Modelling the future of cities using cellular automata: the MOLAND methodology

José I. Barredo, Marjo Kasanko, Luca Demicheli, Niall McCormick, Carlo Lavalle
European Commission, Joint Research Centre
Institute for Environment and Sustainability, 21020 Ispra (VA), Italy

1. Introduction

In the last years cellular automata (CA) have gained popularity as modelling tools for urban process simulation. Several approaches have been proposed for modifying standard CA in order to make it suitable for urban simulation (White and Engelen 1993a, Itami 1994, White et al. 1997, Wu 1998, Clarke and Gaydos 1998, White et al. 1999, White and Engelen 2000, Semboloni 2000, Li and Yeh 2000, Sui and Zeng 2001). The results of the previous applications are promising and have shown realistic results in several cities in different parts of the world.

The popularity of CA may be due to the fact that CA are systems able to reproduce and mimic complex systems with self–organizing properties. Despite that, some questions remain to be addressed when CA are used as modelling tools in urban studies. How to get in use all the modelling potential of CA in order to make it suitable for urban processes is a question still to be addressed.

Cities have been defined as complex systems considering their intrinsic properties and the process of land use dynamics, and therefore CA are particularly well suited for modelling urban simulations (White and Engelen 1993a, Torrens and O'Sullivan 2001). However, cities have different characteristics due to several causes, such as the level of economic development, social and cultural issues, historical aspects, geographical location, etc. This paper addresses an experiment for modelling urban land use scenarios in Prague using an urban cellular automaton. The aim of this paper is to test the capability of an urban CA in simulating urban scenarios. We calibrated the model using historical and reference land use datasets for a thirty years period between 1968 and 1998. The aim of this model prototype is to predict future land use development under existing spatial plans and policies, and to compare alternative planning and policy scenarios in terms of their effects on future land use development.

2. Characteristics and factors of the urban land use dynamics

Cities are among the most complex structures created by human societies. They reflect the collective characteristics of their society. Cities of different regions of the world may also be different from several points of view, but despite these differences, cities have some characteristics that identify all of them as features of the same set. Dynamism and growth are two of the elements which characterize most urban areas, but to understand how and why they actuate may in some instances be a hard task or become almost impossible without tools which embrace their complexity.

Cities are characterized by complex patterns of land use. Indeed, cities can be defined as complex objects from the point of view of their intricate mix of urban activities (White and Engelen, 1993a). Urban areas represent a mix of related units, but the degree and nature of the relationships are sometimes hard to establish. In addition, cities' complexity can be seen from two points of view: the complexity represents the information-rich nature of the system, and the complexity is necessary for the successful functioning of the city as system (White et al., 1997).

"Everything is related to everything else, but near things are more related than distant things". The meaning of Tobler's (1970, p. 236) first law of Geography is of central significance for understanding urban dynamics. Tobler's assertion offers the basis for some applications in spatial analysis in which the neighbourhood space of a feature, even beyond the adjacent space, can influence or be related to the feature as a function of distance. For example, a new industrial area in a city can influence not only the areas in its immediate neighbourhood but in a buffer around it in a distance decay way. On the other hand the place where the industrial area is situated, before the creation of the industrial area, has also been influenced by a buffer of other areas with several land uses which have attracted or repulsed other land use types in a function of distance decay. Nevertheless it does not seem that Tobler's law alone is enough to understand urban dynamics; some more factors would have to be taken into account.

Urban land use dynamics are the direct consequence of the action of individuals, and public and private corporations acting simultaneously in time over the urban space. As a consequence, cities are the spatial result in time of all these influences, which continuously contribute to shape the city. Considering all these influences acting simultaneously, the "messiness" of cities is not surprising.

From a practical point of view, several land use allocation factors have been identified for urban activities in the science of spatial decision-making (see Eastman et al., 1993; Voogd, 1983; Carver, 1991). Five groups of factors can be identified:

- Environmental characteristics
- Local-scale neighbourhood characteristics
- Spatial characteristics of the cities (i.e. accessibility)
- Urban and regional planning policies
- Factors related to individual preferences, level of economic development, socio-economic and political systems

The first group is related to environmental characteristics, which can sometimes be represented as constraints on urban growth. For example slopes, prone areas to natural hazards and natural barriers belong to the first group.

It should be noted that the second factor – i.e. local-scale neighbourhood characteristics – is related with Tobler's Geography first law. It can be defined as the present and past land use patterns and their dynamics. Land use patterns usually represent the strongest influence for land use urban dynamics at local scale. Distance from new features to existing land uses and the type of these land uses control in certain measure the urban dynamics at local scale.

It is logical to think that new residential areas grow near or adjacent to existent residential areas, but they are influenced by other land uses, for example in this case the industrial land use could represent a repulsive factor. As a result a sort of equilibrium is reached between all actual land uses and their dynamics in a defined neighbourhood. Distance from new features to existing land uses and the type of these land uses control in some way urban dynamics at local scale.

The third group of factors is related to the spatial characteristics of cities. Factors like distance to the centre, accessibility, flows or transport networks, are included in this group. For example, new links in the road network can contribute enormously to urban dynamics as an attractor to new urban land uses.

The fourth group is related to urban and regional planning policies. From a practical point of view, this group is represented by cities zoning status. Through zoning plans the city is regulated to be occupied by the land uses in space and time.

The fifth group comprises factors related to individual preferences, level of economic development and socio-economic and political system. They are the most complicated to understand and model. This group of factors is also related to human decision-making processes, which in most cases are qualitative, evolve in time and can be intransitive and therefore difficult or almost impossible to predict. For example a new residential area could be placed in an area because it is more "beautiful" than other areas. Usually human decision-making processes include some level of unpredictability; Couclelis (1988) defined human systems as "terribly complex". On the other hand from a practical point of view, the related complexity of human systems could be modelled as some degree of stochasticity in a probabilistic schema. Therefore it can be considered as a stochastic factor in urban dynamics modelling. The problem arises in how it can be defined and calibrated.

The sum of all the factors which participate in urban dynamics, plus the human decision component, generates a complex dynamic system, whose behaviour is influenced by some degree of stochasticity. Where and when some features will change in a city is a spatio-temporal multi-factor process which necessarily includes some stochastic degree.

3. Methods: The urban cellular automaton

A simulation of future land use for Prague has been produced in an urban cellular automaton prototype; the results of the model are analyzed and compared through the radial dimension analysis.

The urban CA used comprises several factors that drive urban land use dynamics in a probabilistic approach. Previous studies in the urban-CA arena have shown that the transportation network and the suitabilities are the determinant factors of the 'visual urban form' (White et al. 1997). In addition, the zoning status is also a factor which participates in the land use allocation in a city, since it establishes the regulations for future land uses.

In the urban land use system dynamics, accessibility (transport network), suitabilities and zoning act together as a linear deterministic function, they determine for each point of the territory the potential for each of the possible land uses as a linear function.

In urban CA simulations the factor which reproduces the non–linear dynamics of the urban system is the iterative neighbourhood effect, this factor is based in the 'philosophy' of standard CA, it simulates a nonlinear spatial dynamic process, in which the actual land use pattern and their dynamics combine to create the distribution of new built–up areas, and changes from one urban land use to another.

The urban CA prototype included as well a stochastic parameter; it can be calibrated empirically in order to simulate the behaviour of the actual urban system. The sum of all the factors which participate in urban dynamics generates a complex dynamic system whose behaviour is influenced by some degree of stochasticity as happens in most of social and economic processes.

The digital space in the CA consists of a rectangular grid of square cells each representing an area 10 000 m^2. This is the same size as the minimum area mapped in urban areas in the land use datasets for Prague. Each cell of the CA can assume a state; the model uses 24 cell states representing the land uses existing in Prague. Six of the classes represent fixed features in the model, that is, states which are assumed not to change and which therefore do not participate in the dynamics. They do, however, affect the dynamics of the active land uses, since in the cell neighbourhood they may represent an attractive or repulsive effect. Examples of fixed features are: airports, mineral extraction sites, and dump sites. Another eight are passive functions, that is, functions that participate in the land use dynamics, but the dynamics are not driven by an exogenous demand for land; they appear or disappear in response to land being taken or abandoned by the active functions, examples of passive functions are: arable land, permanent crops and pastures. The active functions are the nine urban land uses, these functions are forced by demands for land generated exogenously to the cellular automaton in response to the growth of the urban area, some examples are: residential continuous dense, industrial, and commercial. Construction site represents a transitional state between one function and another.

In standard CA the fundamental idea is that the state of a cell at any time depends on the states of the cells within its neighbourhood based on the predefined transition rules. In the urban cellular automaton this aspect is modified as follows. A vector of transition potentials (one potential for each function) is calculated for each cell from the suitabilities, accessibilities, zoning, and neighbourhood space effect, and the deterministic value is then given a stochastic perturbation using a modified extreme value distribution, such that most values are changed very little but a few are changed significantly. The probabilistic function is thus obtained by the equation:

$$P_{ij} = A_{ij} S_{ij} Z_{ij} N_{ij} v \tag{1}$$

where

P_{ij} is the transition potential of the cell i for land use j;
A_{ij} is accessibility of the cell i to the transportation network for land use j;
S_{ij} is the intrinsic suitability of the cell i for land use j;
Z_{ij} is the zoning status of the cell i for land use j;
N_{ij} is the neighbourhood space effect on the cell i for land use j;
v is a scalable random perturbation term defined as: $v = 1 + [-\ln(\text{rand})]^{\alpha}$, where $(0 < \text{rand} < 1)$ is an uniform random variable, and α is a parameter that allows the size of the perturbation to be adjusted.

The transition rule works changing each cell to the state for which it has the highest potential, however, subject to the constraint that the number of cells in each state must be equal to the number demanded in that iteration. Cell demands are generated outside the CA. On each iteration all cells are ranked by their highest potential, and cell transitions begin with the highest ranked cell and proceed downwards until a sufficient number of cells of a particular land use has been achieved. Each cell is subject to this transition algorithm at each iteration, although most of the resulting transitions are from a state to itself, that is, the cell remains in its current state.

In this urban cellular automaton the neighbourhood space is defined as a circular region around the cell with a radius of eight cells. The neighbourhood thus contains 196 cells that are arranged in 30 discrete distance zones, the neighbourhood radius represents 0.8 km; this distance delimits an area that can be defined as the influence area for urban land uses. That is similar to what residents of a city commonly perceive to be their neighbourhood, and thus should be sufficient to allow local–scale spatial processes to be captured in the CA transition rules.

In the urban CA a neighbourhood effect is calculated for each of the 17 function states (passive and active) to which the cell could be converted. It represents the attraction (positive) and repulsion (negative) effects of the various states within the neighbourhood. In general, cells that are more distant in the neighbourhood will have a smaller effect; a positive weight of a cell on itself (zero–distance weight) represents an inertia effect due to the implicit and monetary costs of changing from one land use to another. Thus each cell in a neighbourhood will receive a weight according to its state and its distance from the central cell. The neighbourhood effect is calculated as:

$$N_{ij} = \Sigma_x \Sigma_d W_{kxd} I_{xd} \tag{2}$$

In equation 2, N_{ij} is the neighbourhood effect of the cell i for land use j, W_{kxd} is the weighting parameter applied to cells with land use k at position x in distance zone d of the neighbourhood, and I_{xd} is the Dirac delta function (inertia effect), $I_{xd} = 1$ if the cell is occupied by land use k; otherwise, $I_{xd} = 0$.

The accessibility factor represent the importance of access to transportation networks for various land uses for each cell, again one for each land use type. Some activities, like commerce, require better accessibility than others, such as residential discontinuous sparse. Accessibilities are calculated as a function of distance from the cell to the nearest point in the transport network as follows:

$$A_{ij} = (1 + D / a_j)^{-1} \tag{3}$$

In the equation 3, A_{ij} is the accessibility of the cell i in land use j to the road network, D is the Euclidean distance from the cell to the nearest cell through which the network passes, and a_j is a coefficient representing the importance of accessibility to the network for land use j.

Finally, each cell is associated with a set of codes representing its zoning status for various land uses, and for various periods. Due to the combined effect of suitabilities, accessibilities, and zoning every cell is essentially unique in its qualities with respect to possible land uses. It is on this highly differentiated digital space where the dynamics of the urban cellular automata take place.

In constrained CA the land use demands are generated exogenously to the cellular model (White et al. 1997) such as in this case. Demands reflect the growth of a city rather than the local configurational dynamics captured by the urban CA. Thus in the present model, cell demands for each land use type are generated exogenously to the CA.

4. Results and discussion

A simulation for Prague has been produced for the period 1968–1998 using the urban CA model. The period of thirty years was established in order to start the model using the historical datasets for the year 1968 and to test the simulation results using the reference datasets for the year 1998. Through this approach the simulation has been tested by comparing them with the actual reference land use datasets. Often the testing of the simulation results has been considered as a weakness in urban CA. A practical way of testing the model is to use historical datasets if available. Once the results of a calibration are satisfactory, the future simulation of land use can be done using the parameters of the already calibrated model, but assuming that the land use growth, distribution, and other trends will remain stable during the studied period. CA models can support 'what if' experiments (White and Engelen 1997), offering the possibility of exploring the future within some known accuracy degree.

The increase or decrease in the number of cells for each land use in the modelled period has been calculated from the historical and reference datasets, thus the simulation accounts for an exact evolution in the land use surfaces. This is obviously not possible in simulations for future scenarios where the land use surface trends must be defined by the analyst. During the thirty years period the built–up area for Prague has grown 61.0 km^2. The total build-up area for Prague in 1998 is 284.3 km^2. Figures 1a and b show the build–up area in Prague for 1968 and 1998 respectively, and figure 1c shows the simulated built–up area in 1998. In order to make the maps clearer, the large number of land use classes has been grouped into residential and other urban build up areas.

Accurate simulations in urban CA depend on several factors, among them one of the most important is the calibration of the weighting parameters of equation 2, which define the neighbourhood attraction and repulsion effects. These parameters are calibrated in order to minimise the differences between the simulated land use map for 1998 and the actual land use map for that year. The pattern of weighting parameters for any pair of land uses is based on a rationale evaluation of the actual land use pattern in the city and their evolution. For example, residential continuous dense land use is attracted to itself, much more so at close distances, and also, but less strongly, to commerce and to other residential land uses, while it is slightly repelled by industry at close distances.

Another calibrated factor is the random perturbation (see equation 1). It was set at $\alpha = 0.6$ by means of a trial and error approach. In general it is set to reproduce the radial (fractal) dimension of the urbanized 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, i.e. rural areas, which will subsequently grow into, for example, new industrial, commercial, or residential areas.

The random perturbation parameter allows non–continuous (i.e. leap–frog) growth of urban land uses based on a stochastic function. However the problem remains in how to make match the stochasticity of the systems, the simulation and the actual city. The present simulations make no use of suitabilities or zoning, since these data are not yet available, nevertheless, the preliminary results are a useful demonstration of the extent to which the urban form is determined by neighbourhood effects and local accessibility.

The first very intuitive approach intended for testing the simulation results is a visual comparison between the simulated land use map for the 1998 and the actual land use map. The main result of this analysis is the resemblance between the maps, and what is in addition important, the simulation looks like a city. It is difficult to differentiate the simulation from the actual city map (figures 1b and c) which can be considered as a very positive signal. As a preliminary conclusion, we can state that the urban CA has produced, from a visual point of view, good results.

Despite the promising results of the simulations some constraints have been identified. Although the cellular model simulates reasonably well the pattern distribution of land uses of the actual city, it is noticeable that the urban CA is not able to reproduce, for example, a new residential area in a place where there were originally pastures and where no residential areas were in the neighbouring zones, unless the random perturbation (i.e. stochastic perturbation) puts a seed cell in the same place, what is not very likely. A different situation could be if the place is near to some link in the transport network or, if the datasets are available, the development takes place in a place with high suitability and the right zoning conditions. In this case the place for the new residential area could be more foreseeable. Yet what is important, is that the land use pattern distribution in the whole area is similar to or resembles the actual city pattern, which actually happened in the simulation. Although the visual comparison produces a first idea of what the urban CA is able to do, statistical tests are needed in order to obtain accuracy values.

4.1. Simulation results testing

The urban CA model was tested by comparing the simulation results with the actual land use map. To this end a measure of similarity between both maps has been produced based on the comparison of the fractal dimension of land uses between the simulation and the actual city map. Fractal dimension (D) can be understood as a quantitative measure of wiggliness in the case of curves (Voss 1988). A straight line shows a fractal dimension of 1.00, which means that the object is one–dimensional, but fractal dimension is a measure intended for fractal objects which does not respond to the principles of Euclidean geometry, but to the ones of the fractal geometry, in which fractal dimensions need not be an integer. Thus, for example, a curve that shows a little winding has, for example, $D = 1.05$; whilst a very winding curve has a $D = 1.26$ (Mandelbrot 1982). This means that the two curves show a non–integer dimension, greater than one but less than two, the curves fill more space than a straight line but less than a Euclidean area of the plane for which $D = 2$.

The concept of fractal dimension can be applied to self–similar objects (Voss 1988) like digital cities or coast lines. Measures of fractal dimension for real coast lines show D values of about 1.15 to 1.25 (Mandelbrot 1982), on the other hand rough fractal surfaces with $D = 2.2$ are more than a simple surface ($D = 2$); other unrealistic rough surfaces can reach D values of 2.8 and clouds around 3.3 (Voss 1988).

The fractal or radial dimension has also been used for studying the fractal structure of urban areas (Frankhauser 1991, 1994, Frankhauser and Saddler 1991) and even for testing urban CA models (White and Engelen 1993a, White et al. 1997). Formally the radial dimension can be understood as the slope of the relationship between the size of an object, as measured by the number of cells composing it, and its diameter. This is a practical measure of the radial dimension for irregular or stochastic spatial distributions (White and Engelen 1993a) or patterns as in the case of urban areas. In this study the fractal dimension was obtained by calculating the total area occupied by individual land uses within a given radius from the centre of the city by using a set of radii of increasing length of 1000 m, which produced 21 radii areas for Prague. The slope of the simple regression line in the area–radius plot for each land use corresponds to the radial dimension of that land use (figure 2).

Experiments carried out in several cities of the world by Frankhauser (1991, 1994), White and Engelen (1993) and White et al. (1997) have shown that cities are bifractal structures. From this point of view cities are structured in two zones, the first one is a fully urbanized inner zone in which the urbanization process has reached a sort of equilibrium; in this area the urbanization process is complete and radial dimension values are usually higher than in the outer zone. The latter is an area where land use is less intensive and the urbanization process continues to evolve. There are still a number of vacant areas that can be taken over by urban land uses; consequently the urban structure is dynamic and the radial dimension is therefore smaller.

The results for Prague match with the aforementioned experiments of radial dimension. Both the actual city and the simulation display a bifractal structure in the evaluated four land use classes: commercial, industrial, residential (the sum of residential dense, residential medium dense, residential continuous, and residential discontinuous sparse) and urbanized (the sum of residential dense, residential medium dense, residential continuous, residential discontinuous sparse, industrial, commercial, and public and private services). It should be noted that the used datasets comprise not only the area corresponding to the urbanized area of the city, but also a buffer beyond this area which allows calculating the radial dimension for the inner and the outer zone.

In the area–radius plots of figure 2, the inner zone, represented by a steep slope, is evident for the four land use classes, as well as the outer zone by a flatter slope. The border of the two zones is in the range of the 10 km. From the point of view of the similarities between the actual city and the simulation it is noticeable that the same bifractal structure is shown in both of them for particular urban land uses and also for the urbanized area as is shown in figure 1d. An exception to the overall good matching between the plots of actual land uses and the simulated ones is the commercial land use, for which the simulation does not seem to work very well (figure 2b).

Despite some slight differences in the area–radius plots, the general agreement of the plots is an evidence of the similarity of the pattern distribution in both maps. The clear bifractal structure is a consequence of the concentric zonation of land uses in the simulation and in the actual city. In addition the simulation match with the actual city not only in the inner zone were few cells were available at the beginning of the simulation, but also in the outer zone, where most of changes in land use took place in the simulation period of 30 years.

In the area–radius plot of figure 1b for commercial land use the poor fit between the simulation and the actual city is clear. In the first four radii the simulation underestimates the commercial area, and in the range of the radius 9 to 11 km overestimates it slightly. It should be noted that in Prague the commercial land use has grown more than 280% from the 1968 to the 1998, showing the more explosive growth among the urban land uses. Most of the new commercial areas have appeared as non–contiguous to existent commercial areas and in addition, this land use shows a very splitted pattern composed by a series of relatively small clusters distributed in the whole area. All these factors acting simultaneously made it difficult to model the commercial land use in Prague.

Values of radial dimension was calculated considering the overall 21 km radius zone for the evaluated four land use types in the real city and in the simulation. They are shown in table 1. By comparing the radial dimension values between the actual city and the simulation the similarity between them is striking. The similar values of radial dimension mean that the simulation reproduces accurately the spatial pattern for the evaluated land uses during the simulated period of thirty years. But how the urban CA is able to reproduce patterns without any long–range iteration procedure? The answer must be looked for in the capability of systems with self–organizing properties as standard CA. In the urban CA the pattern structure is a consequence of the local level iterations which produce the global structure of the simulation map.

Land use	Prague	Simulation
Commercial	1.50	1.54
Industrial	2.34	2.33
Residential	2.93	2.92
Urbanized	3.11	3.09

Table 1. Radial dimension for individual land use classes in Prague and simulation.

5. Concluding remarks

The results of the land use simulation for Prague together with the radial dimension analysis have demonstrated that the urban CA prototype can provide reasonable representations of the future of the cities. Added to this should be considered the small amount of data available and the considerable length of the simulated period: thirty years. On the other hand, the capability of the urban CA to reproduce urban sprawl processes is also significant. This is remarkable considering the aim of the prototype for planning purposes. Obviously the inclusion of the suitabilities and zoning datasets and a more realistic modelling period of twenty or twenty five years could yield more reliable results in an adequate time scenario for planning purposes. The inclusion of single land uses, such as several types of residential uses, as states in the model together with the fine detail of the datasets increase the experimental potential of the model, given that it can be used by planners like a simulation box, in which a number of spatial conditions ‘if…then’ can be tested easily in a realistic way within a known accuracy degree.

The promising results of this urban CA model are comparable with previous results in the arena of the urban modelling using CA (White and Engelen 1993a, White et al. 1997, Wu 1998, Clarke and Gaydos 1998, White et al. 1999, White and Engelen 2000, Semboloni 2000, Li and Yeh 2000, Sui and Zeng 2001). However some aspects should be considered for future developments. One of the more relevant weaknesses when future events are modelled is represented by the testing phase. Clarke and Gaydos (1998) are right when saying 'only the real future, as it slowly unfolds, can verify our model'. It is obvious that models for future events are difficult to test. An added complication is when modelling is made for human or social systems like cities, because these systems may be affected by a large series of events, such as economic crisis, changes in planning policies, natural disasters, wars, and other events that can obviously modify profoundly the aspect and evolution of cities. Furthermore the stochastic degree and complexity of this kind of systems makes it particularly difficult to simulate and predict their future development, in particular for long for periods of time. Complex systems are also complex to predict and sometimes intractable.

Acknowledgements

This research was funded by the European Commission, Directorate General Joint Research Centre, postdoctoral grant # 17646–2001–03 P1B30 ISP IT 'Monitoring sustainable urban and regional development using spatial dynamics models' awarded to J.I. Barredo; and undertaken as part of the European Commission's (EC) Directorate General Joint Research Centre (DG JRC) EUROLANDSCAPE/MOLAND (Monitoring Land Cover / Use Dynamics) project.
The cellular automaton prototype has been designed and developed with the support of the EC's Directorate General Joint Research Centre (DG JRC) EUROLANDSCAPE/MOLAND Project (Monitoring Land Cover / Use Dynamics) in collaboration with the Research Institute of Knowledge Systems (RIKS) (White et al. 1999, Lavalle et al. 2001), in the framework of the contract # 14518–1998–11 F1ED ISP NL awarded by the European Commission, Directorate General Joint Research Centre.

References

Allen, P.M., 1997, *Cities and Regions as Self–Organizing Systems: Models of Complexity* (Amsterdam: Gordon and Breach Science Publishers).

Barredo, J.I. and Bosque–Sendra, J., 1998, Multi–criteria evaluation methods for ordinal data in a GIS environment. *Geographical Systems*, **5**, 313–327.

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

Batty, M., 1997, Editorial: Urban systems as cellular automata. *Environment and Planning B*, **24**, 159–164.

Batty, M., 2000, Editorial: Less is more, more is different: complexity, morphology, cities, and emergence. *Environment and Planning B*, **27**, 166–168.

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

Bertalanffy, L. von, 1972, *General System Theory* (Harmondsworth, Middx: Penguin Books).

Carver, S.J., 1991, Integrating multi–criteria evaluation with geographical information systems. *International Journal of Geographical Information Systems*, **5**, 321–339.

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**, 699–714.

Couclelis, H., 1986, Artificial intelligence in geography: conjectures on the shape of the things to come. *The Professional Geographer*, **38**, 1–11.

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., 1997, From cellular automata to urban models: new principles for model development and implementation. *Environment and Planning B*, **24**, 165–174.

Douady, A., 1986, Julia Sets and the Mandelbrot Set. In *The Beauty of Fractals, Images of Complex Dynamical Systems*, edited by H.O. Peitgen and P.H. Richter, (Berlin: Springer–Verlag), pp 161-173.

Eastman, J.R., Kyem, P.A., Toledano, J. and Jin, W., 1993, *GIS and decision making* (Geneva: United Nations Institute for Training and Research, UNITAR).

Eastman, J.R., 2001, The Evolution of Modeling Tools in GIS. *Directions Magazine*, http://www.directionsmag.com.

Ewing, R., 1997, Is Los Angeles–style sprawl desirable?. *Journal of the American Planning Association*, **63**, 107–126.

Frankhauser, P., 1991, Aspects fractals des structures urbaines. L'Espace Geographique, **1**, 45–69.

Frankhauser, P., 1994, *La Fractilité des Structures Urbaines*. (Paris: Economica).

Frankhauser, P. and Sadler, R., 1991, Fractal analysis of agglomerations. In *Proceedings of the Second International Colloquium of the Sonderforshungsbereich 230: Naturliche Konstruktionen*, (Stuttgart: University of Stuttgart), pp. 57–65.

Huhdanmaki, A., Timo, H., Reijo, M., and Pekka, L., 1999, *Yhdyskuntarakenteen hajautumisen ja pirstoutumisen mallintaminen*, Ympäristövaikutuksiltaan edullinen yhdyskuntarakenne ja liikennejarjestelmä (LYYLI), Helsinki, raporttisarja No. 9.

Itami, R.M., 1994, Simulating spatial dynamics: cellular automata theory. *Landscape and Urban Planning*, **30**, 27–47.

Johnson, M.P., 2001, Environmental impacts of urban sprawl: a survey of the literature and proposed research agenda. *Environment and Planning A*, **33**, 717–735.

Krugman, P., 1996, *The Self–Organizing Economy* (Malden, MA: Blackwell).

Lavalle, C., Demicheli, L., Turchini, M., Casals–Carrasco, P. and Niederhuber, M., 2001, Monitoring megacities: the MURBANDY/MOLAND approach. *Development in Practice*, **11**, 350–357.

Li, X. and Yeh, A.G., 2000, Modelling sustainable urban development by the integration of constrained cellular automata and GIS. *International Journal of Geographical Information Science*, **14**, 131–152.

Mandelbrot, B.B., 1982, *The Fractal Geometry of Nature* (New York: W.H. Freeman and Co.).

May, R.M., 1976, Simple mathematical models with very complicated dynamics. *Nature*, **261**, 459–467.

Meiss, J.D., 2000, *Frequently Asked Questions about Nonlinear Science*. The Internet: http://amath.colorado.edu/faculty/jdm.

Portugali, J., 2000, *Self–Organization and the City* (Berlin: Springer–Verlag).

Semboloni, F., 2000, The dynamic of an urban cellular automata model in a 3–D spatial pattern. In *XXI National Conference Aisre: Regional and Urban Growth in a Global Market*, (Palermo).

Shi, W. and Pang, M.Y.C., 2000, Development of Voronoi–based cellular automata –an integrated dynamic model for Geographical Information Systems. *International Journal of Geographical Information Science*, **14**, 455– 474.

Sui, D.Z. and Zeng, H., 2001, Modeling the dynamics of landscape structure in Asia's emerging desakota regions: a case study in Shenzhen. *Landscape and Urban Planning*, **53**, 37–52.

Tobler, W., 1970, A computer movie simulating urban growth in the Detroit region. *Economic Geography*, **46**, 234–240.

Torrens, P.M., 2000, How cellular models of urban systems work, WP–28, Centre for Advanced Spatial Analysis (CASA), University College London.

Torrens, P.M. and O'Sullivan, D., 2001, Editorial: Cellular automata and urban simulation: where do we go from here. *Environment and Planning B*, **28**, 163–168.

The Sierra Club, 2001, Sprawl Harms Our Health, Sprawl Report 2001, The Sierra Club, San Francisco, CA.

Voogd, H., 1983, *Multicriteria Evaluation for Urban and Regional Planning* (London: Pion).

White, R. and Engelen, G., 1993a, 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., 1993b, Complex dynamics and fractal urban form. In *Nonlinear evolution of Spatial Economics Systems*, edited by P. Nijkamp and A. Reggiani, (Berlin: Springer), pp. 223–247.

White, R. and Engelen, G., 1997, Cellular automata as the basis of integrated dynamic regional modelling. *Environment and Planning B*, **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*, **24**, 323–343.

White, R., Engelen, C., Uljee, I., Lavalle, C. and Erlich, D., 1999, Developing an Urban Land Use Simulator for European Cities. In *Proceedings of the 5th EC–GIS workshop*, 28–30 June, 1999 (Italy: European Communities, 2000).

Wolfram, S., 1984a, Preface. *Physica*, **10D**, vii–xii.

Wolfram, S., 1984b, Universality and Complexity in Cellular Automata. *Physica*, **10D**, 1–35.

Wolfram, S., 1988, Complex Systems Theory. In *Emerging Syntheses in Science: Proceedings of the Founding Workshops of the Santa Fe Institute* (Reading, MA.: Addison–Wesley), pp. 183–189.

Wolfram, S., 1994, *Cellular Automata and Complexity* (Reading, MA.: Addison–Wesley).

Wu, F., 1998, 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**, 63–82.

Wu, F. and Webster, C.J., 2000, Simulating artificial cities in a GIS environment: urban growth under alternative regulation regimes. *International Journal of Geographical Information Science*, **14**, 625–648.

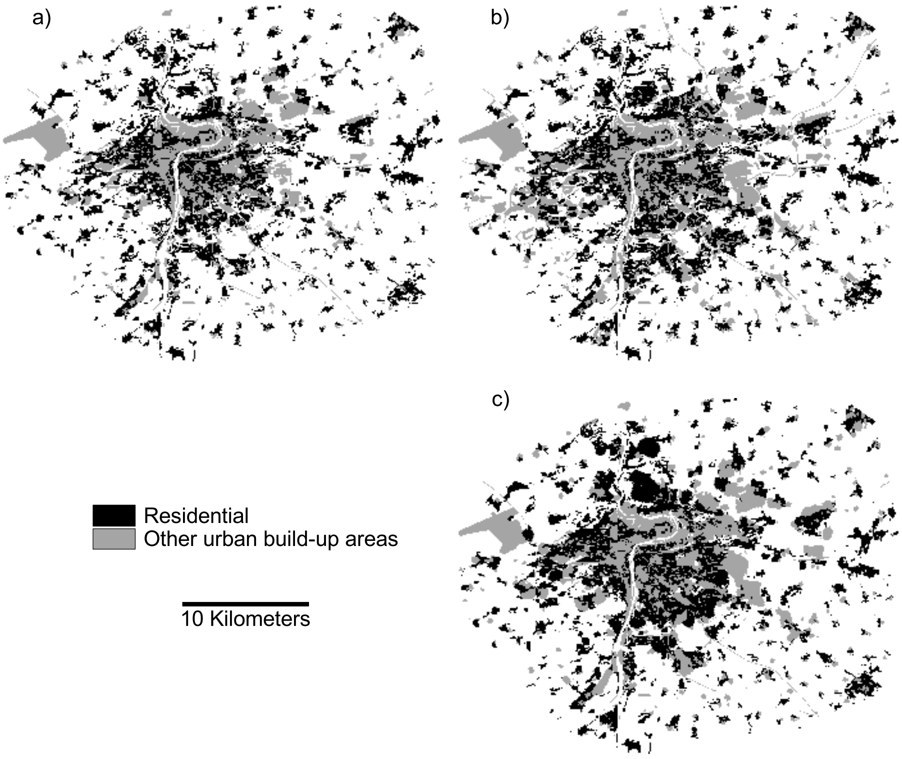

Figure 1. Prague maps: a) urbanized area in 1968; b) urbanized area in 1998; c) simulated urbanized area in 1998.

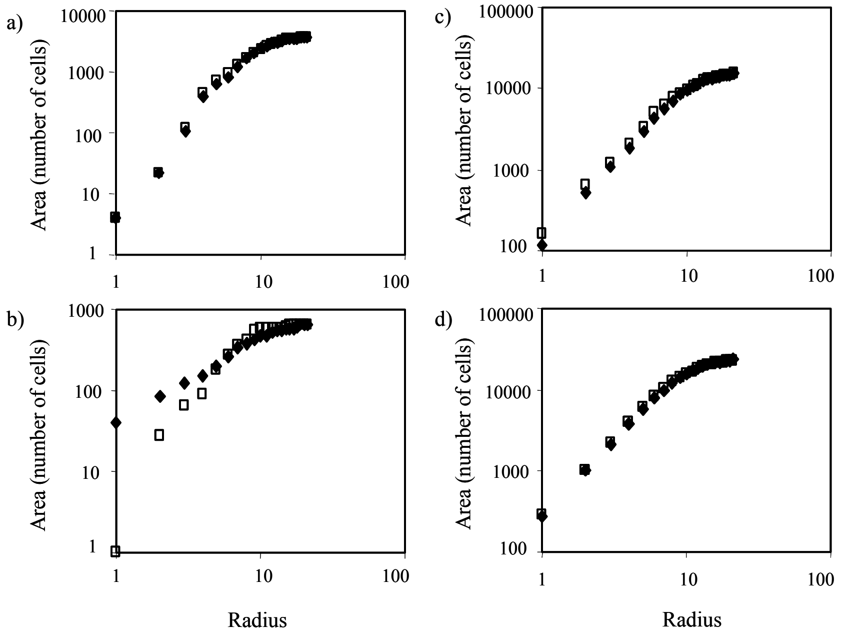

Figure 2. Area–radius plots for the actual city (♦) and the simulation (□). Land uses: a) industrial; b) commercial; c) residential; d) urbanized area.