as is. In the course of scenario definition, these datasets are manually altered, representing the creation of an alternate future to study.

Chapter 4. Simulations and methods of analysis

4.1. At the metropolitan scale

4.1.1. "Business as Usual": the baseline scenario

The model framework is calibrated over the period 1988-1998 and then run forward to 2008. The calibration procedures are beyond the focus of the present thesis and will not be discussed here. This period between 1998 and 2008 is called the "business-as-usual" scenario, where the settings are left with their calibrated values. The results from this are used to perform an initial analysis of the unique Dublin geo-economic settings and as a base for the creation of experimental scenarios. The model settings for the baseline scenarios are as follows:

- **neighbourhood influence rules** are kept to their calibrated values. This decision is supported in many ways. The current influence rules depict the underlying forces of attraction/repulsion between land uses. Previous research has shown that a set of calibration rules can be applied to different cities with only minor changes (White and Engelen 1993). It is thus the city-specific factors such as local topography, the geometry of the transportation network, and local planning regulations which are responsible for the observed morphological differences between cities (White et al. 2001). In addition, results from fractal analysis of urban patterns (Batty and Longley 1994, Frankhauser and Sadler 1991, White et al. 2001) suggest a generic underlying structure of urban morphogenesis similar for all cities. From a practical standpoint, changing the influence rules of the would change the validated calibration of the model, making it unusable for testing the effectiveness of the planning strategies created in the scenarios. The influence rules could be changed, however, if a pure exploratory approach is taken. The focus would be to explore insights about the functioning of urban dynamics, with dynamic relationships and interdependences between specific agents playing a part in shaping the city; rather than on using the model as a planning tool to test the effectiveness of plans;

- the **suitability maps** used are the ones accompanying the most recent calibrated version in both metropolitan and regional versions of the model;
- the **transportation network** is kept unchanged. No roads are deleted nor added. The **accessibility parameters** are also kept unaltered at their calibrated values;
- no **zoning maps** are used for the initial analysis. It is designed so that the resulting land use maps display the patterns emerging from the region's physical characteristics, rather than displaying any constraints imposed by legal boundaries;
- the **growth rates,** represented by the **cell demand file** in the metropolitan version and by the **global population growth** in the regional version – built into the model - are also kept unchanged. They represent the real growth between the years where there was data available – up to 1998 in the metropolitan version and up to 2000 in the regional version. The built-in forecast values represent a

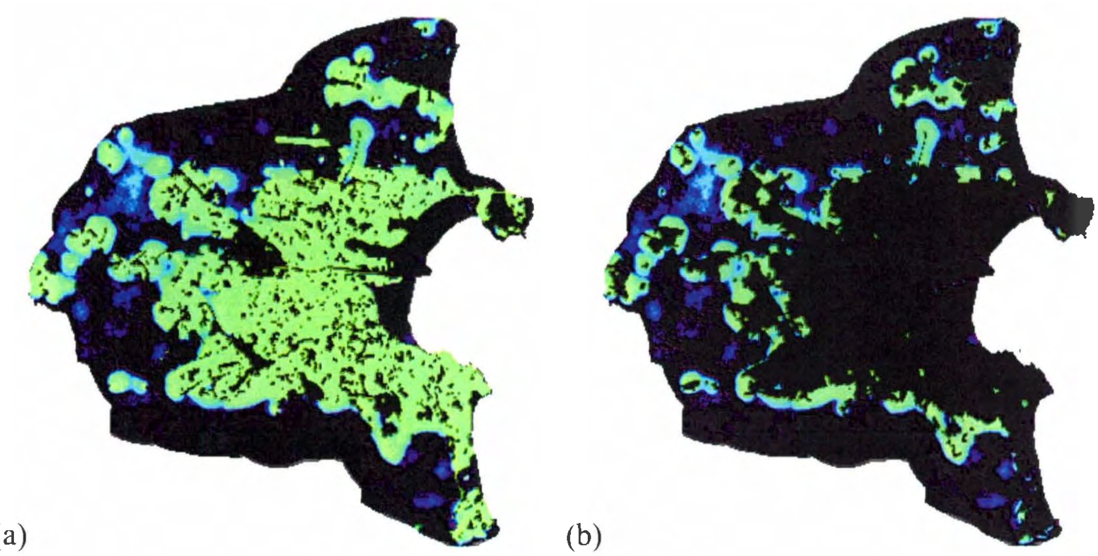
continued growth trend. Growth rates are fed to the model at every timestep, with each of the latter representing a full calendar year. A time span of 20 years is considered for the metropolitan version while the regional model comprises a 35 year period.

- the **stochastic perturbation** is kept unaltered at the calibrated value;
- the **random number generator seed** changes with each run. Reliance on results in this type of modelling is highly dependent on running the model repeatedly, for the kind of prediction to be made is probabilistic rather than deterministic. In addition, a large number of predictions - made under a variety of assumptions as to parameter values - allows the formation of insights into the morphological behaviour of urban settlements. This procedure also allows for the identification of possible bifurcation points in the future of the city and a determination of which of the city's features are robust, resisting almost any parameter modification, or showing high sensitivity to small changes in the system.

The models are run a number of times with these settings[1] and for both versions of the model. The growth rate is fully defined by the cell demand values for the metropolitan version. The location pattern of new development, on the other hand, is subject to the model's stochasticity and can only be assessed through the analysis of repeated runs of the model. The model is run numerous times with the settings described above. The maps

[1] An initial analysis was made by running the "no change" scenario with 160 different random perturbators for the metropolitan model. The comparison of results with the first 80 runs displayed similar behaviour in the location patterns. This behaviour is also carried out through time under the current constraints, as a comparison between the years of 1998 and 2008 suggests. In order to decrease computation time, the number of 80 simulations is chosen to perform the same initial analysis for the regional model.

of the last modeled year are then reclassified into Boolean maps (developed or undeveloped) and overlaid to produce a frequency map of areas being developed for urban use. Higher values represent cells which change into urban use more often, whereas lower values represent cells which are seldom converted into urban use. The frequency maps are then rescaled and presented as probability maps (fig. 4.1).



(a) (b)

Figure 4 Probability maps with (left) and without (right) initial urban land uses. Green represents areas with a high probability of being developed for urban use; dark blue, those with a low probability.

In the baseline scenario runs infill development, defined as urban land uses replacing small enclaves of arable land and pastures, does occur. Growth occurs, however, preferentially on the fringe of the already built landscape, emphasizing the dependence of newly established activities on existing ones. The location of dark blue (infrequently developed) cells can be attributed to the stochasticity of the simulation, as well as to the constraints imposed by the suitability or accessibility maps and influence rules. Still, there are some specific locations where clustering of blue cells (low to intermediate probabilities of developing) is more likely to occur. These locations appear in the probability maps as isolated areas with a core of lighter blue cells (higher probabilities) than their surrounding neighbours. This happens because once a cell is located in an isolated area it will in turn influence the potential values of its neighbouring cells by increasing them. In the next time step it is more likely for cells around the seed cell to be developed. This recursive effect leads to the creation of poles of attraction in non-contiguous areas of urban settlement.

Most urban development occurs adjacent to already developed areas—both the city of Dublin itself and outlying towns. However, one notable feature of the baseline scenario pattern of urban development occurs inside the triangular area defined by Leixlip, Mulhuddart and Duboyne, in the NW area of the modeled region. These urban centres seem to increase the attractiveness of the land inside the triangle, creating a basin of attraction for the location of industry. The presence of a road network helps to strengthen this attraction. The probability map shows this area in with intermediate values[2], in cyan, similar to the values displayed on the edge of the main urbanized zone. This means that the area is frequently being chosen for development but without a seed of urban development initially being present: growth in that area is initially permitted by the stochasticity of the model which occasionally seeds development there. Although industry is attracted to this area, its precise location is not determined, because the action

[2] Representing up to a fifth of the probabilities for land to be developed for urban use.

of the stochastic element on industrial land use generates a different pattern of location for that area in each run of the model.

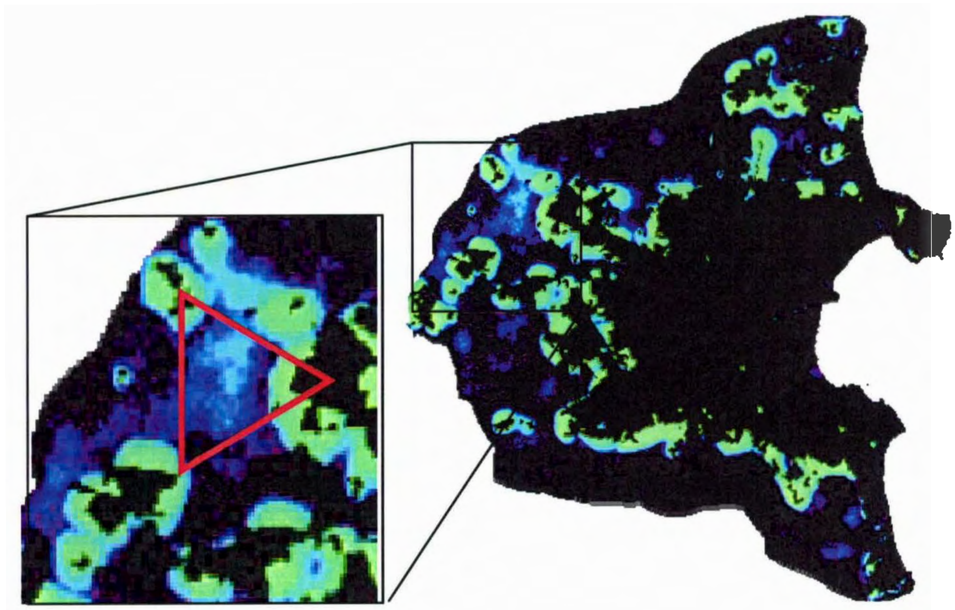


Figure 5 The Leix Ip, Mulhuddart and Duboyne triangle, enlarged at left.

In aggregate terms, the pattern of urbanization shown in the baseline scenario can be characterized by the radial dimension. The plot for the radial dimension of the entire urbanized area for the end year of the simulation, 2008 (Figure) displays a typical kinked line dividing the city into inner (black) and outer (yellow) zones. This is not the case, however, for the industrial and commercial land uses where strong peripheral growth is observed beyond the outer zone (Table 33). This results in an increase in the fractal dimension beyond the outer zone. This behaviour is a result of a continued trend in the Dublin metropolitan area observed in the datasets for 1998 by White et al. (2001). Rapid residential development took over the adjacent land of potential interest to industrial and commercial land uses. As a consequence, both were forced to leapfrog to a more peripheral zone and begin again. The repulsive effect of residential land use on industry explains the leapfrogging behaviour to outlying areas of the city.

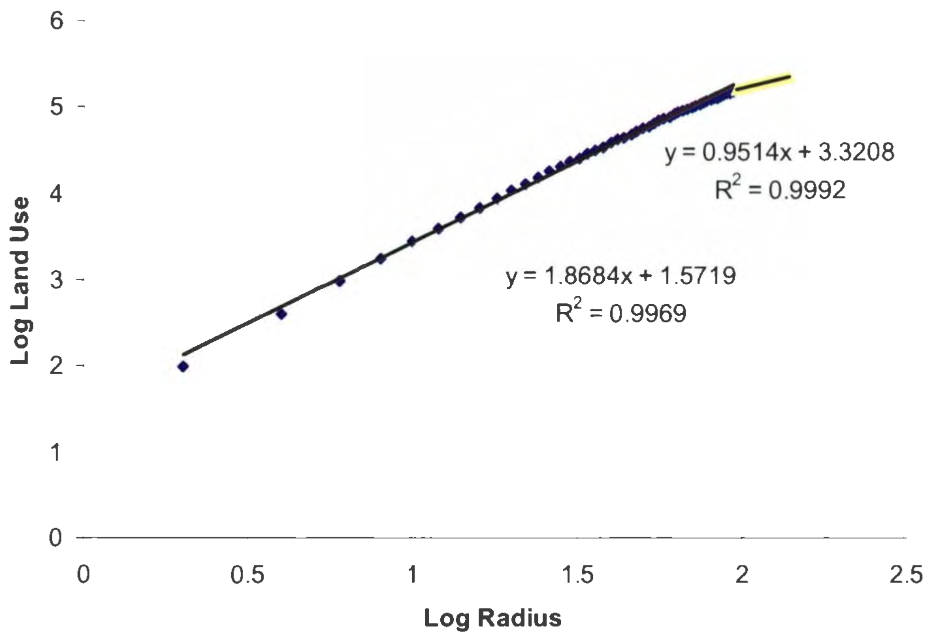


Figure 6 Radial dimension plot for all built landscape in 2008; coefficients on x represent radial (fractal) dimensions. Baseline scenario.

Table 3 Fractal Radial Dimensions for Commerce and Industry in 2008. baseline scenario.

	Commerce	Industry
Inner Zone	1,79	2,61
Outer Zone	0,29	1,98
Leapfrogging Zone	0,78	2,43

4.1.2. Using growth constraints

Alternative scenarios are developed based on two main issues stemming from the initial analysis. Can leapfrogging be prevented? How will the current region's growth dynamics react if the appearance of outlying clusters is not allowed? To obtain an answer, several experimental scenarios are created. The policies represented by these scenarios are based on loose approaches to two main principles in recent planning theory - growth boundaries and transit enhancement. New Urbanism criteria are used as a general reference for creating these scenarios. This reflects the fact that the New Urbanism framework is a highly proscriptive approach, thus allowing for a relatively easy translation of such policies into zoning maps.

At the metropolitan scale, growth boundaries are established in order to assess their effects on urban morphogenesis. The growth boundaries are set based on Peter Calthorpe's proposed New Urbanism framework(Calthorpe 1993, Calthorpe and Fulton 2001). Growth boundaries, described as *regional boundaries*, are composed of three interactive components: habitat protection and farmland preservation, the growth demands of the region, and the cost of new infrastructure and services (Calthorpe and Fulton 2001 p. 64). The *greenline* sets an expansion limit based on environmental and agricultural factors; the *urban growth boundary*[3] sets a limit based on land capacity needed to house a growing population; and the *urban service boundary* is a delineation of

[3]Although bearing the same name, the term *"urban growth boundary"* is also applied by Calthorpe to one of the interactive elements comprising the composite Urban Growth Boundary. The one which this footnote refers to represents a limit imposed on the growth demands of the region, while the composite Boundary accounts for all referred elements. In the present thesis, the distinction is made by capitalizing the initials of the latter.

the logical extension of infrastructure or the land area most efficiently served. These three components combined should allow the creation of an optimal regional urban growth boundary (UGB) comprising the essence of the above mentioned regional boundaries.

Greenline

The *greenline* boundary for the Dublin region is set according to updated environmental information made available to the general public. Two sources are used: the Sustainable Recreational Use of Natural Assets (SRUNA) project (SRUNA 2002); and the National Parks and Wildlife Division of the Department of Arts, Heritage, Gaeltacht and the Islands (2002).

SRUNA's datasets map the Natural Recreational Assets sites for sustainable recreational use. The data acquired from the National Parks and Wildlife division allows the identification of Special Areas of Conservation (SACs), Natural Heritage Areas (NHAs), Special Protection Areas (SPAs), statutory Nature Reserves (NRs) and National Parks (NPs). All of these areas are recognized as important environmental resources, whether at the European or national level, and are protected by EU directives or national acts. All the data made available on-line by these entities is compiled into a land use map of the protected areas, in case this land should become the object of urbanization.

This information is then superimposed on the natural land use datasets already in the model. Some corrections are made due to different degrees of resolution in the datasets.

All areas defined by these two sources are marked as excluded from urbanization. The current land use is maintained in the remaining zones but is subject to change if required.

Figure 7 Compiled environmental data; protected areas shown in yellow.

Urban Service Boundary (USB)

The Urban Service Boundary is an infrastructure related boundary. It is defined by the extent of areas serviced by infrastructure such as roads, electricity or sewage networks. Due to the model's resolution, only the transportation network is displayed. For simulation purposes it is assumed that the infrastructure-serviced area matches the transportation network as this is most often the case.

Urban Growth Boundary (UGB) – population growth related

This boundary differs from the previous one as it is connected with the predicted population growth. This element is likely to be the most flexible and changeable of all three. While the *greenlines* and the *urban service boundary* may be less liable to change, due to legal protection of natural areas and the rigidity of administrative boundaries, respectively; the *urban growth boundary* may be changed as growth occurs. The information on the two other boundaries remains fixed while the growth related boundary is changed between scenario variants. This will allow the observation of how the city will accommodate a fixed growth rate, given differing growth limits imposed by zoning maps.

The assumed rate of growth - translated into 6046 new cells - for the time span of 20 years is kept unaltered. The variants of this scenario pertaining to the number of areas made available for urban expansion are as follows:

(a) a single expansion zone, capable of containing all the new cells;
(b) one initial expansion zone up to the middle of the modeling time span and then making all land available for urban land use.

The greenbelt scenarios are divided into two variants:

(c) surrounding all built landscape from time step one;

(d) surrounding only the city of Dublin's built landscape;

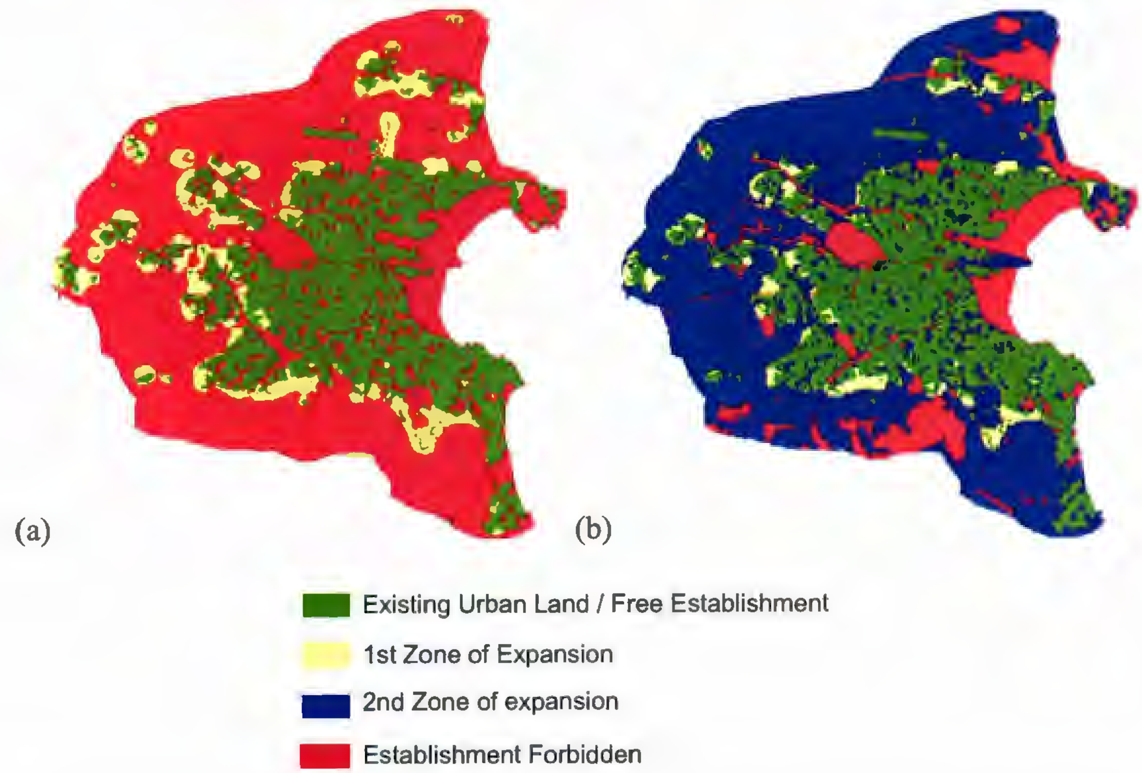


Figure 8 Zoning maps used in each scenario. (a) yellow shows area in which development is permitted; (b) yellow: development permitted in first (10 year) period, blue, development permitted in second period. Letters relate to the description key above in the text.

Scenarios (a) and (b) have as their main goals to force the system to accommodate outlying growth in a compact zone around the urbanized area and to look for changes in underlying dynamics mirrored in the fractal dimensions. The variant (b) was created specifically in an attempt to block the establishment of seed-cells that might be triggering the leapfrogging behaviour and to stop the appearance of scattered clusters of urban land use. The greenbelts used in scenarios (c) and (d) are wide enough so that the neighbourhood effect does not necessarily determine the location of new cells. Scattered patterns of development are thus expected to emerge. Scenario (d) is designed to force the new cells to locate outside the excluded greenbelt area in response to natural suitabilities and access to transportation in the region. How much growth is absorbed by satellite settlements can be observed in scenario (d)

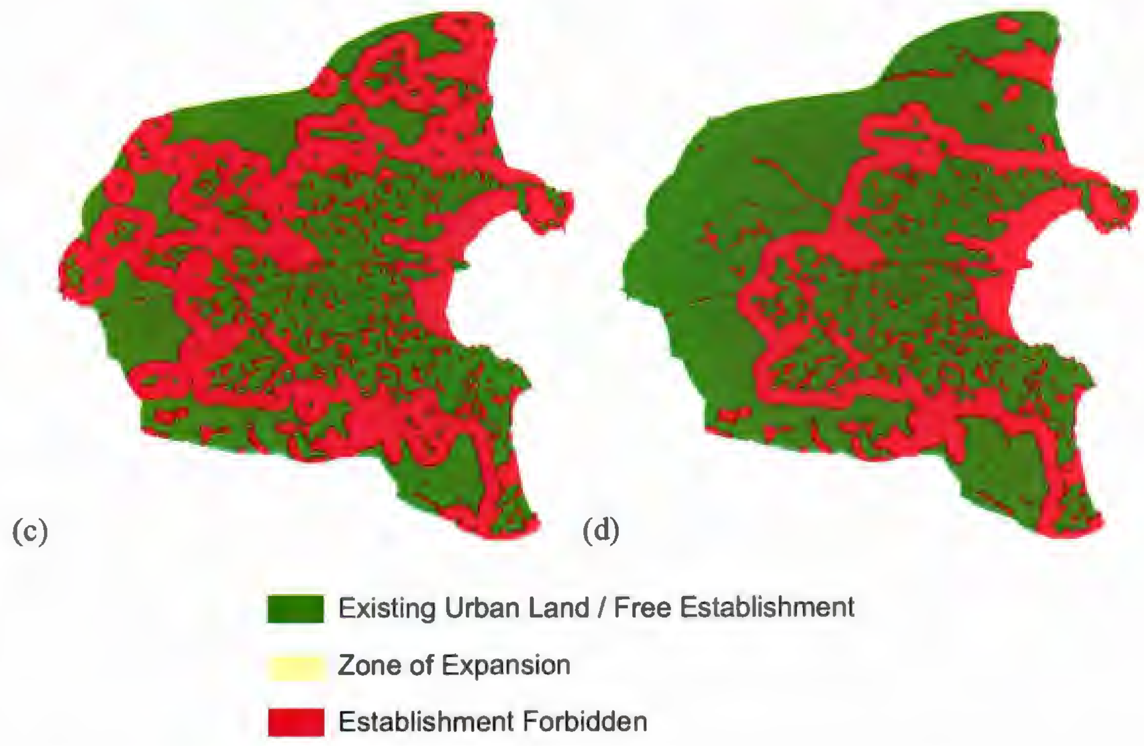


Figure 9 Zoning maps used in each scenario. Development is prohibited in red areas. Letters relate to the description key above in the text.

4.1.2.1. *Case (a): "Single Expansion Zone"*

This scenario variant differs from the baseline or "Business As Usual" scenario in the area made available for urbanization. In the latter growth is not constrained – all cells are made available for urbanization, the development patterns being defined only by the influence rules, suitability values, transportation network, neighbourhood-scale interactions and a certain amount of stochasticity. This scenario imposes a narrow zone in which growth can occur. The area of this zone is calculated so that the number of cells made available for urbanization matches the numbers for new urban cells for the next 20 years.

The new number of available cells is obtained through the use of probability maps generated by the overlayering of the several "business-as-usual" runs. A sum is calculated, starting from the cells with higher probability values and from there down until the number of future cell demands is satisfied[4]. This is translated into a zoning map applied to all urban land uses.

4.1.2.2. *Case (b): "Phased Growth"*

Phased growth is modelled by making land available gradually as the city expands. There are two distinct periods of expansion, with the dividing point being the year 1998 – the midpoint in the whole simulation time. Each zone accommodates the cell demand values

[4] It was not possible to match exactly the number of cell demands with the number of cells in the probability maps. Because of this, the nearest value right above the one needed was used.

for each time period. Growth is constrained for the first period and then allowed to establish itself freely in the second one.

4.1.2.3. Cases (c) and (d): Greenbelts

Another variant of bounded growth is attempted, this time depicting a situation where the growth limits are reached and new growth needs to relocate itself. Greenbelts are thus used to create a buffer zone around the existing urban land uses. The greenbelt width is set to a value higher than the neighbourhood radius – 1000 meters wide - so that the latter's effect does not bias the location of urban activities outside the urbanized area.

Following these criteria, two approaches are taken. In the first, a greenbelt is defined only around the city of Dublin's built landscape (case c). In the second, greenbelts are defined around all the built landscape in the region. The first approach allows the observation of which peripheral urban clusters are more attractive to urban expansion, and the latter allows the identification of vacant areas that are likely to be attractive to urban growth. This could be useful within the context of decentralization. .

The making of the zoning maps was carried out through the use of IDRISI (Clark Labs 2001), a popular software with powerful raster analytical functions, and by directly changing the values on the zoning map windows of GEONAMICA (RIKS BV 2000).

4.2. At the regional scale

The second group of scenarios is focused on the enhancement of a transit system, using the 9-county regional version of the model. This version has a wider range of transportation infrastructure types than the metropolitan version, thus allowing for the creation of more detailed scenarios focusing on the transportation network. Consequently it allows the analysis of the long-range impact a transit system has on land use patterns, as the effects of transit enhancement are considered to be more visible at a regional scale. However, the trade-off between scale and resolution must be kept in mind, since the regional model represents land use with a resolution of 200m as opposed to 100m for the metropolitan model. For this reason, a full comparison between the results obtained with these scenarios cannot be made with the ones developed in the metropolitan version of the model.

4.2.1. *"Business as Usual"*: the baseline scenario

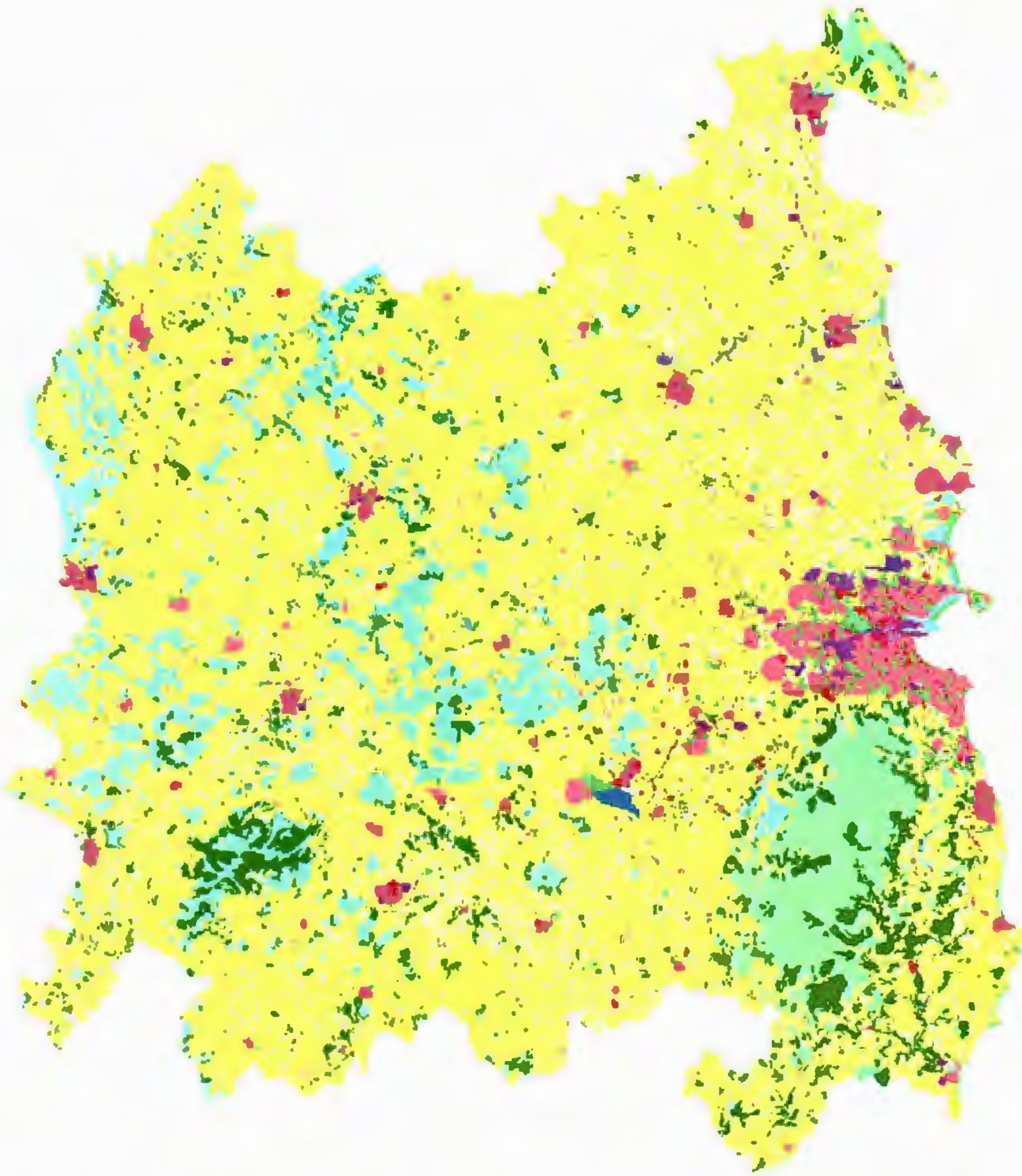


Figure 10 "Business as Usual" scenario: land use map for 2025.

A quick analysis of the values for the baseline simulation shows how the different land uses relate to the different link types. The values for the accessibility maps, in Table 4, show that commerce and services are attracted to roads of medium average speeds – from regional roads to dual carriage ways. The main preference goes to regional roads, with a relative importance coefficient of 0.9 and a short distance decay showing that it is more crucial for commerce to locate near this type of transportation link. An intermediate value of 0.5 is attributed to railway stations, mirroring their moderate influence on the location of these kinds of activities.

The higher density residential areas – res1 and res2 – present a relatively different orientation. They show a relative preference for locations near regional roads over other road categories. Secondarily they show a preference for locations near and railway stations and light rail transit, but also motorway junctions. The lower density residential categories—res3 and res4—show a strong attraction to all categories of roads, but a relatively weaker attraction to railway stations and light rail transit.

Table 4 "Business as Usual" scenario: relative importance values for different infrastructure transportation elements for each urban land use (calibrated values).

Link Type	Avg.	Res1		Res2		Res3		Res4		Ind		Comm		Ppriv		Ports	
	speed	ri	dd	ri	dd	ri	dd	ri	dd	ri	dd	ri	dd	ri	dd	ri	dd
Motorways	110	0	0	0	0	0.3	2	0.3	2	0.7	5	0.3	5	0	0	0.3	1
Motorway junctions	90	0.7	5	0.7	5	0.8	8	0.8	8	0.9	10	0.6	8	0.6	8	0.9	8
dual carriage ways	80	0.4	3	0.4	3	0.8	6	0.8	6	0.8	12	0.9	6	0.7	5	0.7	6
national and primary routes	60	0.6	3	0.6	3	0.9	5	0.9	5	0.8	5	0.8	5	0.8	6	0.7	5
regional roads	40	0.9	4	0.9	4	0.9	4	0.9	4	0.6	4	0.9	3	0.9	5	0.6	4
local roads	30	0.5	2	0.5	2	0.9	3	0.9	3	0.5	3	0.6	1	0.6	4	0.4	3
railways	1	0	0	0	0	0	0	0	0	0.9	3	0	0	0	0	0.9	4
Railway stations	1	0.7	5	0.7	5	0.5	10	0.5	10	0.7	3	0.5	2	0.5	6	0.9	6
Lightrail	1	0.7	4	0.7	4	0.4	5	0.4	5	0	3	0.8	5	0.6	3	0.4	3

* ri – relative importance of infrastructure element r for the local accessibility of land use K;

dd – distance decay accessibility coefficient expressing the maximum distance at which land use K is still benefiting from the presence of infrastructure element r.

4.2.2. "Preference For Transit"

People's preference for the transit system is modeled by encouraging the location of commerce, services and high residential areas near the transit nodes and main routes. Concurrently, the development of commercial areas near freeways is discouraged but not completely banned. The rationale behind this scenario is that if people are more willing to use the transportation network there will be an increased flux of activity in the transit nodes, making these preferential locations for the establishment of commercial and services activities and for high density residential areas as well. In practice, this is achieved by increasing the accessibility of commerce, public and private services and high density residential land to railway stations and lightrail routes, and by decreasing their attraction to roads other than local roads (see Table 5).

Table 5 Parameters for the Preference for Transit Scenario[5].

Link Type	Avg. speed	Res1		Res2		Res3		Res4		Ind		Comm		Ppriv		Ports	
		ri	dd	ri	dd	ri	dd	ri	dd	ri	dd	ri	dd	ri	dd	ri	dd
Motorways	110	0	0	0	0	0.3	2	0.3	2	0.7	5	0	5	0	0	0.3	1
Motorway junctions	90	0.6	5	0.6	5	0.8	8	0.8	8	0.9	10	0.1	8	0.1	8	0.9	8
dual carriage ways	80	0.4	3	0.4	3	0.8	6	0.8	6	0.8	12	0.1	6	0.1	5	0.7	6
national and primary routes	60	0.6	3	0.6	3	0.9	5	0.9	5	0.8	5	0.1	5	0.1	6	0.7	5
regional roads	40	0.9	4	0.9	4	0.9	4	0.9	4	0.6	4	0.1	3	0.1	5	0.6	4
local roads	30	0.5	2	0.5	2	0.9	3	0.9	3	0.5	3	0.6	1	0.6	4	0.4	3
railways	1	0	0	0	0	0	0	0	0	0.9	3	0	0	0	0	0.9	4
railway stations	1	0.7	5	0.7	5	0.5	10	0.5	10	0.7	3	1	1	1	1	0.9	6
Lightrail	1	0.7	4	0.7	4	0.4	5	0.4	5	0	3	1	1	1	1	0.4	3

* ri – relative importance values

dd – distance decay values

For all purposes, it is assumed that railway stations represent the transit nodes of the system. Although there might be cases in the real world where this does not occur, railway stations often operate as transit interfaces. The extension of public transportation is made by connecting other modes of transportation offering different levels of service - i.e. bus, subway – to the railway service. The lightrail network is the other link type that can be easily identified as part of the transit system. It is used to represent the main urban

[5]As a result of the application of these figures to the accessibility parameters, commerce and private and public services "abandoned" the city. A variant was tested where the distance decay values for these two land use functions was increased to 4 for the railstations and lightrails. As a result, public and private services did not usually leave the city core, although there were not significant changes to the commercial land use.

transit routes. The values for local roads are kept unaltered, because the average speed they have - 40 Km/h – is low enough to sustain a walkable neighbourhood.

4.3. Methods of analysis

The results of the scenarios described above are analysed qualitatively and quantitatively through the use of different spatial metrics and map comparison techniques. This analysis is conducted with the use of several spatial analysis tools, namely, WCluster, FRAGSTATS (McGarigal et al. 2002); and the Map Comparison Kit, provided with GEONAMICA (RIKS BV 2000). These are described briefly here.

4.3.1. WCluster

WCluster is software initially developed to ease the performance of fractal analysis - namely, the cluster size frequency and the radial fractal analyses – from log files of simulation runs by extracting raster based land use data into excel files. The fractal characteristics of the land use patterns can then be established by doing the appropriate plots of the data.

The cluster size frequency measurement represents the size spectrum of land use clusters. The log-log plot of cluster frequency against cluster size is linear for all land use patterns examined, and the slope of the relationship (the fractal dimension) is apparently relatively stable over time. Therefore it is a reliable though very general measure of the realism of simulated land use patterns. This measurement is widely used in physics and in studies of self-organization, but its application to geographical studies of cities has apparently only been done by White and Engelen (1993). Considering that a particular urban land use can be thought of as a fractal object - an object consisting of a number of clusters of various sizes – it is self-similar. With no characteristic cluster size, the relationship between frequency of occurrence and cluster size is hyperbolic, thus log linear (White and Engelen 1993). The cluster definition method is taken from the work of White and Engelen (1993), who have used only the horizontal and vertical adjacencies.

The fractal radial dimension provides a measure of how fast the density of a land use changes with distance from the centre of a city. The higher the fractal dimension, the more peripheral, relatively, the land use is. This fractal dimension is present in the work of Frankhauser (1988, 1994), Frankhauser and Sadler (1991) and White et al. (2001). White and Engelen (1993) have been using it to study cities. The fractal radial dimension has already generated insights into the bi-fractal structure of cities. Cities can be described as composed of two distinct fractal zones: the inner zone, with a high radial dimension value, and an outer zone, with a lower value for the same measurement. The transition between zones is revealed by a sharp kink in the area-radius plot used to calculate the fractal dimension. The inner zone represents the consolidated part of the city where huge changes are less likely whereas the outer zone is where the urbanization process is underway.

This analysis applies to both the sum of all urban land uses and to each individual land use. Although they may differ from each other, each land use has its own fractal dimension and inner and outer zones. The inner zone fractal dimension of each land use determines its relative location in the urbanized area. The land use with the lowest inner zone fractal dimension is most concentrated near the centre of the city, with land uses characterized by successively higher radial dimensions having locations that are on average at successively greater distances from the centre. This is similar to the traditional Alonzo-Muth urban land use model, with the difference that each concentric ring is not occupied exclusively by a particular land use but rather that there is a predominant land use.

4.3.2. FRAGSTATS

FRAGSTATS (McGarigal et al. 2002) is a spatial pattern analysis program for categorical maps, allowing the quantification of the aerial extent and spatial configuration of patches within a landscape. A wide variety of spatial metrics is thus available at three different levels: the Patch level, for individual patches, characterizing the spatial character and context of patches; Class level, with metrics integrated over all the patches of a given type (class); and Landscape level, for all patch types or classes over the full extent of the data.

Due to its characteristics, FRAGSTATS is highly suited to measure fragmented landscapes such as urban ones. Quantitative data comparison is still a very common, and to a certain extent reliable, method to compare different data sets. The conversion of qualitative information like land use patterns into numerical measures allows the derivation of indicators related to the quality of life of citizens. These can then be used as a basis for monitoring and evaluating the creation, validation and assessment of planning policies and strategies aimed at promoting sustainable urban development. An adapted version of FRAGSTATS is used here to compute various metrics that quantify different aspects of landscape pattern, such as total urban edge and edge-contrast metrics. These values are then used to monitor changes in landscape fragmentation.

The metrics used are *Total Edge* (TE) and *Perimeter-Area Fractal Dimension* (PAFRAC). The first equals the sum of the lengths (m) of all edge segments in the landscape of a particular patch type. The second reflects shape complexity across a range of patch sizes. The values for the latter are between 1 and 2 where a fractal dimension greater than 1 for a 2-dimensional landscape mosaic indicates a departure from Euclidean geometry (i.e., an increase in patch shape complexity).

4.3.3. Map Comparison Kit

The Map Comparison Kit allows for quantitative and qualitative comparison of two categorical maps. Categories can be compared on a cell by cell basis, per category, or using a fuzzy set comparison algorithm. The crispness of the cell by cell method is not considered suitable for the comparison of maps containing a certain level of stochasticity in their final outputs. For that reason, only the latter two other methods will be used to analyse the simulation results.

The comparison by category allows the analysis of location changes per land use. This is a quick way to analyse whether there were radical changes in the behaviour of a particular land use; for instance, if different scenarios generated different basins of attraction for the same land use. Here, however, the analysis is mostly used as an aid to sensitivity analysis. Summary measures of agreement, by category, between two maps are given as Kappa statistics.

Finally, the fuzzy Kappa map comparison algorithm provides a more detailed qualitative analysis of land use patterns. This method of comparison was developed by Hagen (2003). More recently, it has been used in the calibration of dynamic land use models. This method differs greatly from the cell by cell comparison because it takes into consideration not only the exact coordinates of a particular cell but its context as well i.e. its geographic relation to all the other cells within a specified neighbourhood. For this reason, it is a more reliable way to compare different categorical maps.

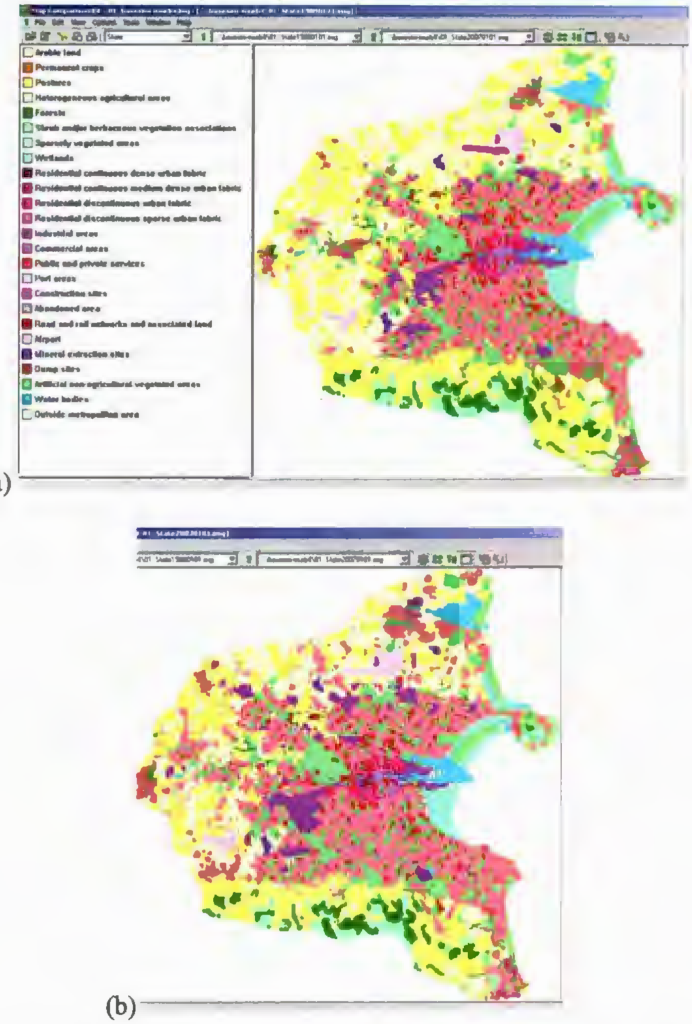
Chapter 5. Results from metropolitan scenarios

The result of each metropolitan scenario will first be presented individually, and then an overall comparison will be made on the basis of the various measures being discussed. Sensitivity analysis will also be performed using the Map Comparison Kit, as visual comparison is needed to detect different pattern characteristics not detected by fractal measurements. At the end of the chapter, an overall spatial metrics comparison is presented and discussed.

5.1.1. "Business as Usual"

The degree of similitude between different simulations, run under the same parameters and differing only in the seed number, is confirmed by the Fuzzy Kappa (KFuzzy) method of analysis. The KFuzzy values for the metropolitan model decrease as the number of iterations increases. At the last iteration, the lowest KFuzzy value of 0.97 is achieved, higher than the 0.90 value used by Hagen (2003) as a threshold for acceptable similarity values. A sensitive map comparison between log files by category also reveals behaviour similarities per land use. Thus by the final iteration, any of the logged base simulations is practically the same as all the others, and hence representative of a "Business as Usual" scenario for Dublin.

5.1.1.1. Overall urban land use behaviour



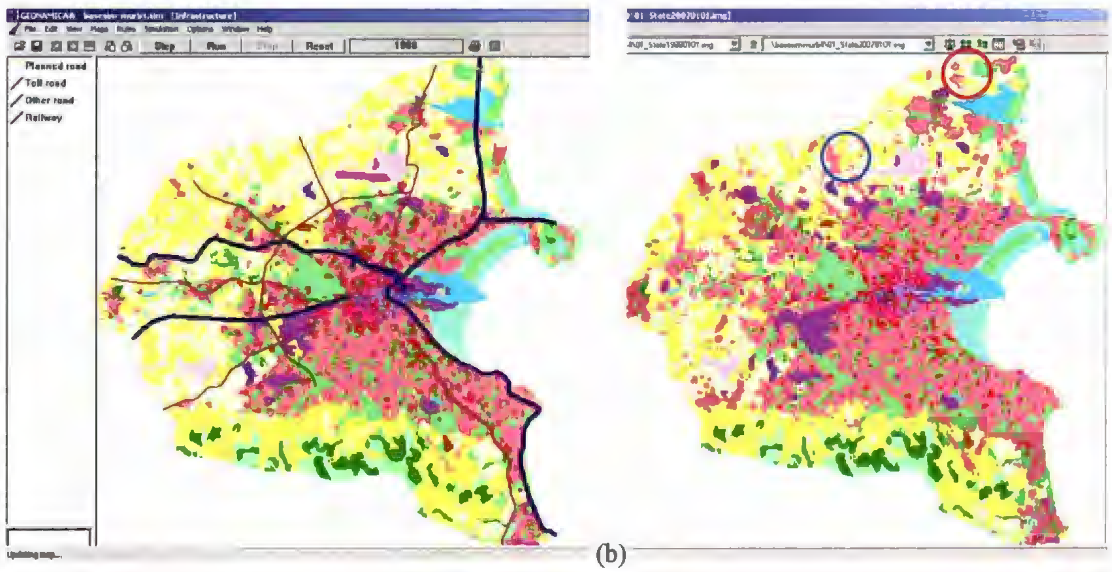
(a)

(b)

Figure 11 "Business as Usual" scenario: land use map for (a) 1988 and (b) 2007. Results shown represent a single run.

Urban growth takes place mostly near the urban fringe (Figs. 11, 12, 13). Cells that get developed in more than half of the simulations are located adjacent to the areas already occupied by urban land uses (Figure 12). The model's stochastic perturbation is observed in the high number of cells getting developed only once in all the 16 simulation runs used to generate the map. This development is also influenced to some extent by the region's unique characteristics. Although the randomness is stronger in these cells, a certain amount of attraction to the communication routes is exerted, revealing trends of linear development.

Special attention must be paid to two zones that emerged during the simulation. These are located west of Dublin's Airport (Figure 11, blue circle) and north of Swords (Figure 11, red circle) Both of these new clusters are heavily influenced by the existence of toll roads in an area of vacant land and are composed of the residential sparse category.



(a) (b)

Figure 11 "Business as Usual" scenario: land use map for (a) 1988 with overlaid network map showing motorways and rail lines; and (b) 2007. Results shown represent a single run.

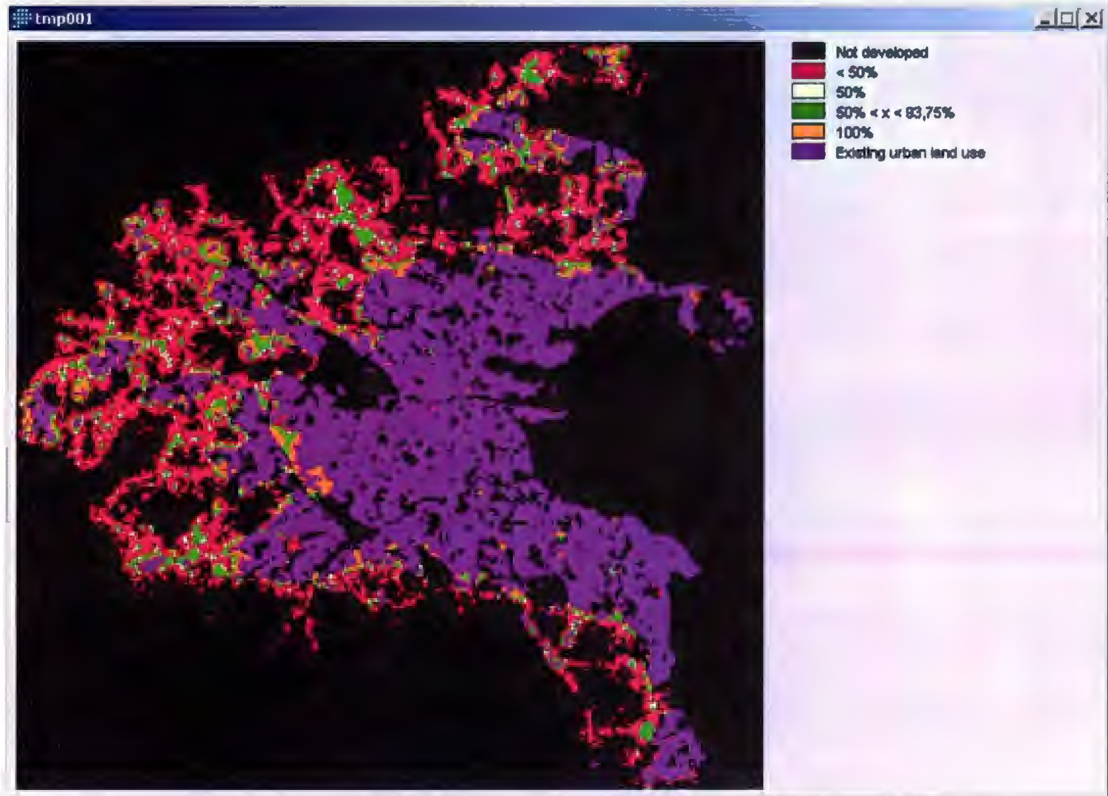


Figure 12 "Business as Usual" scenario: probability map for 16 simulations differing in stochastic perturbation seed.

5.1.1.2. Radial fractal analysis

The results analyzed will be focused on the Commerce, Industry, Public and Private Services, and residential land use categories. For the latter, the analysis will be carried out for both combined residential land use (all residential categories combined) and for the Residential Continuous Dense and the Discontinuous Sparse Urban Fabric; the other two residential categories (Medium Dense and Discontinuous) are considered not to have enough change in cell numbers to justify an individual analysis.

An analysis of the fractal radial measurements shows that Dublin's outer zone was consolidated in the last 10 simulation years. There was an increase in the radial dimension of the outer zone for the dominant land use there – Residential Discontinuous Sparse. The third zone of expansion, on the other hand, still shows signs of "leapfrogging" activity in 1998 for Industry and Commerce.

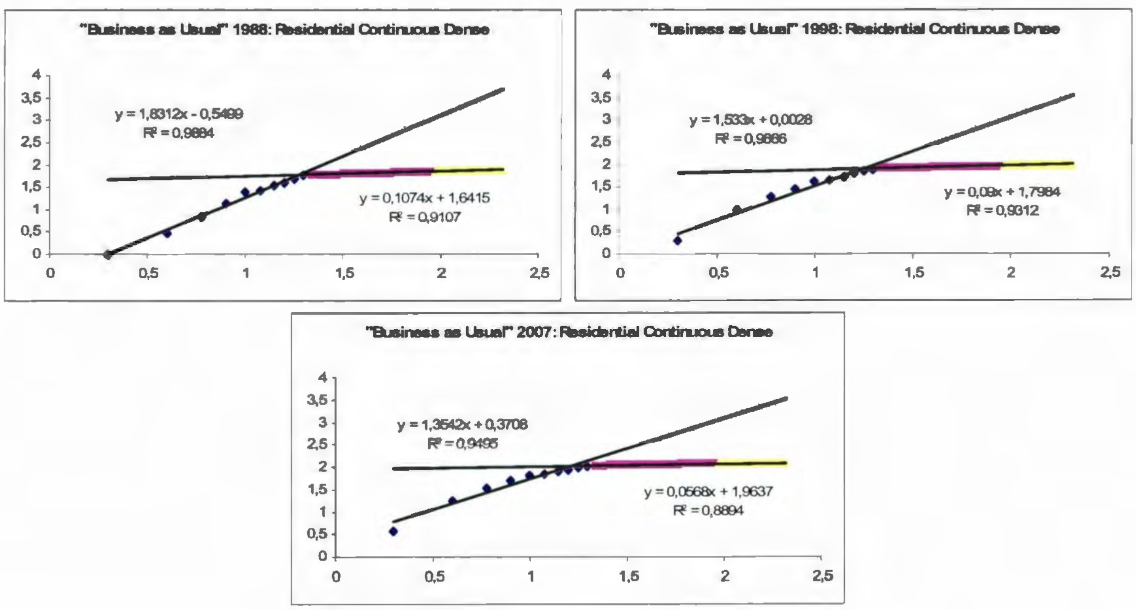


Figure 13 "Business as Usual" scenario: radial fractal dimension graphs for combined residential continuous dense for 1988, 1998 and 2007.

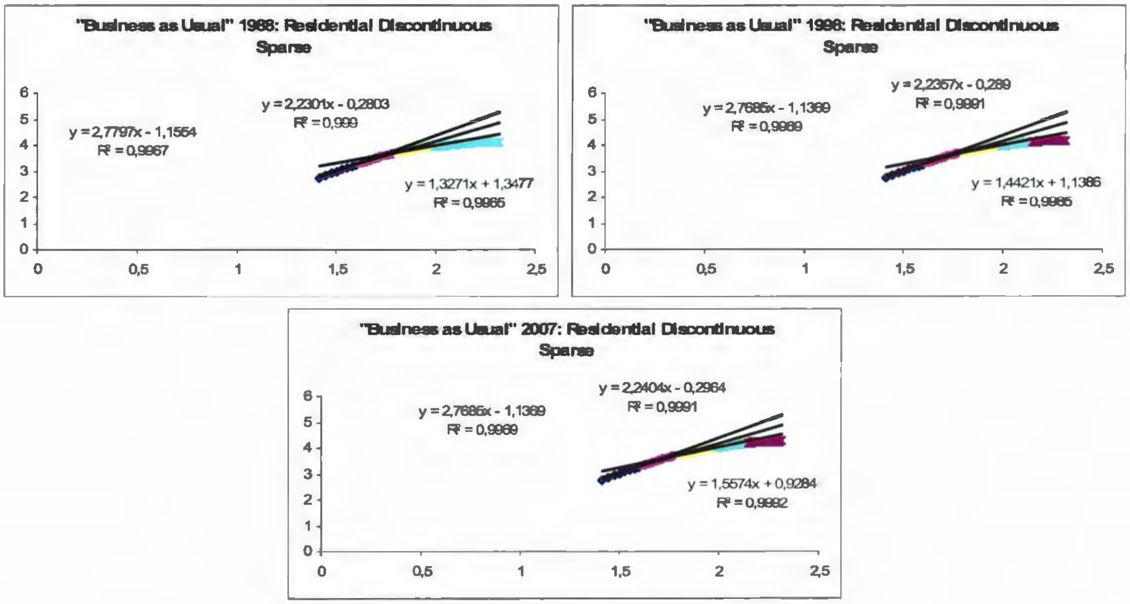


Figure 14 "Business as Usual" scenario: radial fractal dimension graphs for combined residential discontinuous sparse for 1988, 1998 and 2007.

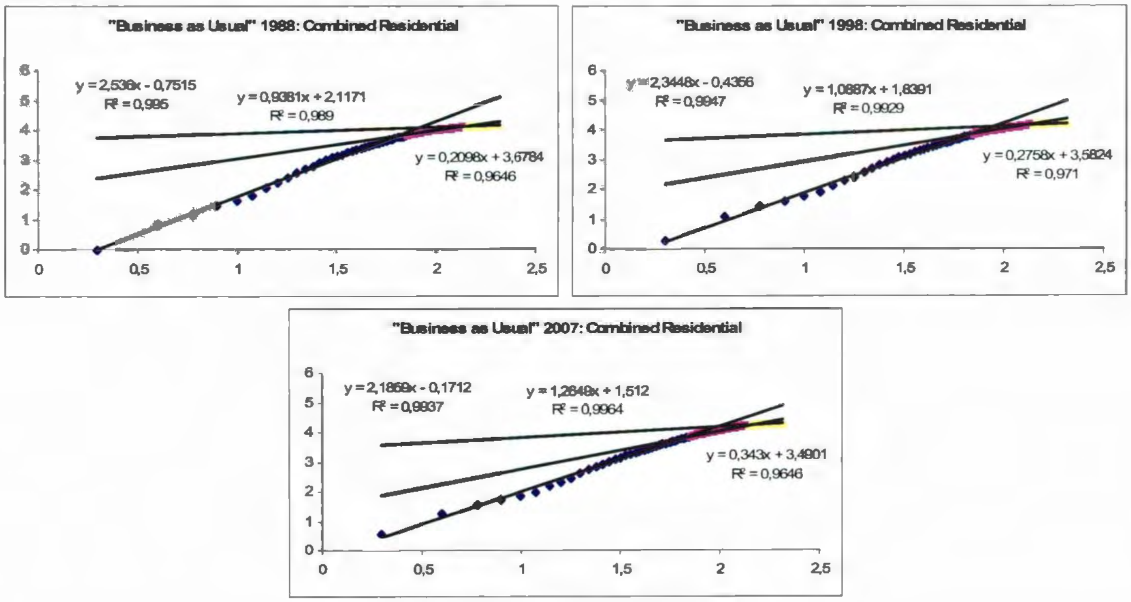


Figure 15 "Business as Usual" scenario: radial fractal dimension graphs for combined residential for 1988, 1998 and 2007.

Residential fractal variance, mostly driven by Residential Discontinuous Sparse land use, displayed few changes, with most of its growth occurring at the urban fringe. Even though there seems to be an overall abandonment of housing from the city's inner zone, results do not point to low density residency as the behaviour responsible. Industry's behaviour remained practically unaltered, aside from a small increase in the third zone, which is related to an increase of industrial cells in that area of the city. The evolution of commercial activity for the 1988-2008 period is marked by scattered growth close to the urban fringe and nearby existing urban clusters. A slight abandonment of the city core can also be observed. The third zone not only endures but also becomes a bit more consolidated, as the increase in its fractal radial dimension suggests, and is also easily recognized with a visual inspection of the commercial land use maps (Figure 18). The growth behaviour of public and private services for the period of 1988-2007 remains almost exactly the same, resulting in practically unaltered fractal radial dimensions. Public and Private Services' growth is characterized by scattered emergence of new Public and Private Services cells on the urban fringe, accompanying the growth of Commerce and sparse residential areas.

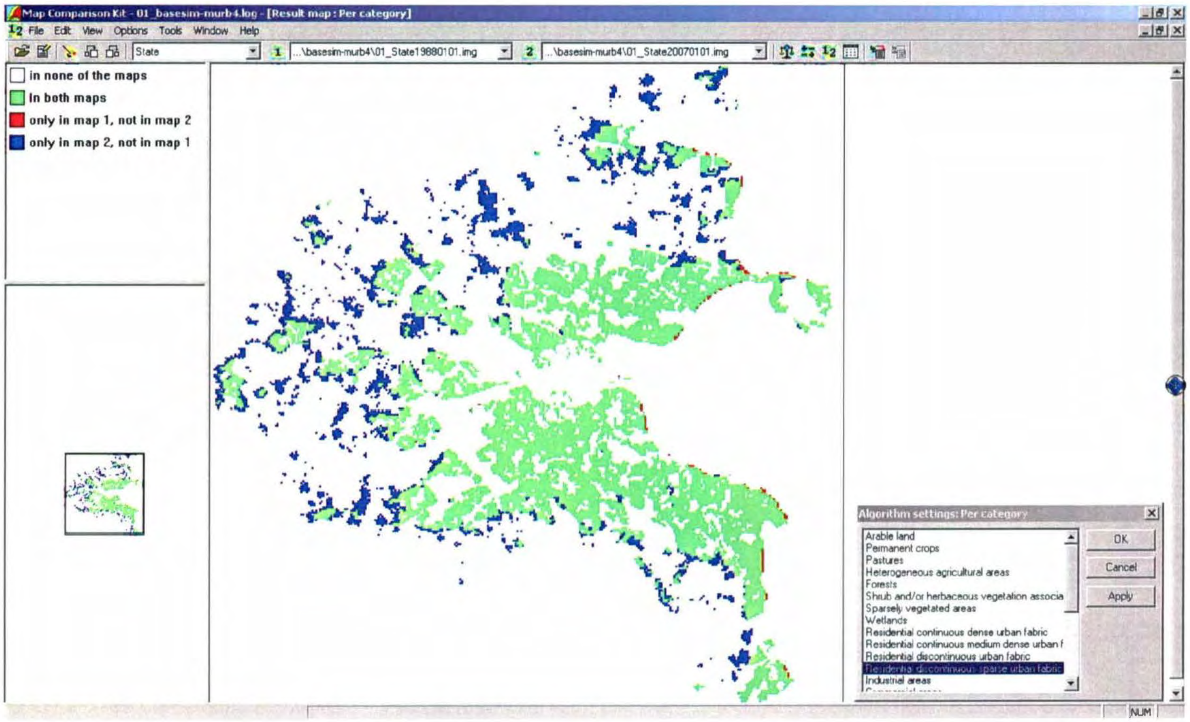


Figure 16 "Business as Usual" scenario: Residential Discontinuous Sparse land use comparison between the years of 1988 and 2007. Green represents the cells common to both maps; red for cells only present in the 1988 land use map; blue for cells only present in the 2007 land use map. Results shown represent a single run.

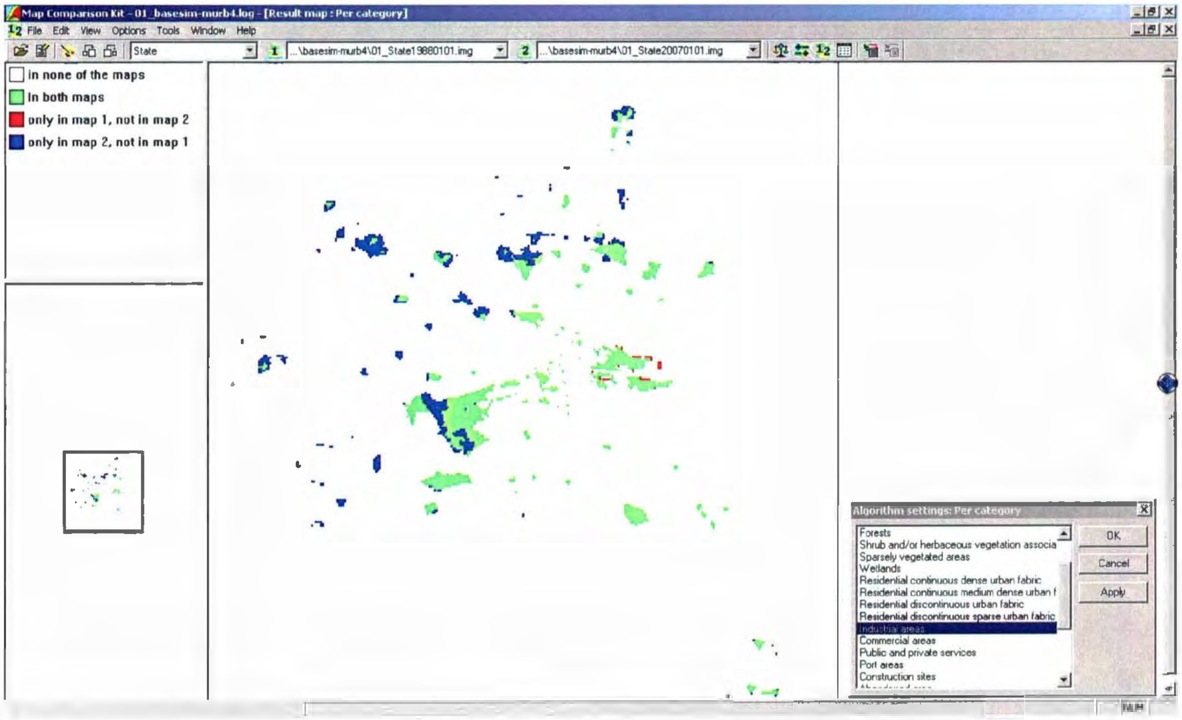


Figure 17 "Business as Usual" scenario: Industrial land use comparison between the years of 1988 and 2007. Green represents the cells common to both maps; red for cells only present in the 1988 land use map; blue for cells only present in the 2007 land use map. Results shown represent a single run.

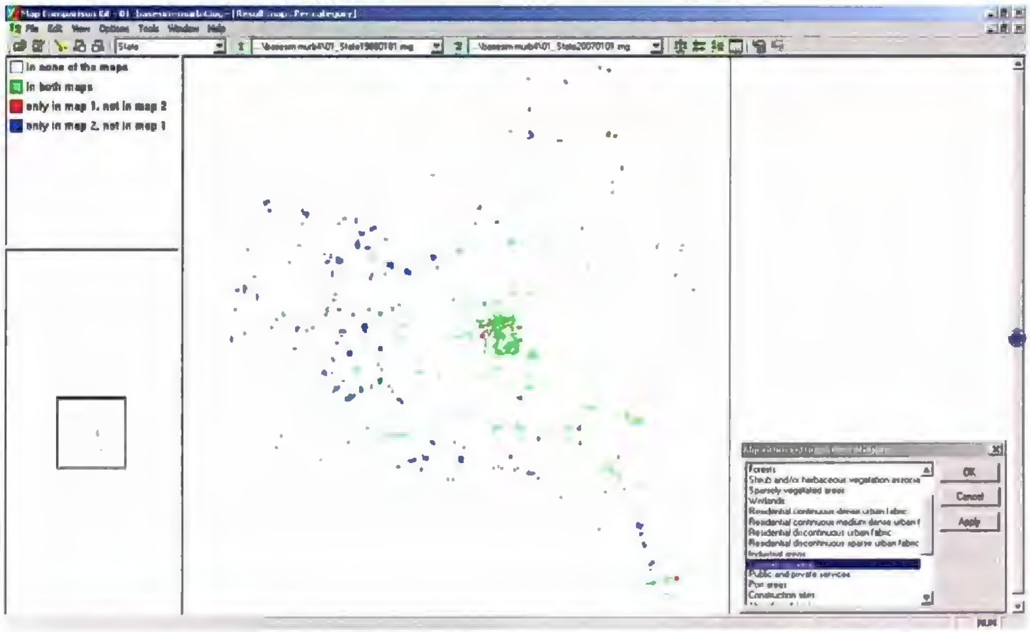


Figure 18 “Business as Usual” scenario: Commercial land use comparison between the years of 1988 and 2007. Green represents the cells common to both maps; red for cells only present in the 1988 land use map; blue for cells only present in the 2007 land use map. Results shown represent a single run.

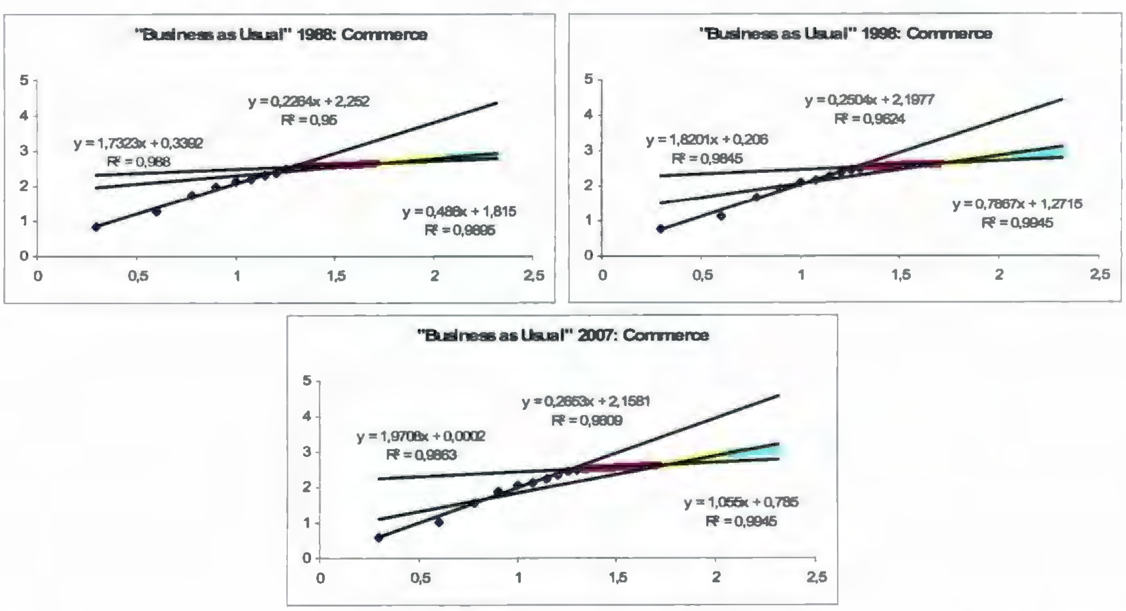


Figure 20 “Business as Usual” scenario: radial fractal dimension graphs for commerce for 1988, 1998 and 2007.

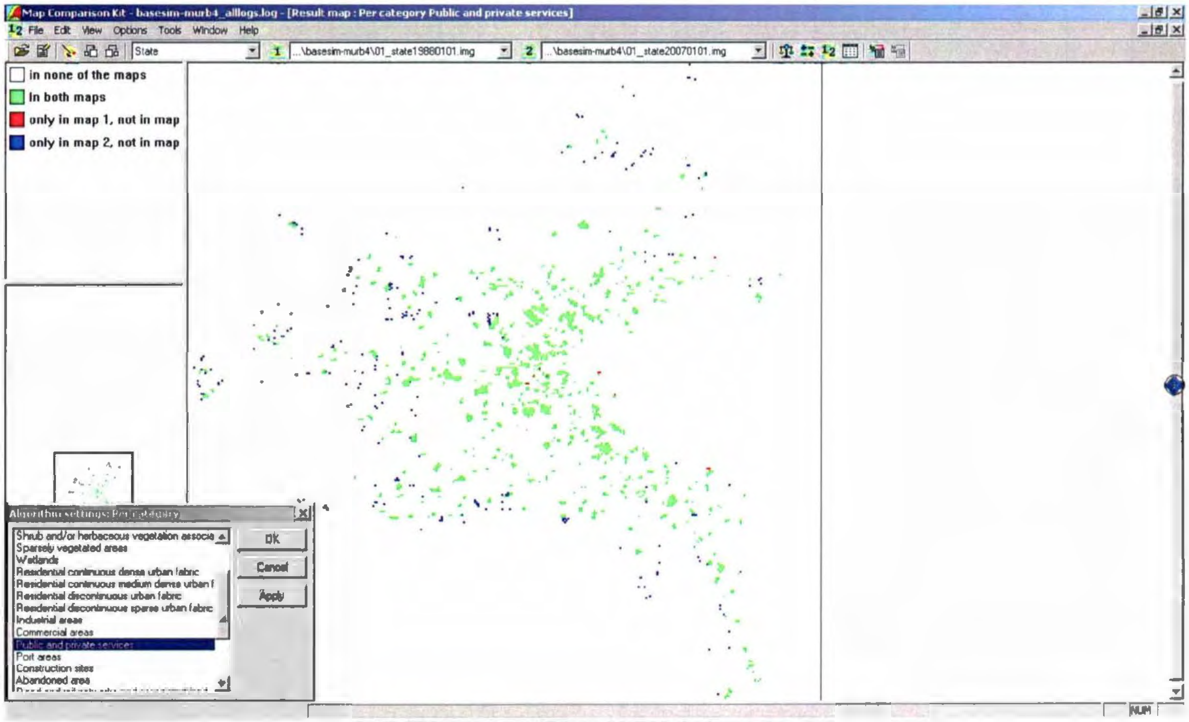


Figure 21 "Business as Usual" scenario: Public and Private Services land use comparison between the years of 1988 and 2007. Green represents the cells common to both maps; red for cells only present in the 1988 land use map; blue for cells only present in the 2007 land use map. Results shown represent a single run.

5.1.1.3. Cluster size-frequency fractal analysis

Considering their relevancy, only the land uses for Industry, Commerce and Public and Private Services were analysed in terms of their fractal cluster size-frequency measure. No cluster size graphs were found to be relevant for residential land use.

All these three land uses saw their cluster size-frequency fractal dimension decrease slightly at the end of the simulation period. This decline was not, however, linear. Private

Services displayed a concave behaviour while Commerce's curve, on the other, hand, showed a convex evolution. Only industry revealed a steady, though slow, decrease.

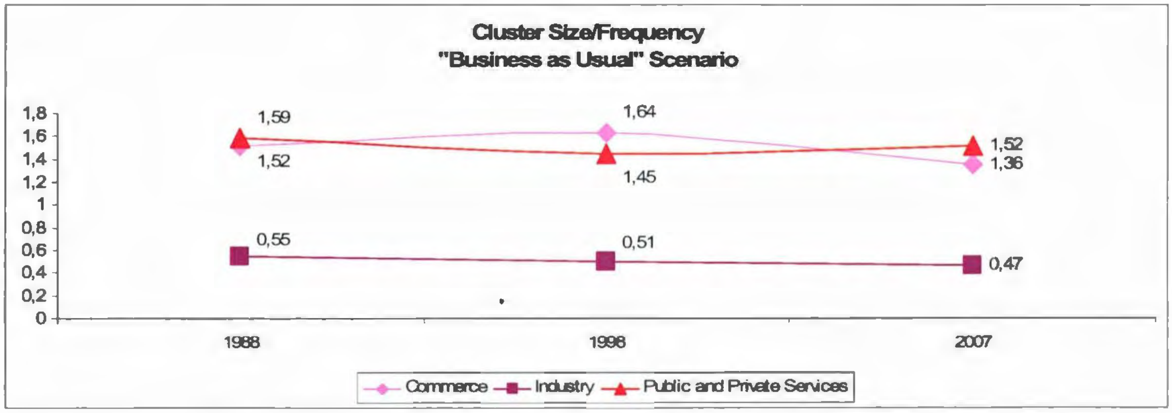


Figure 22 "Business as Usual" scenario: cluster size-frequency dimensions for Commerce, Industry and Public and Private Services for 1988, 1998 and 2007.

The evolution of Commerce clusters is toward the creation of a unique larger industrial cluster separated by a gap from mid-sized and smaller ones. Industry shows a tendency to increase its middle-sized clusters while maintaining the size of the larger ones. Public and Private Services' ones, on the other hand, are more stable when they evolve, and still maintain the size-frequency relationship.

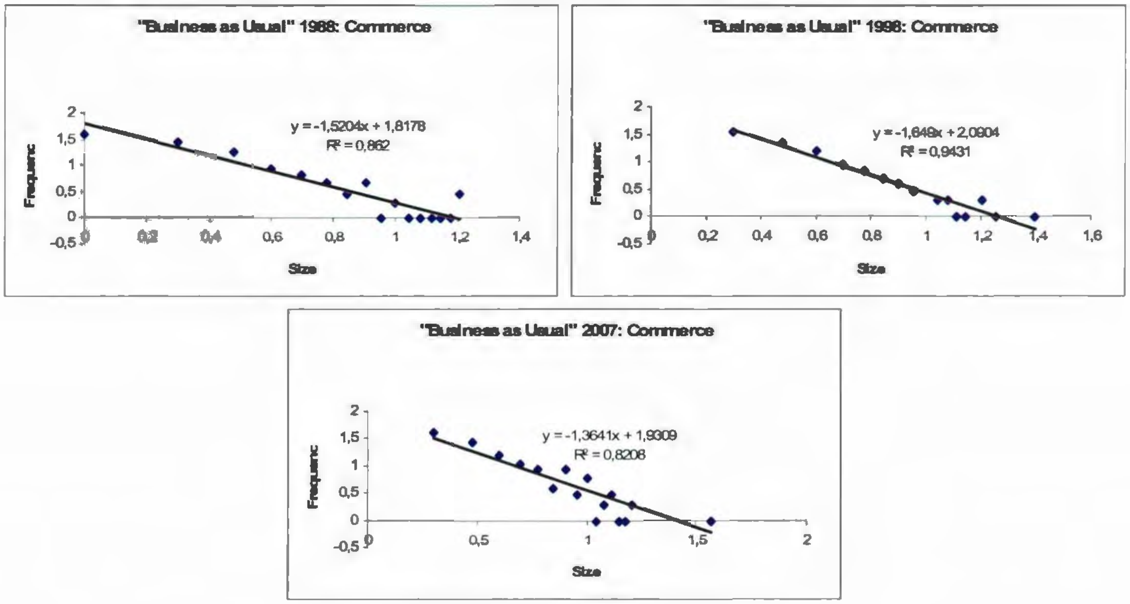


Figure 23 "Business as Usual" scenario: fractal cluster size-frequency graphs for Commerce in 1988, 1998 and 2007.

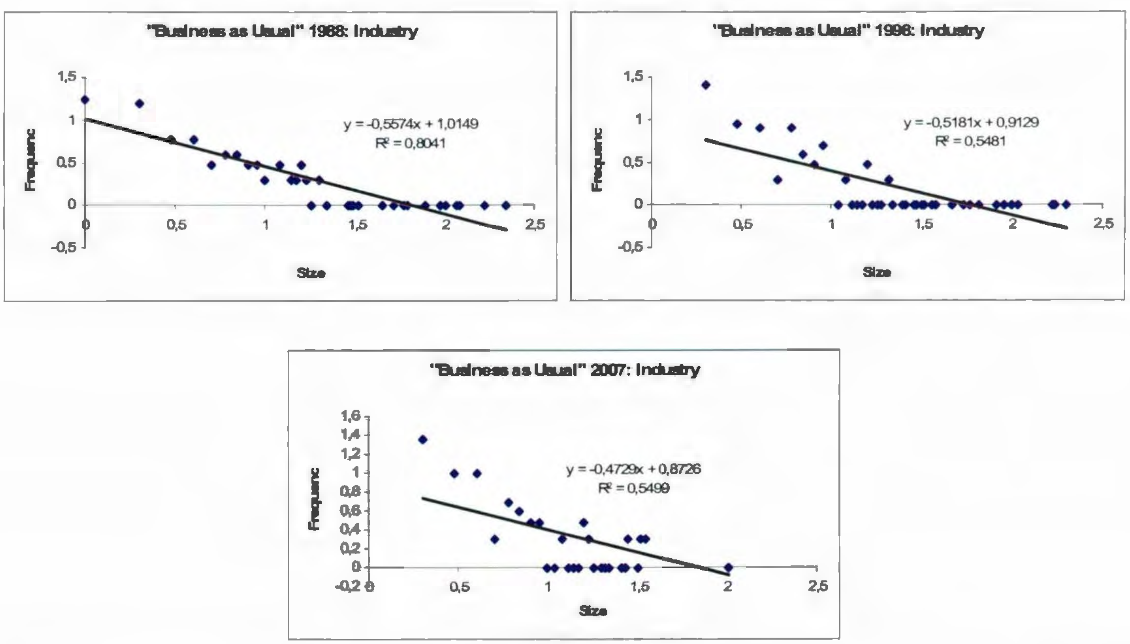


Figure 24 "Business as Usual" scenario: Fractal cluster size-frequency graphs for Industry in 1988, 1998 and 2007.

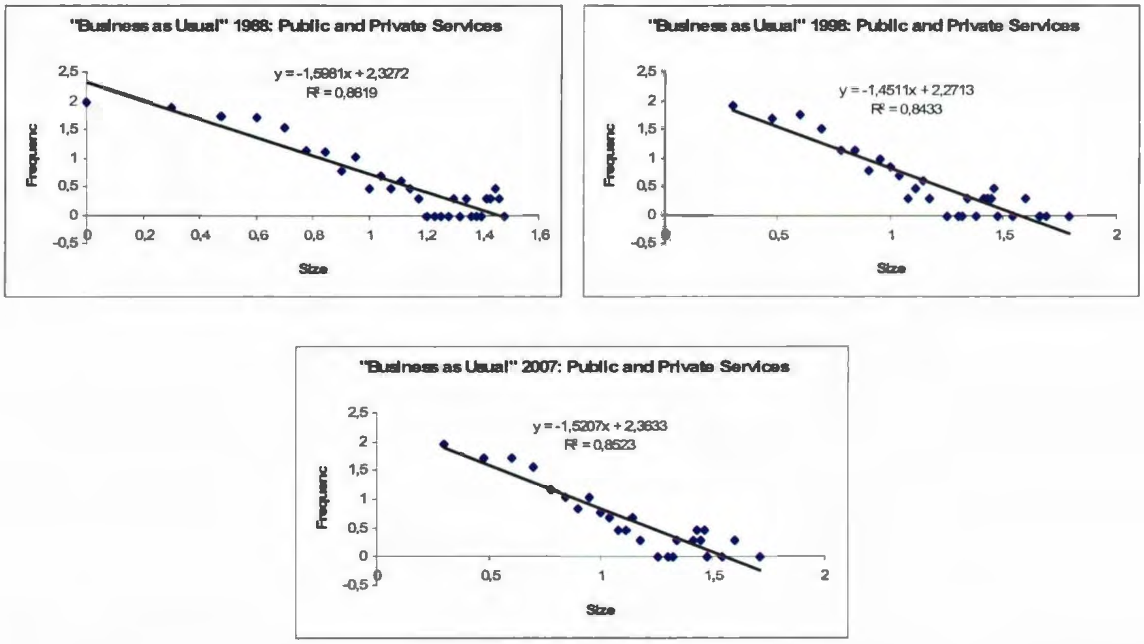


Figure 25 "Business as Usual" scenario: Fractal cluster size-frequency graphs for Public and Private Services in 1988, 1998 and 2007.

5.1.1.4. FRAGSTATS measurements

The evolution of the modeled region in terms of Total Edge (TE) metrics is stable throughout the entire simulation period. This trend is not, however, in agreement with the Perimeter-Area Fractal Dimension (PAFRAC) results.. All land uses saw their TE values increase with time as a consequence of continual cell growth (Fig. 25). As to their PAFRAC results, all analysed land uses showed a tendency to assume a simpler shape with the exception of the residential continuous dense land use, which evolved a more complex shape (Figure). However the urbanized area (all urban land uses combined seemed to show a cycle of complexity as measured by the PAFRAC dimension (Fig. 24).

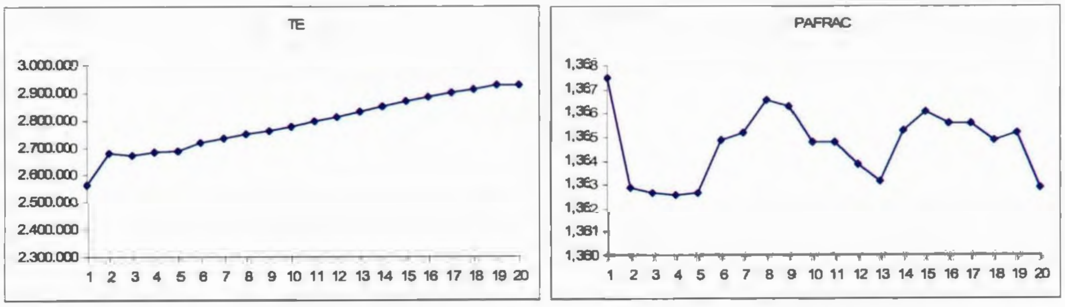


Figure 26 "Business as Usual" scenario: Total Edge and PAFRAC metrics for all urban land uses combined from 1988 to 2007.

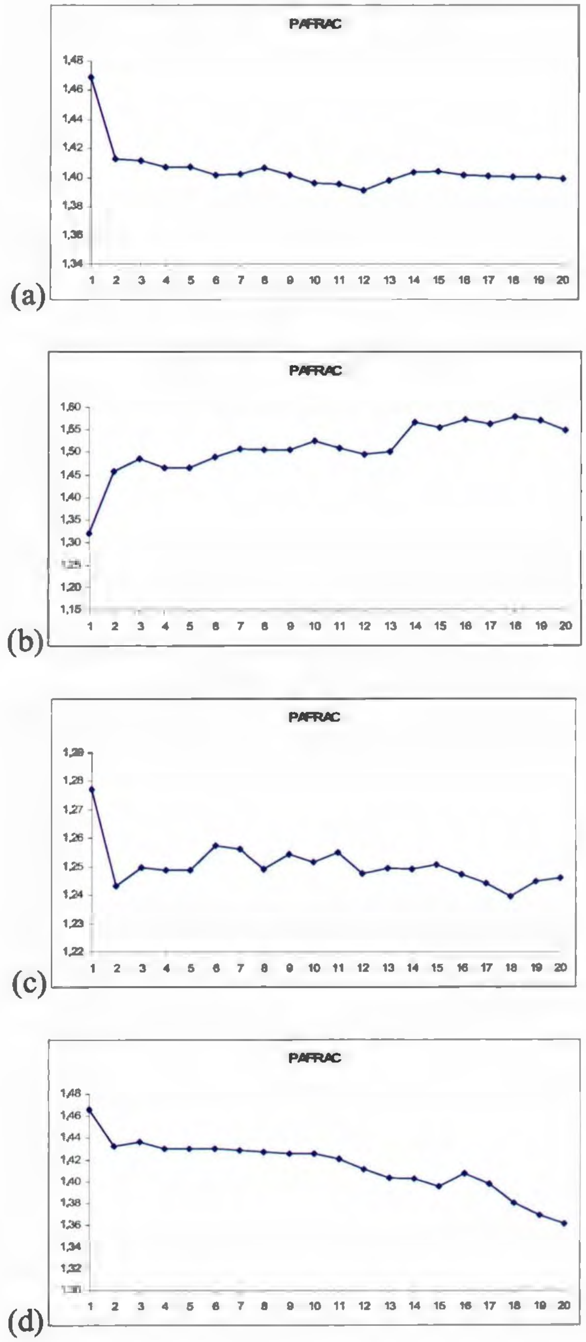


Figure 27 "Business as Usual" scenario: PAFRAC metrics for (a) Residential Discontinuous Sparse, (b) Residential Continuous Dense, (c) Industry and (d) Commerce, from 1988 to 2007.

5.1.2. "Single Expansion Zone"

5.1.2.1. Overall urban land use behaviour

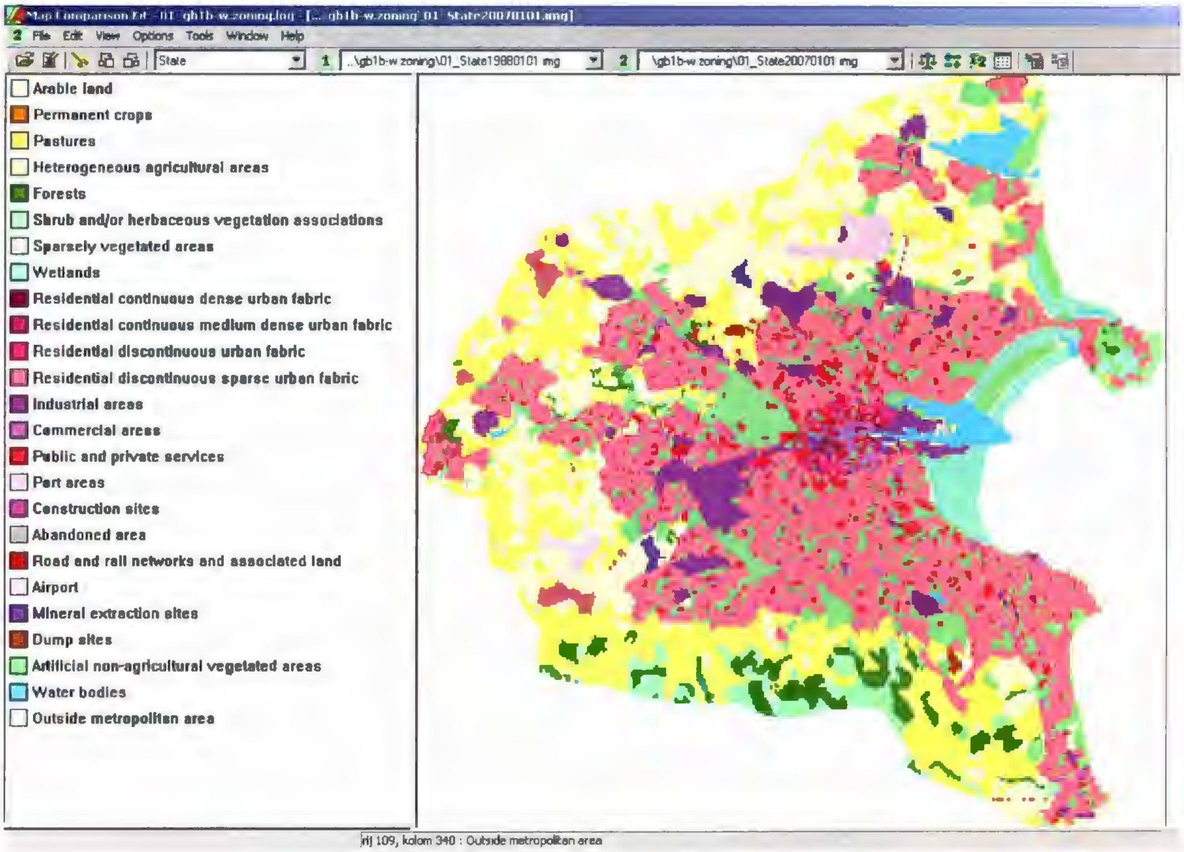


Figure 28 "Single Expansion Zone" scenario: land use map for 2007. Results shown represent a single run.

The imposition of a single expansion zone for all urban growth has led to an obviously more compact urban shape. Spontaneous growth in vacant areas was completely prevented, forcing the new growth into the belt around the existing urban fringe where development is permitted.

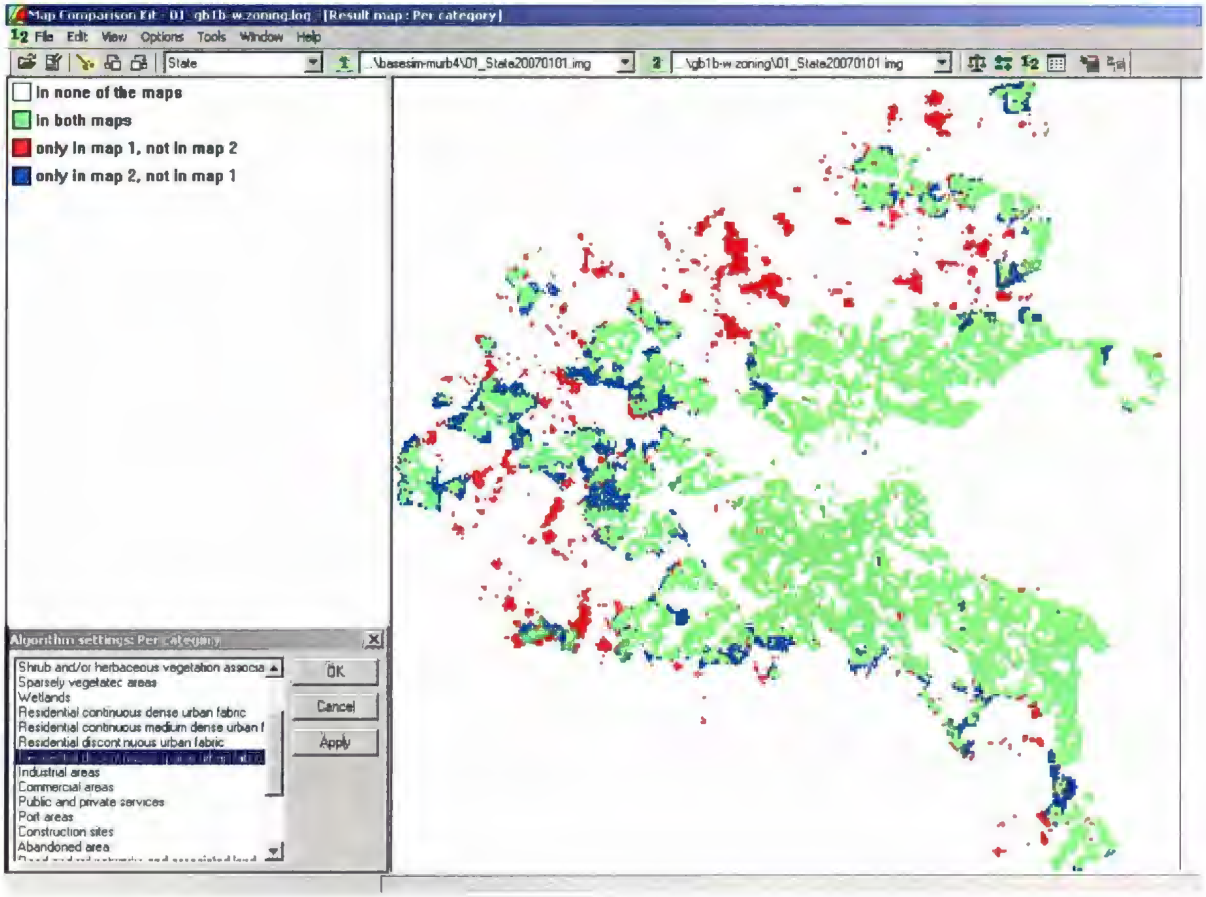


Figure 29 Category comparison of Residential Discontinuous Sparse land use for 2007. Map 1 (red) is the "Business as Usual" scenario. Map 2 (blue) is the "Single Expansion Zone" scenario. Results shown represent a single run.

5.1.2.2. Radial fractal analysis

The "Single Expansion Zone" scenario yielded a decrease in the radial fractal measurements of all three zones for overall Urban Land Use. The same occurred with the Residential Discontinuous Sparse land use category, with the minor difference that the Third Zone values increased in 1998, unlike the global Urban Land Use. Combined

Residential radial analysis revealed opposite behaviours between the Inner Zone and the Outer and Third Zones. The Inner Zone values decreased while the other two increased. Industrial Outer Zone radial values increased while decreasing in the other two zones. Commercial's figures increased in time for all zones while Public and Private Services was relatively stable, showing only small increases in the Third Zone. Since the pattern of growth is so highly constrained, the radial dimensions are not very useful in this case, and the graphs are not shown.

5.1.2.3. Cluster size-frequency fractal analysis

Industry and Public and Private Services see their cluster size-frequency fractal dimension decrease towards the end of the simulation period. The difference is more pronounced in the case of the former. Commerce ends with the same value with which it started, although a minimal increase is observed in the middle of the run.

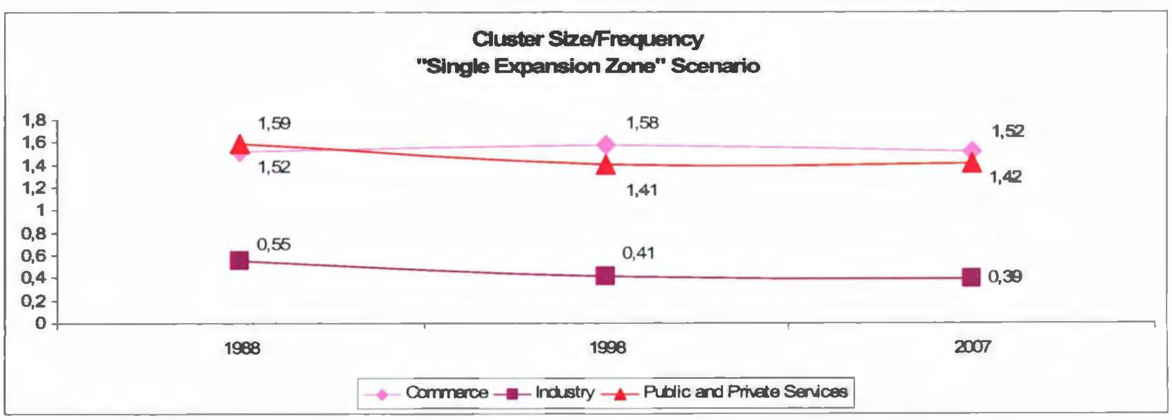


Figure 30 "Single Expansion Zone" scenario: cluster size-frequency graph lines for Commerce, Industry and Public and Private Services for 1988, 1998 and 2007.

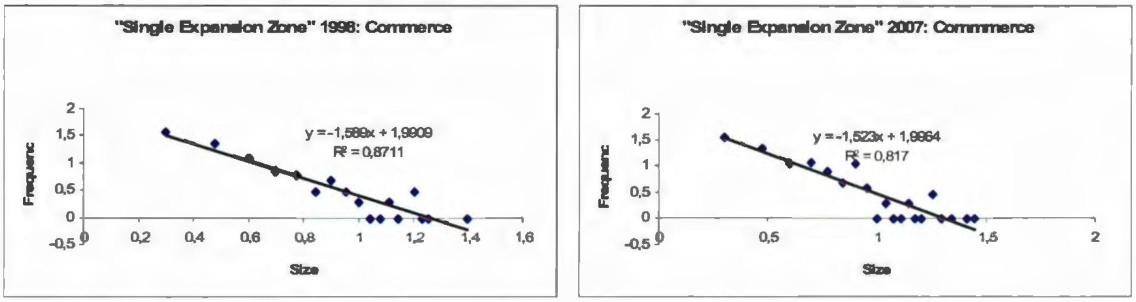


Figure 31 "Single Expansion Zone" scenario: cluster size-frequency fractal measure for Commerce for 1998 and 2007.

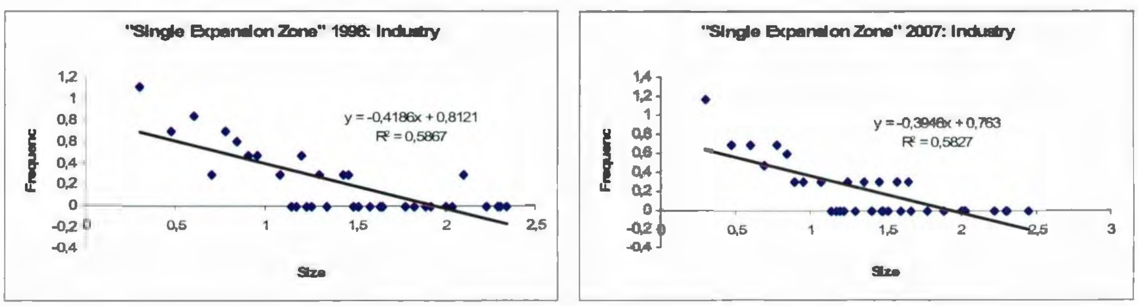


Figure 32 "Single Expansion Zone" scenario: cluster size-frequency fractal measure for Industry for 1998 and 2007.

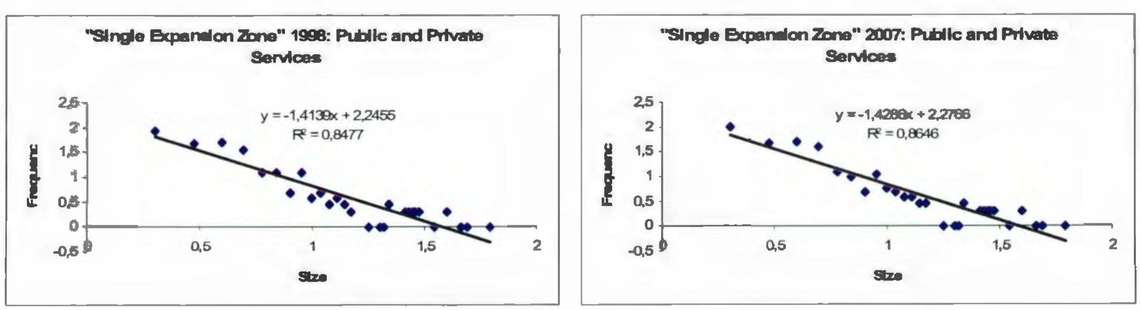


Figure 33 "Single Expansion Zone" scenario: cluster size-frequency fractal measure for Public and Private Services for 1998 and 2007.

The Single Expansion Zone scenario yielded no significant changes in the cluster size-frequency values for the most significant land uses for this fractal measurement.

5.1.2.4. *FRAGSTATS measurements*

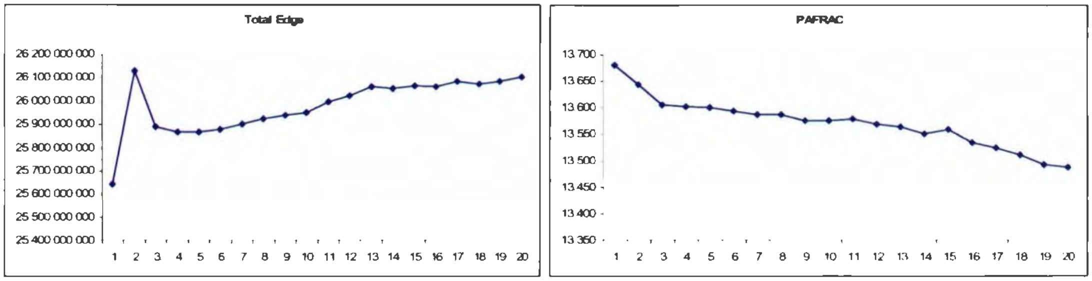


Figure 34 "Single Expansion Zone" scenario: Total Edge and PAFRAC metrics for all urban land uses combined from 1988 to 2007.

The application of a single growth expansion belt resulted in an enlarged and more simply shaped urban land use pattern, mirrored by an increase in the Total Edge values, and accompanied by a gradual decrease of PAFRAC figures. Total Edge values increased as a result of the cell demand file, set to model overall urban growth.

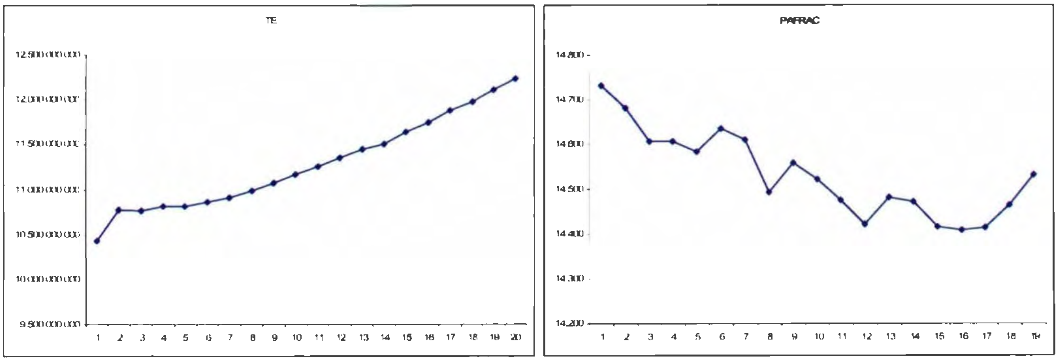


Figure 35 "Single Expansion Zone" scenario: Total Edge and PAFRAC metrics for Residential Discontinuous Sparse land use from 1988 to 2007.

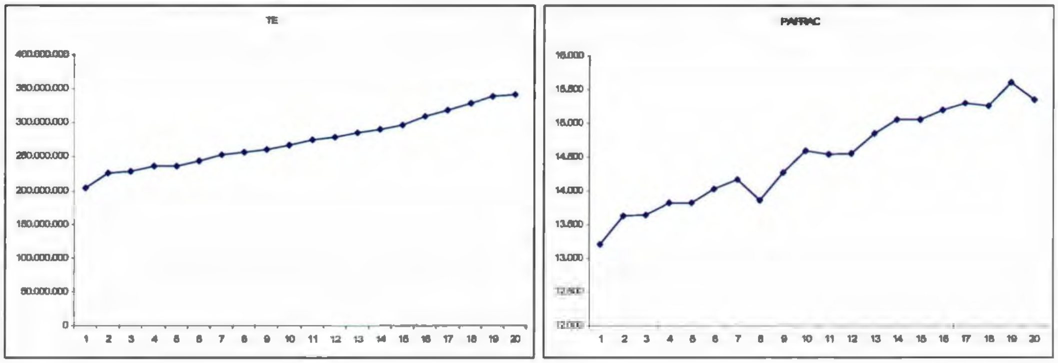


Figure 36 "Single Expansion Zone" scenario: Total Edge and PAFRAC metrics for Residential Continuous Dense land use from 1988 to 2007.

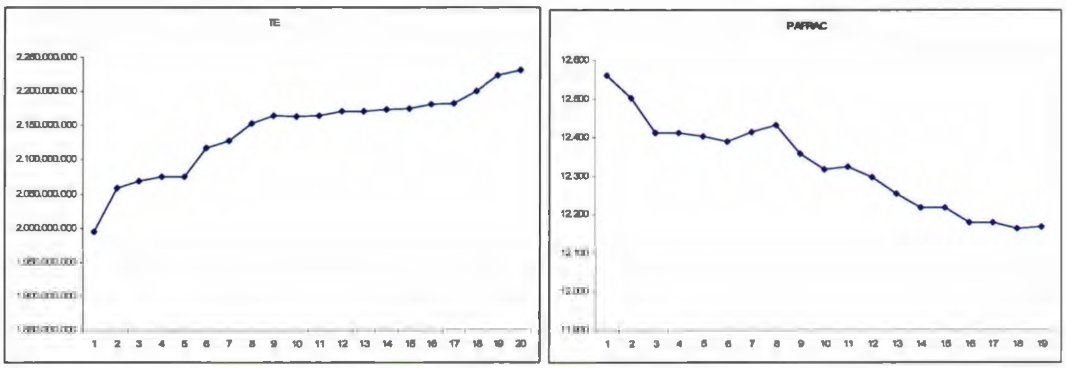


Figure 37 "Single Expansion Zone" scenario: Total Edge and PAFRAC metrics for Industry from 1988 to 2007.

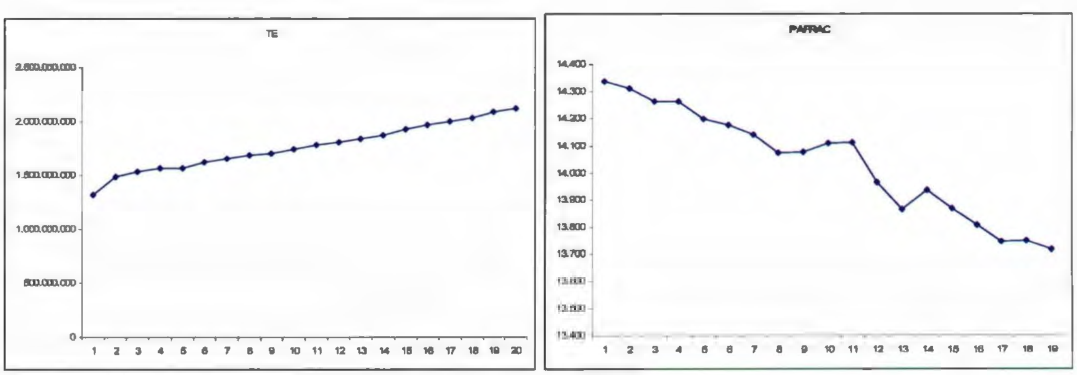


Figure 38 "Single Expansion Zone" scenario: Total Edge and PAFRAC metrics for Commerce from 1988 to 2007.

The Residential Continuous Dense urban land use has evolved throughout the simulations, in spite of minor fluctuations, towards a significantly more complex shape according to the PAFRAC measue. The same trend was present in the business as usual scenario, but was much weaker. The same, however, has not happened in its counterpart land use – Discontinuous Sparse residential. The industrial and commercial urban land uses have both evolved into simpler urban shapes by the PAFRAC measure.

5.1.3. "Phased Growth"

5.1.3.1. Overall urban land use behaviour

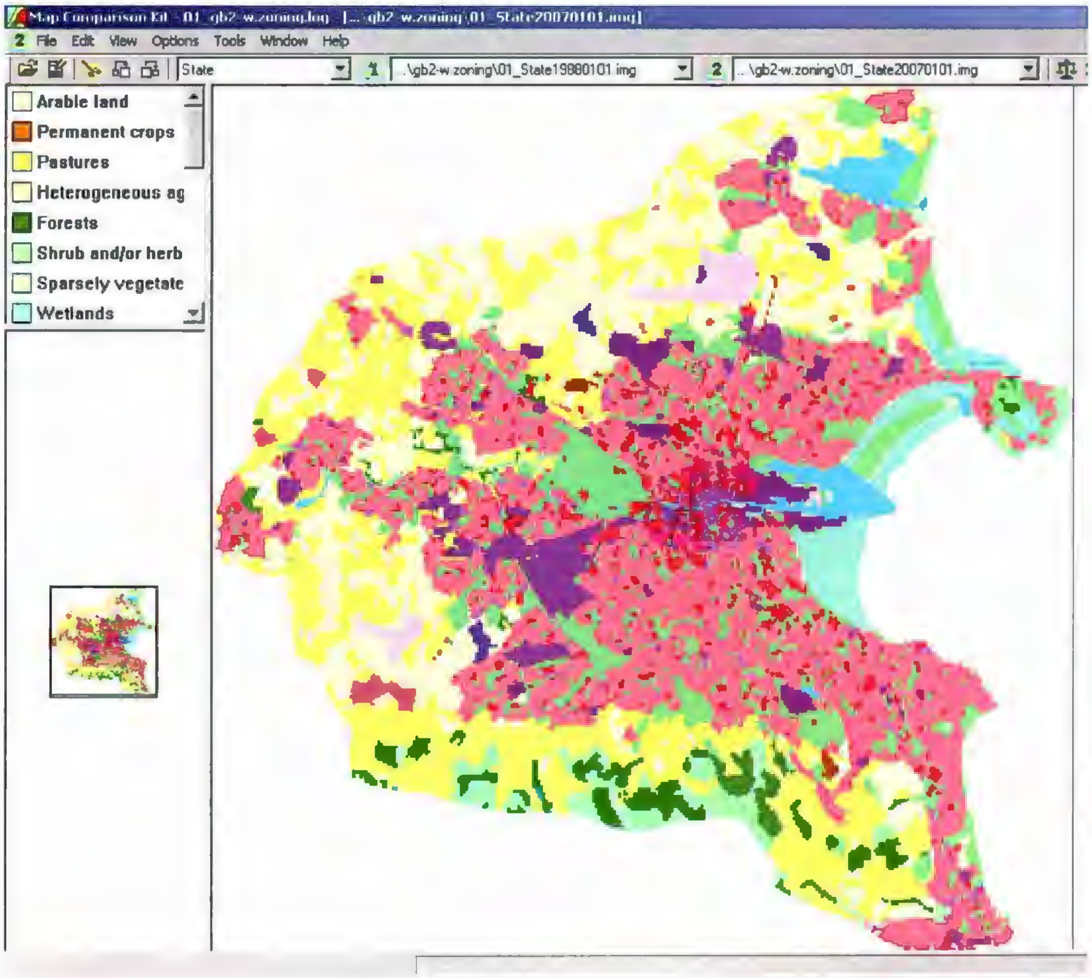


Figure 39 "Phased growth" scenario: land use for 2007. Results shown represent a single run.

The resulting overall urban form is similar to the one generated by the scenario using a single expansion belt, as the used vacant cells were the same. The Fuzzy Kappa map comparison between the "Business as Usual" and the phased growth scenarios reveals no significant differences compared to the "Single Expansion Zone" scenario. However, when comparing the "Single Expansion Zone" and the "Phased Growth" scenarios (Fig. 38), a visible area of dissimilarity can be observed where the industrial land use dynamics presented some changes in its location behaviour as shown in Figures 39 and 40: the blue areas in these maps representt cells that developed as industrial areas in the phased growth scenario but not in either of the other two. For other land uses, differences between the two scenarios was minimal.

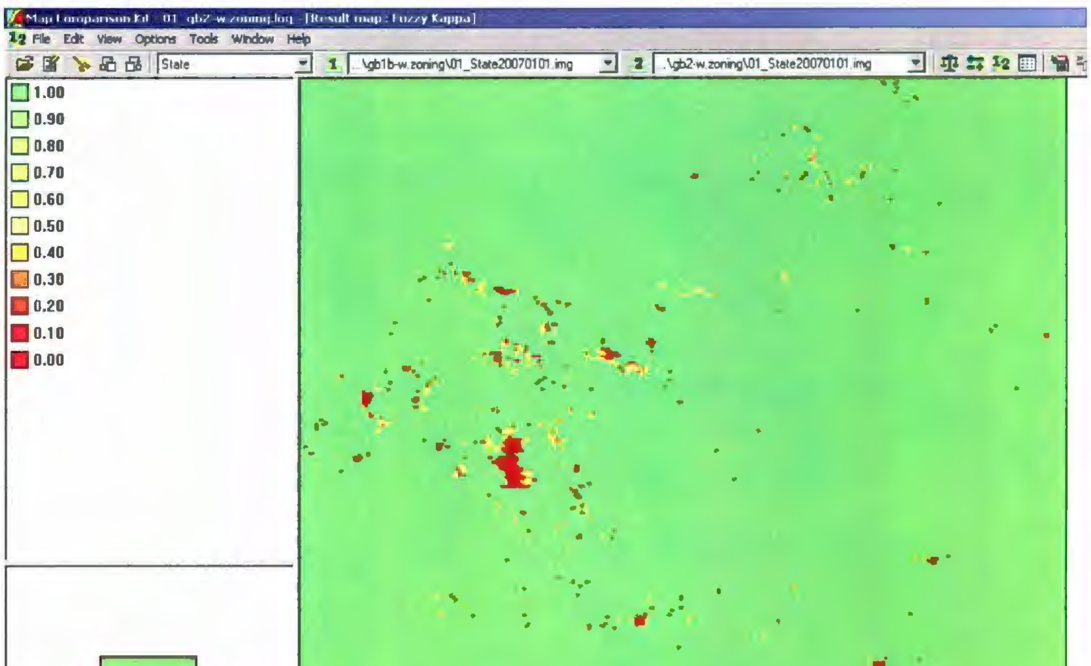


Figure 40 Fuzzy Kappa comparison between the "Single Expansion Zone" and the "Phased Growth" scenarios for the last modeled year. Results presented in gradient from green to red. Green represents highly similar and red highly dissimilar areas. The large red area in the lower right corner should be disregarded; it is an artefact of the software. Results shown represent a single run.

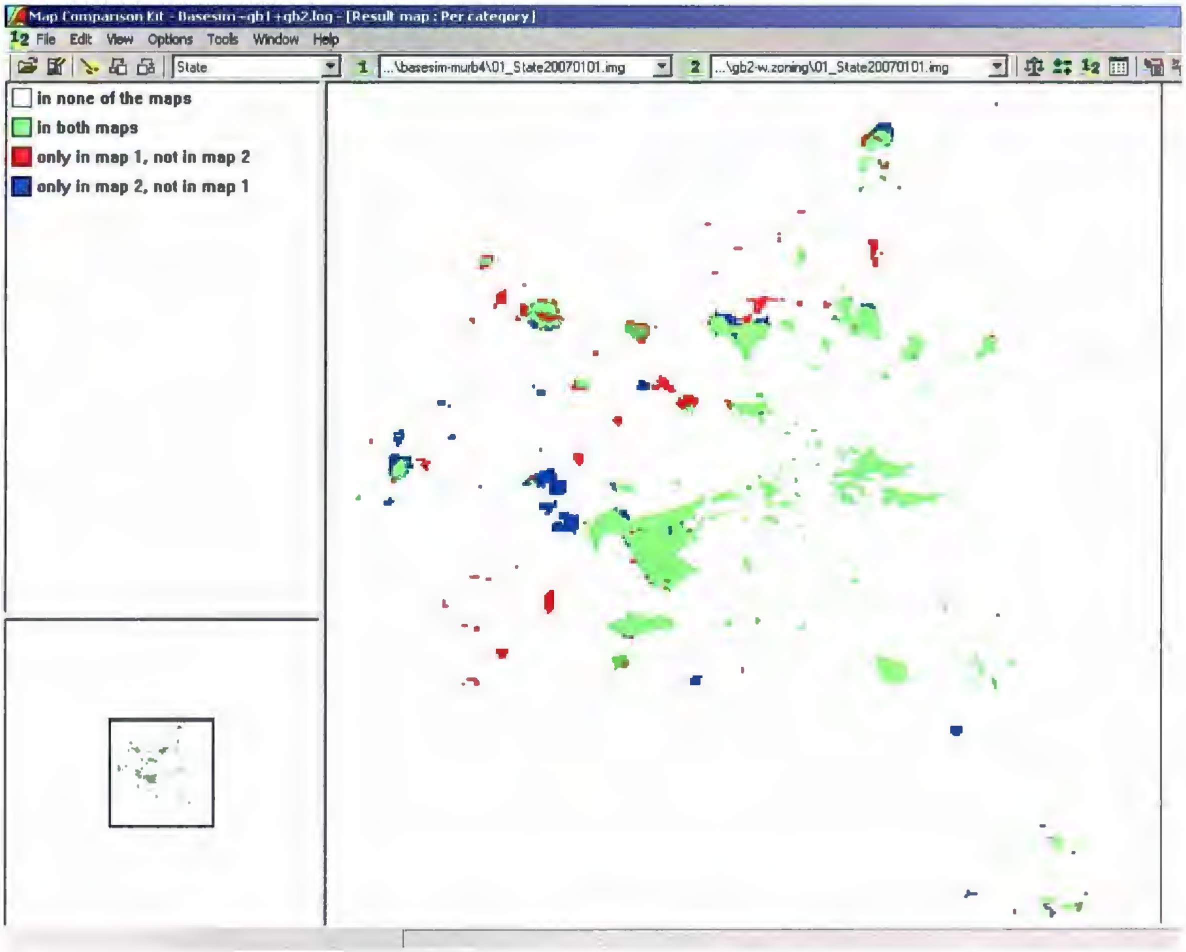


Figure 41 Category comparison of Industry land use for 2007. Map 1 (red) is the "Business as Usual" scenario. Map 2 (blue) is the "Phased Growth" scenario. Results shown represent a single run.

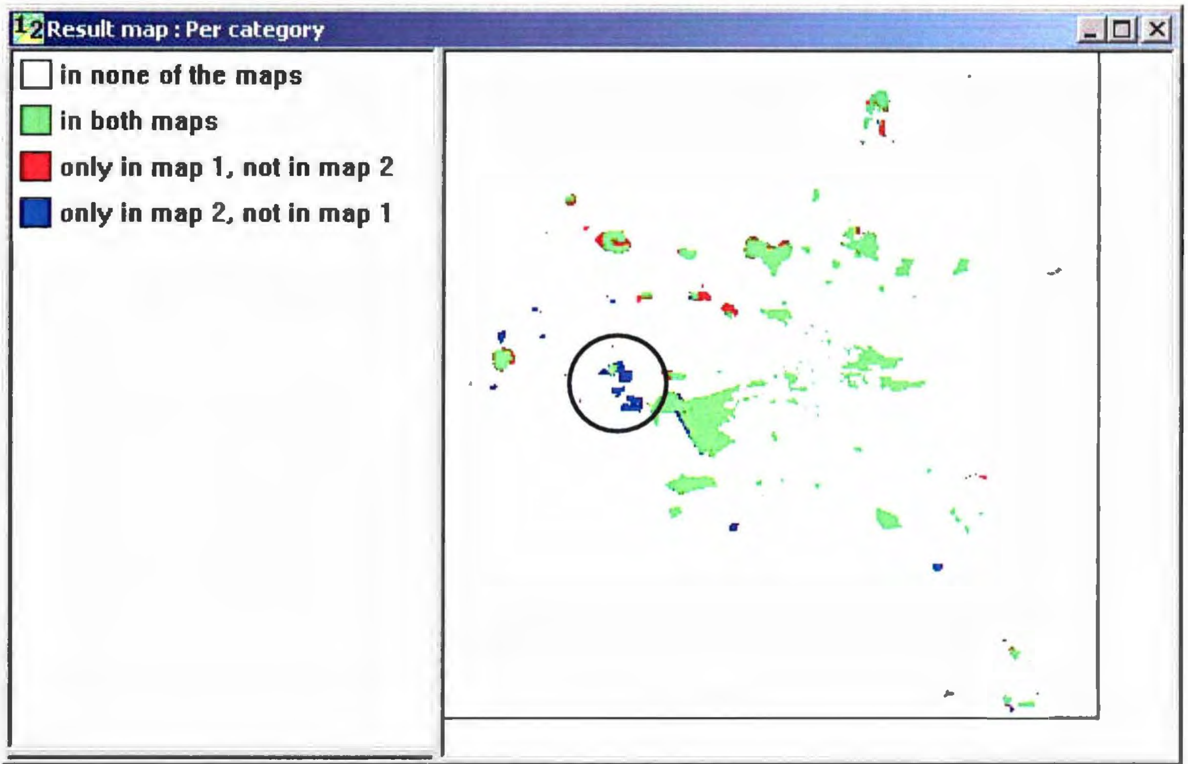


Figure 42 Category comparison of Industry land use for 2007. Map 1 (red) is the "Single Expansion Zone" scenario. Map 2 (blue) is the "Phased Growth" scenario. Results shown represent a single run.

5.1.3.2. Radial fractal analysis

In the phased growth scenario all land uses exhibited only small changes in their radial fractal measurements. The Inner Zone dimensions remained practically unaltered. The same behaviour is observed in the Outer Zone values with the exception of the value for the combined residential category, which increased somewhat. This was responsible for a similar increase in the value of the radial dimension of the urbanized area (all urban land uses combined). Combined residential land use was also characterized by an increasing radial dimension in the Third Zone, possibly due primarily to the growth of Discontinuous Sparse residential land use in this zone. Commerce and Public and Private Services also saw their radial dimensions increase in this zone.

5.1.3.3. Cluster size-frequency fractal analysis

Between 1998 and 2007 Industry and Public and Private land uses remained practically static in their cluster size-frequency distributions. Their commercial counterpart, however, saw its dimension decrease as a result of the increase in the number of larger clusters.

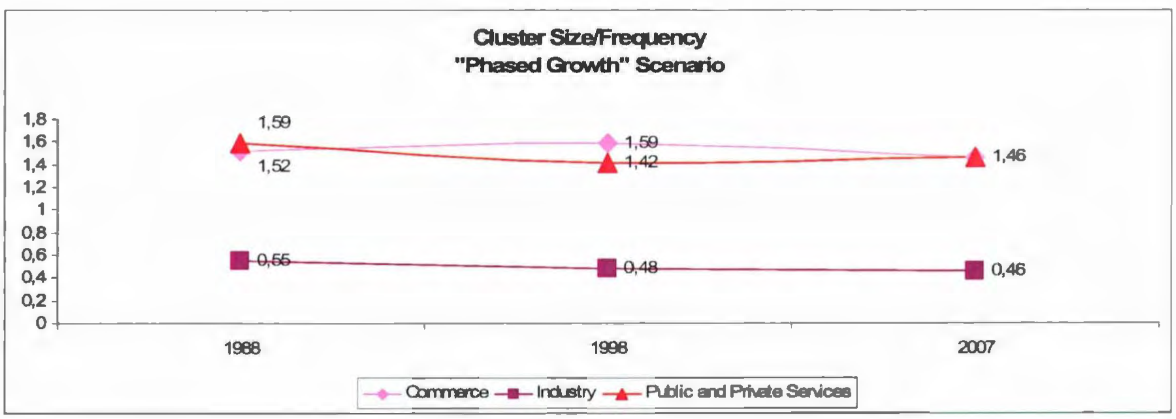


Figure 43 "Phased Growth" scenario: cluster size-frequency graph lines for Commerce, Industry and Public and Private Services for 1988, 1998 and 2007.

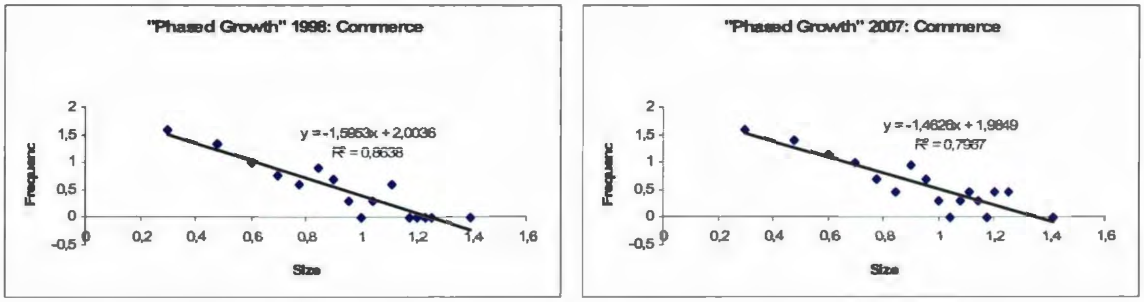


Figure 44 "Phased Growth" scenario: cluster size-frequency fractal measure for Commerce for 1998 and 2007.

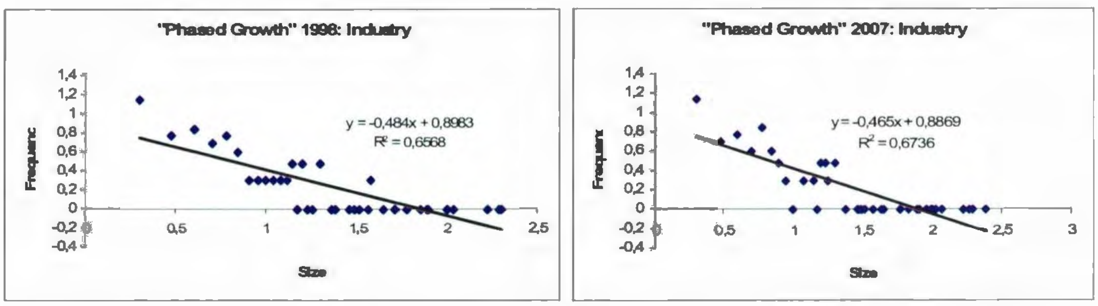


Figure 45 "Phased Growth" scenario: cluster size-frequency fractal measure for Industry for 1998 and 2007.

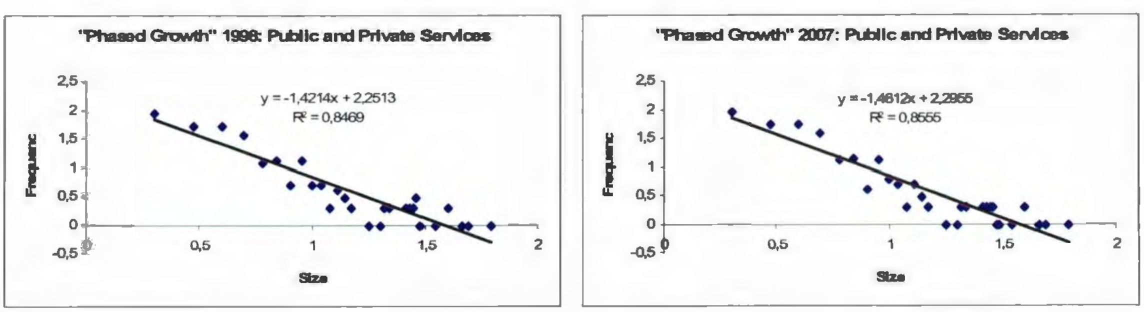


Figure 46 "Phased Growth" scenario: cluster size-frequency fractal measure for Public and Private Services for 1998 and 2007.

5.1.3.4. FRAGSTATS measurements

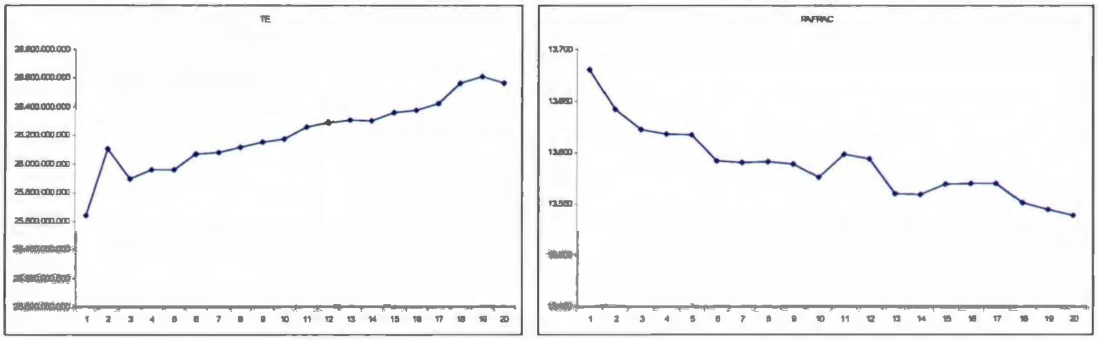


Figure 47 Phased Growth" scenario: Total Edge and PAFRAC metrics for all urban land uses combined from 1988 to 2007.

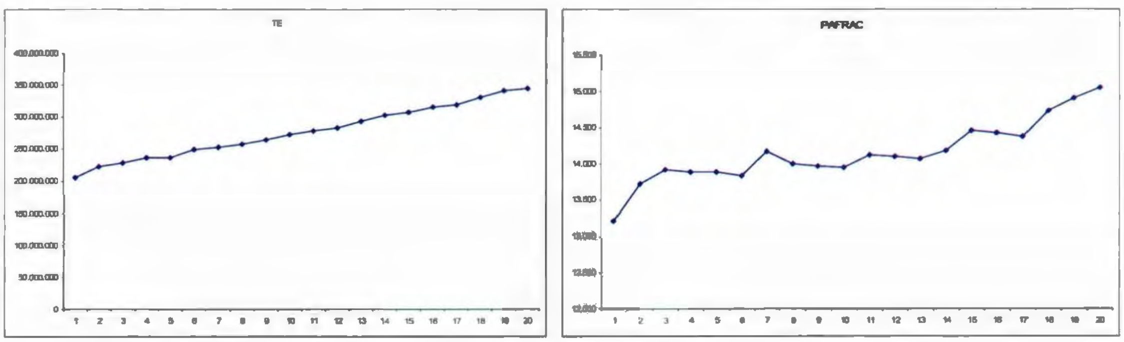


Figure 48 Phased Growth" scenario: Total Edge and PAFRAC metrics for Residential Continuous Dense from 1988 to 2007.

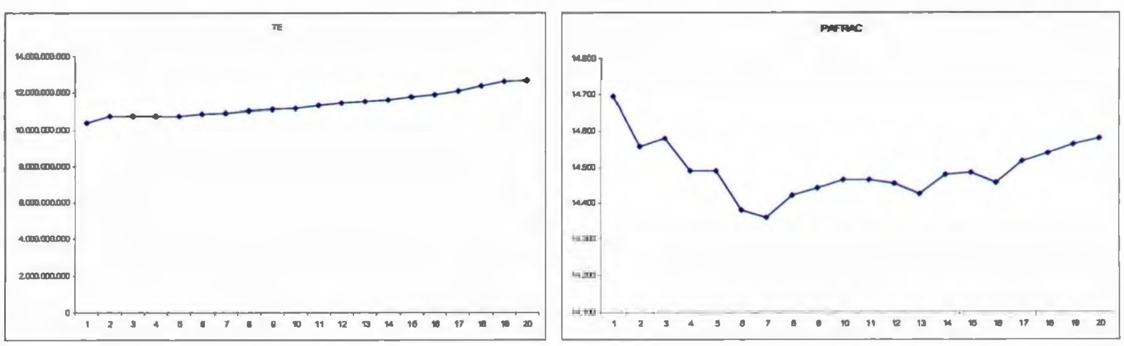


Figure 49 Phased Growth" scenario: Total Edge and PAFRAC metrics for Residential Discontinuous Sparse from 1988 to 2007.

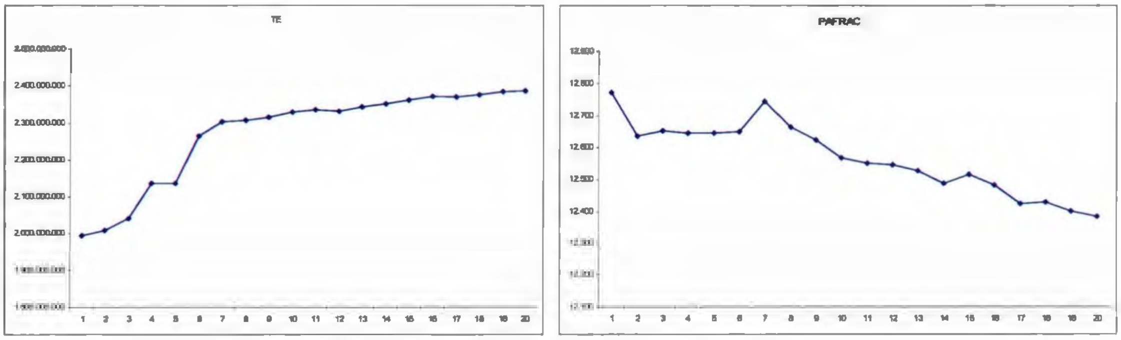


Figure 50 Phased Growth" scenario: Total Edge and PAFRAC metrics for Industry from 1988 to 2007.

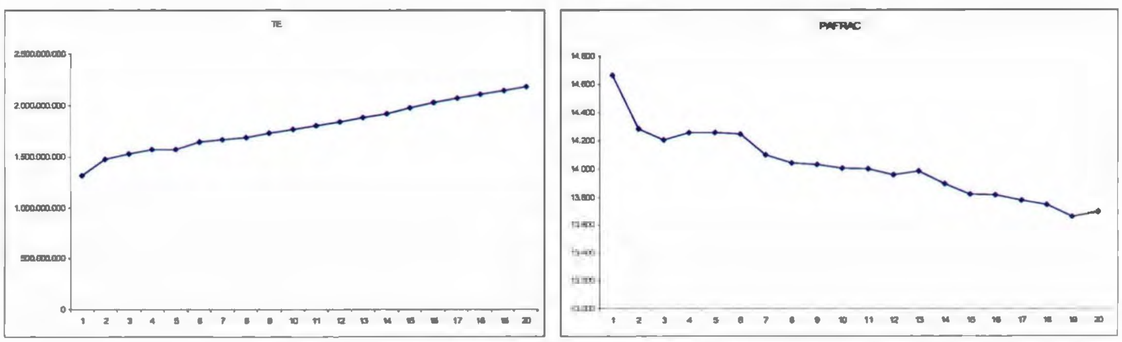


Figure 51 Phased Growth" scenario: Total Edge and PAFRAC metrics for Commerce from 1988 to 2007.

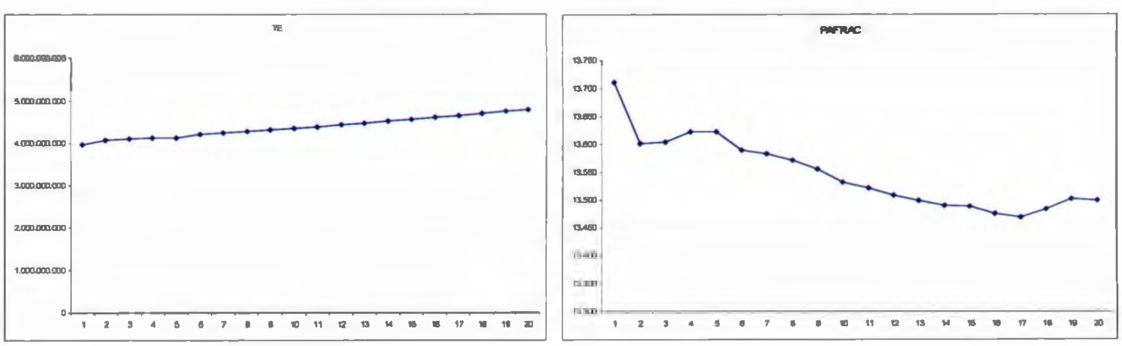


Figure 52 Phased Growth" scenario: Total Edge and PAFRAC metrics for Public and Private Services from 1988 to 2007.

Dublin, under this scenario, overall, evolved a larger but simpler urban shape. Industry, Commerce and Public and Private Services all evolved to simpler shapes whereas the residential land uses became more convoluted in time. Of special note is the Discontinuous Sparse residential land use which, one third of the way through the simulation run, reversed its trend toward a simpler form to begin evolving toward a more complex urban form. Industry's sudden jump in Total Edge metrics early in the simulation period was followed immediately by a small and temporary increase in the PAFRAC metric.

5.1.4. "Greenbelt Just Around Dublin"

5.1.4.1. *Overall urban land use behaviour*

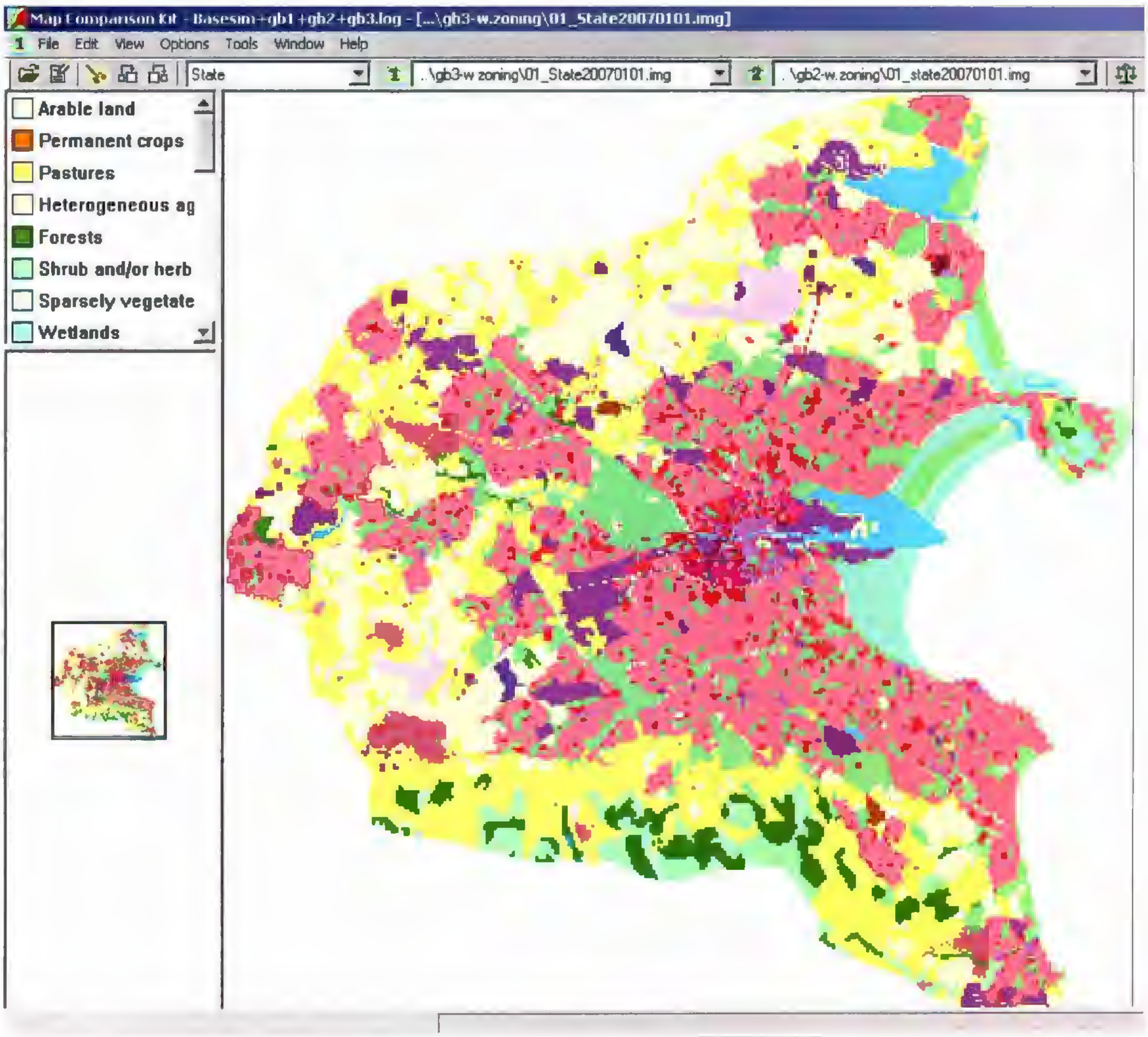


Figure 53 "Greenbelt Just Around Dublin" scenario: land use map for 2007. Results shown represent a single run.

Although constraints were applied solely to the Dublin City built area, the resulting urban expansion was mostly on the urban fringe. Scattered growth was practically nonexistent.

However the Public and Private Services land use tended to scatter more in the outlying urban areas, creating smaller clusters in the peripheral zones and bigger clusters as it approached the city core.

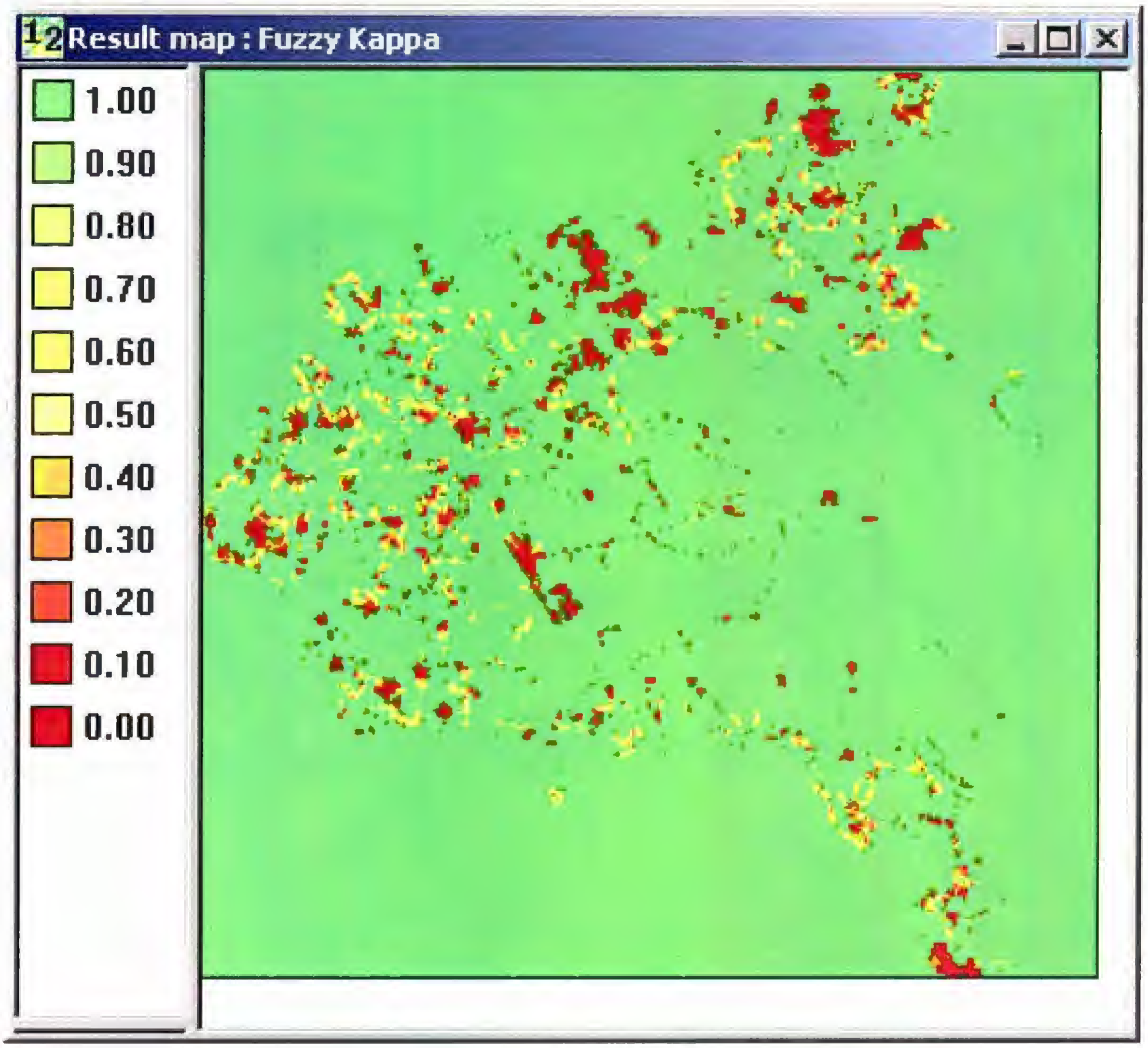


Figure 54 Fuzzy Kappa comparison between the "Business as Usual" and the "Greenbelt Just Around Dublin City" scenarios. Green represents highly similar cells. Red represents highly dissimilar cells. Yellow represents cells of intermediate similarity. Results shown represent a single run.

The application of a greenbelt surrounding the entire Dublin City built landscape has created a new land use map with very dissimilar peripheral areas. These differences are achieved mostly with the new aggregation dynamics of Discontinuous Sparse residential and Industry. No significant changes are observed in the commercial land use dynamics. All new commercial cells exhibit the same location pattern outside the protective greenbelt.

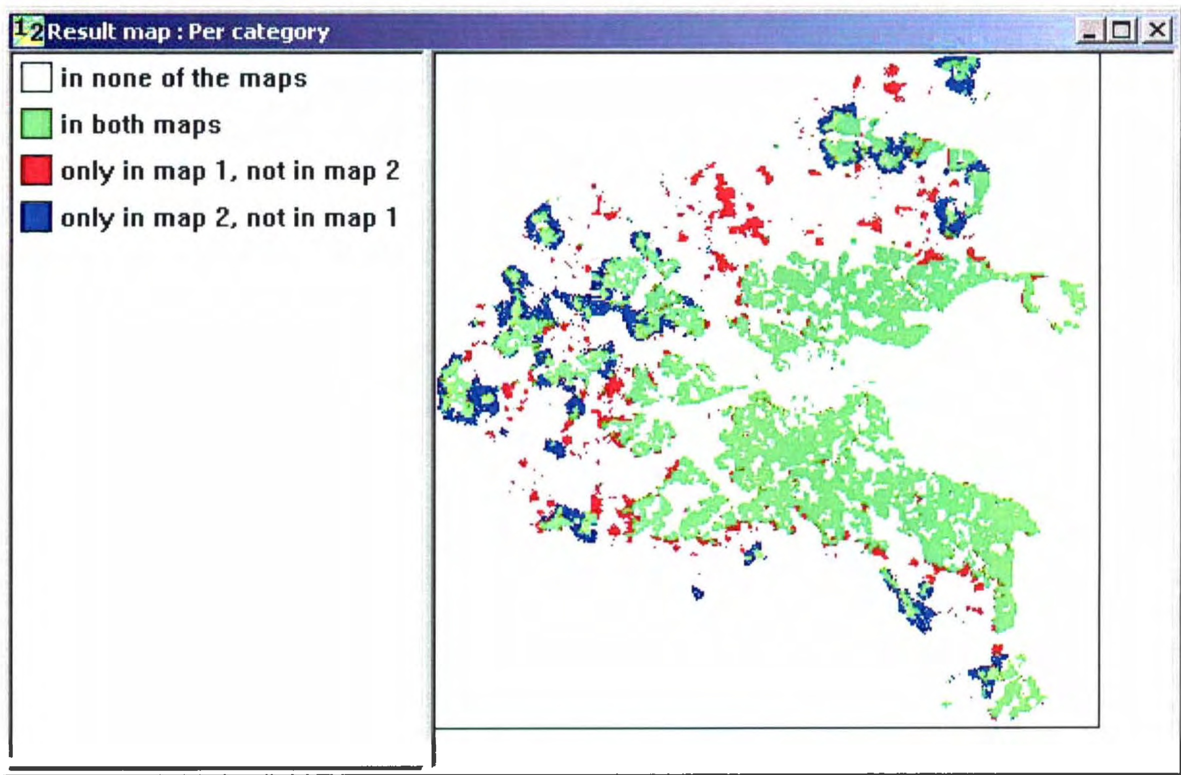


Figure 55 Category comparison of Residential Discontinuous Sparse land use for 2007. Map 1 (red) is the "Business as Usual" scenario. Map 2 (blue) is the "Greenbelt Around Dublin City" scenario. Results shown represent a single run.

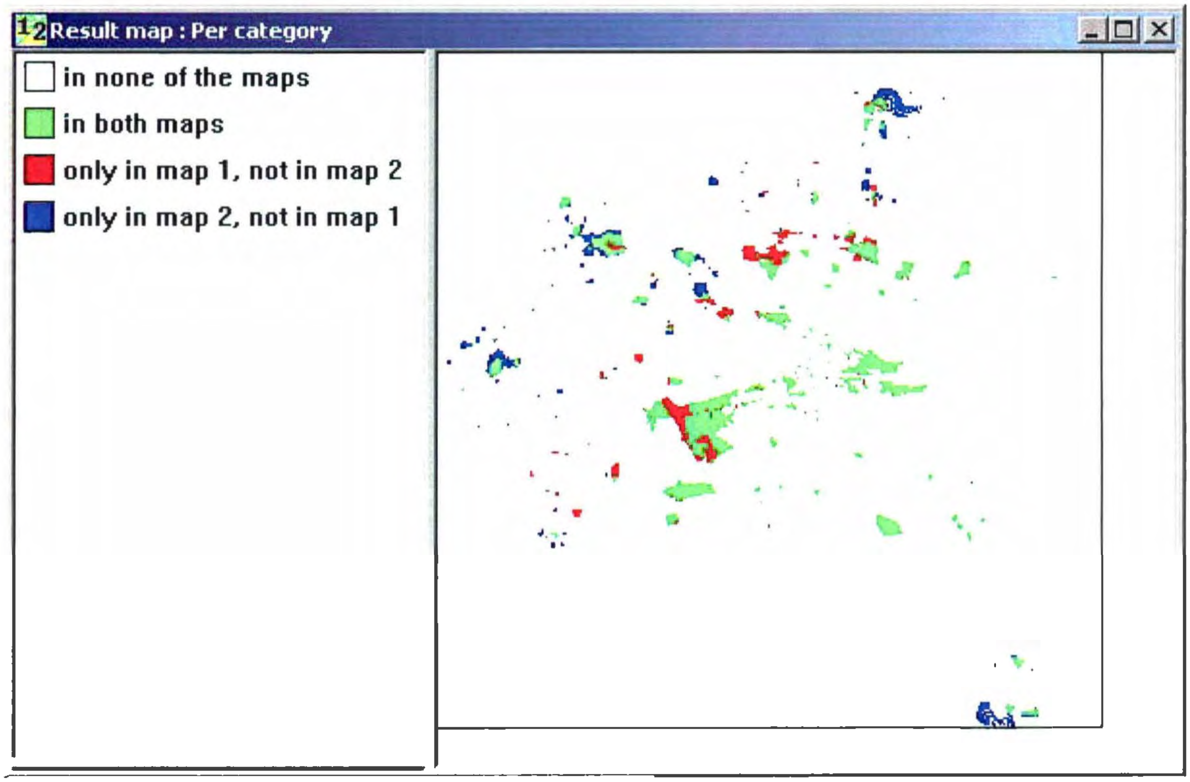


Figure 56 Category comparison of Industry land use for 2007. Map 1 (red) is the "Business as Usual" scenario. Map 2 (blue) is the "Greenbelt Around Dublin City" scenario. Results shown represent a single run.

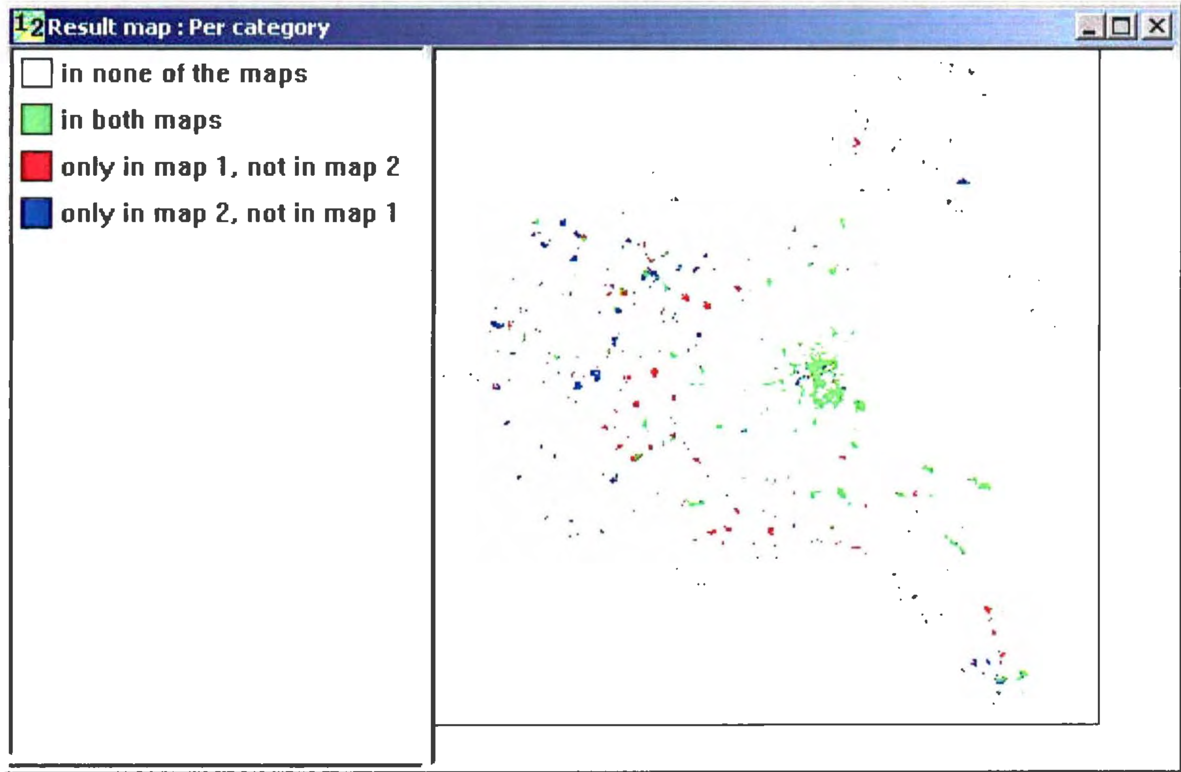


Figure 57 Category comparison of Commerce land use for 2007. Map 1 (red) is the "Business as Usual" scenario. Map 2 (blue) is the "Greenbelt Around Dublin City" scenario. Results shown represent a single run.

5.1.4.2. Radial fractal analysis

The city's Inner Zone showed no changes at all. The Outer Zone results showed differences in the Urban, combined residential and Discontinuous Sparse residential land uses. The dimension for all urban land uses combined increased, as did the dimension of the combination of all residential land uses, in spite of the fact that the dominant land use of the residential group –Discontinuous Sparse residential – saw its radial dimension decrease in the last simulation period. The Third Zone – the leapfrog zone – was mostly occupied by commercial and residential activity.

5.1.4.3. Cluster size-frequency fractal analysis

The "Greenbelt Just Around Dublin" yielded no major changes in the cluster size-frequency distributions of Commerce and Public and Private Services . Industry, on the contrary, registered an increase in its cluster size frequency dimension during the period 1988-98 as a result of the growth of medium-sized clusters; but this increase was stabilized or even somewhat reversed in the second period.

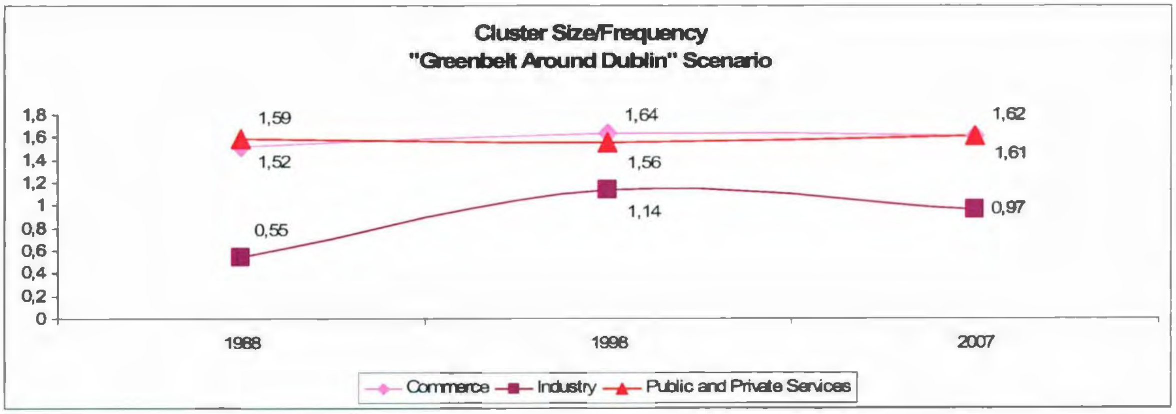


Figure 58 "Greenbelt Around Dublin" scenario: cluster size-frequency graph lines for Commerce, Industry and Public and Private Services for 1988, 1998 and 2007.

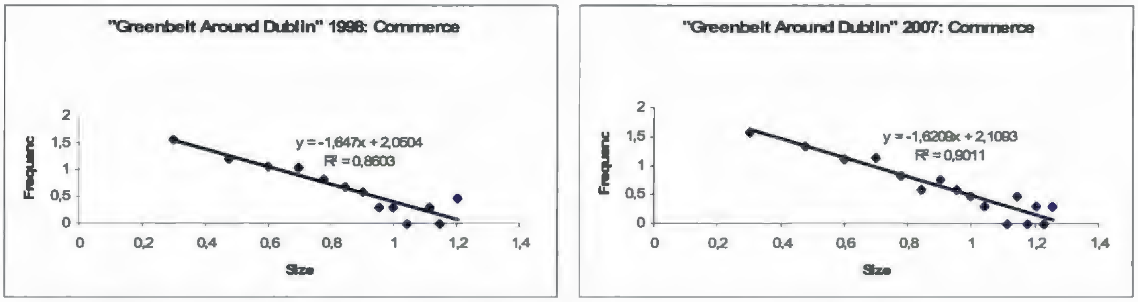


Figure 59 "Greenbelt Around Dublin" scenario: fractal cluster size-frequency graphs for Commerce in 1988, 1998 and 2007.

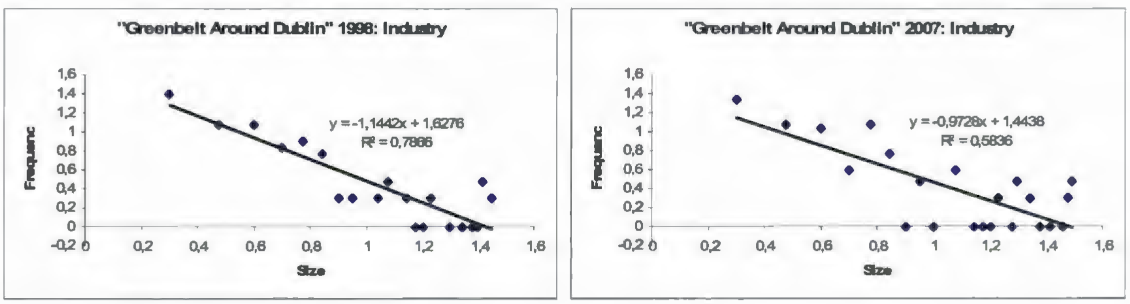


Figure 60 "Greenbelt Around Dublin" scenario: fractal cluster size-frequency graphs for Industry for 1988, 1998 and 2007.

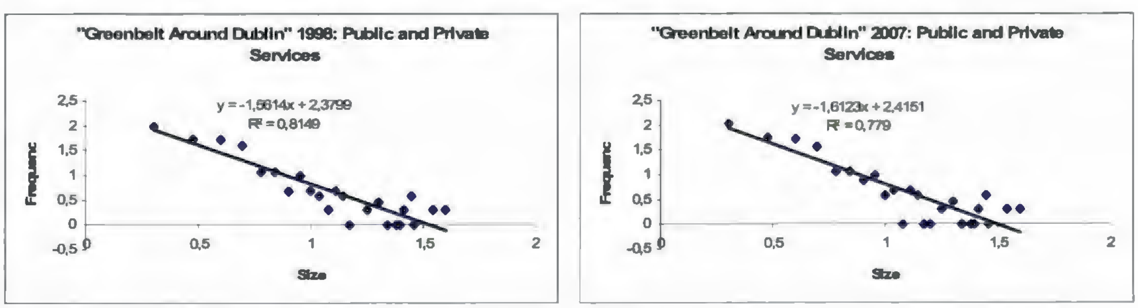


Figure 61 "Greenbelt Around Dublin" scenario: fractal cluster size-frequency graphs for Public and Private Services in 1988, 1998 and 2007.

5.1.4.4. *FRAGSTATS measurements*

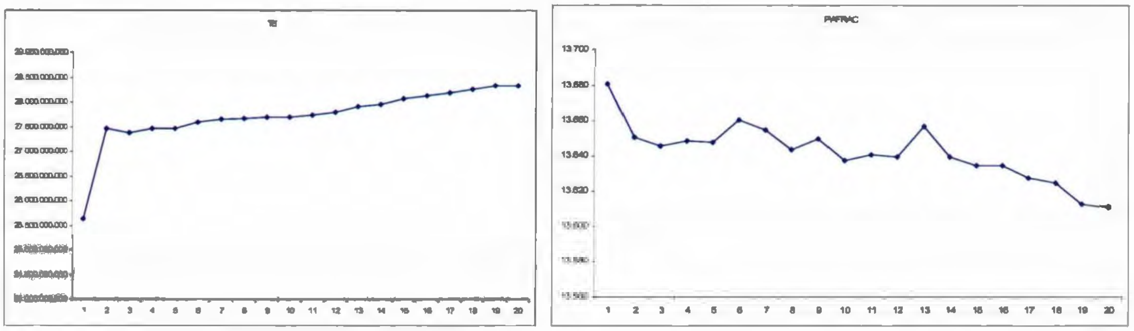


Figure 62 "Greenbelt Around Dublin City" scenario: Total Edge and PAFRAC metrics for all urban land uses combined from 1988 to 2007.

As expected, all land uses increased their total edge values. The whole land use map evolved into a simpler shape, the new cells always being located on the urban fringe. The commercial land use evolved into a much simpler form. Residential land uses show a similar behaviour although small differences stand out. With the Residential Continuous Dense, a trend towards a simpler shape is observed, notwithstanding that at the last iteration a jump is observed in the PAFRAC, nearly levelling the figures to their initial values. The Industrial and Public and Private Services land uses showed, after an initial fall in their PAFRAC measures, a slow upward. trend, indicating a return to a more complex shape.

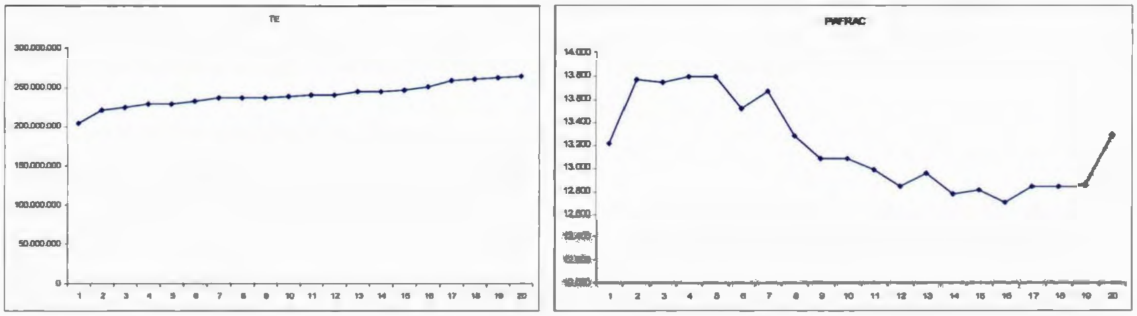


Figure 63 “Greenbelt Around Dublin City” scenario: Total Edge and PAFRAC metrics for Residential Continuous Dense from 1988 to 2007.

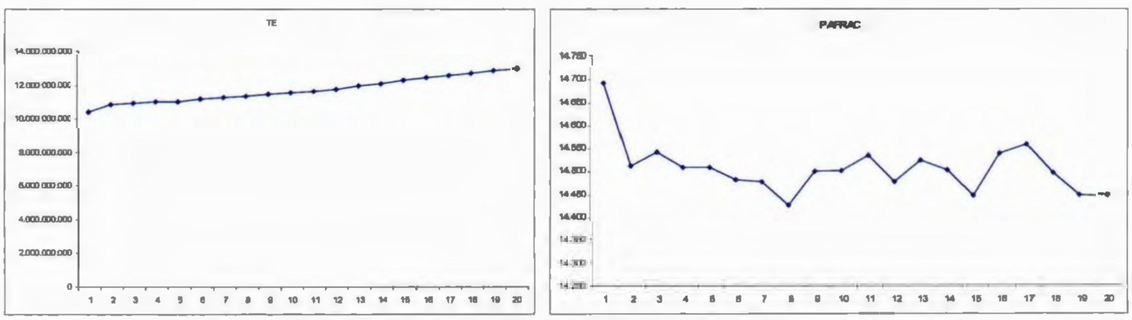


Figure 64 “Greenbelt Around Dublin City” scenario: Total Edge and PAFRAC metrics for Residential Discontinuous Sparse from 1988 to 2007.

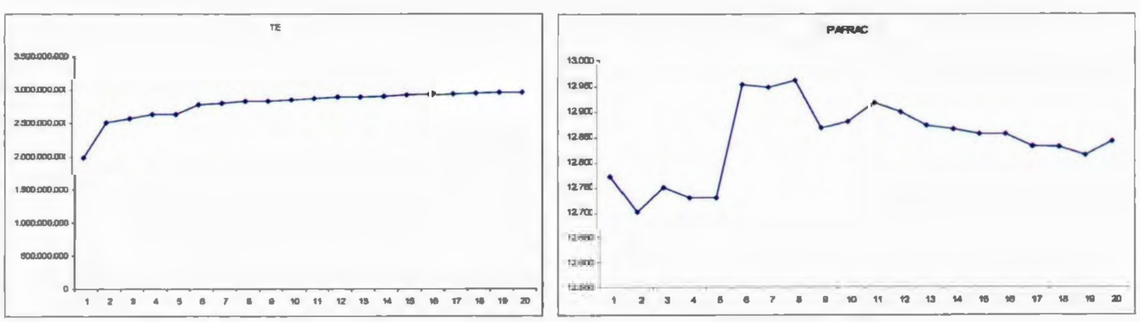


Figure 65 “Greenbelt Around Dublin City” scenario: Total Edge and PAFRAC metrics for Industry from 1988 to 2007.

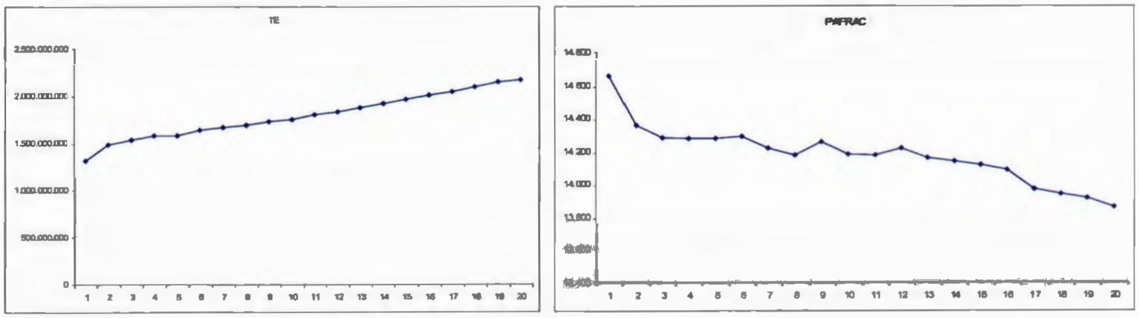


Figure 66 "Greenbelt Around Dublin City" scenario: Total Edge and PAFRAC metrics for Commerce from 1988 to 2007.

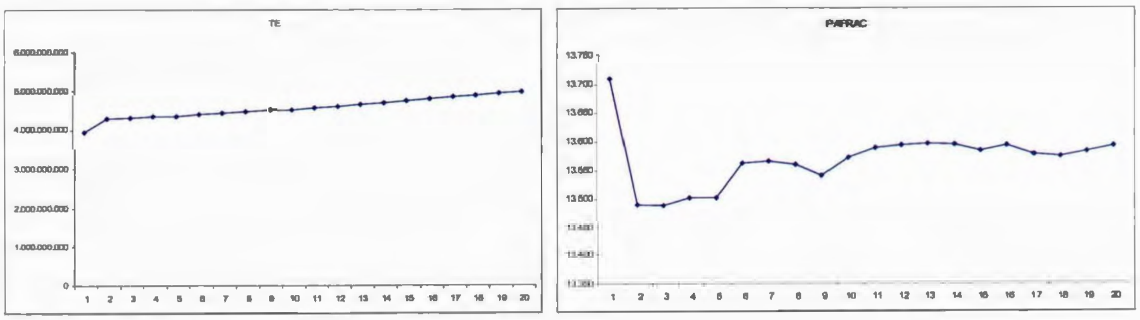


Figure 67 "Greenbelt Around Dublin City" scenario: Total Edge and PAFRAC metrics for Public and Private Services from 1988 to 2007.

5.1.5. "Greenbelt Around The Entire Built Landscape"

5.1.5.1. Overall urban land use behaviour

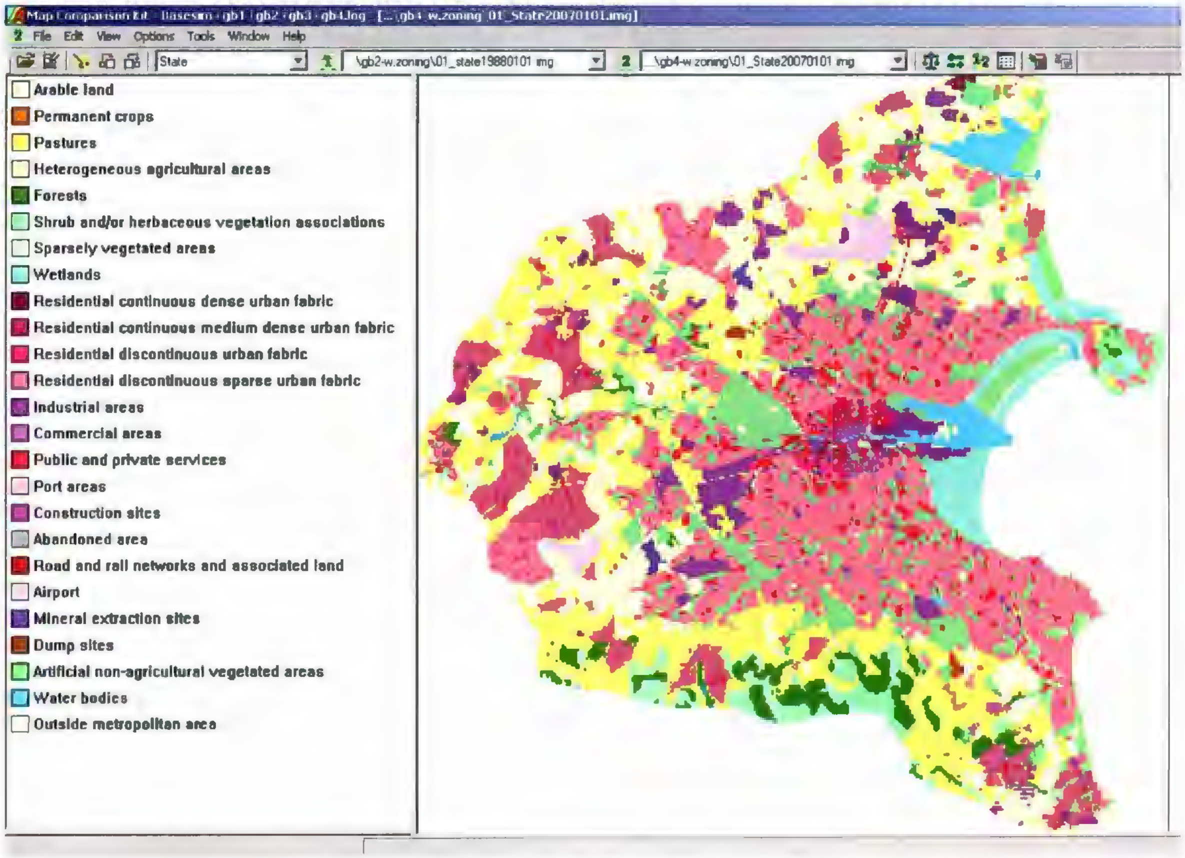


Figure 68 "Greenbelt Around The Entire Built Landscape" scenario: land use map for 2007. Results shown represent a single run.

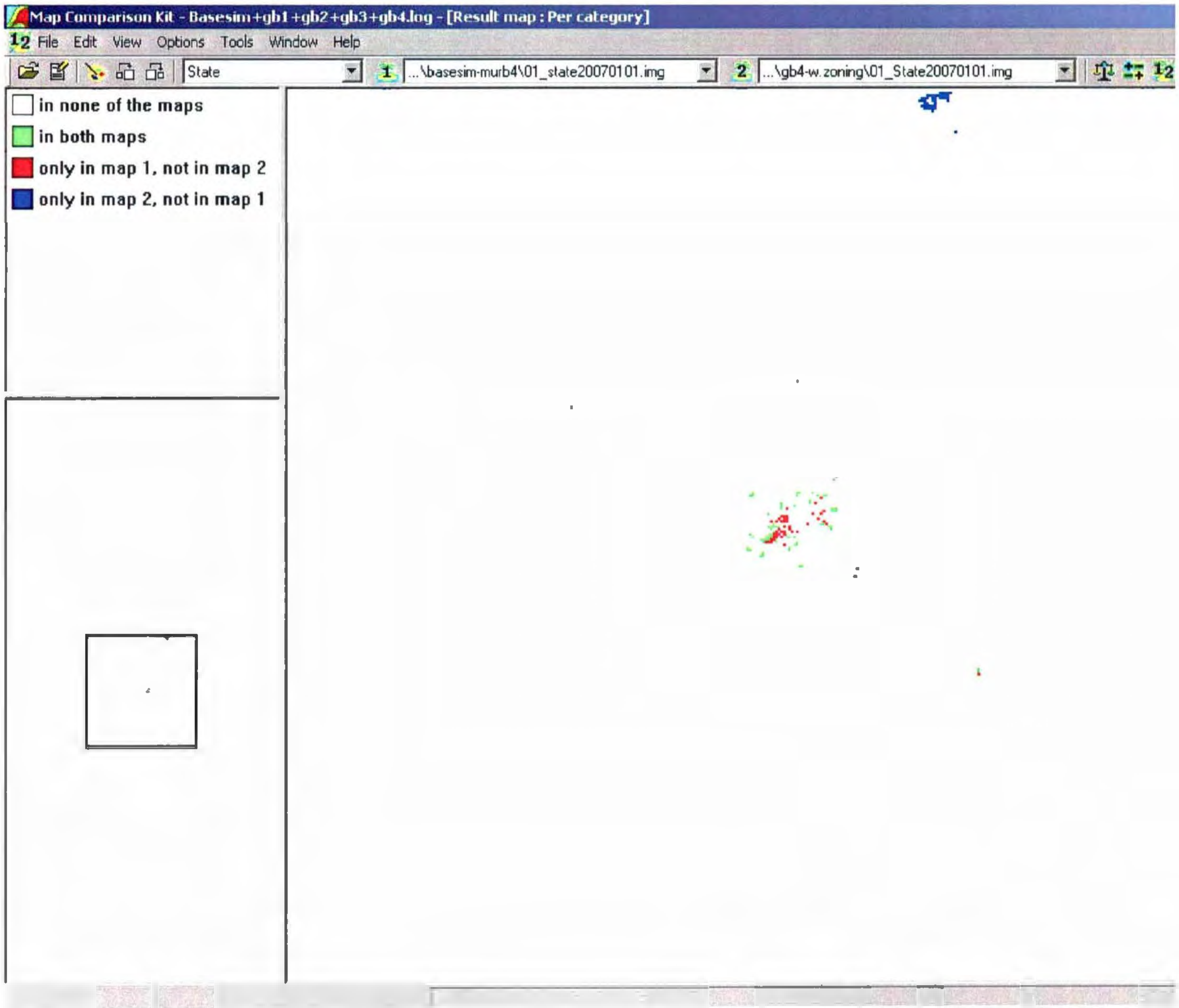


Figure 69 Category comparison of Residential Continuous Dense land use for 2007. Map 1 (red) is the "Business as Usual" scenario. Map 2 (blue) is the "Greenbelt Around the Entire Built Landscape" scenario. Results shown represent a single run.

The behaviour of Residential Continuous Dense land use was severely disturbed by the introduction of the land use constraints that characterize this scenario. A significant number of the city's core cells for this land use were displaced towards the north of the modelled region (Fig. 67) where they formed a large cluster with the additional cells of this land use entering the region during the simulation period; many cells moving from the core area seem to have been displaced by Commerce (Fig. 70) . This may represent a subtle problem with the calibration, or it may possibly reflect a real consequence of the kind of zoning modelled in this scenario. As for the Discontinuous Sparse residential cells, with no urban fringe to attach themselves to, all new land use of this type forms large blobby clusters in the vacant areas of the periphery (Fig 68).

New industrial clusters emerged (Fig 69), although they were very similar in shape and size to the already existing ones. Commercial (Fig. 59) and Public and Private Services (Fig. 61) activities showed no major differences in behaviour.

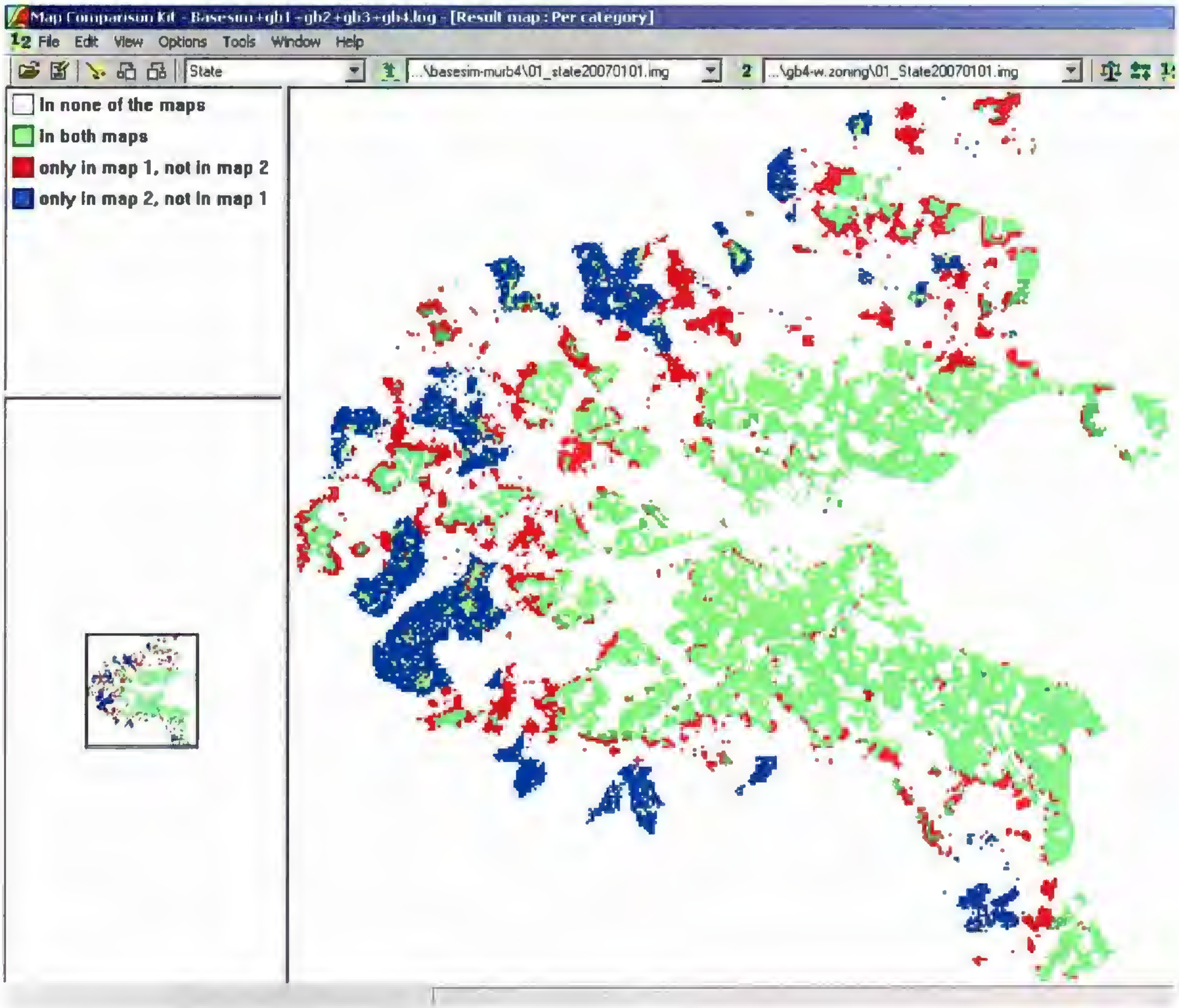


Figure 70 Category comparison of Residential Discontinuous Sparse land use for 2007. Map 1 (red) is the "Business as Usual" scenario. Map 2 (blue) is the "Greenbelt Around the Entire Built Landscape" scenario. Results shown represent a single run.

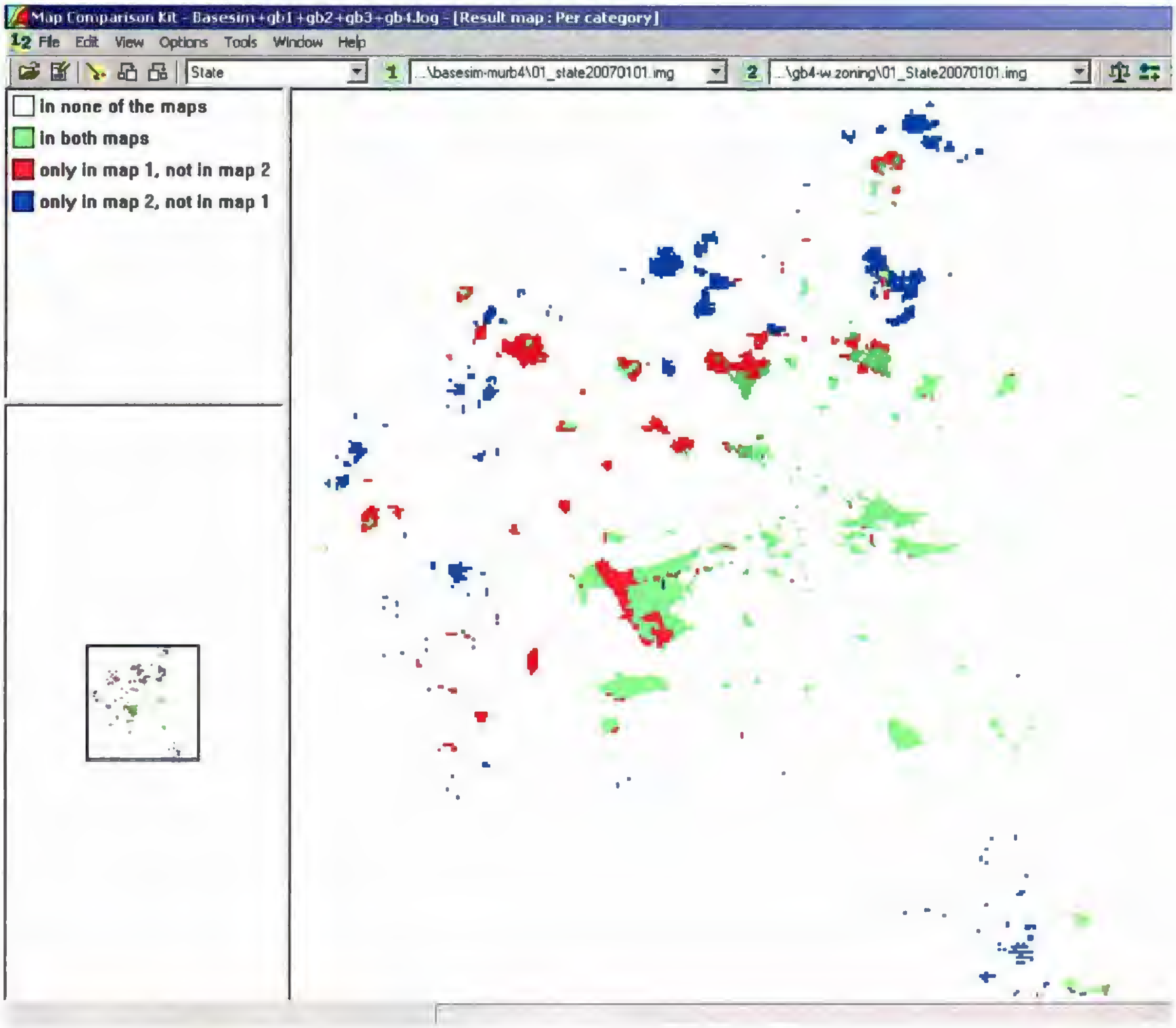


Figure 71 Category comparison of Industry land use for 2007. Map 1 (red) is the "Business as Usual" scenario. Map 2 (blue) is the "Greenbelt Around the Entire Built Landscape" scenario. Results shown represent a single run.

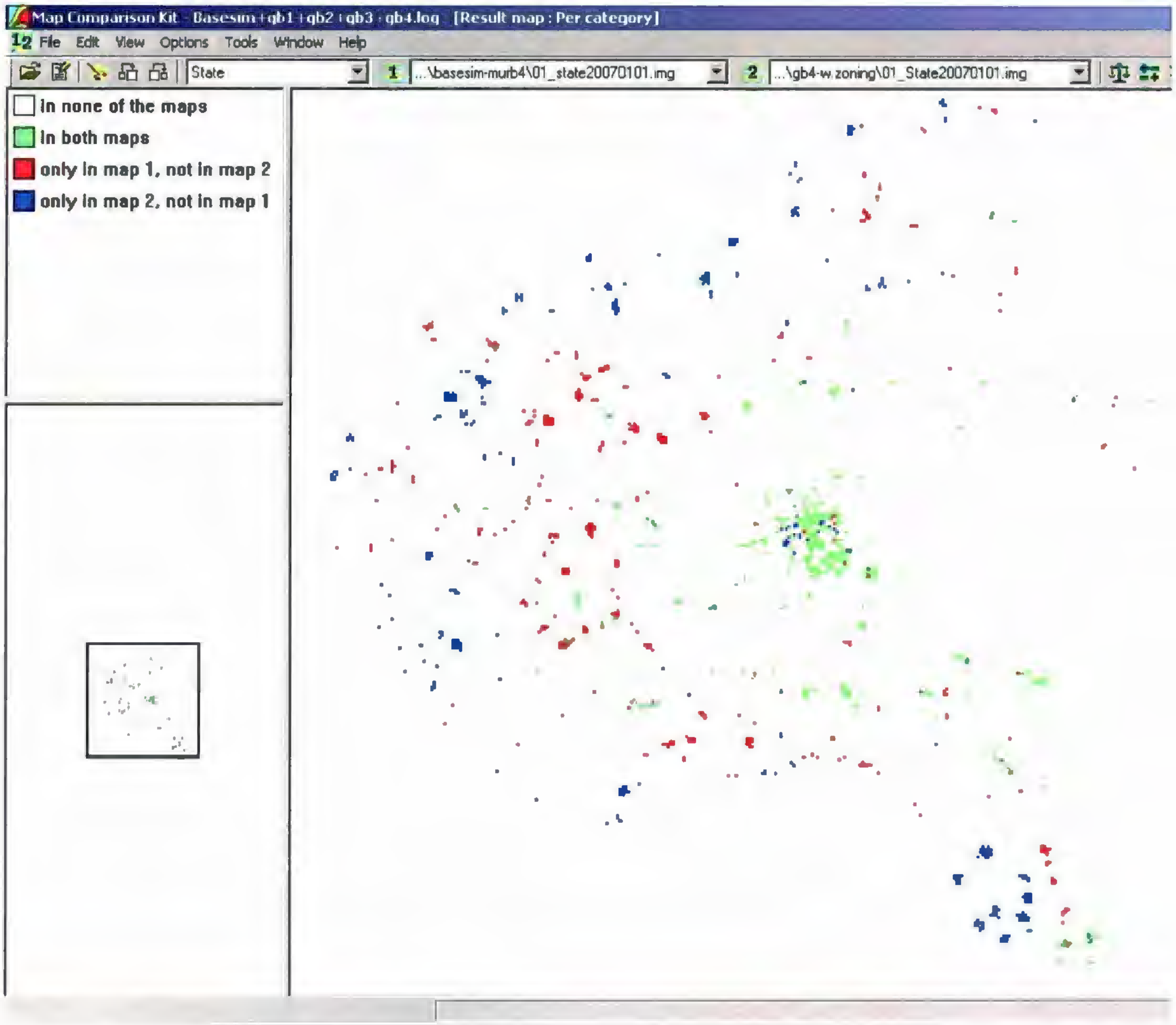


Figure 72 Category comparison of Commerce land use for 2007. Map 1 (red) is the "Business as Usual" scenario. Map 2 (blue) is the "Greenbelt Around the Entire Built Landscape" scenario. Results shown represent a single run.

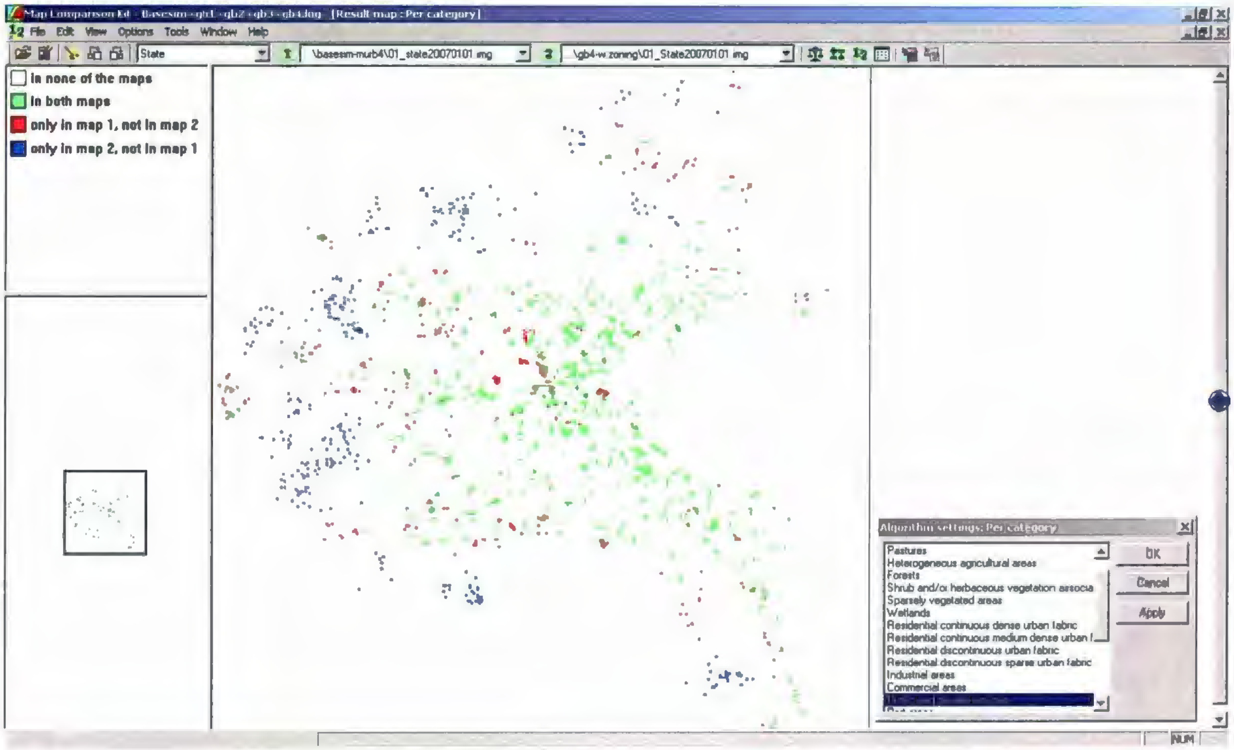


Figure 73 Category comparison of Public and Private Services land use for 2007. Map 1 (red) is the "Business as Usual" scenario. Map 2 (blue) is the "Greenbelt Around the Entire Built Landscape" scenario. Results shown represent a single run.

5.1.5.2. Radial fractal analysis

For the urbanized area (all urban land uses combined) this scenario has led to a decrease of the Inner Zone's radial dimension. In the Outer Zone the radial dimension shows little change between the initial and final years of the simulation. However, a slight decrease is observed for the 1998 value. In the Third Zone the radial dimension fluctuates slightly. As for each land use individually, prohibiting growth around all built areas translates to hardly any changes in radial dimension values for any of the three zones. Only the combined residential land use displays some change in radial dimension value.

5.1.5.3. *Cluster size-frequency fractal analysis*

Industry and Commerce have evolved to lower cluster size-frequency dimensions under this scenario, whereas Public and Private Services has increased its cluster size frequency dimension. Industry saw an enlargement of the large clusters. Commerce has increased the number of commercial clusters while keeping rheir relative sizes constant. Public and Private Services values change due to a decrease in the number of smaller clusters. Note that the number of smaller decreases because these clusters grow to become medium size or large.

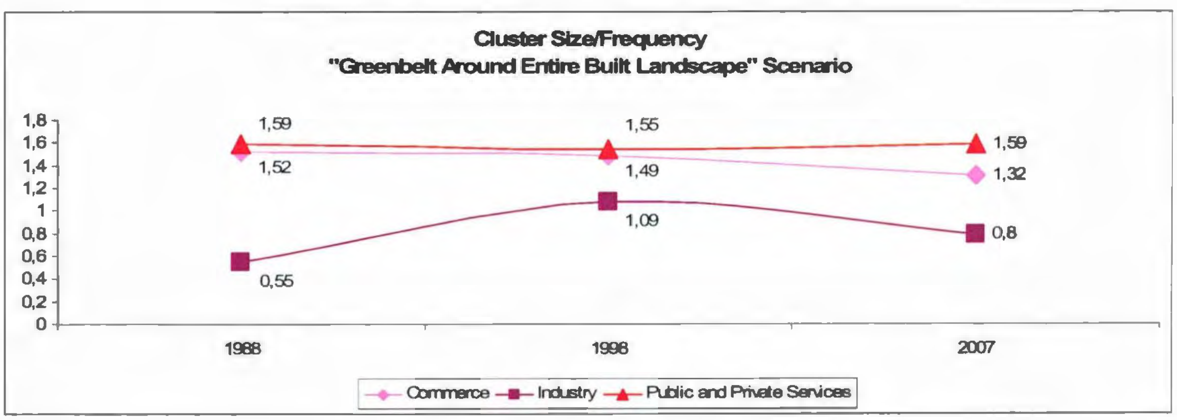


Figure 74 "Greenbelt Around Entire Built Landscape" scenario: cluster size-frequency graph lines for Commerce, Industry and Public and Private Services for 1988, 1998 and 2007.

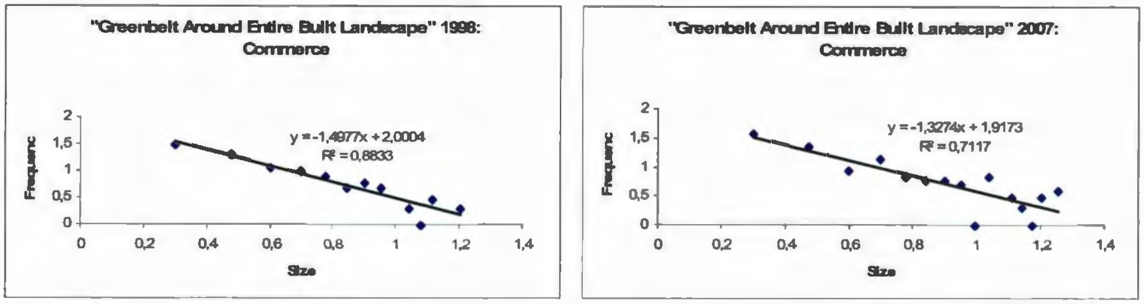


Figure 75 "Greenbelt Around Entire Landscape" scenario: fractal cluster size-frequency graphs for Commerce in 1998 and 2007.

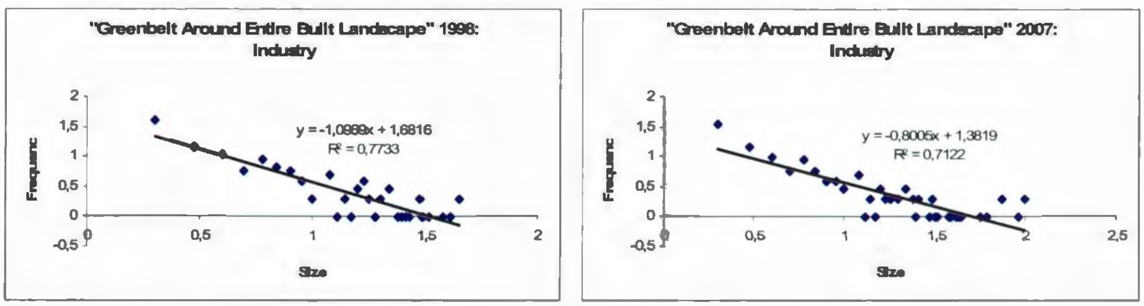


Figure 76 "Greenbelt Around Entire Landscape" scenario: fractal cluster size-frequency graphs for Industry in 1998 and 2007.

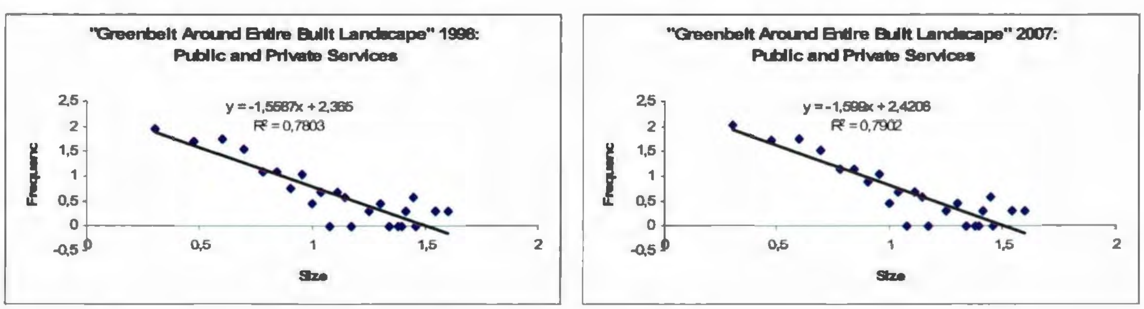


Figure 77 "Greenbelt Around Entire Landscape" scenario: fractal cluster size-frequency graphs for Public and Private Services in 1998 and 2007.

5.1.5.4. FRAGSTATS measurements

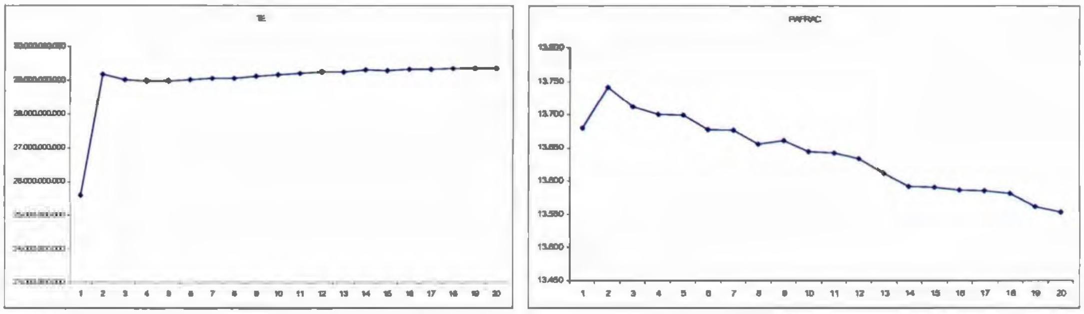


Figure 78 "Greenbelt Around Entire Landscape" scenario: Total Edge and PAFRAC metrics for all urban land uses from 1988 to 2007.

The entire settlement's blobbed evolution is well mirrored in the PAFRAC values evolution, in spite of the Total Edge values remaining practically unaltered. All land uses evolved into simpler shapes with the exception of the Residential Continuous Dense and Public and Private Services which increased their shape complexity.

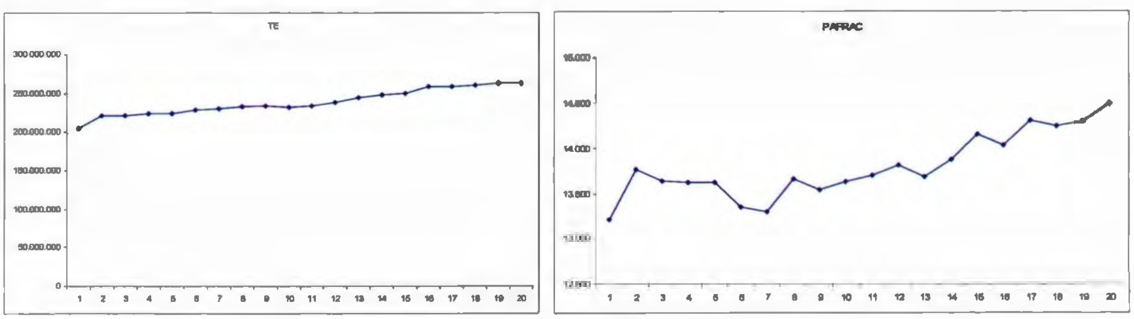


Figure 79 "Greenbelt Around Entire Landscape" scenario: Total Edge and PAFRAC metrics for Residential Continuous Dense from 1988 to 2007.

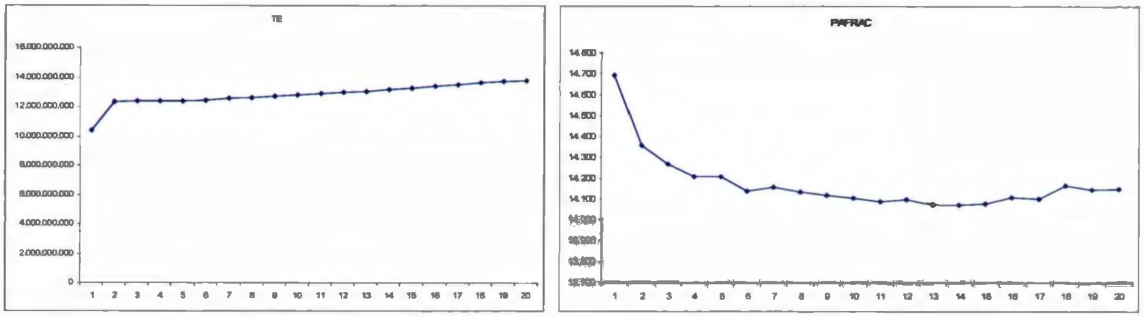


Figure 80 "Greenbelt Around Entire Landscape" scenario: Total Edge and PAFRAC metrics for Residential Discontinuous Sparse land from 1988 to 2007.

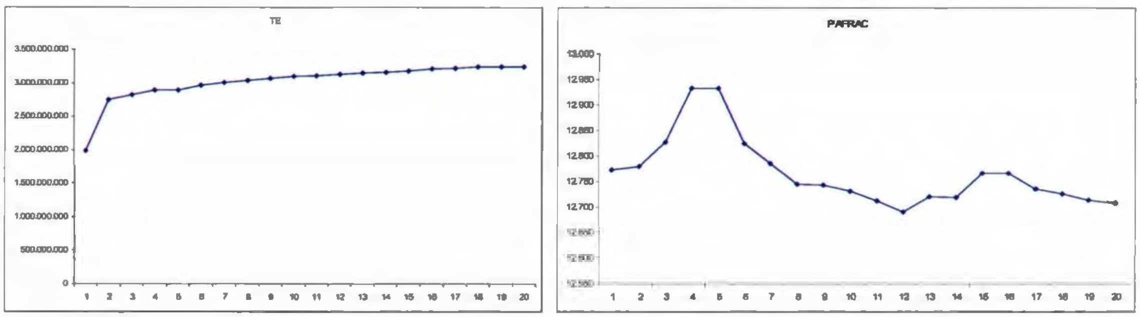


Figure 81 "Greenbelt Around Entire Landscape" scenario: Total Edge and PAFRAC metrics for Industry from 1988 to 2007.

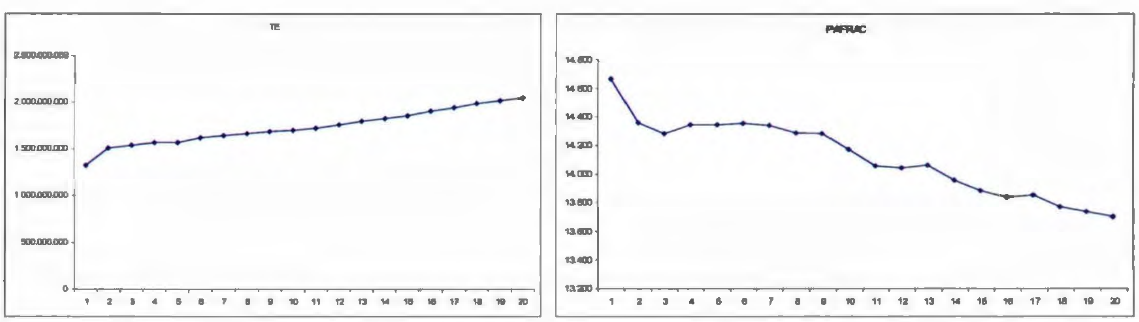
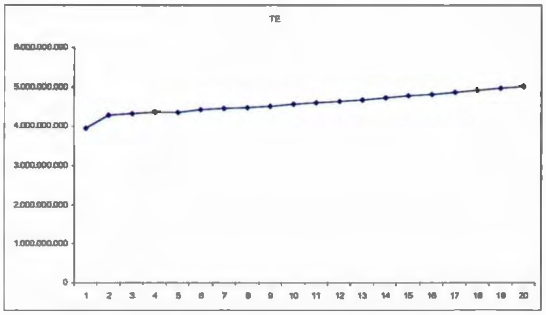


Figure 82 "Greenbelt Around Entire Landscape" scenario: Total Edge and PAFRAC metrics for Commerce from 1988 to 2007.



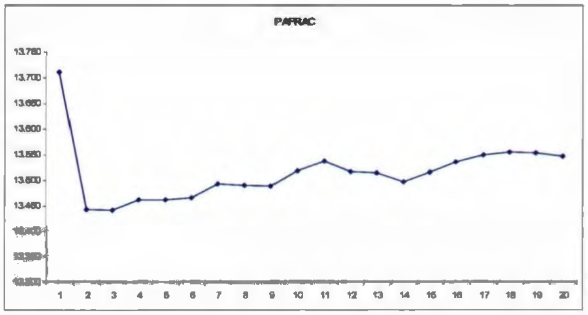


Figure 83 "Greenbelt Around Entire Landscape" scenario: Total Edge and PAFRAC metrics for Private and Public Services from 1988 to 2007.

5.1.6. Overall Spatial Metrics Comparison

5.1.6.1. Radial fractal analysis

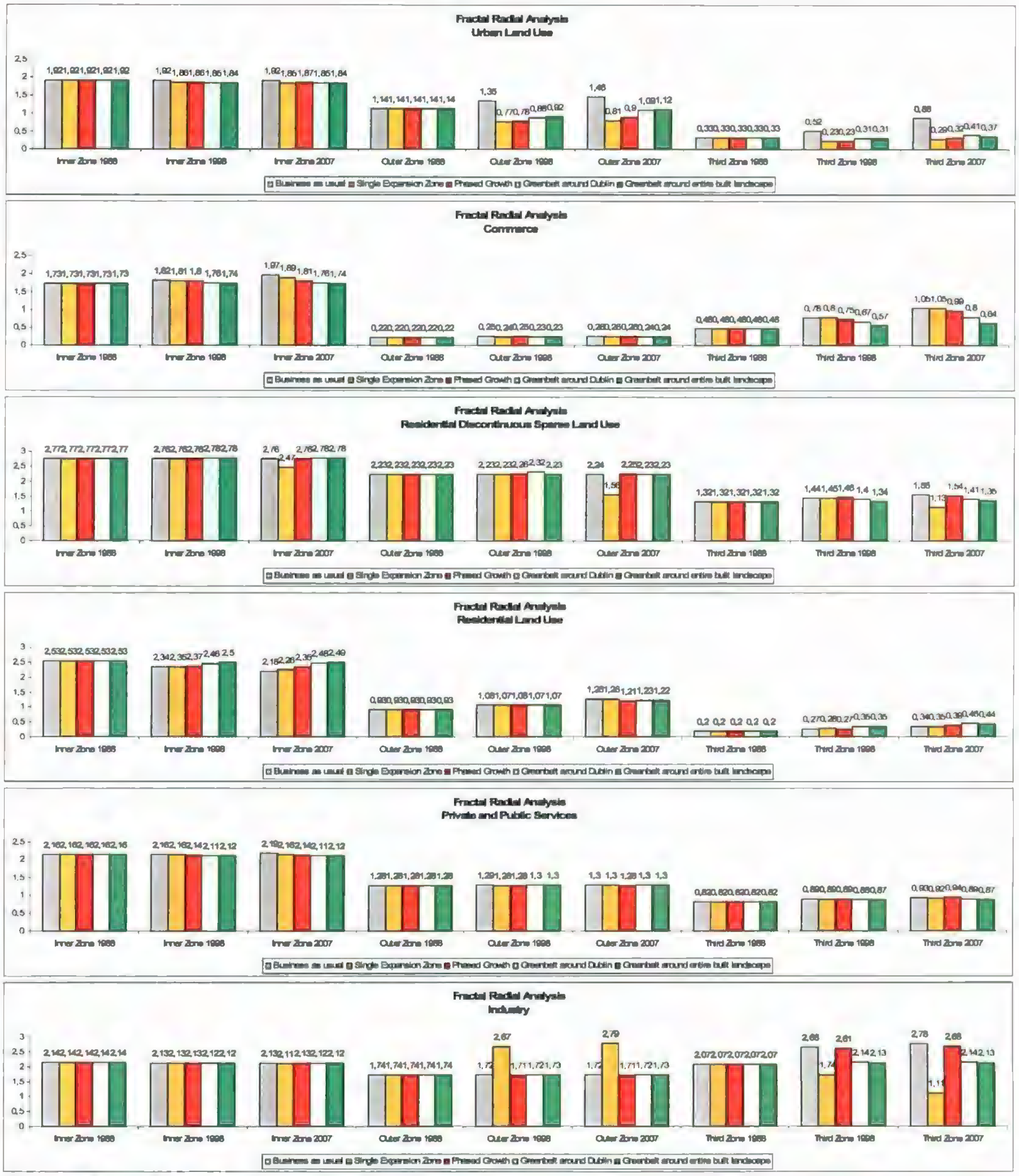


Figure 84 Graphs for all scenarios Showing radial dimensions for all tree city zones for the years 1988, 1998 and 2007.

Comparison of the values from the radial analysis (Fig. 84) shows that, in spite of constraining city growth, few changes take place in the city's Inner Zone. However A decrease, is observed for the Commercial and Private and Public Service land uses. These two land uses are the main constituents of the city's core; thus, a shift in their dynamics will affect the combined urban land use category. A contrary trend is observed in the combined residential land use, showing larger values for all scenarios relative to the business-as-usual scenario.

It is evident that the various scenarios bring about definite changes in the Outer and Third Zones. This is confirmed with the resulting overall fractal radial measurement values. The lowering of these values is because the setup of scenarios is essentially geographic. Constraints introduced via the use of zoning maps thus confine growth to a limited portion of the territory. Scenarios that allow, or force, new cells to establish in a larger portion of territory display larger values of fractal radial analysis. A breakdown of the overall values reveals dissimilarities between land uses.

The resulting Outer Zone graphs seem fairly untouched with the exception of the Industrial and Discontinuous Sparse residential land uses in the single expansion zone scenario: the former, in both the simulation's mid- and final-iterations, and the latter at the last iteration. All other land uses display "Business as Usual" in their underlying structure in the Outer Zone in all scenarios.

The creation of greenbelts is more effective in decreasing commerce's Third Zone values whereas other scenarios yielded few changes. Conversely, the imposition of a single expansion zone induced Industry to display considerably lower values in the Third Zone. This same scenario also resulted in a decrease of the Third Zone values for the residential discontinuous sparse.

5.1.6.2. Cluster size-frequency fractal analysis

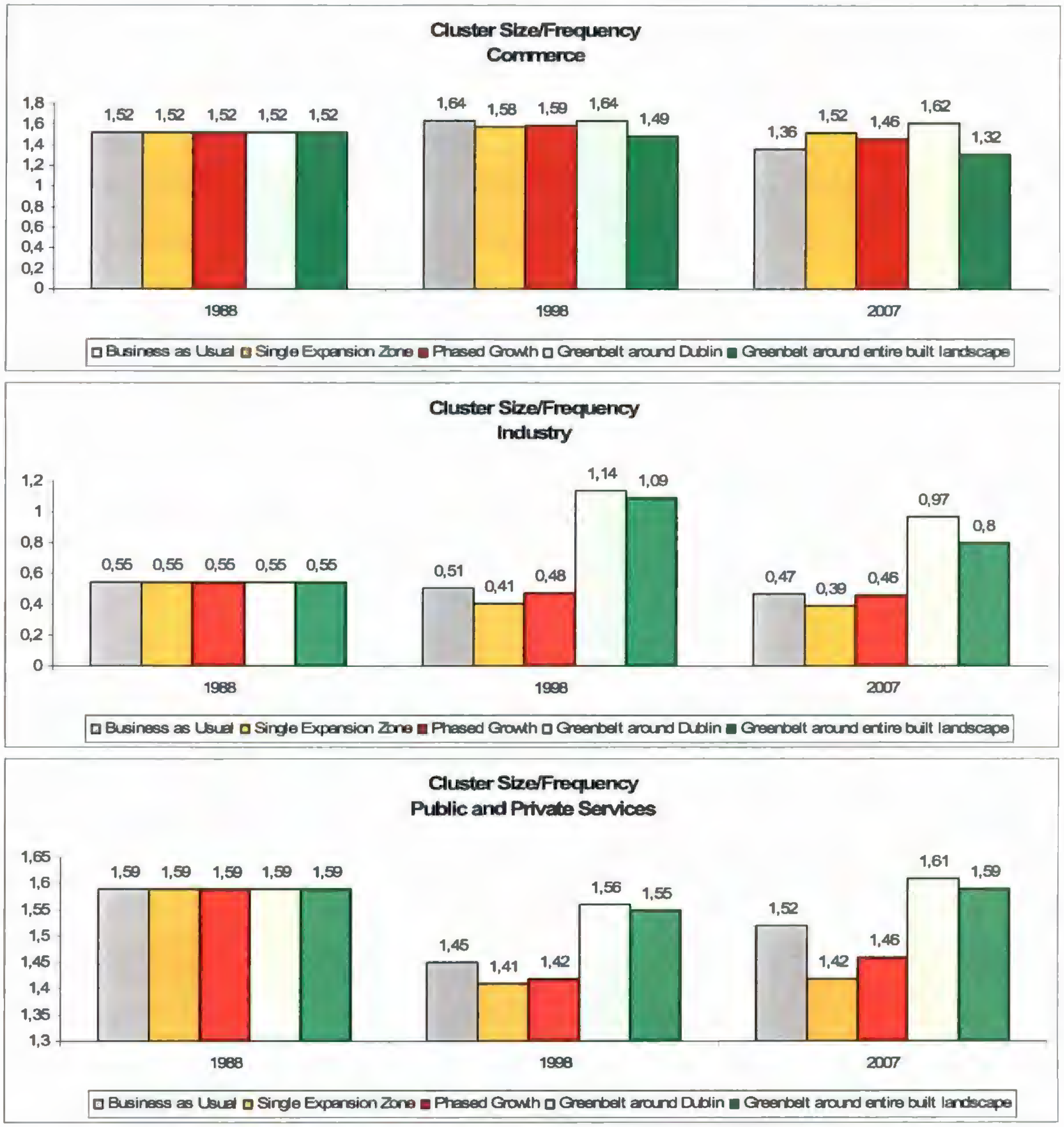


Figure 85 Graphs for all scenarios showing Cluster Size-Frequency dimensions for all urban land uses for the years of 1988, 1998 and 2007.

According to the results shown in Figure 85, the cluster size-frequency of commercial clusters does not seem to be affected by the choice of scenario. For the Industry and Public and Private Services, however, the creation of greenbelts results in an increase in the cluster size-frequency dimension. Conversely, the use of expansion zones produces lower values of the same measure for the Single Expansion Zone and Phased Growth scenarios.

5.1.6.3. *FRAGSTATS measurements*

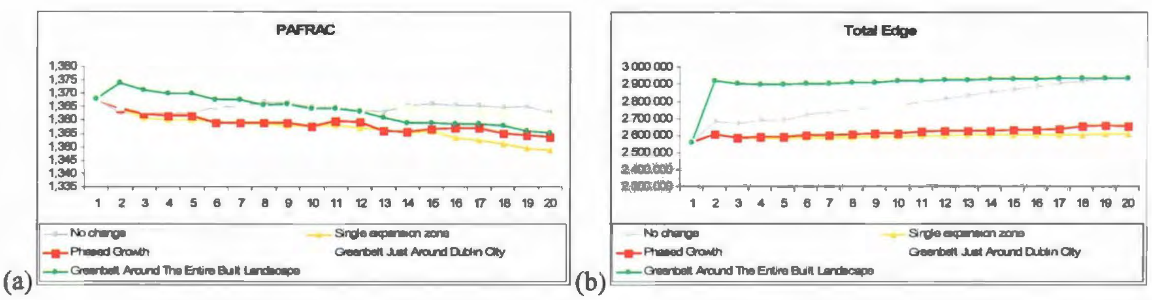


Figure 86 (a) PAFRAC and (b) Total Edge measurements for Urban Land use between 1988 and 2008.

In the "Business as Usual" scenario, the PAFRAC trend for the overall Urban Land Use is to maintain its morphological complexity throughout the simulation period. With the exception of the "Greenbelt Just Around Dublin City" scenario – which follows the same trend – all the other scenarios result in the evolution of the Dublin urbanized area toward a simpler shape. At the end of the simulation period, all new scenarios display lower

PAFRAC marks than the "Business as Usual" scenario. This is also observed in the "Greenbelt Around the Entire Built Landscape" scenario, which, in the first third of the simulation period, started to exceed the value for the "Business as Usual" scenario. In regards to the Total Edge measurements of the urbanized area, most scenarios are able to maintain the initial value even as the area enclosed by the Total Edge increases, whereas the "Business as Usual" and "Green Belt Just Around Dublin scenarios produce an increase in this value.

(a) (b)

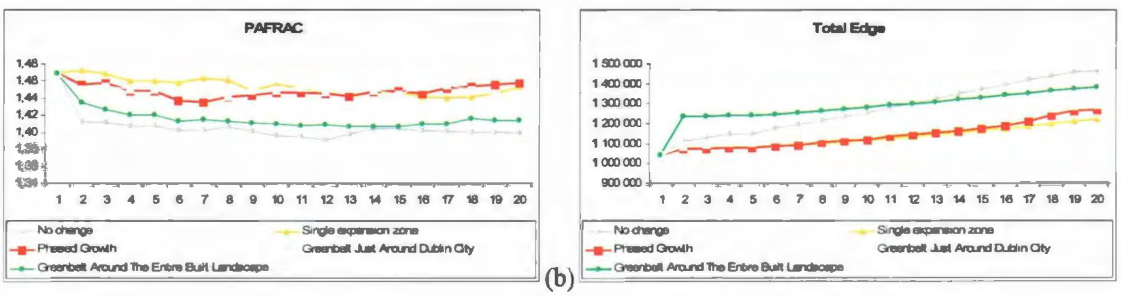


Figure 87 (a) PAFRAC and (b) Total Edge measurements for Residential Discontinuous Sparse land use between 1988 and 2008.

Residential Discontinuous Sparse land use responded to the new scenarios with increased PAFRAC values in comparison with the base simulation. Only the "Greenbelt Around the Entire Built Landscape" scenario resembled the "Business as Usual" ones. All new scenarios ended with lower Total Edge values when compared with the base simulation ones.

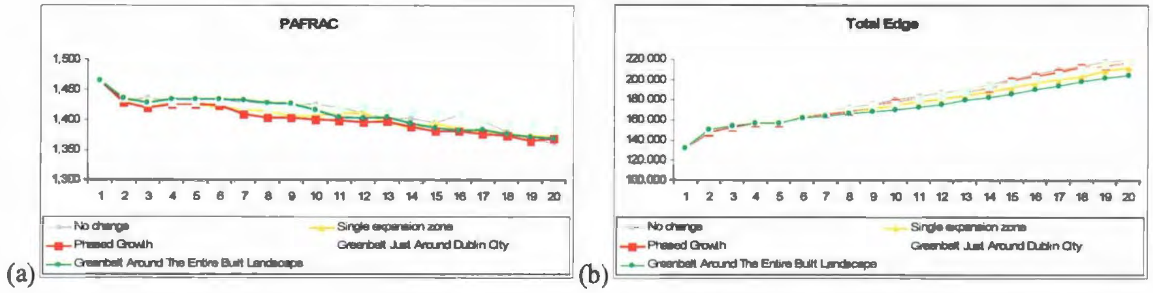


Figure 88 (a) PAFRAC and (b) Total Edge measurements for Commerce land use between 1988 and 2008.

Commercial land use PAFRAC and Total Edge figures' behaviour consistency is present in all modeled scenarios.

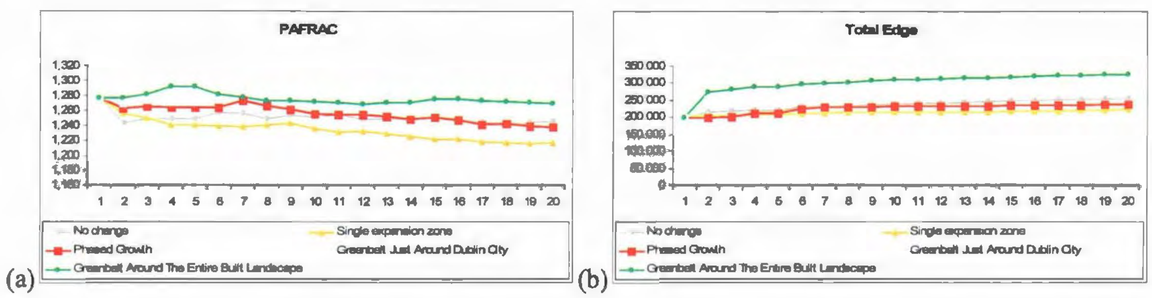


Figure 89 (a) PAFRAC and (b) Total Edge measurements for Industry land use between 1988 and 2008.

Greenbelt scenarios display more complex industrial morphological patterns with higher Total Edge values. The "Phased Growth" scenario is more like the "Business as Usual" one.

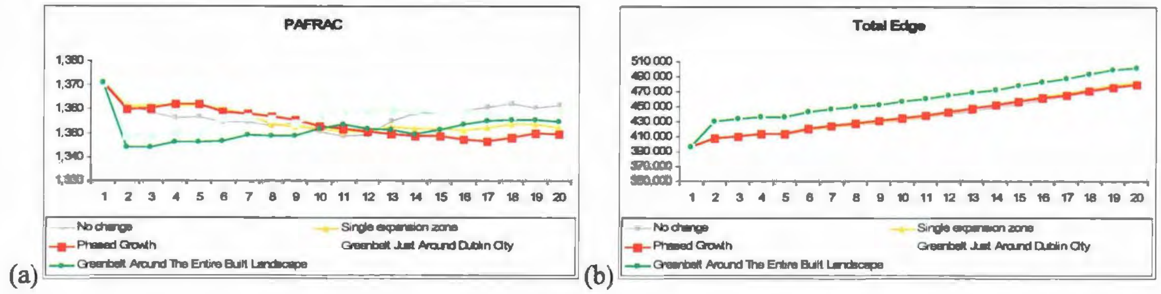


Figure 90 (a) PAFRAC and (b) Total Edge measurements for Public and Private land use between 1988 and 2008.

Public and Private Services land use shows highly dissimilar PAFRAC evolutions between scenarios but consistent evolution in the Total Edge ones, although the greenbelt scenarios yield higher values for the latter.

Two questions were formulated in the Simulations chapter in the plans for the metropolitan scenarios: can leapfrogging be prevented; and how will the current region's growth dynamics react if the appearance of outlying clusters are not allowed? The discussion of the metropolitan results is based on these two questions.

The morphological characteristics of urban land uses varied greatly. Total Edge and PAFRAC values were significantly altered in the different scenarios with only one or two exceptions. Growth evolved in a more compact way with the "Single Expansion Zone" and "Phased Growth" scenarios, as expected. Also for the greenbelt scenarios, the one surrounding just Dublin provoked an expected enlargement of nearby urban clusters, as they constituted the only poles of urban attraction for development. The one locking all built landscape pushed all new cells to the isolated vacant quadrants of the modelled region. These new urban clusters were mostly made up of Residential Discontinuous Sparse cells with randomly sprinkled Public and Private Services land use cells. The cluster size-frequency graphs also displayed consistent information, most obviously for the greenbelt scenarios where a dramatic increase characterized the creation of smaller sized industrial and services clusters.

There is no immediate correlation between the PAFRAC and Total Edge. The increase in one of them does not seem to have an immediate effect on the other. The PAFRAC measurement, like the majority of all other fractal measurements, can be useful to monitor urban development compared to the model. A shift from an average PAFRAC value may represent an alternative path taken by urban expansion that may not be considered "natural" and thus may be the object of a closer look. Cities, in general, do not evolve into completely scattered, or blobby, patterns. The enforcement of a planning policy that yields, concurrently, the desired and maintained level of the perimeter-area fractal relationship could thus be considered in harmony with the natural development of the urban lattice. In the charted results for the entire Urban Land Use (Figure (a)), only the "Greenbelt Around Dublin City" scenario was able to maintain its PAFRAC measure close to the initial one.

The same reading cannot, however, be considered true for the measurement of the individual land uses. Although some may continue to display a relatively flat line evolution in their PAFRAC measure, such as for Residential Discontinuous Sparse

(Figure (a)) and Industry (Figure (a)), others may not, like Commerce (Figure (a)) and Public and Private Services (Figure (a)).Therefore, it is advised that each individual land use should be studied separately according to its PAFRAC value. The analysis of these measurements in other datasets, i.e. cities, could also provide a means of comparison and a way to develop a stronger theory of significance for this subject.

The Total Edge measurement is a more straightforward type of measurement and has important repercussions on the boundary effects present on the urban-rural fringe. It represents the amount of urban perimeter in direct contact with the rural landscape. Due to the proximity of natural spaces, it is a preferable area for residential land use location. But from an environmental standpoint, the increase of the Total Edge area also represents a context where ecological values are more at risk.

For the modelled scenarios, the Total Edge graph reveals that, at the urban land use level (Figure), it is the "Phased Growth" and "Single Expansion Zone" scenarios that yield lower values. It is also these two scenarios that, when compared to the "Business as Usual" scenario, show the lowest value for industrial land use. Considering that it is likely to be the most damaging land use to the environment, the distinguished scenarios are considered the most beneficial to the city's quality of life.

By looking at these values and maps, one would initially think that the scenarios had some effect on the resulting maps. However, the underlying structure characterized by the radial fractal measurements show a somewhat different reality. The overall Urban Land

Use area-radius graph shows that the Outer and Third zones suffer changes induced by the new scenarios, but a look at the individual land uses shows otherwise. With the exception of Industry, and most obviously in the "Single Expansion Zone" scenario, there are hardly any other values that stand out: i.e. the inner structure of the urban area remained generally unaltered in spite of the imposition of constrained growth. What we are observing is a new city map with essentially the same underlying structure.

The problem of leapfrogging development is only partially solved. Commerce shows lower values for the greenbelt scenarios but still higher than their Outer Zone counterparts, revealing the same, though weaker, leapfrogging behaviour. In the case of Industry, on the other hand, the problem seems solved with the "Single Expansion Zone" scenario by some sort of "compensation device". What increased in the Outer Zone declined in the Third Zone. The "Single Expansion Zone" scenario may have had a very strong influence in restraining the growth of industrial activity on the urban expansion fringe, leading to the rapid enlargement of the already existing industrial clusters – small at the start – that were further away from the city's core, though still within the Outer Zone.

The spatial metrics analysis is not complete, or conclusive, without a more detailed analysis of the specific urban patterns shown in the output maps, since spatial metrics results present very similar values for clearly different maps. This is because fractal measures are not sensitive in distinguishing one map from another in precisely those characteristic patterns that leap out at the human eye. Here, map comparison tools, such as the Map Comparison Kit, are very useful for a quick analysis of such differences. Nevertheless, none has yet proved to substitute entirely and effectively for human visual analysis, in spite of all the subjectivity that such analysis implies.

A visual map comparison quickly reveals that, for instance, the "Single Expansion Zone" and "Greenbelt Around Entire Built Landscape", are conceptually very different from each other, and generate very different land use maps: the former with highly compact growth, showing enlargement of the existing built land use; and the latter with new urban clusters occupying the once vacant peripheral spaces. A visual inspection of the resulting "Greenbelt Around Entire Built Landscape" scenario land use map is more likely to lead to the conclusion that there was more "leapfrogging" occurring which, in turn, would dramatically increase the fragmentation of the natural habitats on the urban fringe. However, observation of the fractal radial analysis for the combined urban land use category does not immediately support such an assumption. The differences are observed at their best in Industry's fractal radial measurements, where the "Single Expansion Zone" scenario stood out from all the other scenarios. Both analyses are thus complementary for a more complete analysis of the results.

Chapter 6. Results from regional scenarios

As in Chapter 5, each scenario is analysed separately. Then a comparison between them is performed on the basis of the various measures being discussed. For the particular case of the regional scenarios, the FRAGSTATS spatial metrics are not used since the software was unable to read the corresponding land use files .Only the fractal radial dimension and cluster size-frequency measures are discussed.

6.1.1. "Business as Usual"

Comparing stochastically different runs of the baseline scenario of the regional model, the Fuzzy Kappa values show that all runs produce essentially the same map. Values between 0.98 and 1.00 are obtained when the same iteration is compared in different log files. Map comparison between log files by category also reveals strong similarities among runs for each individual land use. Thus, and for the same reasons described in the metropolitan case, any of these logged baseline simulations can be taken as representative of a "Business as Usual" scenario for the region.

6.1.1.1. Overall land use behaviour

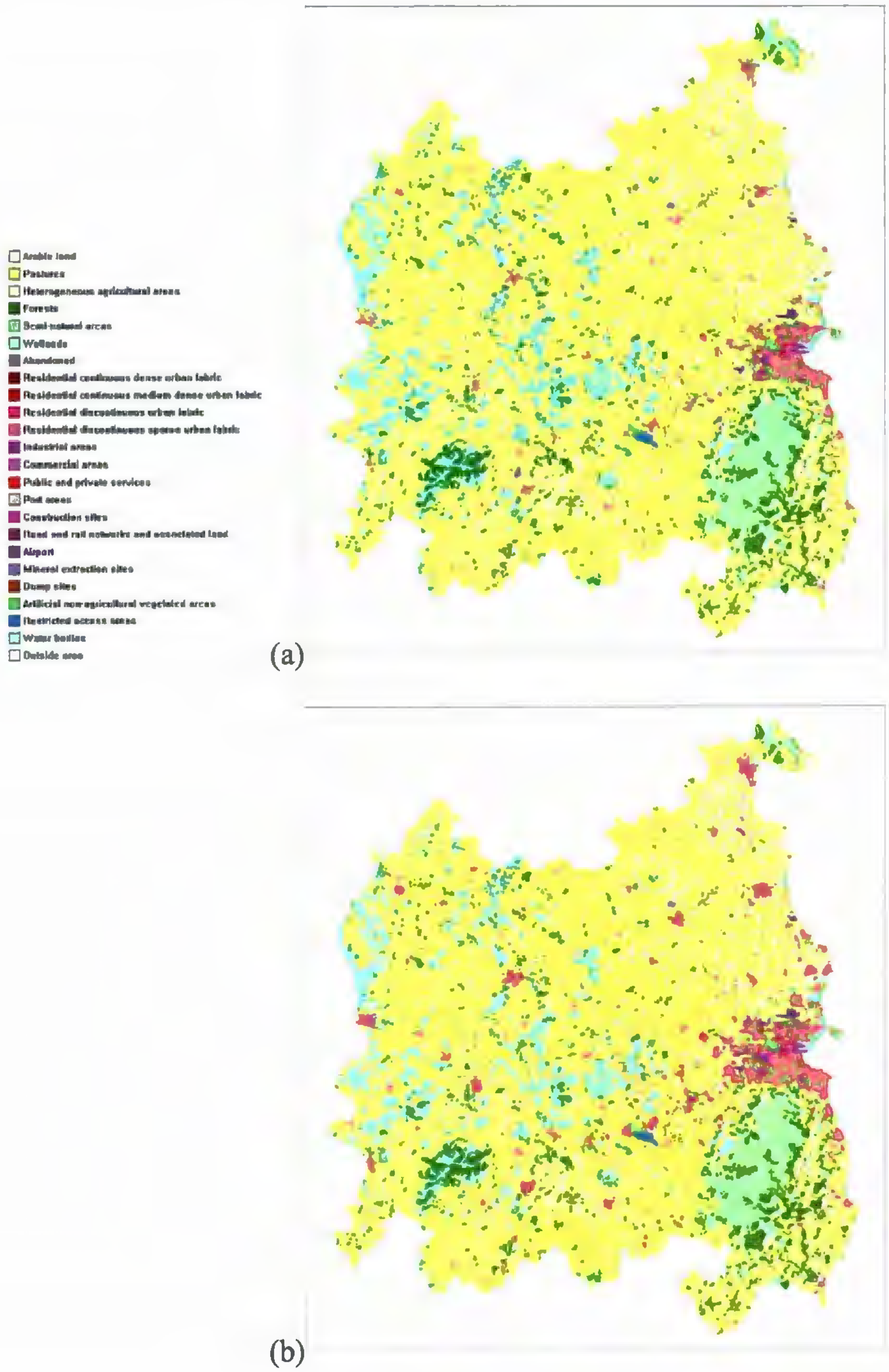


Figure 91 "Business as Usual" scenario: land use map for (a) 1990 and (b) 2025. Results shown represent a single run.

Figure 92 Probability map for 8 simulations differing in seed for stochastic perturbation. Purple cells are existing urban land use in the initial timestep. Blue cells represent lower probabilities of getting developed and green cells higher probabilities.

Figure 93 Probability map for 8 simulations differing in seed for stochastic perturbation. Existing initial urban land use was removed and the map shows only the new cells. Red cells represent lower probabilities of getting developed, green cells intermediate probabilities and purple cells higher probabilities.

Similar to what happens at the metropolitan scale, regional urban expansion occurs mostly at the urban fringe. The new urban cells with the lowest probability of being developed more likely to be found farthest from the existing urban settlements.

Nevertheless, although their location is highly influenced by the stochastic perturbation, a look at the probability map above (Figure 93) reveals that these new urban cells fall mostly in the main transportation corridors.

The fringe growth is mostly composed of cells of the Residential Discontinuous Sparse category (Figure 94), which is also the most common urban class. Industrial land use (Figure 95) evolves both by the growth of existing clusters and the creation of new ones; Near the City of Dublin the new industrial clusters tend to grow large, while in the nearby surrounding urban settlements they remain smaller . Isolated industrial clusters also occur but remain small. In spite of the regional model's lower resolution, it is possible to observe how new commercial cells establish themselves throughout the simulation (Figure 96). The area with the highest level of activity is the one also present in the metropolitan model. This is the Third Zone, beyond the residential buffer. Nevertheless, at the regional scale, new clusters of commercial activity can be observed, not only located near the existing urban settlements but also of a size that suggests the emergence of major retail centres. The Public and Private Services' land use (Figure 97) expands near the existing urban settlements. Its expansion is, however, marked by a type of growth that suggests a fixed maximum size for its clusters.

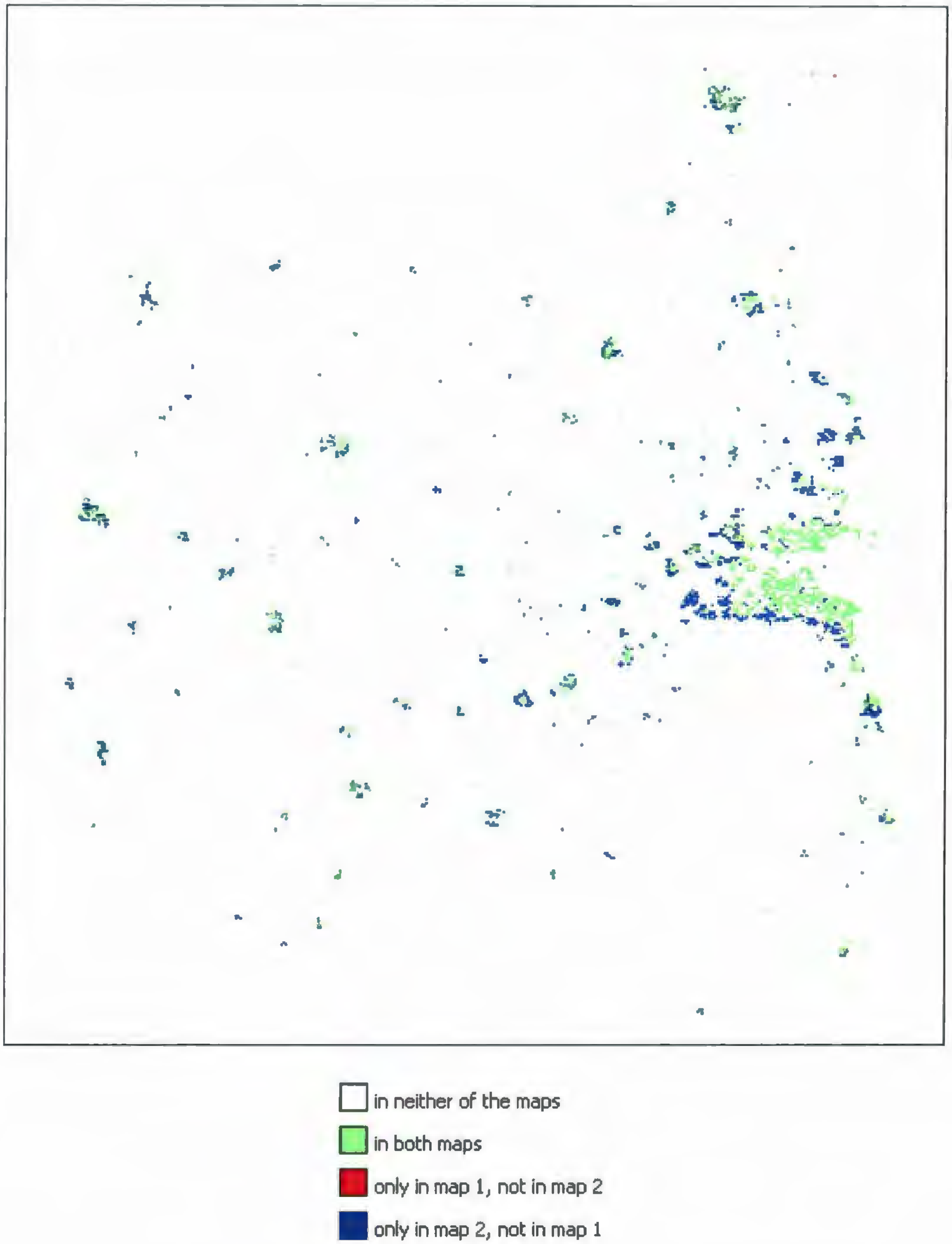


Figure 94 "Business as Usual" scenario: Residential Discontinuous Sparse evolution between 1990 and 2025. Map 1 (red) is 1990. Map 2 (blue) is 2025. Results shown represent a single run.

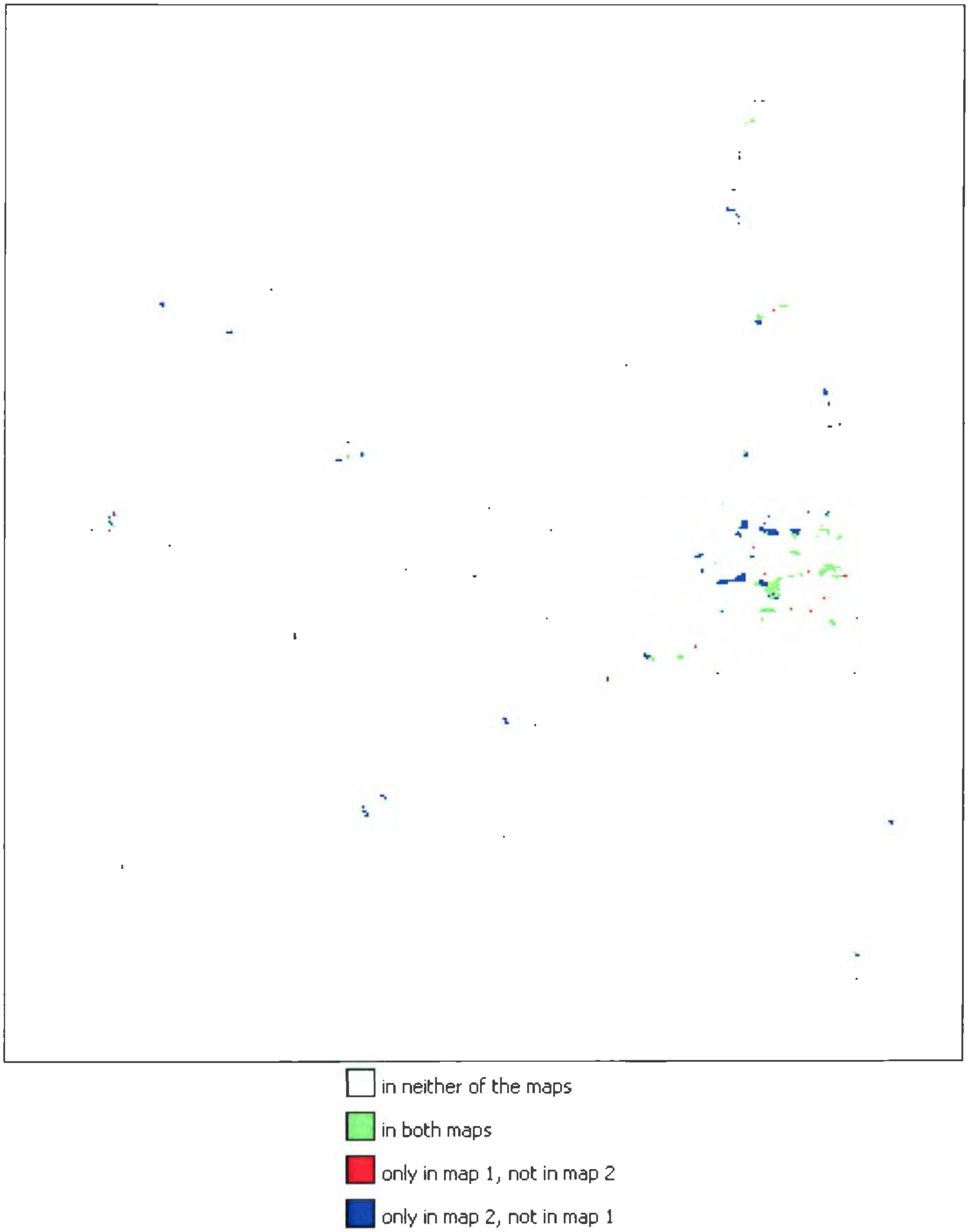


Figure 95 "Business as Usual" scenario: Industry evolution between 1990 and 2025. Map 1 (red) is 1990. Map 2 (blue) is 2025. Results shown represent a single run.

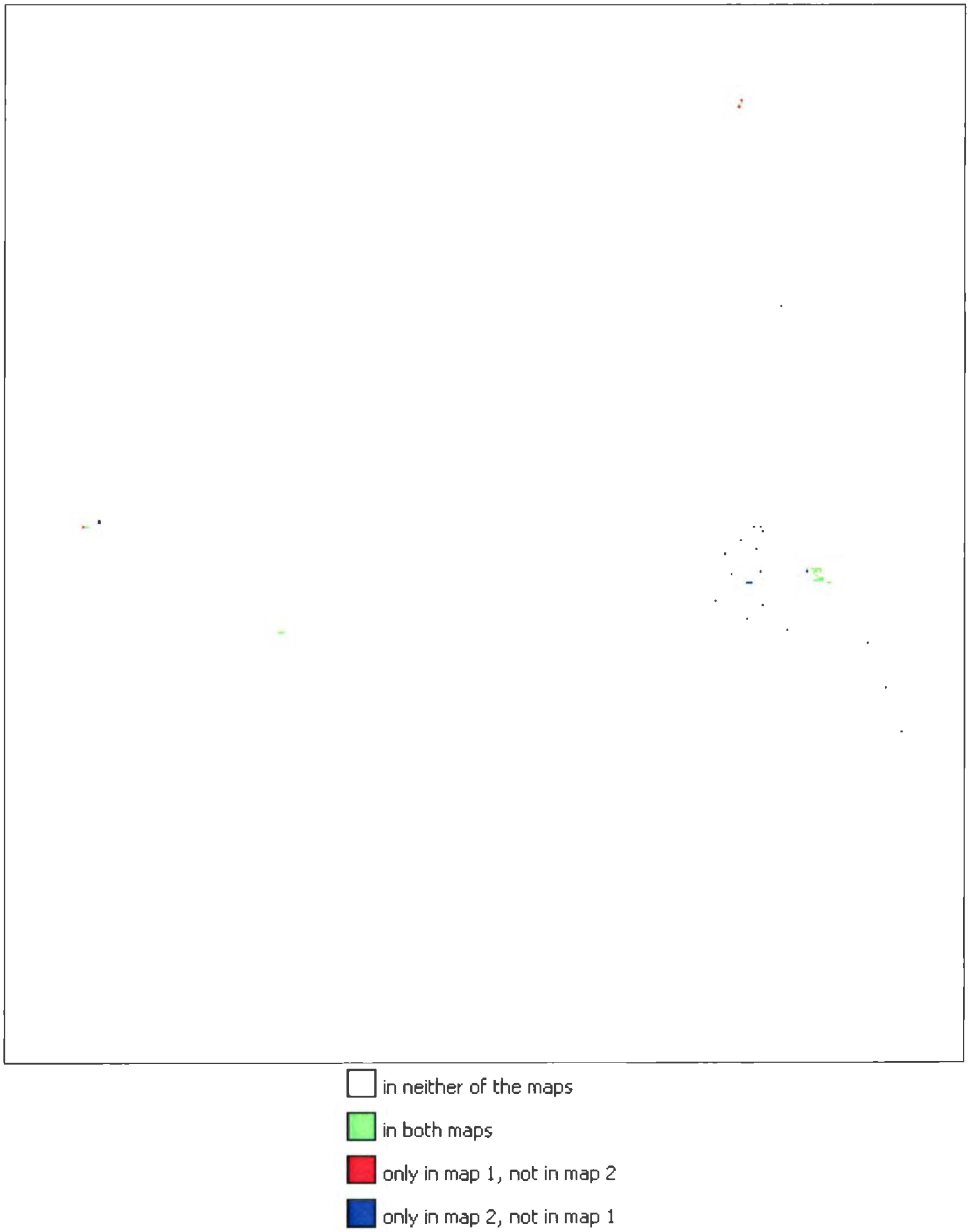


Figure 96 "Business as Usual" scenario: Commerce evolution between 1990 and 2025. Map 1 (red) is 1990. Map 2 (blue) is 2025. Results shown represent a single run.

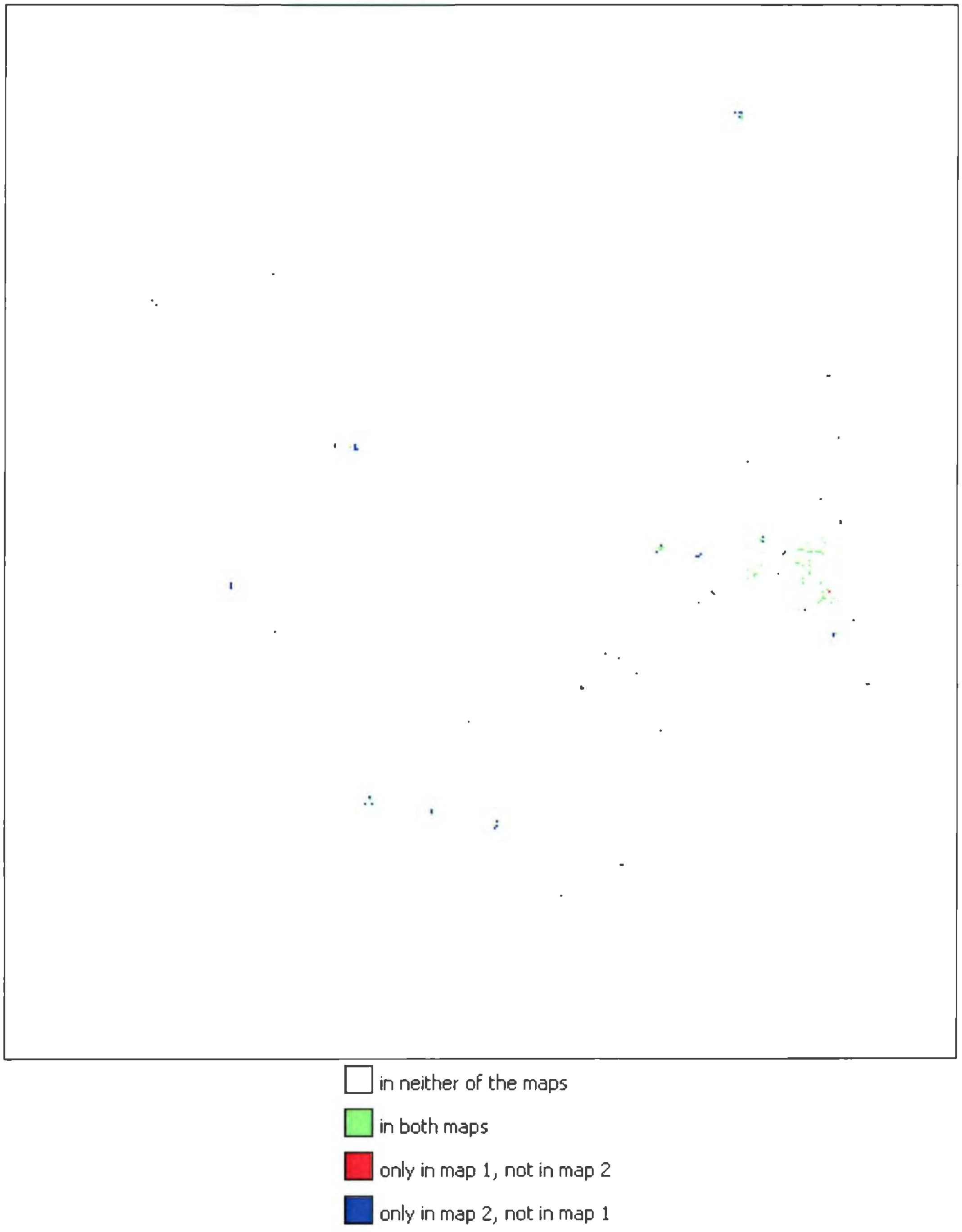


Figure 97 "Business as Usual" scenario: Public and Private Services evolution between 1990 and 2025. Map 1 (red) is 1990. Map 2 (blue) is 2025. Results shown represent a single run.

6.1.1.2. *Radial fractal analysis*

The business-as-usual scenario reveals urban dynamics that lead to an increase in almost all fractal radial measurements for all city areas (inner, outer and third zones). An exception is, however, displayed by the Residential Discontinuous Sparse for its Inner Zone values, which deeply influence the overall Residential land use.

6.1.1.3. *Cluster size-frequency fractal analysis*

The trends of the "Business as Usual" scenario lead to a decrease in the cluster size-frequency fractal measures for Industry and Public and Private Services while Commerce experiences an increase in its figures. The latter results from an increase in the number of small commercial clusters. For Industry and Public and Private Services, the decrease is mainly due to an increase in the size and number of larger clusters.

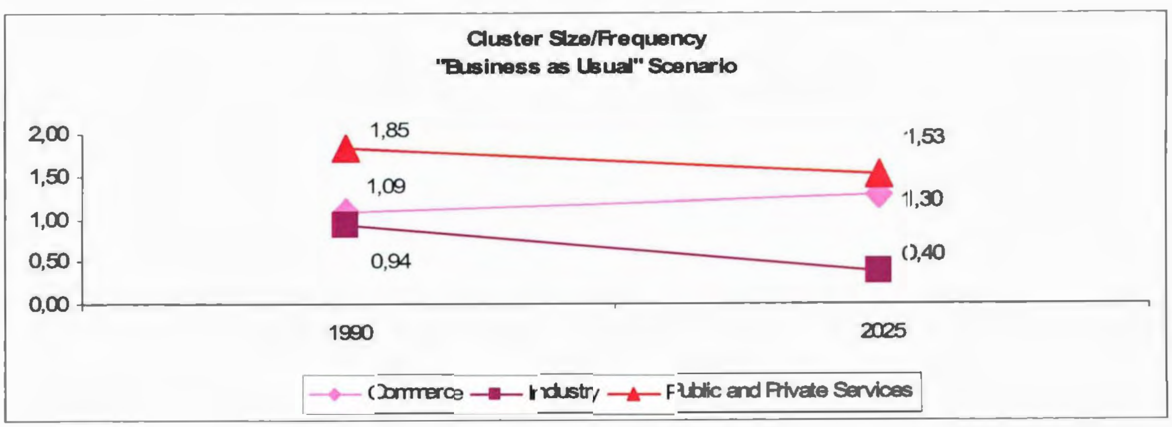


Figure 98 "Business as Usual"" scenario: cluster size-frequency graph lines for Commerce, Industry and Public and Private Services for 1990 and 2025.

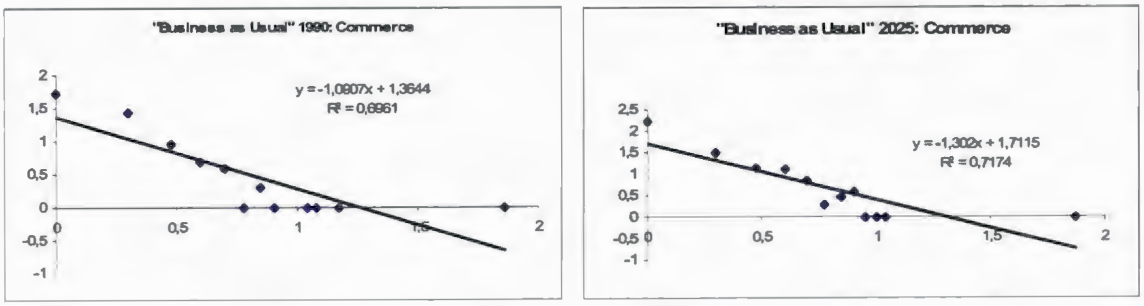


Figure 99 "Business as Usual"" scenario: fractal cluster size-frequency graphs for Commerce in 1990 and 2025.

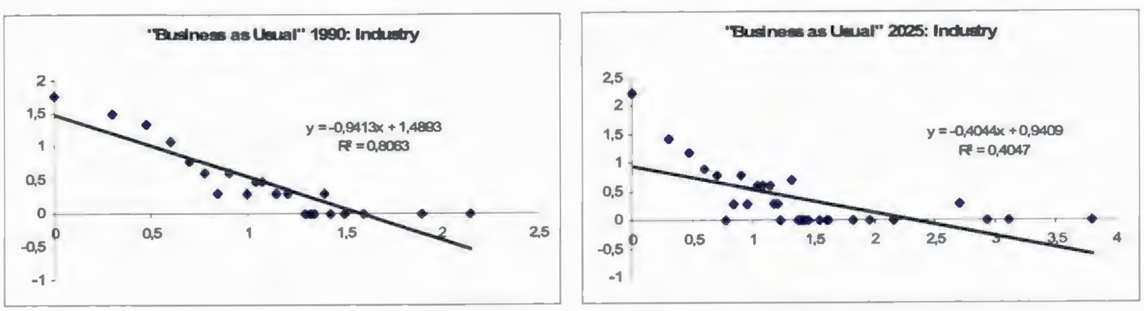


Figure 100 "Business as Usual"" scenario: fractal cluster size-frequency graphs for Industry in 1990 and 2025.

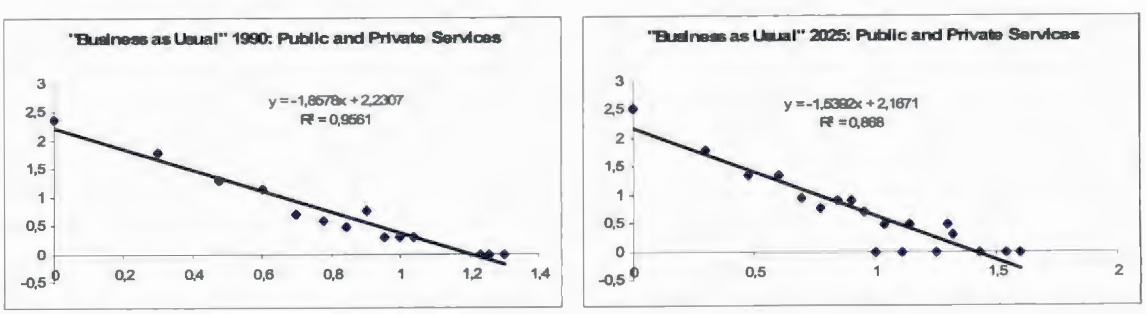


Figure 101 "Business as Usual"" scenario: fractal cluster size-frequency graphs for Public and Private Services in 1990 and 2025.

6.1.2. "Preference For Transit"

6.1.2.1. Overall comparison

Comparing the "Business as Usual" map with this the result from this scenario, a Fuzzy Kappa value of 0,98 is obtained. This describes the two maps resulting from different planning policies as practically the same. In order to find differences between them, a closer look should be taken. This is carried out by a visual comparison by category.

The preference for transit resulted largely in the growth of existing clusters of each of the four urban land uses (Residential Discontinuous Sparse, Industry, Commerce and Public and Private Services), whereas the "Business as Usual" scenario generated more new clusters for each of these four activities. Residential Discontinuous Sparse is characterized by an avoidance of the fringe of the City of Dublin, when compared to the business-as-usual-scenario, in which it prefers locations on the periphery of existing settlements beyond Dublin city. The same behaviour is, however, not followed by industrial land use. Dublin City's new industrial cells emerge in new locations but do not, generally speaking, abandon the city's boundaries. At the regional scale, another phenomenon is observed. Isolated industrial cells existing in the "Business as Usual" scenario are now more attracted to the existing industrial clusters. Larger industrial clusters thus appear more often in this scenario. Commercial land use follows the Residential Discontinuous Sparse trend. Preference for transit does not seem to affect Dublin City's Public and Private Services' cell counts. Its effect is reflected instead in the creation of fewer but larger Public and Private Services clusters in this area. At the regional level, a preference for transit seems to generate a centrifugal movement as new clusters of this land use appear further from the main city.

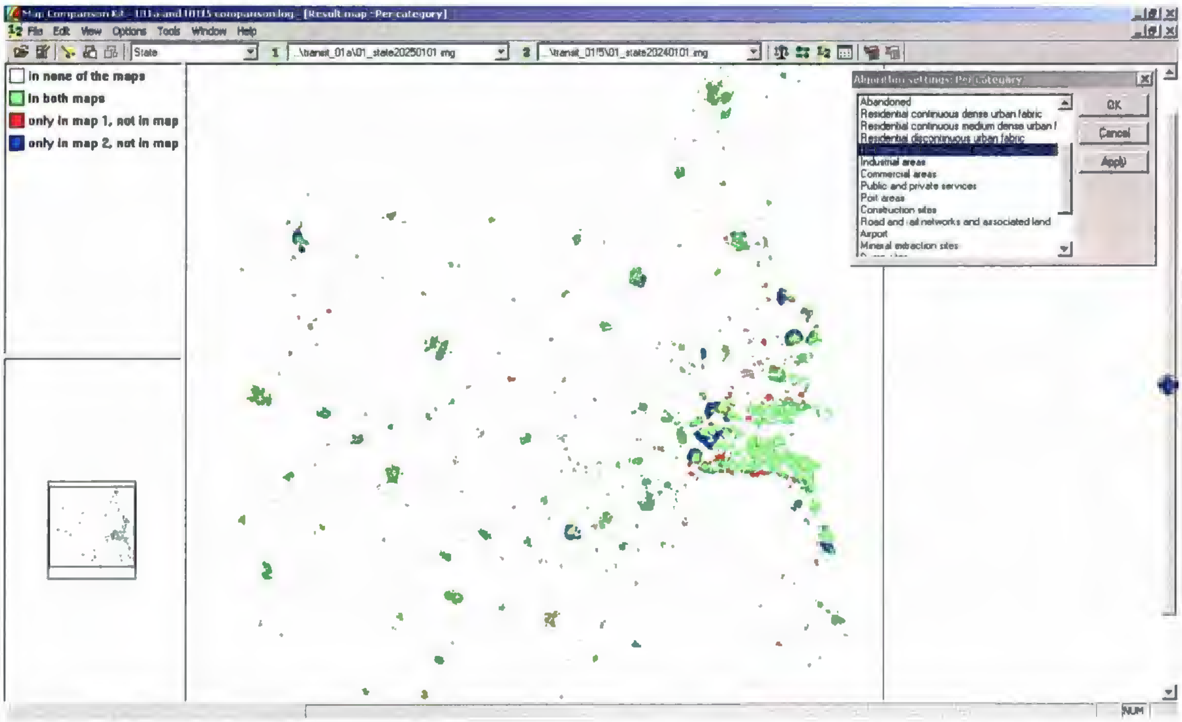


Figure 102 Category comparison of Residential Discontinuous Sparse land use for 2007. Map 1 (red) is the "Business as Usual" scenario. Map 2 (blue) is the "Preference For Transit" scenario. Results shown represent a single run.

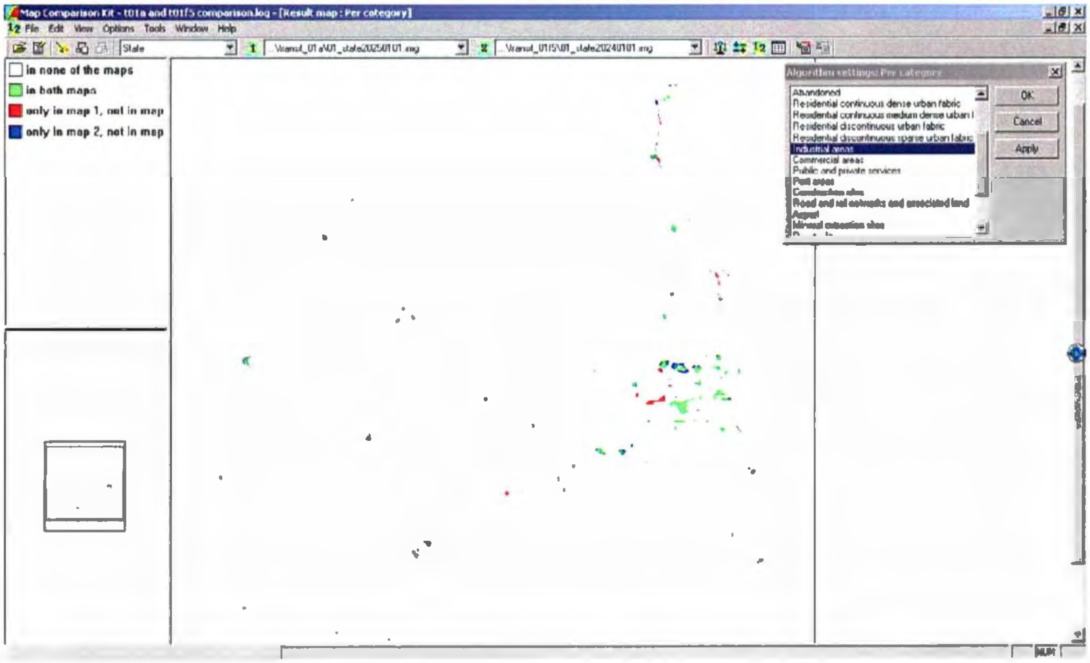


Figure 103 Category comparison of Industry land use for 2007. Map 1 (red) is the "Business as Usual" scenario. Map 2 (blue) is the "Preference For Transit" scenario. Results shown represent a single run.

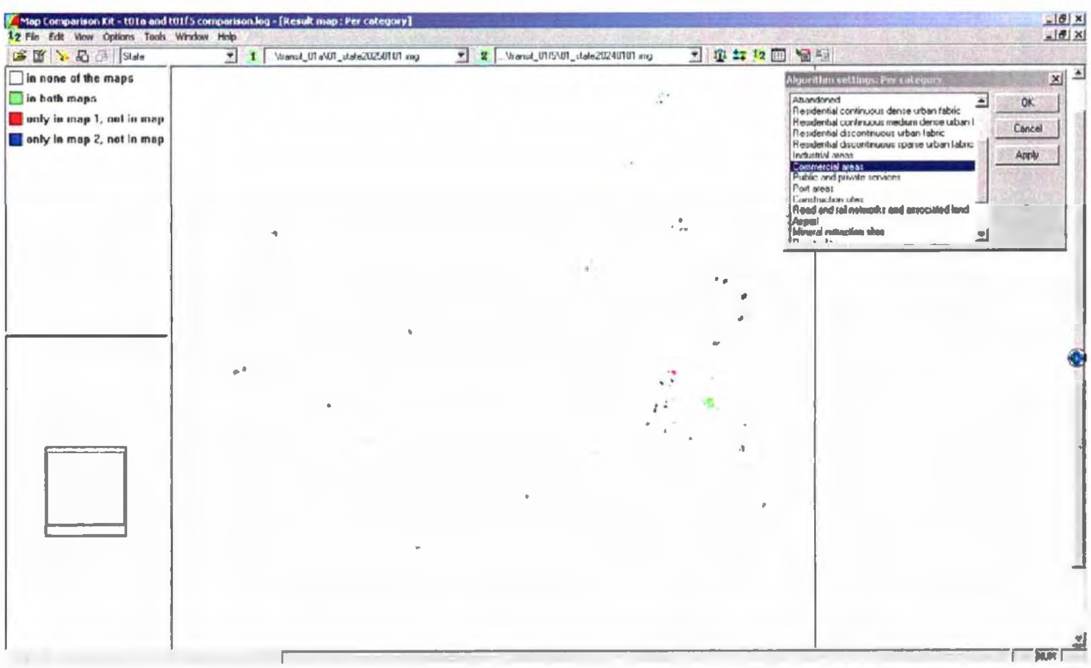


Figure 104 Category comparison of Commerce land use for 2007. Map 1 (red) is the "Business as Usual" scenario. Map 2 (blue) is the "Preference For Transit" scenario. Results shown represent a single run.

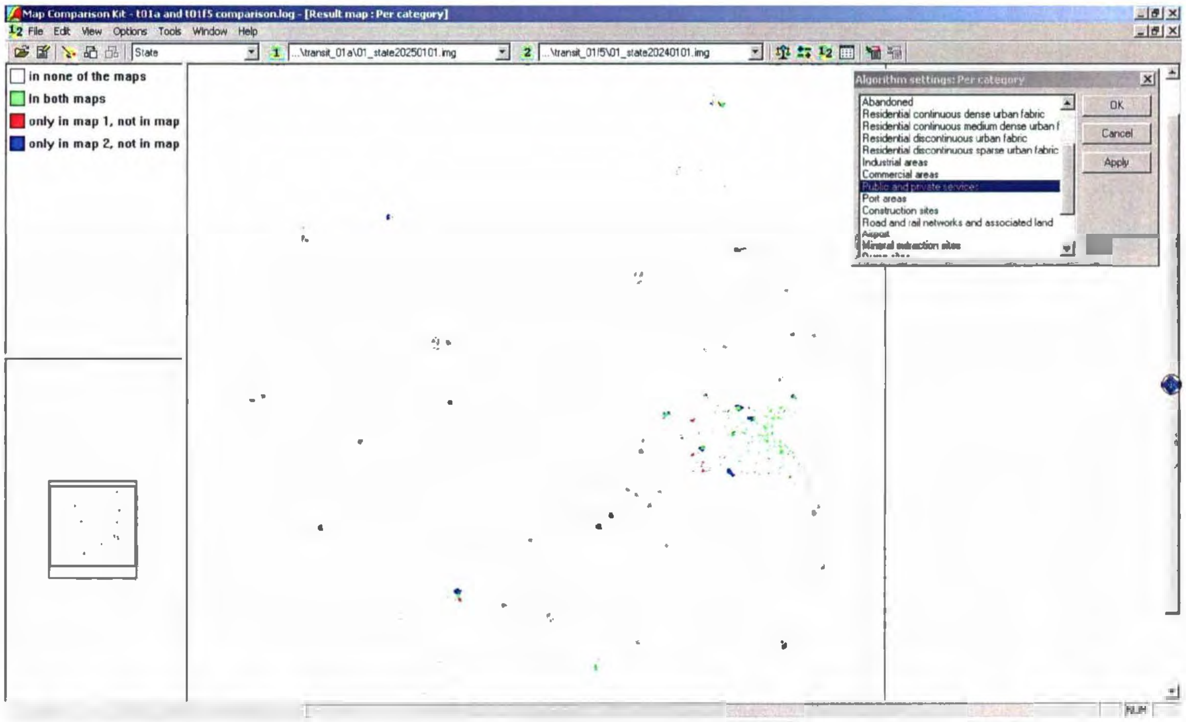


Figure 105 Category comparison of Public and Private Services land use for 2007. Map 1 (red) is the "Business as Usual" scenario. Map 2 (blue) is the "Preference For Transit" scenario. Results shown represent a single run.

6.1.2.2. Radial fractal analysis

Results of the radial analysis are shown in Figure 106. In terms of overall urban measurements, the two scenarios display hardly any differences. The same, however, cannot be said for each individual land use. The preference for transit use leads to the decrease of the Inner Zone fractal radial measurement value with the most dramatic drop occurring in the radial dimension of Industrial land use. The behaviour in the outer zone is two-fold, with Residential Discontinuous Sparse and Commerce yielding lower values, and Public and Private Services and Industry showing a slight increase,. Third zone values are slightly raised, with the exception of Industry, which drops.

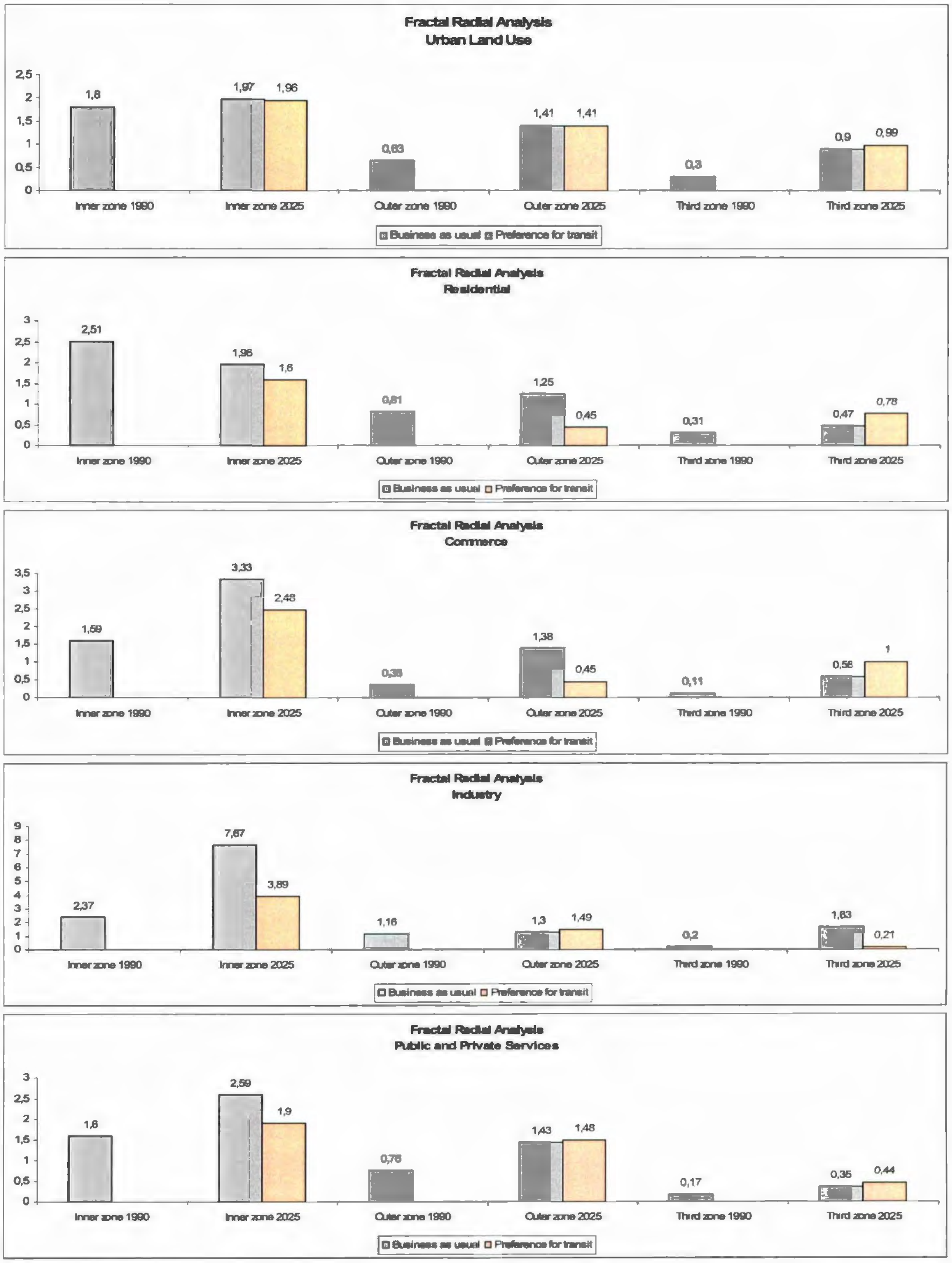


Figure 106 "Preference for Transit" scenario: Radial Dimensions for combined urban and all individual land use categories, for all city zones for the years 1990 and 2025.

6.1.2.3. Cluster size-frequency analysis

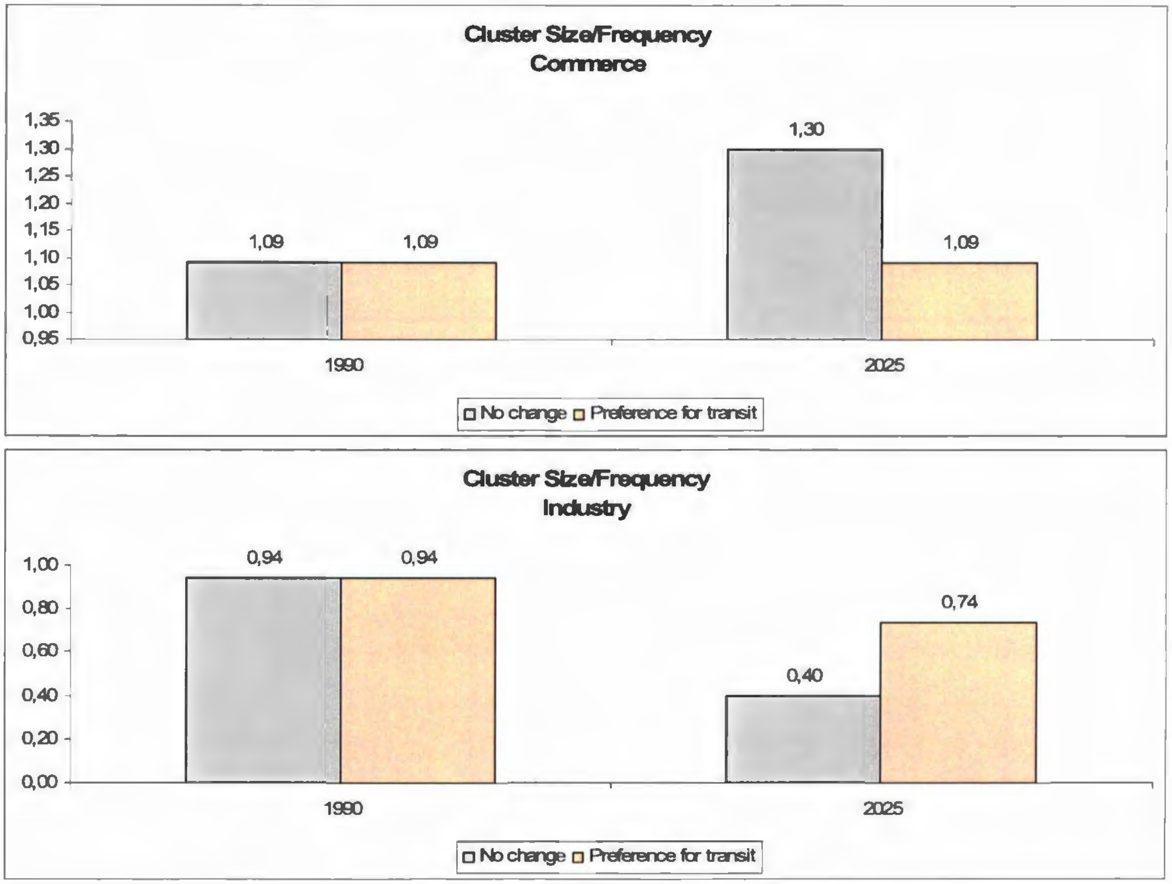


Figure 107 "Preference for Transit" scenario: Cluster Size-Frequency fractal measurements for Commerce and Industry for the years 1990 and 2025.

This scenario, in which commercial activity is more attracted to rail stations and routes maintains the cluster size-frequency dimension for that land use, unlike the situation in the business as usual scenario, in which this dimension increases significantly, from 1.09 to 1.30 (Figure 107). For Industry, a small change in behaviour is also observed.

Although a drop in the value occurs, this difference is less than in the "Business as Usual" scenario (Figure 107). The opposite happens with Public and Private Services, as its observed initial drop is reinforced.

Chapter 7. Discussion and conclusions

7.1. On the scenario results

Growth boundaries such as the ones used in the "Single Expansion Zone" and "Phased Growth" scenarios are good to control the overall urban morphology. Such growth constraints provides a way to develop compact growth and can hence minimize the sprawl that otherwise tends to develop on the rural-urban fringe and that fragments natural areas. It would also seem to be the case that such strategies would have a less disruptive effect on the normal self-organization of the land use pattern sublevel as they do not interfere so directly in the underlying land use dynamics.

Compared to growth boundaries, greenbelt planning practices are prone to encourage sprawl as measured by the Total Edge values. Whereas natural areas in the greenbelts are protected from further development and hence fragmentation, growth is simply forced to areas beyond the greenbelt, where sprawl is unconstrained. Contrary to the results for the growth boundary scenarios for Industry, the effect of implementing greenbelts is to lead to larger values of the cluster size-frequency dimensions reflecting a relatively more scattered pattern of smaller industrial areas.

None of the scenarios tested was completely able to suppress the leapfrogging development. Greenbelt scenarios seem more effective for commercial land use whereas the "Single Expansion Zone" scenario displays better results for Industry. It is believed that this is related to each land use's unique relationship with all the other land uses. It is suggested that in order to develop a practice that will effectively override completely the leapfrogging phenomenon, these relationships between land uses must be studied closely. One way of doing this is through an extensive analysis of the calibrated transition rules.

The regional scale modelling shows growth occurring along the main communication routes in the "Business as Usual" scenario. This behaviour is easily observed by analyzing the probability maps, since the number of new cells per scenario is not enough to allow a quick visual confirmation. Although still displaying strong evidence of contiguous growth on the urbanized fringe, urban expansion in this scenario may nevertheless be characterized as scattered, with new clusters of urban activity emerging in the outlying areas.

The "Preference For Transit" scenario result maps show a somewhat unrealistic growth pattern, characterized by "blobby" development. This is thought to be caused by less than optimal calibration settings. Still, the results are considered good enough to explore the model's potential. This scenario leads to Commerce, Industry and Public and Private Services clustering nearer the main transit nodes, thus successfully portraying human activity near those areas as a consequence of increased usage of the transit network. Such clustering, however, is somewhat different than in the "Business as Usual" scenario. There the number of clusters is lower but their sizes are larger.

In spite of displaying some significant changes in the Industrial clusters, the more consolidated Inner Zone of the city of Dublin displays few changes in its land use pattern. But changes are more obvious in the less developed peripheral areas of the Outer and Third Zones. The attraction exerted by the transit nodes is, thus, more effective in the periphery than in the consolidated city. This is due to two main factors: the availability of vacant cells near the nodes, and the distance-decay effect of such attraction. The further away from the transit node, the less effectively are the designated land uses attracted. This, allied with the fact that the consolidated part of the city lacks available land around the transit nodes, makes it difficult to have new cells cluster around them.

Due to the relatively simple approach to the modeling of transit encouragement policies, these results are not very nuanced. Nevertheless, they address regional questions. For instance, they provide the insight that, if the intention is to equip transit nodes with commercial and service activities, a policy that merely creates basins of attraction for the desired land uses is not enough. If this were the case, the transit nodes located in the consolidated part of the city would change their land use structure to accommodate the cells of new commercial and services activity. This is not the case, as those areas remain unchanged. The market pressure ruling the land use dynamics is still too feeble to induce these changes to the land use pattern, even though more pressure is put on the transit nodes' surrounding areas through the creation of an attraction policy. So, what the model is telling us is that in order to achieve the transit oriented development, other actions need to be carried out for the areas more resistant to change: for example, direct governmental intervention in land use through the expropriation of land for later conversion to commerce or services.

The Fuzzy Kappa comparison between the "Business as Usual" and the "Preference For Transit" scenarios shows a relatively high value of 0,98. This figure should mean that both maps are very similar, but that is not entirely true, since the later scenario yields a somewhat unrealistic "blobby" land use pattern. And the difference between the maps in terms of transit oriented development in the peripheral zones confirm this dissimilarity. This suggests that no method of analysis should be taken *per se* as an indicator of accuracy, but rather that a whole set of measures should be used for purposes of validation and evaluation.

7.2. On the model's usefulness as a planning tool

The main consideration in evaluating the usefulness of an urban model as a planning tool is to keep in mind that its purpose is not to substitute for the planner but rather to be a planning aid tool. One of the strong features of the dynamic model used here, as well as other similar models, is that it does not propose itself as a tool to yield accurate predictions. Instead, it takes randomness and uncertainty as important characteristics of the urban system. Starting from this premise, the model does allow for the prediction of *possible* futures. It should thus be used as just one of a number of tools for the planner, to help make better decisions about what might be the most appropriate plan for a given situation, producing insights about particular moments in time when the system could shift to a radically different pattern, such as increased sprawl, for instance.

7.2.1. Probability and potential maps

Models like the present one are also able to produce new base data for analysis, such as the probability maps used to display the output of a number of runs of the model. These maps can be useful to the planner, providing insights about the areas more likely to become urbanized, but the predictive limitations of the model must always be kept in mind. Because these types of models deal with unpredictability, and a proliferation of bifurcation points (which we have already discussed) the predictive capability declines as the length of the prediction period increases. As the model runs further into the future, the quality of the prediction will decrease at a faster rate. Therefore, probability maps should be used carefully.

Also of some benefit are the potential maps used to calculate the cell transitions. These are different from the probability maps. Probability maps are calculated based on the actual cell growth. Potential maps are used to determine the likelihood that a cell will change state. Each land use has, its own potential map. These maps are more easily read, and can provide contextual information about the areas more subject to pressures for a certain land use by quantifying all the macro- and micro-scale influences affecting a particular cell. Because they can be monitored through time, they can also provide a good historic overview on how the desirability of a given area changes through the years due to changes in its context. The transition potential of each cell is closely related to the land price. A tracking of the evolution of land prices could thus aid the identification of areas more vulnerable to real estate speculation.

7.2.2. Models and fractals

Another advantage of these new types of models is their capability to generate fractal structures. Due to their nature, fractals can reveal new phenomena and consequently produce new insights. Such applications have not, however, been developing hand-in-hand. Although we can now easily measure the fractility of things, there is still little that we know about how these measures relate to specific properties and processes of geographic systems. But in order to be useful, such new fractal measures need to be linked to existing concepts and knowledge. It is likely that using CA and fractals together will facilitate a deeper scrutiny of morphogenetic structures and processes, as both are highly connected and suited to characterize real-world phenomena. In the case of predictive modelling of urban land-use, such an alliance may be used towards a more pragmatic end, because fractal dimensions are not only used as a calibration parameter but also as qualitative indicators of quality of place.

7.3. On further research and development

Cellular automata land use models have made large strides in their application to urban phenomena since Tobler's pioneering work (1970). Not only have they proved successful in representing real-world urban phenomena, but also they have themselves produced new insights about urban dynamics and structure. This new breed of urban models has regained the attention of planners by giving results more in agreement with observed reality. Nevertheless, as of today, models are still most often used by modellers, and the practice of using models has not really infiltrated into planning. This may be due to the fact that models are still seen as resource- and time-consuming tools unable to deliver a positive cost-benefit balance. The use of a model as a planning tool should be simple and should not monopolize the planner's attention and resources.

Before these models can be used to their full extent by planners, several issues outside the modelling milieu still need to be addressed and worked out. The issue of model validity is of the utmost importance to planners, as it is crucial to whether or not the tool is capable of delivering the best and most reliable simulation possible. This is more important in operational than in theoretical models. The latter are most used to generate insights and develop urban theory, and the link to real-world cities can be relaxed a bit. For the operational models, on the other hand, these links need strengthening if the models are to be used as planning tools. This is because, in spite of all the supporting theoretical background, from the planner's perspective, the model is unique, adapted and fine-tuned to the particular city to give reliable indications of the likely consequences of the specific plans and policies that are under consideration. If it is not able to function reliably in this way, it is useless or even dangerous.

Another key feature to bear in mind about the development of models as planning tools is the need for them to be developed not just as models, but also in a way that allows for easy and quick extraction and analysis of results. The time-consuming task of starting with raw data in order—after a long process of data preparation, modelling, and output analysis—finally to arrive at a clear picture of what is happening in the city is one that the typical planner cannot afford. From the user's perspective, the focus should be on the analysis of the results and not on the task of generating them. Moreover, the systematization of data extraction and analysis through automatic processes minimizes human error and thus leads to quicker, more reliable results. Model developers should thus focus on the creation of modelling frameworks capable of delivering such results in a more usable way. Modelling is, however, still a relatively new and rapidly changing field of practice. There are a number of modellers working on different types of approaches, and although there is general acknowledgement of the benefits of the insights generated by these models, such as the ones produced by fractal measures, there is as yet no consensus about which measures to incorporate as models are developed. Filling this gap would be useful for both the fields of modelling and planning, and eventually, through joint efforts, would deliver more useful and reliable models.

References

Anon. (2002a). *CNU Homepage*. Congress for the New Urbanism. From the World Wide Web: http://www.cnu.org.

Anon. (2002b). *Metadata for the National Parks and Wildlife Service Datasets*. Department of Arts, Heritage, Gaeltacht and the Islands. From the World Wide Web: http://www.heritagedata.ie/en/. Accessed on 11-11-2002b.

Anon. (2002c). *Moland - Monitoring Land Use/Cover Dynamics*. Moland Homepage. From the World Wide Web: http://moland.jrc.it/. Accessed on 2-21-2002c.

Abler R., Adams J.S. and Gould P. (1971). *Spatial organization the geographer's view of the world*. Prentice-Hall, Englewood Cliffs, N.J.

Alexander C. (1965a). A City is not a Tree (Part I). *Architectural Forum* **122**(1): 58-62

Alexander C. (1965b). A City is not a Tree (Part II). *Architectural Forum* **122**(2): 58-62

Allen P.M. (1983). Self-organization and evolution in urban systems. Pages - *In* Cities and Regions as Nonlinear Decision Systems. *Edited by* Crosby R. Westview Press.

Allen P.M. and Sanglier M. (1981). Urban evolution, self-organization, and decision making. *Environment and Planning A* **13**: 167-183

Alonso W. (1964). *Location and land use*. Harvard University Press, Cambridge, MA.

Batty M. (1976). *Urban modelling: algorithms, calibrations, predictions*. Cambridge University Press, Cambridge.

Batty M. (1991). Cities as fractals: simulating growth and form. Pages 43-69 *In* Fractals and Chaos. *Edited by* Crilly A.J., Earnshaw R.A. and Jones H. Springer, Berlin.

Batty M. (1994). A chronicle of scientific planning: the anglo-american modeling experience. *Journal of the American Planning Association* **60**(1): 7-16

Batty M. (1997). Possible cellular automata. *Environment and Planning B: Planning and Design* **24**: 175-192

Batty M. (2001). Polynucleated urban landscapes. *Urban Studies* **38**(4): 635-655

Batty M. and Longley P. (1994). *Fractal cities*. Academic Press, London.

Batty M. and Torrens P. (2001). Modeling Complexity: The Limits to Prediction. *12th European Colloquium on Quantitative and Theoretical Geography*. St-Valery-en-Caux, Normandy.

Batty M. and Xie Y. (1994). From cells to cities. *Environment and Planning B: Planning and Design* **21**: s31-s48

Benguigui L., Czamanski D. and Marinov M. (2001). The dynamics of urban morphology: the case of Petah Tikvah. *Environment and Planning B: Planning and Design* **28**: 447-460

Benguigui L., Czamanski D., Marinov M. and Portugali Y. (2000). When and where is a city fractal? *Environment and Planning B: Planning and Design* **27**: 507-519

Benguigui L. and Daoud M. (1991). Is the Suburban Railway System a Fractal? *Geographical Analysis* **23**(4): 362-368

Calthorpe P. (1993). *The next American metropolis: ecology, community, and the American dream*. Princeton Architectural Press, New York.

Calthorpe P. and Fulton W.B. (2001). *The regional city: planning for the end of sprawl*. Island Press, Washington, DC.

Chapin F.S.Jr. (1965). A model for simulating residential development. *Journal of the American Planning Association* **31**(2): 120-136

Chapin F.S.Jr. and Weiss S.F. (1968). A probabilistic model for residential growth. *Transportation Research* **2**: 375-390

Christaller W. (1966). *Central places in southern Germany / Translated from Die zentralen Orte in Süddeutschland by Carlisle W. Baskin*. Prentice Hall, Englewood Cliffs, N.J.

Clark Labs (2001). IDRISI32 (Version I32.2) [Computer software].

Clarke K.C., Hoppen S. and Gaydos L. (1997). A self-modifying cellular automaton model of historical urbanization in the San Francisco Bay area. *Environment and Planning B: Planning and Design* **24**: 247-261

Clarke K.C. and Gaydos L. (1998). Loose coupling a cellular automata model and GIS: long-term growth prediction for San Francisco and Washington/Baltimore. *International Journal of Geographical Information Science* **12**(7): 699-714

CNU (1998). *Charter of the New Urbanism.* Congress for the New Urbanism. From the World Wide Web: http://www.cnu.org/cnu_reports/Charter.pdf.

Corbett J. and Velasquez J. (1994). *Ahwahnee principles.* reprinted from Western City. From the World Wide Web: http://www.lgc.org/ahwahnee/principles.html. Accessed on 8-14-2002.

Couclelis H. (1985). Cellular worlds: a framework for modeling micro-macro dynamics. *Environment and Planning A* **17**: 585-596

Couclelis H. (1988). Of mice and men: what rodent populations can teach us about complex spatial dynamics. *Environment and Planning A* **20**: 99-109

Couclelis H. (1989). Macrostructure and behaviour in a metropolitan area. *Environment and Planning B: Planning and Design* **16**: 141-154

Couclelis H. (1997). From cellular automata to urban models: new principles for model development and implementation. *Environment and Planning B: Planning and Design* **24**: 165-174

Dunlop B. (1997). The new urbanists: the second generation. *Architectural record*(January): 132-137

Eastman J.R. (2001). *IDRISI Release 2 - Guide to GIS and Image Processing.* (Vol. 2) Clark Labs, Clark University, Worcester, MA.

Engelen G., White R. and Uljee I. (1997). Integrating constrained cellular automata models, GIS, and decision support tools for urban planning and policy making. Pages 125-155 *In* Decision Support Systems in Urban Planning. *Edited by* Timmermans H.P.J. E & FN Spon, London.

Engelen G., White R. and Uljee I. (2002). *The MURBANDY and MOLAND models for Dublin.* (Final Report).

European Commission (1999). *The European Spatial Development Perspective (E.S.D.P.): Comments and recommendations from the European Consultative Forum on the Environment and Sustainable Development.* last accessed at April 23, 2003.

Frankhauser P. (1988). Fractal Structures of Urban Systems. Fuchssteiner B., Lengauer T. and Skala H.J. (Editors). *Methods of Operations Research.* Paderborn.

Frankhauser P. (1994). *La fractalité des structures urbaines.* Anthropos, Paris.

Frankhauser P. and Sadler R. (1991). Fractal Analysis of Agglomerations. *Second International Colloquium of the Sonderforschungsbereich 230 "Natüraliche Konstruktionen".* (Pp. 57-65). Stuttgart.

Gardner M. (1970). Mathematical games: the fantastic combinations of John Conway's new solitaire game "life". *Scientific American* **223**(October): 120-123

Hagen A. (2003). Fuzzy set approach to assessing similarity of categorical maps. *International Journal of Geographical Information Science* **17**(3): 235-249

Harmon T. (2002). *Portland, Oregon: Who pays the price for regional planning?* Planners Network. From the World Wide Web: http://www.plannersnetwork.org/htm/pub/archives/128/harmon.htm.

Herbert J.D. and Stevens B.H. (1960). A model for the distribution of residential activity in urban areas. *Journal of Regional Science* **2**: 21-36

Hutchinson B. and Batty M. (1986). *Advances in urban systems modelling.* North-Holland, Amsterdam.

Jacobs J. (1961). *The death and life of great American cities.* Vintage Books, New York.

Katz P., Scully V.J. and Bressi T.W. (1994). *The new urbanism: toward an architecture of community.* McGraw-Hill, New York.

Lavalle C., Demicheli L., Kasanko M., McCormick N., Barredo J., Turchini M., Saraiva M.d.G., da Silva F.N., Ramos I.L., Monteiro F.P., Caetano M. and Martins I.P. (2002). *Towards and urban atlas.* (Rep. No. 30). European Environment Agency, Copenhagen, Denmark.

Lee D.B. (1973). Requiem for large-scale models. *Journal of the American Institute of Planners* **39**(3): 163-178

Li X. and Yeh A.G.O. (2001). Zoning land for agricultural protection by the integration of remote sensing, GIS, and cellular automata. *Photogrammetric Engineering and Remote Sensing* **67**(4): 471-477

Lösch A. (1954). *The economics of location / Translated from the 2d rev. ed. by William H. Woglom with the assistance of Wolfgang F. Stolper.* Yale University Press, New Haven.

Lowry I.S. (1964). *A model of metropolis.* (Rep. No. RM-4035-RC). cited in Batty JAPA 1994 as the example par excellence of an early urban transportation model. The RAND Corporation, Santa Monica, CA.

Lynch K. (1960). *The image of the city.* M.I.T. Press & Harvard University Press, Cambridge.

Mandelbrot B. (1967). How Long Is The Coast of Britain? Statistical Self-Similarity and Fractional Dimension. *Science* **156**(3775): 636-638

McGarigal, K., Cushman, S. A., Neel, M. C., & Ene, E. (2002). FRAGSTATS: Spatial Pattern Analysis Program for Categorical Maps [Computer software]. University of Massachusetts.

Phipps M. (1989). Dynamical behavior of cellular automata under the constraint of neighborhood coherence. *Geographical Analysis* **21**(3): 197-215

Phipps M.J. (1992). From local to global: the lesson of cellular automata. Pages 165-187 *In* Individual-Based Models and Approaches in Ecology. *Edited by* DeAngelis D.L. and Gross L.J. Chapman & Hall, New York.

Portugali J. (2000). *Self-organization and the City.* Springer Verlag, Berlin.

Portugali J. and Benenson I. (1995). Artificial planning experience by means of a heuristic cell-space model: simulating international migration in the urban process. *Environment and Planning A* **27**: 1647-1665

Portugali J., Benenson I. and Omer I. (1997). Spatial cognitive dissonance and sociospatial emergence in a self-organizing city. *Environment and Planning B: Planning and Design* **24**: 263-285

Poundstone W. and Wainwright R.T. (1985). *The recursive universe: cosmic complexity and the limits of scientific knowledge.* (1st ed ed.) Morrow, New York.

Power C., Simms A. and White R. (2001). Hierarchical fuzzy pattern matching for the regional comparison of land use maps. *International Journal of Geographical Information Science*(15): 77-100

RIKS BV (2000). GEONAMICA (Version 2.9.0.0) [Computer software].

Semboloni F. (1997). An urban and regional model based on cellular automata. *Environment and Planning B: Planning and Design* **24**: 589-612

Simmonds D. (1986). Modelling contexts and purposes: defining alternative paths of model development. Pages 75-87 *In* Advances in Urban Systems Modelling. *Edited by* Hutchinson B. and Batty M. Elsevier Science Publishers B.V., North-Holland.

SRUNA (2002). *The SRUNA project - Sustainable Recreational Use of Natural Assets.* SRUNA Homepage. From the World Wide Web: http://www.dra.ie/sruna/index.html. Accessed on 10-5-2002.

Talen E. (2005). *New urbanism and American planning: the conflict of cultures.* Routledge, New York.

Tobler W.R. (1970). A computer movie simulating urban growth in the Detroit region. *Economic Geography* **26**: 234-240

Tobler W.R. (1979). Cellular Geography. Pages 279-386 *In* Philosophy in Geography. *Edited by* Gale S. and Olson G. D. Reidel Publishing Company, Dordrecht.

Toffoli T. and Margolus N. (1987). *Cellular automata machines: a new environment for modeling.* MIT Press, Cambridge, Mass.

Torrens P. and O'Sullivan D. (2001). Cellular automata and urban simulation: where do we go from here? *Environment and Planning B: Planning and Design* **28**: 163-168

Thünen J.H.v. (1966). *Isolated state; an English edition of Der isolierte Staat.* Pergamon Press, New York.

Wagner D.F. (1997). Cellular automata and geographic information systems. *Environment and Planning B: Planning and Design* **24**: 219-234

Wheeler S.M. (2001). *Book review: The Regional City: Planning for the End of Sprawl.* Berkeley Planning Journal. From the World Wide Web: http://www-dcrp.ced.berkeley.edu/bpj/pdf/15-Wheeler2.pdf.

White R. (1977). Dynamic central place theory: results of a simulation approach. *Geographical Analysis* **9**: 227-243

White R. (1978). The simulation of central place dynamics: two sector systems and the rank-size distribution. *Geographical Analysis* **10**: 201-208

White R. and Engelen G. (1993). Cellular automata and fractal urban form: a cellular modelling approach to the evolution of urban land-use patterns. *Environment and Planning A* **25**: 1175-1199

White R. and Engelen G. (1994). Urban systems dynamics and cellular automata: fractal structures between order and chaos. *Chaos Solitons & Fractals* **4**(4): 563-583

White R. and Engelen G. (1997). Cellular automata as the basis of integrated dynamic regional modelling. *Environment and Planning B: Planning and Design* **24**: 235-246

White R. and Engelen G. (2000). High resolution integrated modelling of the spatial dynamics of urban and regional systems. *Computers, Environment and Urban Systems* **24**: 383-400

White R., Engelen G. and Uljee I. (1997). The use of constrained cellular automata for high-resolution modelling of urban land-use dynamics. *Environment and Planning B: Planning and Design* **24**: 323-343

White R., Engelen G., Uljee I., Lavalle C. and Erlich D. (1999). Developing and urban land use simulator for european cities. Fullerton K. (Editor). *5th EC-GIS Workshops.* European Comission, Joint Research Centre, Stresa, Italy.

White R., Luo W. and Hatna E. (2001). Fractal Structures in Land Use Patterns of European Cities: Form and Process. *European Coloquium on Quantitative and Theoretical Geography.*

Wilson A.G. (1981). *Catastrophe theory and bifurcation: applications to urban and regional systems*. Croom Helm, London.

Wilson A.G. (1974). *Urban and regional models in geography and planning*. Wiley, London.

Wolfram S. (1984). Universality and complexity in cellular automata. *Physica D* **10**: 1-35

World Commission on Environment and Development (1987). *Our common future*. Oxford University Press, Oxford.

Wu F. (1998a). An experiment on the generic polycentricity of urban growth in a cellular city. *Environment and Planning B: Planning and Design* **25**: 731-752

Wu F. (1998b). SimLand: a prototype to simulate land conversion through the integrated GIS and CA with AHP-derived transition rules. *International Journal of Geographical Information Science* **12**(1): 63-82

Xiang W.-N. and Clarke K.C. (2003). The use of scenarios in land-use planning. *Environment and Planning B: Planning and Design* **30**: 885-909

Appendices

Appendix A • Metropolitan Scale Data

Table 6 "Business as Usual" scenario: evolution of the radial fractal measurements for Dublin, for 1988, 1998 and 2007) for Urban Land Use, Overall Residential, Residential Discontinuous Sparse, Industry, Commerce and Public and Private Services land uses.

	Urban Land Use	Overall Resid.	Resid. Disc. Sparse	Commerc e	Industry	Public and Private Services
Inner Zone						
1988	1,92	2,53	2,77	1,73	2,14	2,16
1998	1,92	2,34	2,76	1,82	2,13	2,16
2007	1,92	2,18	2,76	1,97	2,13	2,19
Outer Zone						
1988	1,14	0,93	2,23	0,22	1,74	1,28
1998	1,35	1,08	2,23	0,25	1,72	1,29
2007	1,46	1,26	2,24	0,26	1,72	1,30
Third Zone						
1988	0,33	0,20	1,32	0,48	2,07	0,82
1998	0,52	0,27	1,44	0,78	2,66	0,89
2007	0,88	0,34	1,55	1,05	2,75	0,93

Table 7 "Business as Usual" scenario: evolution of the cluster size frequency fractal dimension for Commerce, Industry and Public and Private Services for Dublin for 1988, 1998 and 2008.

	Commerce	Industry	Public and Private Services
1988	1,52	0,55	1,59
1998	1,64	0,51	1,45
2007	1,36	0,47	1,52

Table 8 "Single Expansion Zone" scenario: evolution of the radial fractal measurements for different land uses for Dublin for the years of 1988, 1998 and 2007.

	Urban Land Use	Overall Residential	Residential Discont. Sparse	Commerce	Industry	Public and Private Services
Inner Zone						
1988	1,92	2,53	2,77	1,73	2,14	2,16
1998	1,86	2,35	2,76	1,81	2,13	2,16
2007	1,85	2,26	2,47	1,89	2,11	2,16
Outer Zone						
1988	1,14	0,93	2,23	0,22	1,74	1,28
1998	0,77	1,07	2,23	0,24	2,67	1,28
2007	0,81	1,26	1,56	0,26	2,79	1,30
Third Zone						
1988	0,33	0,20	1,32	0,48	2,07	0,82
1998	0,23	0,28	1,45	0,80	1,74	0,89
2007	0,29	0,35	1,13	1,05	1,11	0,92

Table 9 "Single Expansion Zone" scenario: evolution of the cluster size frequency fractal dimension for Commerce, Industry and Public and Private Services for Dublin 1988, 1998 and 2008.

	Commerce	Industry	Public and Private Services
1988	1,52	0,55	1,59
1998	1,58	0,41	1,41
2007	1,52	0,39	1,42

Table 10 "Phased Growth" scenario: evolution of the radial fractal measurements for Dublin 1988, 1998 and 2007.

	Overall Urban Land Use	Overall Residential	Residential Discont. Sparse	Commerce	Industry	Public and Private Services
Inner Zone						
1988	1,92	2,53	2,77	1,73	2,14	2,16
1998	1,86	2,37	2,76	1,80	2,13	2,14
2007	1,87	2,35	2,76	1,81	2,13	2,14
Outer Zone						
1988	1,14	0,93	2,23	0,22	1,74	1,28
1998	0,78	1,08	2,26	0,25	1,71	1,28
2007	0,90	1,21	2,25	0,26	1,71	1,28
Third Zone						
1988	0,33	0,20	1,32	0,48	2,07	0,82
1998	0,23	0,27	1,46	0,75	2,61	0,89
2007	0,32	0,39	1,54	0,99	2,68	0,94

Table 11 "Phased Growth" scenario: evolution of the cluster size-frequency fractal dimension for Commerce, Industry and Public and Private Services for Dublin 1988, 1998 and 2007.

	Commerce	Industry	Private and Public Services
1988	1,52	0,55	1,59
1998	1,59	0,48	1,42
2007	1,46	0,46	1,46

Table 12 "Greenbelt Around Dublin City" scenario: evolution of the radial fractal measurements for Dublin for 1988, 1998 and 2007.

	Urban Land Use	Overall Resid.	Resid. Disc. Sparse	Commerce	Industry	Private and Public Services
Inner Zone						
1988	1,92	2,53	2,77	1,73	2,14	2,16
1998	1,85	2,46	2,78	1,76	2,12	2,11
2007	1,85	2,48	2,78	1,76	2,12	2,11
Outer Zone						
1988	1,14	0,93	2,23	0,22	1,74	1,28
1998	0,88	1,07	2,32	0,23	1,72	1,3
2007	1,09	1,23	2,23	0,24	1,72	1,3
Third Zone						
1988	0,33	0,20	1,32	0,48	2,07	0,82
1998	0,31	0,35	1,4	0,67	2,14	0,88
2007	0,41	0,46	1,41	0,8	2,14	0,89

Table 13 "Greenbelt Around Dublin" scenario: evolution of the cluster size frequency fractal dimension for Commerce, Industry and Public and Private Services for Dublin for 1988, 1998 and 2008.

	Commerce	Industry	Private and Public Services
1988	1,52	0,55	1,59
1998	1,64	1,14	1,56
2007	1,62	0,97	1,61

Table 14 "Greenbelt Around the Entire Built Landscape" scenario: evolution of the radial fractal measurements for Dublin for 1988, 1998 and 2007, for Urban Land Use, Overall Residential, Residential Discontinuous Sparse, Industry, Commerce and Public and Private Services land uses.

	Urban Land Use	Overall Resid.	Resid. Disc. Sparse	Commerc e	Industry	Public and Private Services
Inner Zone						
1988	1,92	2,53	2,77	1,73	2,14	2,16
1998	1,84	2,5	2,78	1,74	2,12	2,12
2007	1,84	2,49	2,78	1,74	2,12	2.12
Outer Zone						
1988	1,14	0,93	2,23	0,22	1,74	1,28
1998	0,92	1,07	2,23	0,23	1,73	1,3
2007	1,12	1,22	2,23	0,24	1,73	1,3
Third Zone						
1988	0,33	0,20	1,32	0,48	2,07	0,82
1998	0,31	0,35	1,34	0,57	2,13	0,87
2007	0,37	0,44	1,35	0,64	2,13	0,87

Table 15 "Greenbelt Around Entire Built Landscape" scenario: evolution of the cluster size frequency fractal dimension for Commerce, Industry and Public and Private Services for Dublin for 1988, 1998 and 2008.

	Commerce	Industry	Private and Public Services
1988	1,52	0,55	1,59
1998	1,49	1,09	1,55
2007	1,32	0,80	1,59

Appendix B • Regional Scale Data

Table 16 "Business as Usual" scenario: evolution of the radial fractal measurements for Regional Dublin for 1990 and 2025, for Urban Land Use, Overall Residential, Residential Discontinuous Sparse, Industry, Commerce and Public and Private Services land uses.

	Urban Land Use	Overall Resid.	Resid. Disc. Sparse	Commerce	Industry	Public and Private Services
Inner Zone						
1990	1,8	2,51	3,16	1,59	2,37	1,6
2025	1,97	1,96	1,91	3,33	7,67	2,59
Outer Zone						
1990	0,63	0,81	0,84	0,36	1,16	0,76
2025	1,41	1,25	1,47	1,38	1,3	1,43
Third Zone						
1990	0,3	0,31	0,32	0,11	0,2	0,17
2025	0,9	0,47	0,88	0,58	1,63	0,35

Table 17 "Business as Usual" scenario: evolution of the cluster size frequency fractal dimension for Commerce, Industry and Public and Private Services for 1990 and 2025.

	Commerce	Industry	Public and Private Services
1990	1,09	0,94	1,85
2025	1,30	0,40	1,53

Table 18 "Preference For Transit" scenario: evolution of the radial fractal measurements for 1990 and 2025.

	Overall Urban Land Use	Residential	Residential Discont. Sparse	Commerce	Industry	Public and Private Services
Inner Zone						
1990	1,8	2,51	3,16	1,59	2,37	1,6
2025	1,96	1,6	1,9	2,48	3,89	1,9
Outer Zone						
1990	0,63	0,81	0,84	0,36	1,16	0,76
2025	1,41	0,45	1,31	0,45	1,49	1,48
Third Zone						
1990	0,3	0,31	0,32	0,11	0,2	0,17
2025	0,99	0,78	0,66	1	0,21	0,44

Table 19 "Preference For Transit" scenario: evolution of the cluster size frequency fractal dimension for industry, commerce and public and private services for 1990 and 2025.

	Commerce	Industry	Public and Private Services
1990	1,09	0,94	1,85
2025	1,09	0,74	1,29