Huerta, Schade, Granell (Eds): Connecting a Digital Europe through Location and Place. Proceedings of the AGILE'2014 International Conference on Geographic Information Science, Castellón, June, 3-6, 2014. ISBN: 978-90-816960-4-3

Applying a CA-based model to explore land-use policy scenarios to contain sprawl in Thessaloniki, Greece

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Abstract

This study addresses the issue of urban sprawl through the application of a Cellular Automata (CA) based model in the area of Thessaloniki, Greece. To link macro-scale to micro-dynamic processes the model integrates a statistical model at the regional level with a CA model at the local level. The model is used to compare two scenarios of growth of Thessaloniki to year 2030; the first one assuming a continuation of existing trends, whereas the second one assuming the enactment of various land use regulations in order to contain urban sprawl. The comparison of the results demonstrate that in the second scenario there is a smaller degree of leapfrog growth, with high percentage of new developed land being inside the existing city plans with development in areas outside the plans and in agricultural areas being minimized.

Keywords: Cellular Automata, urban sprawl, urban modelling, land-use policy, Thessaloniki

1 Introduction

Urban sprawl represents urban growth characterized by a sharp imbalance between urban spatial expansion and the underlying population growth *[1]*, discontinuous spatial development patterns *[5]* and low densities *[3]*. Critics of sprawl have emphasized its negative impacts and especially the fact that it leads to increasing car-dependency for transportation, need for more infrastructure, loss of agricultural and natural land, higher energy consumption and degradation of periurban ecosystems *[11]*.

This paper addresses the issue of urban sprawl through the application of an urban growth model based on Cellular Automata (CA). Spatially explicit urban expansion models can effectively trace development patterns of the past and assess possible expansion/future scenarios, they can be therefore regarded as important tools in urban sprawl analysis and could be of use to planners *[13]*. The model takes into account a wide range of demographic, accessibility, socioeconomic, environmental and urban planning data, as well as, a set of local characteristics at the cell level.

The model's logic, structure and calibration procedure are briefly outlined in this paper. A more detailed discussion is provided in *[8]*. The case study area is the urban agglomeration of Thessaloniki in Greece, an area in which the traditional monocentric and radial growth has been supplanted in the last 20 years by rapid periurbanization and extensive urban sprawl. The model is used to compare two growth scenarios for the period 2010-2030; one assuming a continuation of the existing trends and the second one assuming the adoption of various land use regulations with the objective to contain urban sprawl.

2 Methodology

2.1 CA models and urban sprawl

Cellular automata (CA) is a class of spatially disaggregate models consisting of a two-dimensional lattice of cells, in which each cell is characterized by a particular state determined by a set of transition rules *[14]*. Each cell corresponds to a patch of land, and the state(s) of the cells represent the different land-uses. CA are discrete, iterative and dynamic mathematical constructs in which the state of each cell depends on its previous state and on the state of the cells in its neighbourhood *[15]*.

Urban sprawl is a dynamic phenomenon that can be modelled through an analysis of land use and land cover changes *[10]*, therefore extensive research has been carried out to demonstrate the CA's model suitability for simulating urban expansion and sprawl. Among various widely applied models reference can be made to SLEUTH *[2, 7]*, MOLAND *[9]*, DUEM *[18]*, the SimLand model *[17]*, the model developed by He *et al.* *[6]*, the model developed by Torrens [12] etc.

2.2 Model framework and structure

In the present context a CA-based model is applied in the region of Thessaloniki, to explore future development scenarios. The model integrates a statistical model at the regional level with a CA model at the local level, in order to capture macro-scale and micro-dynamic processes. The model therefore presents a two level framework for simulating urban growth, taking into account macro-scale characteristics at the aggregate zone level (municipality or district level) and place-specific, local characteristics at the cell level. The statistical model takes the form of a linear regression function of the type

$$Y = b_0 + b_1X_1 + b_2X_2 + \ldots + b_nX_n \quad (1)$$

where Y represents the new urban (developed) land located in zone k, and X_1, X_2,…X_n various explanatory factors (population change, land availability, accessibility, socioeconomic-demographic data, land values, environmental information etc.) and $b_1, b_2, \ldots b_n$ the estimated coefficients.

At the cell level for estimating propensity of development two indexes are used. The first one is similar for all cells within a zone and represents the urbanization potential of the zone. It is defined as:

$$P_{GLk} = ULC_{ch(k)} / \sum_{k=1}^{m} ULC_{ch(k)} \quad (2)$$

where $ULC_{ch(k)}$ urban land cover change in each zone k as estimated by equation (1) and m the total number of zones. The second one, represents the cell urbanization potential based on its location (slope), land use regulations (protected areas), planning regulations (area of buildings allowed to be constructed), adjacency to other developed areas, proximity to major transportation corridors and proximity to major settlement centers. Mathematically, it is expressed as:

$$P_{LCi} = PR_i \cdot G_i \cdot Z_i \cdot (ND_i + RD_i + D_i) \quad (3)$$

where P_{LCi}=the (local) urbanization potential of a non-urban cell i; PR_i = a protection (construction permission) factor according to land use regulations that takes the value of 1 for areas where development/construction is permitted and the value of 0 for protected areas in which development is prohibited; G_i=a geomorphology factor that is equal to 1 in areas where land slope permits building and 0 in steep slope mountainous areas where construction is difficult; Z_i = a cell specific parameter that expresses the "building ratio/factor" that is the max allowed area of the building (in all floors) as defined by the planning regulations; ND_i = a factor describing the density of surrounding urban uses, related to sprawl-coefficient and to a compact-coefficient index, RD_i = a road network proximity factor related to a road-coefficient index; D_i = a distance factor from the nearest settlement center, related to a distance-coefficient index. The $P_{LCi\ I}$ index is normalized so that $\Sigma P_{LCi(k)} = 1$ for i =1, 2… N where N is the number of cells (i) in zone k.

The overall cell urbanization potential for a cell *i* in zone *k* $P_{i(k)}$, results from the multiplication of the two indexes expressed as:

$$P_{i(k)} = P_{GL(k)} \cdot P_{LCi(k)} \quad (4)$$

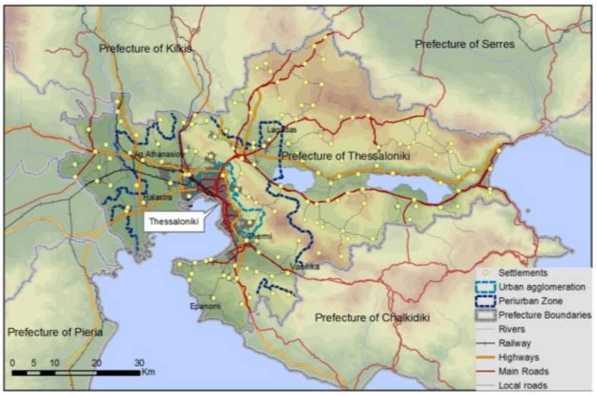
The model has been developed in the Netlogo *[16]* cellular automata and multi-agent programmable modelling environment. The model is loosely coupled to GIS through its inputs and outputs. Data on geomorphology, protected areas, land use zoning status etc. are stored in the GIS and imported to the model through ASCII files. The results of the simulation are exported as a JPEG file and imported in the GIS database for further analysis as a georeferenced raster image.

2.3 Data and calibration procedure

Thessaloniki is the second largest metropolitan area in Greece. It is the capital of the region of Central Macedonia with a population of almost one million people. In the study area (urban agglomeration and periurban zone) there are 29 municipalities, with the city of Thessaloniki being the largest one, and 56 different city-districts. The area, traditionally characterized by a densely built-up and monocentric structure, has seen since the '80s a change in the growth patterns with development in the periurban areas, with population decentralization and rapid urban land expansion. Urban land (developed area) increased between 1990 and 2010 by nearly 5.000 ha, growing by approximately 60% at an average rate of 2.5% per year, while at the same time population increased by 160.000 people, that is almost 20%.

Land cover data were obtained from satellite images for years 1990, 2000 and 2010 (Spot and Landsat images at a resolution 20-30 meters). Essential ancillary data, including 1:50.000 topographic maps, boundaries of protected areas and planning regulations with respect the "building/ratio" factors were obtained from local planning offices. The major transportation network, contour lines, land use zones and other necessary data were digitized from paper maps from various sources. All data layers were registered to the Greek coordinate system (EGSA87). Statistical data were obtained from the National Statistical Service of Greece from the Censuses of 1991, 2001 and 2011.

Figure 1: Case study area within the region of Thessaloniki



The multiple regression model (eq. (1)) estimating developed land change was calibrated for the 1991-2011 time period at the district level. As shown in Table 1 urban expansion is positively related to land available for urbanization (AVarea), population growth (POPrat), population density change (PDENch), population in the age cohort 15–64 years (Fdem) and to areas with significant concentration of services oriented establishments (SERVrat), while it is negatively related to the distance from the city centre (InDis) (city centre was defined to be in Aristotle's square, in Thessaloniki). The variables were inserted in the model through a stepwise process. R square coefficient is estimated to be 0.79, with all variables being significant at the 5% statistical level.

Table 1: Multiple regression results

Variable	Estimate	St.E.
AVarea	0.762***	0.108
POPrat	0.533***	0.157
PDENch	0.002**	0.001
Fdem	0.009**	0.005

SERVrat	0.201***	0.068
InDis	-0.039***	0.010
Constant	0.074**	0.031

**indicates significant at a=0.05 ***indicates significant at a = 0.01

For the calibration of the CA model the area was subdivided into 100x100 meter cells each cell therefore representing an area of 1 ha. A total of 120,536 cells were defined and a 3-cell radius neighbourhood was used in the model. The model was calibrated by running simulations for the period 1990-2010. The calibration process involves running the model forward and comparing the resulting map to the observed land cover data, until converging to a set of coefficient scores that match a set of goodness-of-fit criteria that measure the similarity of the observed and simulated patterns. Five different indexes/metrics were used to test goodness-of-fit of the model, namely a) Index of Compactness, b) Index of Sprawl, c) Index of Road-driven Development, d) Index of Incorporation, and e) Index of Concentration. These indexes express respectively the proportion of new urban land located in areas with high local density of urban land uses, in areas with low local density, in areas adjacent to the road network, in areas incorporated in the city plan and in areas within a two-kilometer radius from the nearest settlement center.

According to the calibration procedure, the sprawl coefficient value is relatively high (sprawl-coef=0.80) while the compact coefficient takes a smaller value (compact-coef=0.20). The significance of planning regulations and plot ratios for attracting development is reported through the building ratio coefficient score (zone-coef=0.20). Important is also the road-driven development (road-coef=0.15) and the role of existing settlement centres (distance-coef=0.10).

The model fits well to the observed changes for the period 1990-2010, as all five of the goodness of fit indexes deviate less than 5% from the observed values. The Absolute Matching Index is equal to 0.38, stating that 38% of observed new urban cells are predicted by the model at their exact location, while the Matching Index with Tolerance is equal to 0.91, stating that 91% of observed new urban cells are predicted by the model at a location closer than 300 meters (same as the size of the CA neighbourhood) from their exact location.

3 Scenarios of sprawl

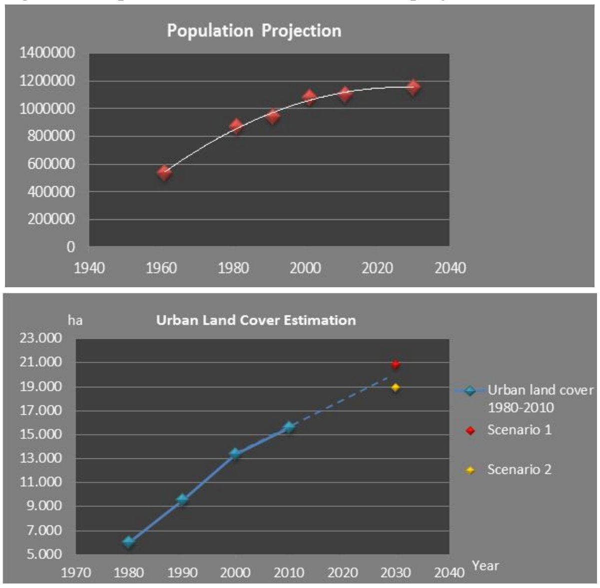
3.1 Scenario assumptions

The calibrated model is used to compare two scenarios for the period 2010-2030, the first assuming continuation of the existing trends - and the current land use planning and policy context, and the second a more sustainable development scenario based on land use zoning policies aiming to contain sprawl.

For both scenarios total population increase and the corresponding urban land cover growth were first estimated and then the model was used to allocate urban growth to the individual cells. To estimate total population increase and age distribution for year 2030 several assumptions were made extrapolating past patterns and using national averages. Most importantly the immigration rates were assumed to be significantly lower than those in the past. Overall, it was estimated that population will increase by about 50,000 people that is about 5%.

To estimate the corresponding urban land growth the concept of the Sprawl Index was used. As defined by EEA *[4]* the Sprawl Index is the ratio of the rate of urban land cover change divided by the rate of population change. Values higher than 1 indicate a sprawling process while values lower than 1 are related to compact development. In the study area the sprawl index during the 1990-2010 period was equal to approximately 3.0 while in the period 2000-2010 it reached a value of almost 10. On the basis of these growth patterns and taking into account a moderate growth scenario as a result of the recent economic recession in Greece, it was assumed that the Sprawl index in the first scenario will not exceed the value of 6 and in the second scenario the value of 4. As shown in Fig 2 both population and land cover estimations follow recent growth trends. Converting these growth assumptions into developed land acreage it is estimated that the land to be urbanized/developed in the two scenarios is 5,255 ha and 3,340 ha respectively.

Figure 2: Population and urban land cover projections



3.2 Scenario 1: Continuation of existing trends (Bussiness-as-usual)

In scenario-1 the following assumptions were made: a) continuation of existing land use/planning regulations with respect construction/development outside the official settlements' boundaries in non-protected areas b) expansion of the city plan permitting the construction of up to 9,500 ha of residential, commercial-housing buildings, c) population decentralization with population growing by up to 2.5% per year in selected periurban settlements and decreasing in the central city zone by 1% per year d) continuation of the existing trends of the location of commercial, office and entertainment facilities in periurban areas and mainly in the south-eastern sector of the city e) Construction of new road infrastructure, as anticipated by the new regional plan of Thessaloniki and the relevant traffic and transportation studies.

According to existing planning regulations, new residential areas are expected to develop as low density with small plot ratios. Low density development is also favored by the land use regulations which permit development on agricultural areas, as long as the lot has a minimum area of 4 ha therefore practically encouraging uncoordinated urban land expansion in agricultural land.

For the allocation of the 2030 developed land to the cells the calibrated equations were used. Results (table 2) show that urban sprawl will continue at rapid rates, with existing designated areas attracting only a small percentage of new urban land (Incorporation Index equal to 36%), while 23% being located in low density neighborhoods (Sprawl Index equal to 23%).

3.3 Scenario 2: Land use policy restrictions to contain sprawl

In scenario-2 the impacts of a land use policy aiming to contain sprawl and to promote a more compact urban growth were examined. It was assumed that: a) there would be smaller expansions of the city plan for residential use, with higher plot ratios than in scenario-1, b) restrictions with respect building construction outside the plan areas will be imposed, c) new protection areas will be established mostly on high yielding agricultural land, mainly in southern periurban zone and in the west periurban zone areas, as well as on the northern mountainous areas. Population decentralization will continue at lower rates and "central" uses will be concentrated in selected large periurban settlements.

Simulation results (table 2) show a smaller degree of urban sprawl, with 45% of new urban land being incorporated into existing designated areas, 19% of new urban areas being located in low density neighborhoods, 29% adjacent to the major road network and 66% located within a distance of 2 km from the settlements located in the periurban zone.

Table 2: Growth trends for both scenarios

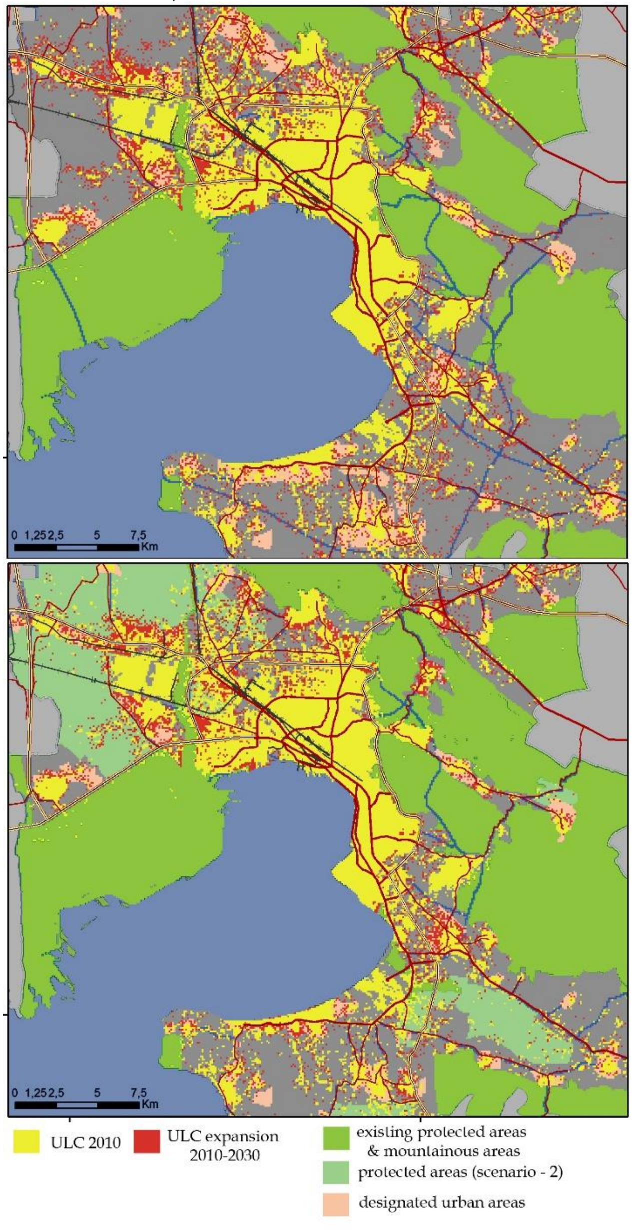
Index	Scenario-1	Scenario-2
Compactness	77%	81%
Sprawl	23%	19%
Road-driven	31%	29%
Incorporation	36%	45%
Concentration	64%	66%

3.4 Results and discussion

In this study a CA-based model of urban growth was used to compare two future development scenarios in the metropolitan area of Thessaloniki, one assuming continuation of existing trends and another one aiming to contain urban sprawl through the adoption of land use regulations. The growth patterns obtained differ to some extent. In scenario-2 there is a lesser degree of leapfrog development with a high percentage of new urban areas occurring inside existing boundaries, while urban sprawl in environmentally important areas and fertile agricultural land is reduced.

Overall it can be stated that spatially explicit urban models can successfully trace development patterns of the past and can be used to assess growth patterns of the future. If appropriately articulated to include variables that are affected by land use policies drawn by decision makers, then they can be used not only for simulating the trends, but most importantly for simulating the impact of alternative policies. They are, therefore, valuable tools for analyzing urban growth and urban sprawl and further development of CA models should concentrate on enriching these models with variables and relationships that can be used for testing the impact of alternative policy measures with respect future urban growth.

Figure 4: Scenario simulation results (scenario-1: above / scenario 2: below)



Acknowledgments:

Parts of the research reported in this paper has been funded by the PEFYKA project of the General Secretariat for Research and Technology.

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