Pergamon

doi:10.1016/S0264-2751(03)00047-7

Cities, Vol. 20, No. 5, p. 297–310, 2003
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Printed in Great Britain
0264-2751 $ - see front matter

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Urban sustainability in developing countries' megacities: modelling and predicting future urban growth in Lagos

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In the first part of the paper urban sustainability issues in African countries are considered with a focus on urban growth. The need for urban management tools that are able to provide prospective scenarios is addressed. Urban simulations can represent a useful approach to an understanding of the consequences of current planning policies or their incompleteness. Simulations of future urban growth are usually quite difficult without tools that embrace the complexity of the urban system. The second part of this paper describes an urban growth simulation for the city of Lagos in Nigeria using a dynamic spatial model prototype. We propose a bottom-up approach, integrating land-use factors with a dynamic approach for modelling future urban land-use scenarios. The model for Lagos was calibrated and tested using measured time-series data on land-use, through a set of spatial metrics and Kappa (κ) coefficients. Afterwards, a twenty-year simulation was run until 2020. The simulation results are realistic and relatively accurate, confirming the effectiveness of the proposed model. This work was performed in the framework of the European Commission's MOLAND project.
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Keywords: urban sustainability, dynamic spatial models, urban simulation, spatial metrics

Introduction

The estimation of future impacts of existing spatial plans and policies on land-use development, and the consideration of alternative planning and policy scenarios for impact minimisation, are of particular interest for urban and regional planners. The consequences of inaccurate planning in megacities of developing countries are also of interest to other stakeholders, such as those involved in research studies and policymaking processes related to sustainable development.

As most of the world's population is living in urban areas, it is in these areas that the main economic, social and environmental processes that affect human societies take place. Urbanisation is now commonly regarded as one of the most important social processes, also having enormous impact on the environment at local, regional and global scales (Turner *et al*., 1990). In general, it is presently recognised that, in order to respond to the idea of sustainability, urban areas have to maintain an internal equilibrium balance between economic activity, population growth, infrastructure and services, pollution, waste, noise etc. in such a way that the urban system and its dynamics evolve in harmony, internally limiting, as much as is possible, impacts on the natural environment.

Urban sprawl reveals that information and existing tools for urban policy are insufficient in providing an adequate understanding of urban systems. Questions on the sustainability of large regions surrounding the metropolitan areas are sometimes posed in global terms. How we anticipate, recognise, measure and interpret urban problems and how we respond to them will determine the overall sustainability of the urban system (UNCHS, 1997). What then happens when human settlements, grouped in enormous urban areas such as megacities, are poorly organised? The environmental and social consequences of a growing

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population in a loosely planned urban system could be dramatic, mainly when urban areas experience tremendous growth in a short period of time. This is the case of Lagos, Nigeria, where the population has grown exponentially in the last 20 years, and is expected to reach 24.4 million people in 2015, doubling in a fifteen year period. The rapid urbanisation process shown in developing countries will continue in the years and decades to come (Torrey, 1998), nevertheless its environmental and social consequences are in most cases not well foreseen, due to a lack of applied research on the urban system, and because of the intrinsic complexity of the system per se.

To anticipate the consequences of urban growth in developing countries' megacities is a difficult task. There are complex rules at work that make difficult the forecasting of urban dynamics. In addition, urban systems comprise a stochastic degree that is not easy to establish, as in the case of most social systems. Couclelis (1988: 99) has defined human systems as "terribly complex", and we have to consider that cities are among the most complex structures created by human societies. That is why the modelling of urban systems may, in some instances, be a hard task or become almost intractable without tools which embrace their complexity, and the question remains—how to model dynamism and growth realistically?

In the last decade, dynamic spatial models have gained popularity as a modelling tool for the simulation of spatially distributed processes. Since the pioneer work of Tobler (1970), several approaches have been proposed for modifying standard cellular automata (CA) in order to make them suitable for urban simulation (Batty and Longley, 1986, 1987; Cecchini and Viola, 1990; White and Engelen, 1993; 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, 2002; Sui and Zeng, 2001). The results of the previous applications are promising and have shown realistic results in cities of different continents. CA are a joint product of the science of complexity and the computational revolution (Couclelis, 1986). Despite their simplicity, CA are models which deal with processes that show complexity or, in other words, with complex systems. CA have been defined as very simple dynamic spatial systems in which the state of each cell in an array depends on the previous state of the cells within a neighbourhood and according to a set of transition rules (White *et al*., 1999). What is surprising in CA is their potential for modelling complex spatio-temporal processes, despite their very simple structure. Very simple CA can produce surprisingly complex forms, through a set of simple deterministic rules. Cities studied as dynamic systems show some complexity characteristics that can be modelled using CA in an integrated approach.

CA have been, as well, considered idealisations of partial differential equations and show behaviours analogous to non-linear ordinary differential equations (Wolfram, 1984a, 1984b). From this point of view, it is not surprising that CA can produce and simulate complex spatial processes which show non-linear dynamics, like some social-spatial processes, such as the spatial segregation of socio-economic groups. Moreover, CA can produce spatial patterns that show chaotic behaviour in the sense of irregular dynamics in a deterministic system. In this kind of systems, the behaviour depends on the system internal logic, and not on the fact that the system is stochastic per se.

The aim of this paper is to produce an urban growth simulation for the city of Lagos in Nigeria using a dynamic spatial model. We propose an approach that integrates land-use factors with a dynamic approach for modelling future urban land-use scenarios. The model for Lagos was calibrated using a set of spatial metrics and Kappa (κ) coefficients. Afterwards, a twenty-year simulation was run until 2020. The aim of this model prototype is to predict future land-use development under existing spatial plans and policies and to produce and compare alternative planning and policy scenarios in terms of their effects on future land-use development. This work was performed in the framework of the European Commission's MOLAND (Monitoring Land Use/Cover Dynamics) project, which is carried out at the Institute for Environment and Sustainability of the Directorate General Joint Research Centre.

African megacities: growth and urban sustainability

Sustainability is a concept whose use is growing. In the last decade it has been considered a relevant issue in most forums on environment (European Environment Agency, 2002). It is evident that sustainable actions focused on the urban environment can improve, in some way, the quality of life of urban settlements. If sustainable urban planning actions are taken into account, the consequences of poorly planned urban growth in the megacities of developing countries can be less dramatic. As a consequence, sustainable urban planning is currently being applied in urban areas as a priority for future development. Unfortunately, "planning" is a sort of dream in many areas of the world, as heavy migration causes cities to expand at incontrollable rates. In developing countries, despite the lack of basic amenities and infrastructure, human agglomerations still attract population from the surrounding regions. As a consequence, the urban population is increasing in developing countries at a much faster rate than in the rest of the world, contributing to the augmentation of existing problems (Lavalle *et al*., 2001). In these immense urban agglomerations, which often show a dramatic sprawl coupled with an explosive population growth, the environmental and social consequences are disastrous. Serious sustainable urban planning measures are usually not coupled with national, regional and local level policies. Very often, the main cause is imputed to inaccurate land-use management. According to Hope and Lekorwe (1999), the basis of all urban problems in Southern Africa are the issues of land-use and housing, from the lack of affordable housing, through to overcrowding, and on to inner cities marred by abandoned buildings and informal settlements. In particular, the availability of spatial information for cities in developing countries is poor or not existent. In many cases, the spatial data are in the form of unscaled sketches. Where current and unclassified maps exist, they are usually at different scales, thus aggravating the problem of sharing information efficiently among various sectors of the city. For the large, rapidly growing cities of developing countries today, which are becoming the engines of economic development, these management practices are woefully inadequate (Bishop *et al*., 2000). If they lead to the impossibility of assessing the current situation, they certainly also exclude any possibilities of planning for the future. The main consequences in these cities can be summarised as unsuitable land-use, traffic congestion, atmospheric pollution, depletion of natural resources, increase of natural and man made risks, urban sprawl, collapse of public services, proliferation of epidemics, and other negative environmental and social effects.

This already problematic situation might even be exacerbated in some African megacities. It is the only continent where rural-urban migration has not been replaced by natural population increase as the principal source of urban growth (Bernstein, 1995). In Lagos, the population is almost 12 million, half of whom are less than 16 years old. There are 5 million children, of whom 60% do not attend school. These numbers are alarming in a country where women have six children on average (El País Semanal, 2002). In many circumstances, survival in Lagos is a daily imperative. In this case, the concept of sustainability assumes other roles. It cannot focus anymore on environmental issues; sustainability has, first, to address survival for most of the urban poor. Although their activity systems usually have detrimental consequences on the environment, the main aspect to be answered is their needs (Wekwete, 1992). In many cases, because of the prevailing poverty, most of the citizens do not worry about pollution. Even the poor people who operate in the informal sector contribute generously to urban pollution, linked to garbage disposal, waste disposal and a general lack of infrastructure. In this way, the problem becomes an increasing loop.

Still, it has to be considered that the problems linked to sustainable urban development cannot be treated at the urban level alone. For an integrated urban planning strategy, it is necessary to recognise, anticipate, measure and understand urban dynamics and their consequences. The complexity of the urban system is usually an impediment, which is even enhanced in the cities of developing countries, where many factors increase the unpredictability of the system.

In the last decades, Lagos has shown tremendous growth. In 1963, the population had reached 665,000, covering 70 km^2 (Abiodun, 1997). In 1970, Lagos had about (it is only possible to estimate given the absence of reliable census data) 1 million inhabitants. Nowadays, estimates vary from 8–12 millions (Rakodi, 1997). The project MOLAND has also carried out a case study for the urban agglomeration of Lagos. *Figure 1* shows the evolution of urbanised areas in Lagos for the years 1962, 1967 1984 and 2000, reconstructed making use of very high resolution satellite imagery, aerial photos and other ancillary data (the scale of the land-use maps is 1:25,000, and the minimum mapping unit is 100×100 m). The surface covered with artificial structures has grown more than five times in size in the last 33 years, passing from 117–682 km^2. In the last 16 years the rate has decreased, although it remains high. The city has grown 157 km^2 in this period. During this growth, planning has been neglected. "Up to 1981, there was no urban transportation plan for the whole Lagos metropolitan area. What often happened was that road networks were laid out in specific areas as they became incorporated into the built-up area of the city" (Abiodun, 1997: 208). The urbanisation process in Lagos possesses some characteristics in common with other cities of the region. Urbanisation has occurred in Lagos with limited industrialisation and rural transformation, therefore it accounts for small clusters of industrial and commercial areas, while the most important land-use classes are represented by residential areas. On the other hand, one of the causes of the enormous increase in population and in the built-up area of Lagos is rural to urban migration. Considering the complex elements which participate in the urban evolution of megacities in Africa, predictions about the future development of these cities account for a high degree of uncertainty, due to the multifactor character of the problem, the dynamic factors of the urban land-use evolution and the intrinsic complexity of urban systems.

Methods

The dynamic spatial model

The dynamic spatial model developed here comprises several factors that drive land-use dynamics in a probabilistic approach. Previous studies in the urban CA arena have shown that the transportation network and land-use suitability are the determinant factors of the "visual urban form" (White *et al*., 1997: 338). These factors drive, to a great degree, the growth of the city: vacant areas in a city with high accessibility and the right suitability conditions are highly prone to urbanisation. In addition, the land-use zoning status is also a factor which influences the land-use allocation in a city, since it establishes the legal regulations for

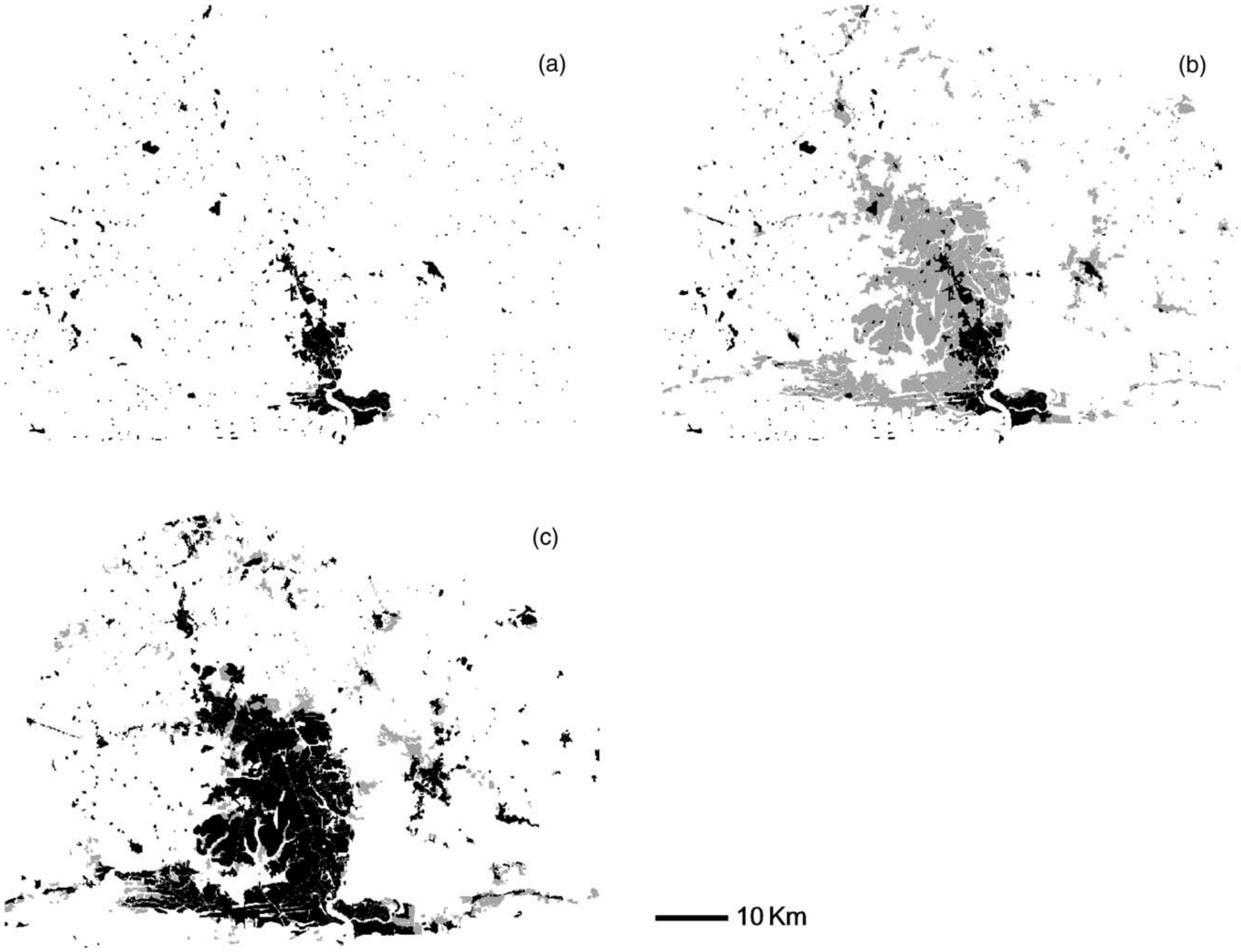

Figure 1 Evolution of urbanised areas in Lagos. (a) in black 1962, in grey 1967; (b) in black 1967, in grey 1984; (c) in black 1984, in grey 2000.

future land uses. The process of urban land-use dynamics can be defined as a probabilistic system in which the probability that a place in a city is occupied by a land use is a function of accessibility, suitabilities, zoning status and the neighbourhood effect measured for that land use. All these factors, in addition to a stochastic parameter, have been included in the urban CA prototype. The stochastic parameter has the function of simulating the degree of stochasticity that is characteristic in most social and economic processes.

The CA used in this application–the MOLAND model–is an improved version inspired by the CA developed by White *et al*., 1997. In this new CA, an extensive number of states are considered, including several types of residential land-use. Other improvements are discussed later in this section. In this urban CA, the probability that an area changes its land use is a function of the aforementioned factors acting together at a defined time. However the factor that makes the system work like a nonlinear system is the iterative neighbourhood effect, whose dynamism and interactivity can be understood as the basis of the land-use dynamics. The iterative neighbourhood effect is founded in the "philosophy" of standard CA, where the current state of the cells and the transition rules define the configuration of the cells in the next time step. From the described approach, a constrained urban CA model has been designed and developed for the simulation of urban land-use dynamics (see White *et al*., 1999). It has the following specificities.

The digital space in the CA model used for this study consists of a rectangular grid of square cells, each representing an area of 100×100 m. This is the same size as the minimum area mapped in urban areas in the land-use datasets for Lagos. Each cell of the CA can assume a state; the model uses 21 cell states representing land-use classes in which Lagos is subdivided. Five 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-use classes, since they may have an attractive or repulsive effect in the cell neighbourhood. The fixed features are: *abandoned areas*, *road and rail networks*, *airports*, *artificial non-agricultural vegetated areas* and *water bodies*. Another seven are passive functions, that is, functions that participate in the land-use dynamics, but whose 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. The passive functions are: *arable land*, *heterogeneous agricultural areas*, *forest*, *pastures*, *shrublands*, *sparsely vegetated areas* and *wetlands*. The active functions are the eight urban land-use classes. These functions are forced by demands for land generated exogenously to the cellular automaton in response to the growth of the urban area. They are: *residential continuous medium dense urban fabric*, *residential discontinuous*, *residential discontinuous sparse*, *informal settlements*, *industrial*, *commercial*, *services* and *port areas*. *Construction sites* represent a transitional state between one function and another. It is remarkable that the model is able to simulate an extensive number of urban land uses, including four types of residential land-use. This aspect is one of the differences of this urban CA model with respect to other CA-based models previously developed.

In standard CA, the fundamental idea is that the state of a cell at any time depends on the state of the cells within its neighbourhood in the previous time step, 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 status and neighbourhood space effect, and the deterministic value is then given a stochastic perturbation using a modified extreme value distribution, so that most values are very slightly modified, while a few others are changed significantly. The probabilistic function is thus obtained by the equation:

$$ {}^tP_{K,x,y} = (1 + {}^tA_{r,K,x,y}).(1 + S_{K,x,y}).(1 + {}^tZ_{K,x,y}).({}^tN_{K,x,y}).{}^tv \quad (1) $$

where: ${}^tP_{K,x,y}$: CA transition potential of the cell (x, y) for land-use K at time t; ${}^tA_{r,K,x,y}$: Accessibility of the cell (x, y) to infrastructure element r for land-use K at time t; $S_{K,x,y}$: Intrinsic suitability of the cell (x, y) for land-use K; ${}^tZ_{K,x,y}$: Zoning status of the cell (x, y) for land-use K at time t; ${}^tN_{K,x,y}$: Neighbourhood space effect on the cell (x, y) for land-use K at time t; ${}^tv$: Scalable random perturbation term at time t; it is 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 by changing each cell to the state for which it has the highest potential. However, it is 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. During 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 the urban cellular automaton described herein, the neighbourhood space is defined as a circular region around the cell with a radius of eight cells. The neighbourhood thus contains 197 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-use classes. This distance is similar to what city dwellers 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:

$$ {}^tN_{K,x,y} = \sum_c \sum_l w_{K,L,c}.{}^tI_{c,l} \quad (2) $$

In Eq. (2), ${}^tN_{K,x,y}$ is the contribution of the CA-transition rules in the calculation of the transition potential of cell (x, y) for land-use K at time t. $w_{k,L,c}$ is the 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 neighbourhood. And ${}^tI_{c,l}$ is the Dirac delta function: ${}^tI_{c,l} = 1$ if cell l at a distance c at time t is in the state L, otherwise ${}^tI_{c,l} = 0$.

The accessibility factor represents 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 urban fabric*. Accessibilities are calculated as a function of distance from the cell to the nearest point in the transport network as follows:

$$ {}^tA_{r,K,x,y} = \frac{1}{1 + \dfrac{D_r}{a_{r,K}}} \quad (3) $$

In the Eq. (3), ${}^{t}A_{r,K,x,y}$ is the accessibility of cell (x, y) to infrastructure element r for land-use K at time t; D_r is the distance between cell (x, y) and the nearest cell (x', y') on infrastructure element r; and $a_{r,K}$ is a calibrated distance decay accessibility coefficient expressing the importance of good access to infrastructure element r for land-use K.

Finally, each cell is associated with a set of codes representing its land-use zoning status for various land-use classes, and for various periods. Due to the combined effect of suitabilities, accessibilities, zoning status and the neighbourhood effect every cell is essentially unique in its qualities with respect to possible land-use classes. It is in this highly differentiated digital space that the dynamics of the 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.

Calibration of the model for Lagos

The model was calibrated by running a simulation for the period 1984–2000. The simulation was initiated using the historical datasets for the year 1984 in order to test the simulation results using the reference datasets for the year 2000 (*Figure 2*(*a*) and (*b*)). Subsequently a simulation for twenty years was undertaken for the period of 2000–2020. Often the testing of the simulation results has been considered as a weakness in urban CA. A practical way for testing the calibration of the model is to run a simulation using historical datasets. Through this approach, the calibrated simulation of sixteen years has been tested by comparing it with the reference land-use dataset for 2000. 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 assuming, however, that the calibrated factors will remain relatively stable during the studied period.

The increase or decrease in the number of cells for each land use in the sixteen year period has been calculated from the historical and reference datasets, thus the calibrated simulation accounts for an exact evolution in the land-use surfaces. In the case of simulations for future scenarios, the land-use surface demands can be defined on the basis of population, economic and other trends. During the sixteen year period (1984–2000), the measured built–up area in Lagos has grown by 157.13 km^2. It is noticeable that the land-use classes with most relevant increase in the studied period were *residential discontinuous urban fabric*, with a growth of 125.5 km^2, *residential continuous medium dense urban fabric* (24.74 km^2) and *industrial areas* (15.18 km^2), whilst *residential discontinuous sparse urban fabric* decreased (32.78 km^2). *Figure 2*(*a*) and (*b*) show the residential and other built–up areas in Lagos for 1984 and 2000 respectively, and *Figure 2*(*c*) shows the simulation for 2000. In order to make the maps clearer, the large number of land-use classes has been grouped into *residential* and *other urban built-up areas*. The sparser low density residential land-use, growing far away from the city centre, is one of the main characteristics of Lagos in the last decades. The city can be thus defined as a sprawled city, showing a continuous urban development style adjacent to former urban zones. This kind of urban growth is also known as "oil spot".

In the present urban CA model, several factors have to be calibrated. One of the most important is the weighting parameters of Eq. (2), which define the neighbourhood attraction and repulsion effects between land uses. The weighting parameters are calibrated in order to minimise the differences between the simulated land-use map for 2000 and the actual land-use map for that year. The calibration of weighting parameters for any pair of land-use classes is based on a rational evaluation of the actual land-use patterns in the city and their historical evolution. For example, *residential continuous medium dense urban fabric* attracts its same land-use class (with a higher intensity at closer distances) and also, but less strongly, other residential land-use classes, as well as *commercial areas*, while it is slightly repelled by industry at close distances.

Following the intuitive calibration method proposed by White *et al*. (1997) and due to previous calibrations experiences in other cities (White *et al*., 1997, 1999) the fine-tuning for Lagos was straightforward. In addition the software prototype interface facilitates this task through an interactive set of charts developed for this purpose. The resulting weighting parameters have corroborated for Lagos the ideas of White *et al*. (1997) about the degree of commonality among cities considering the weighting parameters. Thus although there are obvious differences between the evolution and land-use patterns of different cities, it should be noted that, generally, urban land-use responds with some similarity to several basic location principles such as attraction and repulsion effects and distance decay effects between land-use classes.

The scalable random perturbation term (Eq. (1)) was also calibrated through the parameter α. It was set at 0.6 by means of a trial and error approach. The function of the random perturbation term is to simulate the stochasticity of the urban system. Cities, as most social and economic processes, show some degree of stochasticity, due to the stochastic nature of social processes in which human decisions play an important role. As a result of the random perturbation term, some places that in the simulation have been highly ranked by the other factors of Eq. (1), could be discarded as building sites or can be occupied by a less proper land-use class, as happens in actual cities due to human-related decisions. The random perturbation term also allows non-continuous growth (i.e.

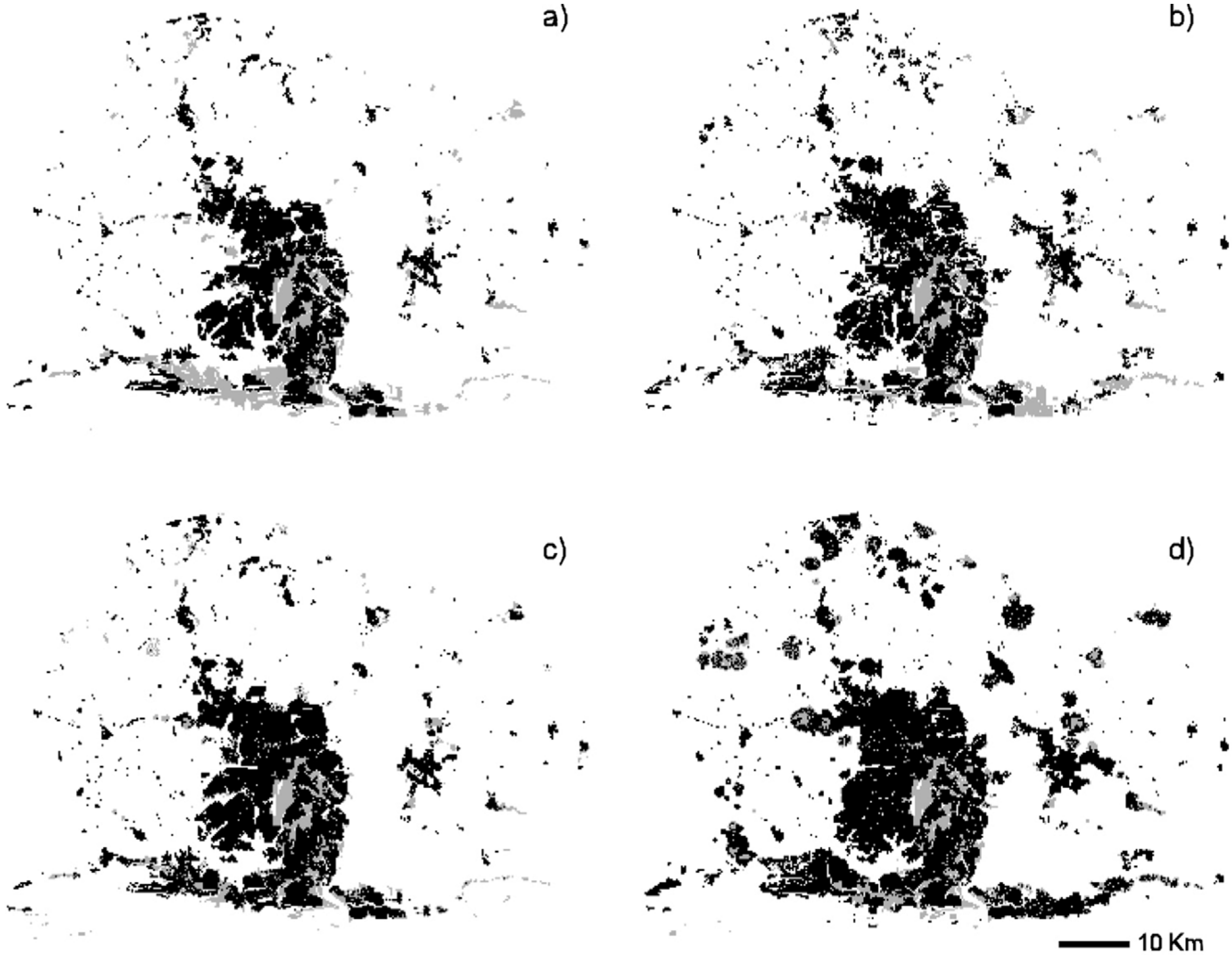

Figure 2 Lagos maps: (a) urbanised area in 1984; (b) urbanised area in 2000; (c) simulated urbanised area from 1984 to 2000; (d) simulated urbanised area from 2000–2020. In black residential areas, grey other built-up areas. Notice that in order to make the maps clearer, the large number of 21 land-use classes have been grouped into *residential* and *other urban built-up areas*.

leapfrogging) of urban land uses based on a stochastic function. However the problem is how to achieve a matching of the stochasticity of both systems: the simulation and the actual city.

The land-use zoning factor was included in the model using the *Lagos State Regional Plan*, prepared in the late 70's. A new master plan is currently under discussion by Lagos authorities (HUGIN, 2001). Thus the available zoning factor may be outdated in some instances. On the other hand, the *Regional Plan* is at 1:100,000 scale, contrasting with the 1:25,000 of the land-use data sets for Lagos created by the MOLAND project, and used for the modelling exercise. Another important inconvenience is that the available *Regional Plan* does not cover the whole city, since the north area of Lagos is growing outside the Plan's area. As a consequence, the simulated land-use in this area will not take into account the established land-use zoning status. On the other hand, the present simulations make no use of suitabilities, since these data are not yet available for Lagos. Nevertheless, the preliminary results are a useful demonstration of the extent to which the model simulates the actual city in the tested sixteen years period and in the 2020 simulation using the available data.

The first approach intended for testing the simulation results is a visual comparison between the simulated land-use map for the 2000 and the actual land-use map for that year (*Figure 2*(*b*) and (*c*)). The main result of this analysis is the resemblance between the maps: the urban form of the simulated map fits reasonably with the actual city map. In fact, it is difficult to differentiate the simulation from the actual city map, which can be considered a very positive sign. As a preliminary conclusion, we can state that the urban CA has produced, from a visual point of view, reasonably good results. Although some differences can be appreciated in both maps, it is important that the land-use pattern distribution in the whole area is "similar to" or resembles the urban form of the actual city, which happened in the simulation. Although the visual comparison produces a first idea of the potential of the urban CA, statistical tests are needed in order to obtain some similarity indexes. For this purpose, the model results were also tested by using Kappa (κ) coefficients (see White *et al*., 1997) and a set of spatial metrics.

Results of the simulation for 1984–2000

It has been shown that procedures using coincidence matrices are not well suited to the testing of urban CA models (White *et al*., 1997; Torrens and O'Sullivan, 2001). The main problem is related to the incapacity of quantifying patterns as such, in view of the fact that this procedure is based on independent comparisons between pairs of cells, and therefore is unable to treat patterns or distributions per se. This means that small displacements in cells within a state will be identified as a discordance. The same discordance will be shown when the displacement is bigger. The problem increases in land uses with a low number of cells, for which the κ value will not yield a useful statistical indicator. Despite this constraint, the κ values for the active land uses were produced (*Table 1*). In *Table 1*, only active land uses that increase their area in the evaluated period have been included.

The κ values obtained from the comparison matrix method show an acceptable fit between the simulated and the actual land-use map for 2000. Despite the aforementioned disadvantages of this method, some land uses show good agreement based on the κ statistic. However, the incapacity of the comparison matrix to treating patterns is clear. The existence of land-use patterns might be understood holistically at the level of the whole city. Thus spatial metrics capable of accounting for the structure of the city should be addressed. Modelling the future of cities should account for the overall future appearance of the city, in the sense of land-use pattern distributions. It is important to simulate the development style of the city, in order to understand the spatial consequences of a planner's actions. This does not mean the production of an "exact" simulation of the future. Aspects such as polycentrism, dispersion, fragmentation, concentration or linearity are not accounted for properly by comparison matrices. On the other hand, urban models that produce perfect simulations of land-use locations are not realistic, considering that cities are complex spatial systems. As a consequence, cities' predictability is usually a hard task and in some instances could be an intractable problem.

Having taken into consideration the aforementioned inconveniences, we additionally tested the model results using a set of spatial metrics. This approach is based on the comparison of spatial metrics obtained for active states in the simulation and in the actual city map. Through a set of spatial statistics, it is possible to better understand the similarities between both maps at land-use class level. The metrics used quantify landscape composition and/or landscape configuration, more specifically the spatial metrics at land-use level can be interpreted as "fragmentation indices", whilst metrics at landscape level–Simpson's diversity index–considering the whole land-use classes can be interpreted as "landscape heterogeneity indices" over the overall landscape (McGarigal *et al*., 2002).

Spatial metrics have been largely used in ecological studies of landscape (Simpson, 1949; Patton, 1975; Gustafson and Parker, 1992; Jaeger, 2000; McGarigal *et al*., 2002). The developed spatial metrics usually measure spatial configuration of landscapes, and "can be used to enhance our understanding of relationships between spatial patterns and ecological processes" (Gustafson and Parker, 1992: 101). Yet the capability of spatial metrics for measuring similarity between spatial patterns made these techniques a powerful instrument for the comparison of land-use maps (simulated and actual) in the urban land-use modelling arena. The selection of the set of spatial metrics was based on a complementary criterion (see Gustafson and Parker, 1992; Jaeger, 2000), in order to have measures capable of detecting and distinguishing spatial patterns between different urban land-use classes. In addition, the selected metrics have different sensitivities to different spatial pattern configurations–i.e. sensitivity to very small patches.

The metrics have been obtained by analysing the land-use raster maps through the Fragstats software (McGarigal *et al*., 2002). The spatial metrics were calculated only for active states in both maps. Afterwards they were compared by regression analyses. The results of the regression analyses are shown in *Table 2*. The regression analyses were carried out following the same methodology for all the metrics. Initially the value for each metric was calculated for each active land use in both maps at class metric level

Table 1 Kappa (κ) coefficients for active land uses for the Lagos's simulation 1984–2000

Land use	κ value
Residential continuous medium dense	0.85
Residential discontinuous	0.68
Informal settlements	0.63
Industrial	0.73
Commercial	0.88
Services	0.79
Port	0.82

Table 2 Spatial metrics. Regression analyses results between the actual and the simulated city for 2000

Metrics	*R*-squared coefficient
Mean patch area	0.98
Total edge	0.91
Shape index	0.84
Proximity index	0.99
Splitting index	0.99
Simpson's diversity index	Actual city: 0.77; simulation: 0.76

in Fragstats. Then the correlation analysis was performed for each metric by using the obtained values for each land use class in both maps. The first remarkable result of this analysis is the overall high R-square coefficient obtained for most of the studied metrics and the similar Simpson's diversity index for both maps.

The *mean patch area* metric measures the weighted mean patch area for each land use class. The area of each patch comprising an urban mosaic is one of the single most important and useful metrics contained in the landscape. The *mean patch area* metric is a function of the number and size of patches in the class and total class area (McGarigal *et al*., 2002). This metric behaves in a complementary manner when compared with the *splitting index*. If a landscape is fragmented over time, then the *mean patch area* decreases whilst the *splitting index* evolves in the opposite way (see Jaeger, 2000). The *R*-squared coefficient of 0.98 shown by the *mean patch area* is a consequence of the high similarity in patch number and size for the active states in both maps.

The *total edge* metric computes the total edge length or perimeter of each of the active states. This metric is usually considered as a landscape configuration metric, however it is not spatially explicit (McGarigal *et al*., 2002). In this case, both maps account for an exact number of cells for the active states. This means the *total edge* is particularly well suited as a comparative metric. Its *R*-squared coefficient of 0.91 is an indicator of good fit between both maps, although not from a strictly spatial point of view, but instead from the point of view of the configuration of the active urban land-use classes.

The weighted *shape index* has been developed by Patton (1975) as a diversity index based on patch shape. It computes the complexity of patch shape compared to a standard-square shape of the same size (McGarigal *et al*., 2002). This metric is based on perimeter-area relationships for each patch of the same land use class. Although the *R*-squared coefficient obtained for both maps is not as high as the previous metrics, it still shows a reasonably good degree of correspondence between the evaluated maps.

The weighted *proximity index* is a measure of isolation of patches based on the nearest neighbour distance between patches of the same type. The distance is calculated based on the nearest cell centre-to-cell centre, which is the distance between the closest cells between two patches. The *proximity index* takes into account the size and proximity of all patches whose edges are within a defined search radius of the evaluated patch. This index is obtained through the overall sum of patches of the corresponding land use class of each patch size, divided by the square of its distance from the focal patch. Thus the index produces a measure of the degree of isolation and fragmentation for each patch type of the map (McGarigal *et al*., 2002). This index has been computed for each of the active land uses in both maps in order to produce the *R*-squared coefficient; their high value of 0.99 is an indicator of similarity between both maps from the point of view of the overall degree of isolation/fragmentation of the active states.

The *splitting index* is a measure of the aggregation/interspersion of patches of the same class in a landscape; this metric reflects both the dispersion and intermixing of patches of the same class, i.e. the texture of the landscape. The *splitting index* can be defined as the number of patches produced when the landscape is divided into patches of equal size, in such a way that this new configuration leads to the same degree of landscape division as obtained for the observed cumulative area distribution. The *splitting index* is expressed as the square of the total landscape area divided by the sum of patch area squared, summed across all patches of the corresponding patch class (McGarigal *et al*., 2002). The *splitting index* can be interpreted as the "effective mesh number" of a patch mosaic with a constant patch size dividing the landscape into *S* patches, where *S* is the *splitting index* (McGarigal *et al*., 2002). The *R*-squared coefficient of 0.99 for this index implies a high degree of similarity between both maps from the point of view of their landscape subdivision. This index is independent of the size of the smallest patch, since it is insensitive to the existence of very small patches.

The *Simpson's diversity index* is a classical measure which quantifies diversity at landscape level. It accounts for the probability that two cells selected randomly would belong to different patch types (Simpson, 1949). Since the *Simpson's diversity index* is a probability, it can be interpreted and compared between both maps directly. In *Table 2* the degree of similarity between both cities can also be seen through this index. In both cases the very similar probabilities of the two cities are the consequence of a fragmented land-use, considering the *Simpson's diversity index* meaning.

The reasonably good results obtained match with previous studies in the urban CA arena (see White and Engelen, 1993; White *et al*., 1997; Wu, 1998; Clarke and Gaydos, 1998; White *et al*., 1999; White and Engelen, 2000; Semboloni, 2000; Li and Yeh, 2000, 2002; Sui and Zeng, 2001). The spatial metrics have shown a relatively good degree of similarity between both maps in aspects such as spatial configuration, pattern morphology, subdivision and dispersion/isolation of patches. However, despite the promising results obtained, it is obvious that both maps are not identical as can be observed in *Figure 2*(*b*) and (*c*). The spatial metrics have shown that both maps are similar from the point of view of their land-use patterns. Strictly speaking, this does not mean that the maps are identical, as can be measured by comparison matrices. However, by comparing the spatial metrics values between the actual city and the simulation, the similarity between them is clear.

The similar values of the spatial metrics mean that the simulation accurately reproduces the spatial pat-

Table 3 Lagos, inhabitants and trends∗

Year	Inhabitants (millions)
1960	0.8 [(a)]
1980	4.4 [(a)]
1990	7.7 [(a)]
2000	11.8∗ [(b)]
2015	24.4∗ [(c)]
2020	> 27.0∗ [(b)]

Source:
[a]Chen and Heligman (1994)
[b]HUGIN (2001)
[c]Federal Ministry of Transport *et al.* (2000)

tern for the evaluated land uses during the simulated period of sixteen years, at least in the sense of the aspects measured by these metrics. But how can the urban CA be able to reproduce patterns without any long–range iteration procedure? The answer must be looked for in the capability of systems with self–organising properties such as standard CA. In the urban CA the pattern structure is a consequence of the local level iterations, which produce the global structure in the simulation map.

Simulation of urban growth for Lagos in 2020

The simulation of future land-use from 2000–2020 was undertaken using the calibrated model for Lagos. In this case the demands for land-use were calculated on the basis of population and land-use growth trends from the previous decades. During these decades, Lagos population had already increased remarkably (*Table 3*), and is foreseen to continue growing considerably in the near future. Between 1980 and 2000, the inhabitants of Lagos have multiplied to almost three times their original number. This has produced several spatial consequences in the city, mainly in the expansion of residential land-use classes. In the period 1984–2000, the *residential discontinuous urban fabric* has shown the most important growth of land-use classes in Lagos, with an increase of 70% (*Table 4*). *Industrial areas* and *informal settlements* have also shown an important increase of 57% and 41% respectively. From an absolute point of view, the area occupied by *residential continuous medium dense urban fabric* is important, and it is the second land-use class by area in Lagos, even if it has had a less accelerated growth in recent years than the aforementioned land-use classes.

Considering the current dynamics and trends of both population and land-use classes, it is foreseeable that there will be an important increase in built-up areas in the next 20 years. Some land-use classes are expected to grow following the development style of the city. For example, this should be the case of the *residential discontinuous urban fabric*, which is the most extensive land-use class in Lagos. However, it is also likely that there will be an increase of more densely populated areas with, as a consequence, main growth of *residential continuous medium dense urban fabric*. On the other hand, taking into consideration the foreseen exponential population growth, it is plausible that there will be an important increase of all residential land-use classes including *informal settlements*, as well as some non-residential classes like *commercial areas*, as a consequence of the overall population increase of the city.

Trends for the year 2020 in *Table 4* have been defined taking into consideration the previous hypotheses and the land-use evolution in the last sixteen years. However, the impact of a population growth of around 15 million people–almost the population of a city like Los Angeles–in land-use evolution, probably will produce an increase of all urban land-use classes in Lagos, as has been stated in *Table 4*. At this stage of the implementation of the simulation, the definition of land-use demands is a key aspect, since it will shape to an important degree the spatial evolution of the simulated city. As can be seen in *Table 4*, the more relevant land-use classes, from the point of view of their area, are foreseen to grow in the order of the 1984–2000 trends, whilst others, like *residential discontinuous sparse urban fabric*, *informal settlements* and *commercial areas* are predicted to increase notably with respect to the previous 20 year period. Although the growth rate trend is relatively high for

Table 4 Land-use in Lagos. Hectares accounted for urban land uses and trends∗ for the 2020. In brackets: growth percentage from 1984 to 2000 and 2000 to 2020 respectively

	Years				
Urban land uses (hectares)	1984		2000		2020∗
Residential continuous medium dense	16360	(15)	18834	(27)	24000
Residential discontinuous	17870	(70)	30422	(64)	50000
Residential discontinuous sparse	9884	(−33)	6606	(12)	7400
Informal settlements	181	(41)	255	(116)	550
Industrial	2686	(57)	4204	(55)	6500
Commercial	109	(14)	124	(100)	248
Public and private services	720	(30)	937	(39)	1300
Port	361	(22)	440	(14)	500

these three land-use classes, from the point of view of their total area, they will not impact greatly or significantly the structure of the city. *Industrial areas*, *port areas* and *public and private services* are foreseen to grow, maintaining approximately their current trends, since their dynamics are more related to economic climate and political issues at local, regional and national level than to population growth per se.

In addition to the aforementioned hypotheses, an interesting option for planners is to produce several simulations following different trend scenarios. For example using current trends, increasing or decreasing them, or imagining the application of certain development mechanisms. In this way it is possible to obtain different scenarios of future land-use based on a variety of assumptions. The addition of planned transport links or changes in the land-use zoning status could represent, as well, additional strategies for predicting future land-use patterns or for the evaluation of different planning actions over the city. In the simulation for Lagos we used the transport network dataset available for 2000. As a result, the land-use demands defined in *Table 4* for the year 2020 have been included in the simulation, obtaining the simulated land-use map for that year (*Figure 2*(*d*)). From a visual point of view the simulated map maintains the general shape of the current city, and the foreseen urban patterns appear to have a logical distribution. Moreover, the size of the city has clearly been augmented and shows increased residential nuclei in peripheral areas, mainly located in the north and east sides of Lagos. Notably, the model has produced iteratively long term predictions based on several hypotheses for diverse urban land-use classes, demonstrating it to be a potentially very useful tool for planning purposes.

In general the simulated development of the city has occurred as expected. The larger built-up areas have grown, in most cases, continuously from the initial city core (*Figure 2*(*b*) and (*d*)). The most important development is encountered in the east and north areas of Lagos due to the constraints presented by water bodies in the south and west sides. Nucleating patches of new urban areas are distributed around the city core, usually in correspondence to transport links. Some of these clusters in the simulation have already been absorbed by the growing main core of the city as actually occurs in real cities. In this case, considering the absence of suitabilities, the transport link represents one of the major factors for the newly developed urban areas together with the initial land-use map and land-use zoning status. These factors drive to a large degree the future land-use scenarios.

Even if suitabilities are an important factor for urban development simulations, their relevance in the case of Lagos could be considered less important than in other areas, due to the plain topography of the city and surrounding areas. The simulation, unconstrained by suitabilities, has produced an extensive development style and consequently an evident sprawl process. The sprawl is additionally corroborated, considering that most of the new built-up areas show low density, as they correspond to *residential discontinuous urban fabric*. On the other hand, the inclusion of an updated land-use zoning dataset might allow a more accurate simulation. However, the calibrated simulation offers the possibility to foresee the future of the megacity with exponential population growth. As we have already mentioned, this would have not been easy to predict from a spatial point of view without tools that embrace the complexity of this kind of spatial system.

A challenge related to future urban simulations is represented by their verification. We agree with Clarke and Gaydos (1998: 712) when they say "only the real future, as it slowly unfolds, can verify our model". An added difficulty is when modelling is made for particular human or social systems as in certain cities in developing countries, where the urban system may be affected by numerous unpredictable events, such as dramatic economic crises, changes in planning policies, natural disasters, wars, and other issues that may possibly modify profoundly the aspect and evolution of urban areas. On the other hand, as in the case of Lagos, loose or outdated urban land-use planning policies increase the stochasticity of the overall system, increasing therefore the difficulty in simulating the urban land-use pattern. Nevertheless, it is clear that simulations with absolute accuracies are not possible considering the stochasticity of the modelled system and the non-foreseeable bifurcations frequent in nonlinear systems. As a consequence, an important aspect is that urban CA models can support "what if" experiments (White and Engelen, 1997), offering the possibility of exploring the future under particular hypotheses within certain degrees of accuracy as defined in the calibration phase.

Conclusions

The spatial result obtained in the simulation for 2020 produces more questions than answers. The spatial growth of Lagos in 2020 is a direct consequence of population growth, thus the city for 2020 is foreseen to become an agglomeration with 27 million inhabitants covering an area close to 969 km^2, more than three times the extent of a city like Paris. Emerging questions can be summarised as follows. What urban development and planning measures can be applied to manage a city with the characteristics of Lagos in 2020, in particular taking into consideration the economic and social constraints in Nigeria? How will the public and private services satisfy the needs of this megacity? The consequences for the quality of life of the Lagos population might be dramatic if serious measures and actions are not applied effectively, but how to do it in a place where sustainability in most cases means survival? In Lagos, infrastructural needs are linked to lack of water, energy, telecommunications, etc. As for environmental sanitation, Lagos seems to be known as one of the dirtiest cities in the world, also due to the inability of city's authorities to cope effectively with waste disposal (Abiodun, 1997).

The MOLAND model has been revealed as an effective tool to foreseen the spatial consequences of loose planning policies in the context of African megacities. Lagos is a city which grows fast and is, relatively, out of control. It is in these cases when forecast tools are needed in order to assess the dangerous future consequences of current urban growth trends, and they thus help in understanding their dynamics and in controlling their growth. On the other hand, the results of the simulation can be considered a useful demonstration of the capabilities of the urban CA model. It has been demonstrated that the urban CA prototype can provide reasonable representations of the future of cities in developing countries. Nevertheless, the addition of suitabilities and updated land-use zoning datasets should significantly improve the quality of this simulation. Furthermore, the capability of the urban CA to reproduce non-continuous urban growth processes is also significant. The possibility to include single land-use classes, such as several types of residential land-use classes, as well as the fine detail of the datasets, increases 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.

One of the more relevant obstacles when future events are modelled is represented by the testing phase, as models developed to simulate situations far away in time are difficult to test. Furthermore, the stochastic degree and complexity of cities in developing countries make the simulation of their future development particularly complicated, mainly for long periods. The testing of calibrated urban CA models against current land-use data sets also presents some constraints. Procedures capable of accounting for land-use patterns per se are necessary in order to measure the similarity degree between simulations and actual cities. However the accurate reconstruction of past trends carried out by the MOLAND project and the fine-tuning of the model on the basis of spatial metrics, has enabled a model adopting the "business as usual" scenario, and ensuring accuracy in the calibration of the model. Spatial metrics appear therefore to be a promising possibility, even if more research is necessary in the methods for model result testing and calibration. How to measure dynamic patterns is not an easy task, consequently dynamic testing procedures might be needed as well.

Taking into account previous experiences using urban CA and the simulation results herewith presented, urban CA modelling appears to be a useful tool for planners. It can be used to study different planning strategies, to measure the spatial consequences of policy decisions and, particularly, future land-use dynamics. However, considering the difficulty of testing future models, the non-foreseeable events that can occur in the urban system and the uncertainty of this kind of modelling per se, future simulations should be treated as hypotheses of events that are likely to occur. Even so, these hypotheses will be verified only with time. Despite these constraints, the capacity of certain CA models to reproduce the actual urban shape through large-scale patterns is remarkable. In particular, the urban CA models are capable of reproducing urban processes through a bottom-up approach. In these systems a set of rules applied dynamically at the local level is capable of generating surprisingly complex patterns in time. In this case, patterns are generated maintaining the resolution and the number of land-use classes of the spatial data originally included in the model.

The calibration phase is of critical relevance for the results of the simulation. The weighting assignment between land-use pairs represents one of the bases of the neighbourhood factors which can be considered as the core of the spatial interaction in the CA model. Good sense and rationality are the keywords in the calibration of the urban CA. Weights and stochastic parameter calibrations can modify the results of the model since land-use dynamics are highly dependent on their values, thus land-use interactions are the basis for the weights assignment. It would be desirable that research focuses more on this area in order to get a better understanding of these interactions. Something similar happens with the stochastic parameter: how can it be measured in real cities? At this moment only previous experiences and empirical trial and error procedures are available. On the other hand, demands for particular land uses in this prototype are inputs defined by the modeller on the basis of socio-economic trends. This aspect of urban CA models is being developed through integrated dynamic regional modelling procedures (see White and Engelen, 1997). In this kind of urban CA modelling approach, standard non-spatial models of regional economics and demographics are linked to urban CA. The aim is to produce a scheme in which changes and trends in various variables, such as population, economics and environmental aspects, have an impact on the spatial dynamics, which are then reproduced by the model. These integrated models will provide planners with more powerful tools for urban and regional scenarios generation.

Acknowledgements

This research was funded by the European Commission, Directorate General Joint Research Centre, postdoctoral fellowship # 17646–2001–03 P1B30 ISP IT "Monitoring sustainable urban and regional development using spatial dynamics models" awarded to J.I. Barredo, and doctoral fellowship # 15784–2000–03 P1B20 1SP IT "Addressing the sustainability of European urban areas throughout land planning considerations" awarded to Luca Demicheli; and undertaken as part of the MOLAND (Monitoring Land

Cover/Use Dynamics) project of the European Commission's Directorate General Joint Research Centre (DG JRC).

The MOLAND urban model prototype has been designed and developed with the support of the MOLAND Project (Monitoring Land Cover/Use Dynamics) of the EC's Directorate General Joint Research Centre (DG JRC) 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.

The authors wish to thank the anonymous referees for the helpful comments on the paper. We also thank the collaboration of Julie Garvey, Vanessa Egan, Fesil Mushtaq and Ana Lisa Vetere Arellano for the assistance with the grammatical revision of the manuscript.

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