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Dynamics of Urban Sprawl: Applying a CA-based Model to Explore Future Development Scenarios in Thessaloniki

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Abstract: This study explores the dynamics of urban sprawl through the application of DYNAMA, a Cellular Automata (CA) based model. The model simulates the urban land use expansion process in a disaggregated field of land units taking into account a set of local characteristics of cells and neighborhood interactions, as well as a wide range of demographic, accessibility, socioeconomic, environmental and urban planning data. The model is applied to explore scenarios of future development in at the urban agglomeration of Thessaloniki in Greece, an area presenting a recent sprawling process resulting to a gradual change of the traditionally highly compact and monocentric structure.

First, the model logic and structure is presented. The model calculates combined urbanization potentials on the global and the local level and uses a stochastic process in order to allocate new urban land in the cell-space. Next, emphasis is placed on the calibration of the model in the study area and on the exploration of future development scenarios. The calibration of the model is based on an automatic calibration process on the CA level and on a multiple regression model which has been used to quantify the influence of macro-scale factors on the regional level. Urban land cover changes for the period 1990-2010 have been examined and the fit of the model to the observed data is evaluated.

The model is then used to explore two different scenarios of urban development. The first scenario is based on current trends concerning urban land expansion rates and assumes that protected area policy and land use regulations will remain stable. In the second scenario we hypothesized a smaller urban land expansion rate and a policy restriction on building in agricultural land as well as an increase in the area of protected zones. From the comparison of the results we observe that in scenario-1, urban sprawl characterized by leapfrog development in the periurban zone is accelerated and that expansion of urban land uses in agricultural land and in the countryside remains intense. On the other hand, in scenario-2 a large part is incorporated inside existing boundaries and urban sprawl in environmentally important areas and fertile agricultural land is reduced.

Key words: Urban sprawl, dynamics, simulation, cellular automata, scenarios, Thessaloniki
JEL classification code: O18, R52, C6

1. Introduction

Urban sprawl is a type of growth related to a sharp imbalance between urban spatial expansion and the underlying population growth (Brueckner, 2001), to discontinuous patterns (Ewing *et al.*, 2002) and to low density development (Couch, Leontidou *et al.*, 2007). Sprawl is the result to population suburbanization and suburban living preferences (Decker, 2011), to the increase of periurban accessibility through the prolific use of automobiles, to the role of developers and to the lack of planning and land use policy (Torrens, 2006; Decker, 2011).

Sprawling cities are considered to be an unsustainable form of urbanization, contrary to the sustainable model of the 'compact cities' characterized by high density, monocentric structure (Gordon & Richardson, 1997), minimization of land consuption for urban uses and an increase of land use mixture (Galster *et al.*, 2001). European cities have historically been characterized by a relatively compact structure, as a cause to the important role of the CBDs and to the persistence of existing settlement patterns through time (Batty, 2005).

During the second half of the 20th century, European cities have expanded rapidly in spatial terms presenting an acceleration of urban sprawl (EEA, 2006). Different urbanization models are observed within Europe, with Mediterranean cities being usually characterized by higher population densities than the cities of North-western Europe. Through a comparison of European population density data, as presented in the Urban Audit database (www.urbanaudit.org), it can be observed that the more densely populated cities are located in Southern Europe, while the two main metropolitan areas of Greece, Athens and Thessaloniki, are characterized by a mean gross density in the central area that surpasses 200 people per hectare and are classified as the two most densely populated cities of Europe. Nevertheless, rapid periurbanization processes have been observed during the past two decades in those areas (Munoz, 2003).

Critics of sprawl have underlined its negative impacts and especially the increasing car-dependency for transportation (Torrens & Alberti, 2000), the need for more infrastructure (Brueckner, 2001), the loss of agricultural and natural land, the higher energy consumption, the degradation of periurban ecosystems etc (Johnson, 2001, Li et al., 2006; Lagarias, 2011). On the contrary, compact urban development is considered as a more economic form in terms of energy consumption (Newman, 2000) following principles such as brownfield development, urban regeneration and refurbishment of old building stock (Lock, 1995).

The study presents a newly developed Cellular Automata (CA) based model of urban sprawl. The model has been presented elsewhere with the code name DYNAMA (Lagarias, 2012) and links macro-scale periurbanization processes to land use dynamics at the local level, in order to simulate the urban expansion process. In the present context, an enhancement of previous work is presented, with the comparison of two future development scenarios in the city of Thessaloniki, an area characterized historically by a very compact structure and presenting recently rapid periurbanization trends.

Modelling of urban sprawl is an important research issue in urban studies. Contrary to previous land use urban models, dating back to the '60s and '70s which were mainly static, deterministic and based on assumptions of equilibrium, the new generation of models has emerged focusing on simulation through cellular automata and agent-based models, complexity theory and micro-dynamics (Benenson & Torrens, 2004). Cellular automata (CA) form 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 (White & Engelen, 1993). Each cell symbolizes a patch of land, and the states of the cells represent the different land-uses. CA are discrete, iterative and dynamic spatial systems in which the state of each cell depends on its previous state and on the state of the cells within its neighborhood (White et al., 1997).

Among the advantages of CA is the fact that they are inherently spatial and therefore compatible with most spatial data sets and the fact that they are dynamic and can thus represent spatial processes in a direct way. In spite of their simplicity, CA can exhibit extraordinarily rich behavior and can represent and execute almost any possible algorithm (White & Engelen, 2000).

Models of this type have been used to analyze urban sprawl and to explore future scenarios of land use changes and urban growth. Urban sprawl is a dynamic phenomenon that can be best described through the monitoring of land cover changes (Schneider & Woodcock, 2008) and therefore many works have demonstrated the CA model's capability for urban expansion and sprawl simulation (Torrens, 2006; Jantz et al., 2003; He et al., 2006; White & Engelen, 2000). Most of these models depart from the basic CA assumptions and form a set of CA-based hybrid models. Various widely applied models exist such as SLEUTH (Clarke et al., 1997), MOLAND (Lavalle et al., 2004), DUEM (Batty et al., 1999, Xie & Batty, 2003), METRONAMICA (Van Delden et al., 2007), SimLand (Wu, 1998), UES model (He et al., 2006) etc. The above models been applied to simulate future scenarios in numerous case study cities.

The DYNAMA model is applied in the area of Thessaloniki to explore future development scenarios. The model integrates a statistical model on the regional level with a CA model on the local level, so as to link macro-scale to micro-dynamic processes. The model simulates the urban land use expansion process in a disaggregated field of land units (cells) taking into account a set of local characteristics of cells and neighborhood interactions as well as a wide range of demographic, accessibility, socioeconomic, environmental and urban planning data. The allocation of new urban land is based on a stochastic process.

The calibration of the model in the case study area is based on an automatic calibration process on the CA level, while a multiple regression model has been used to quantify the influence of macro-scale factors on the regional level. Urban land cover changes for the period 1990-2010 have been examined and the fit of the model to the observed data is evaluated. The calibrated model is used to explore two different scenarios of urban development. The first scenario is based on current trends concerning urban land expansion rates and assumes that protected area policy and land use regulations will remain stable. In the second scenario we hypothesized a smaller urban land expansion rate and a policy restriction on building in agricultural land as well as an expansion of existing protected zones.

Section 2 presents briefly the conceptual underpinnings of the proposed model. Section 3 includes the presentation of the case study area and the calibration of the model using historical data. Section 4 compares the two scenarios and presents the evaluation of the results. Finally, Section 5 provides conclusions drawn from the main results.

2. Basic model principles and calibration procedure

The model examines the allocation of new urban land as a two-scale process, taking into account firstly macro-scale characteristics of a region and secondly place-specific, local characteristics. At first, we assume that urban sprawl within a region is driven by general demographic trends, accessibility and infrastructure, environmental conditions, social and economic characteristics of population, land availability and land use zoning, building regulations etc and that these factors reflect the attractiveness for new urban land uses of each zone which normally correspond to the municipality level.

At the second step the urban region is regarded as a disaggregated system of land units (cells). Cells of 100 m size have been used and therefore every land unit has an area of 1 ha, a size large enough to capture spatial details and small enough to reduce computation time. The basic distinction between cell states is ‘urban’ and ‘non-urban’, while information concerning protected areas, land use zoning status, road network and geomorphology, is also considered.

Urban land expansion in a cell depends on a) the inherent qualities of land (land slope, building ratio, land use regulations etc) b) the effect of neighboring land uses (local urban density, road network adjacency, distance from local residential centre etc).

These characteristics combined together define the advantages and disadvantages for development presented at that each parcel of land and therefore define its urbanization potential. The cellular model is considered to be dynamic and all factors are re-estimated after each time step in order to take into account the dynamic character of the urban expansion process.

The model has been written in the Netlogo cellular automata and multi-agent programmable modelling environment (Wilensky, 1999) and its flowchart is presented in figure 1.

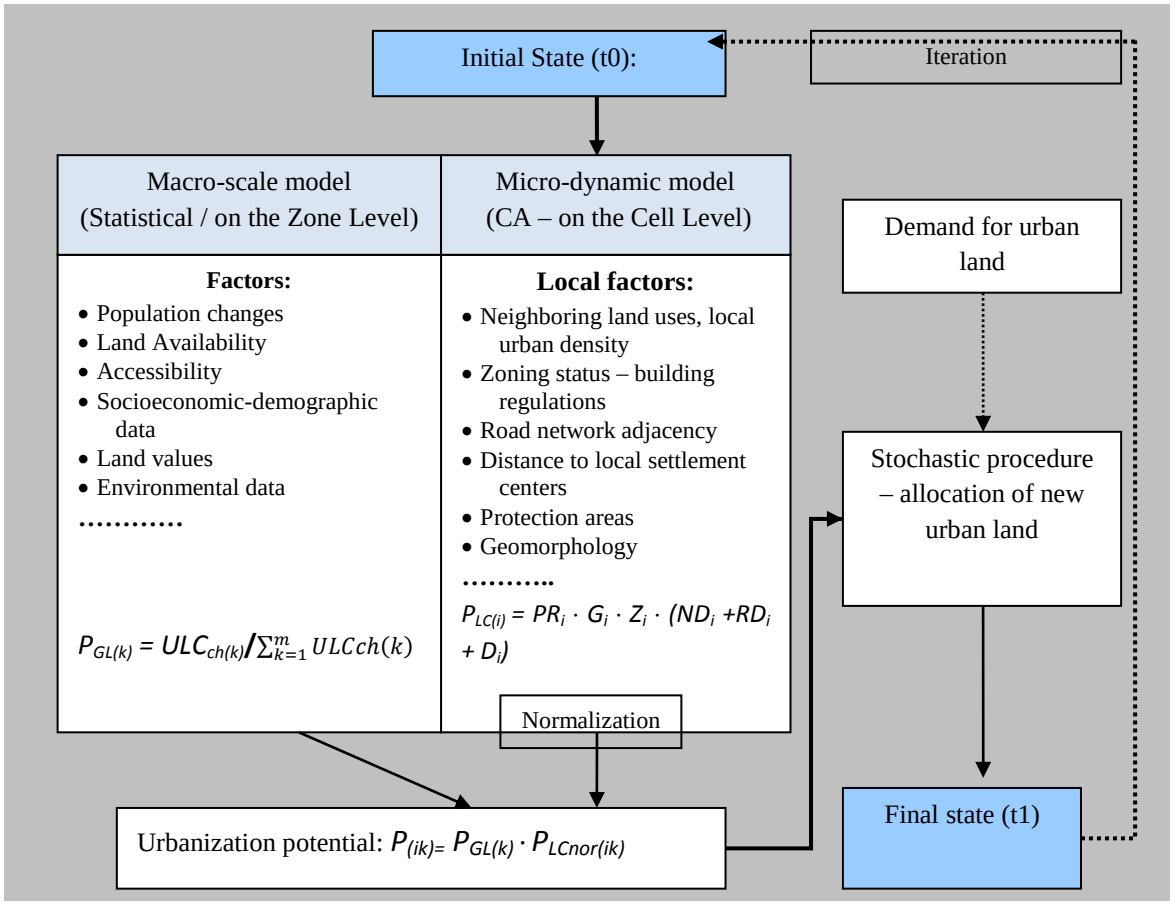


Fig.1 Diagram presenting the general structure of the model

The model calculates combined urbanization potentials on the global (P_{GL}) and the local level (P_{LC}) and includes a stochastic process in order to allocate new urban land through space and time. If a region is subdivided into m large zones, the dynamics of each zone for a given period of time can be quantified through an index noted as P_{GLk} that expresses its 'global' urbanization potential. If urban land cover change in zone k during a given period of time is

$ULC_{ch(k)}$ and F$(ULC_{ch(k)})$ a function of this variable**,** then we hypothesize that a relationship of the following form exists:

$$F(ULC_{ch(k)}) = b_0 + b_1X_1 + b_2X_2 + \ldots\ldots + + b_nX_n \quad (1)$$

where X_1, X_2,…X_n explanatory factors (population changes, land availability accessibility socioeconomic-demographic data, land values, environmental data etc) and $b_1, b_2, \ldots b_n$ the weighting coefficients. A multiple regression model can be used to identify the most important factors driving urban development within a specific urban area and to quantify their weight. Then, the potential of development for new urban land uses in each zone is expressed as

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

Local development potentials (P_{LC}) are than estimated taking into account local characteristics which refer to each land unit and the inherent qualities of land itself (land slope, building ratio, land use zoning etc) and the effects of neighboring land uses (local urban density, road network adjacency, distance from local residential centre etc). We assume that for each cell i, cell characteristics can be quantified through a single index that expresses its 'local' urbanization potential. P_{LCi} 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 development potential index of the cell for urban land use for each non urban cell; PR_i = a protection index according to land use zoning that takes the value 1 for non-protected areas and the value of 0 for protected areas which are excluded from urbanization; G_i = a geomorphology index that takes the value of 1 in areas where land slope permits building and 0 in steep slope mountainous areas where construction is difficult; Z_i = a land use zoning index based on the building ratio of each land unit which expresses the amount of permitted constructed surface per land use on each plot; ND_i = an index describing the density of surrounding urban uses, RD_i = a road network adjacency index; D_i = a distance index from the nearest settlement centre.

From expression (3) we notice that if PR_i, G_i and Z_i take the value of zero, urbanization potential also becomes zero and therefore urban expansion is excluded from protected areas, from areas with extremely steep slopes and from areas where construction is prohibited.

The neighborhood effect of other urban cells is controlled by the ND variable and is calculated within a user-defined radius as follows:

$ND_i = sprawl\text{-}coef \cdot SU_i / SU_{THR}$, *if* $0 < SU_i < SU_{THR}$ and $ND_i = sprawl\text{-}coef + compact\text{-}coef \cdot (SU_i - SU_{THR}) / SU_{THR}$, *if* $SU_i \geq SU_{THR}$ (4)

where *sprawl-coef*, *compact-coef* weighting parameters, SU_i = the total of urbanized neighborhood cells around cell i, SU_{THR} a threshold of urbanized neighborhood cells (taken equal to r^2, where r the radius of the neighborhood size in cells), distinguishing between compact and sprawl development on the local level. This factor is based on the assumption that the presence of neighboring urban uses acts as a driver of new development. According to the values attributed to the weighting parameters the expression takes different forms.

The distance index is estimated through an exponential function expressed as

$$D_i = d_a \cdot exp^{(-dp \cdot dis)} \quad (5)$$

where dis_i = the distance in cells from cell i to the nearest settlement centre; d_a and d_p = coefficients defining the form of the exponential function and its weight in relation to the other factors respectively. The estimation of the land use zoning index of each cell Z_i is based on the ratio of permitted constructed surface on each plot (plot ratio). This factor is considered to be important from the perspective of developers and real estate agents. Generally this index is expressed as

$$Z_i = zone\text{-}coef \cdot sd_i \quad (6)$$

where sd_i = the plot ratio in cell i and *zone-coef* = the corresponding coefficient controlling the weight of the variable. In the case study for the city of Thessaloniki we propose a more elaborated formula that takes into account differentiation between incorporated and unincorporated in the city plans parcels. The corresponding factor is expressed as

$$Z_i = sd_i - [1 - zone\text{-}coef) \cdot (sd_i - sd_{out})] \quad (7)$$

where sd_{out}: the building ratio of plots that are unincorporated in the city or settlement plans; sd_i: the building ratio of plots in cell i; *zone-coef* a coefficient weighting the importance of defined building ratios in incorporated areas.

The road factor is expressed as

$$RD_i = road\text{-}coef \cdot SR_i \quad (8)$$

where SR_i the sum of adjacent road network cells in the von-Neumann neighborhood. *SR* is weighted by the hierarchy of the road network so that high-speed motorways have a higher impact than local roads in the calculation.

P_{LCi} values for each zone *k* with a total of n cells are normalized so that $P_{LCnor(ik)} = P_{LCik} / \sum_{i=1k}^{n} P_{LC(ik)}$ and $\sum_{i=1k}^{nk} P_{LCnor(ik)} = 1$, where $P_{LCnor(ik)}$ the normalized values. From the definition of $P_{GL(k)}$ we understand that $\sum_{k=1}^{m} P_{GL(k)} = 1$. The final urbanization potential index of each cell is estimated through a combination of its local characteristics and the dynamics of

the zone where it is located. The integration of the two indexes is expressed by multiplication as

$$P_{(ik)=} P_{GL(k)} \cdot P_{LCnor(ik)} \quad (9)$$

The model uses an allocation module based on the $P_{(ik)}$ urbanization potential values, and taking into account exogenously defined demand for new urban land. The model uses the stochastic selection process to allocate new urban land in the non-urban cells according to the $P_{(ik)}$ values, at each time step. The system runs in iterative steps with the local characteristics being continuously re-estimated.

The model can be loosely coupled to GIS through its inputs and outputs. GIS data concerning the geomorphology, the zones of analysis, the protected areas or other area excluded from the urbanization process, population growth data, etc can be imported in the model. The model reads the data from corresponding ASCII files and sets the corresponding variable values according to the GIS data. The above process is repeated for all necessary layers of information. The results of the simulation can be exported as a raster image and inserted into the GIS database for further elaboration.

As far as the calibration of the model is concerned, we use an automated calibration procedure along with a set of post-evaluation indexes to evaluate the model's performance. The calibration process involves running the model forward from the initial known state using the current best set of values, and comparing the resulting map to a known map for the same date, to ensure the similarity of the observed and simulated patterns. We use five geometrical indexes which are: **1.** Index of Compactness. **2**. Index of Sprawl **3.** Index of Road-driven Development **4.** Index of Incorporation **5.** Index of Concentration. These indexes are related to the local factors and express the proportion of new urban land located in areas with high density, in areas with low 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 respectively.

During the calibration process, the coefficient values are adjusted in such a way as to reduce the discrepancy between the two maps. The procedure has been automated in order to generate the set of the most appropriate values for the six local coefficient values (compact-coef, sprawl-coef, road-coef, zone-coef, d_a, d_p). An initial set of weights for the five coefficients is defined and the procedure runs testing simulations. Every time the predicted values of the geometrical indexes diverge more than a user-defined tolerance from the

corresponding estimated values of the observed patterns, the coefficient values are adjusted, and the simulation restarts.

After convergence has been reached and all indexes differ are within a user-defined tolerance from the observed data, a set of calibration indexes is estimated for the evaluation of the overall goodness of fit of the model to the historical data: **1**. Absolute Matching Index: counts the percentage of predicted new urban cells that completely coincide with observed new urban cells **2.** Matching Index with Tolerance: counts the percentage of predicted new urban cells that are located close to observed new urban cells, according to a tolerance radius **3**. Fractal Dimensions: Areal and boundary fractal dimensions of the real and the simulated pattern should be similar in order to assure similar geometrical characteristics of the patterns.

3. Calibration of the model in the case study area

3.1. Case study area, data sources and recent changes

The city of Thessaloniki is the capital of the region of Central Macedonia in Northern Greece, with a population that exceeds one million people in the central city and the periurban settlements. In 2011, the population on the prefecture was estimated at 1.104.460 people. The area went through rapid urbanization during the 20th century, presenting important rates of growth and being characterized by a central densely built-up area. The area is crossed by important transportation networks, linking Thessaloniki to Athens and to the Balkan countries, while the geomorphology is characterized by high wooded hills in the north and Thermaikos Gulf on the south, limiting urban expansion mainly to the large plains in the west and the smooth hills in the south-east (fig.2).

The majority of population (about 75%) of the wider prefecture area is located in the central urban agglomeration, with a mean gross density that surpasses 60 people per ha. However, since the ‘80s a relative decentralization process has been observed and this is clearly presented by comparing the rates of population growth between the central area and the periurban area. Population increase is mainly observed in the municipalities of the outer ring of the urban agglomeration as well as in the periurban communities (an increase of over 50% in the period 1991-2001). In the central municipality of thessaloniki (CBD) population slightly decreases in the period 1991-2001 (a decrease of 3%) and recent data show a more rapid decrease of around 16% in the last decade.

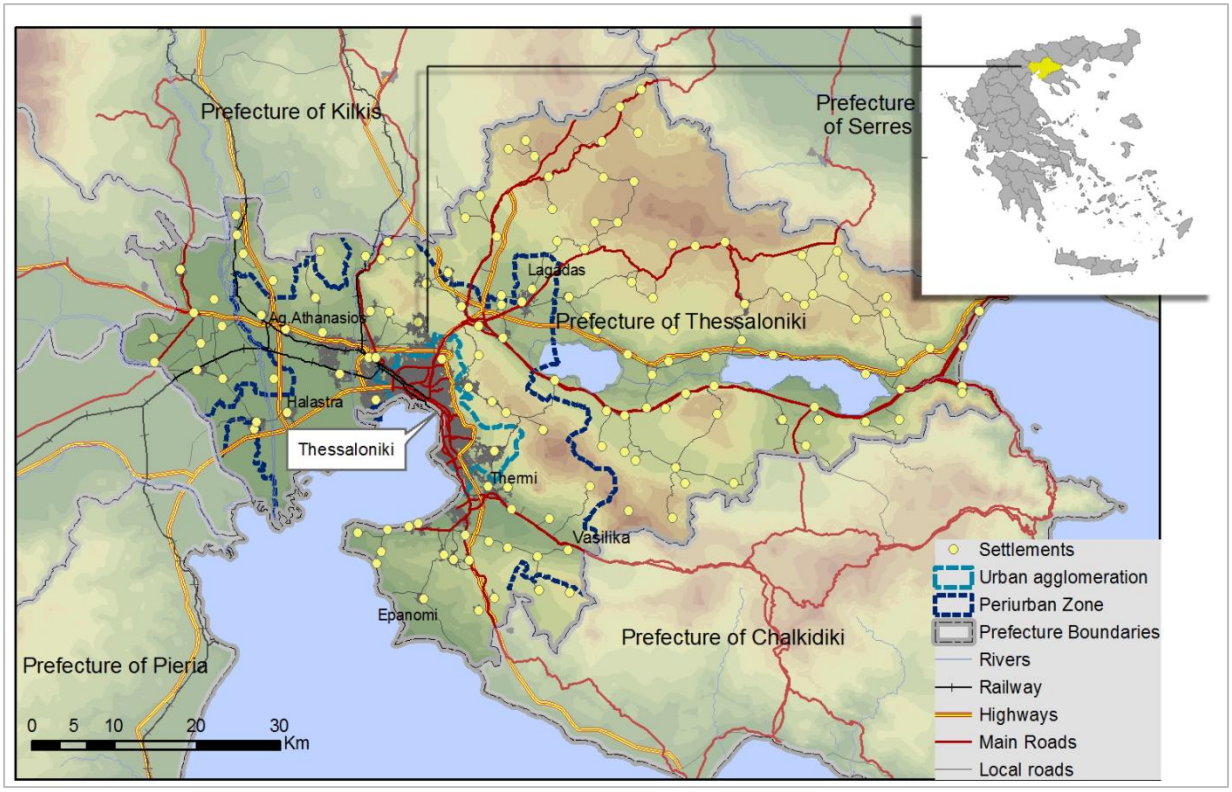


Fig.2 The area of Thessaloniki

As a result to the decentralization process, important land use changes have been observed and the urban boundaries have expanded outwards. Population decentralization has also been followed by an important decentralization of land uses of the tertiary sector. Global firms, offices and commercial centers located in the ex-agricultural periurban land mainly in the southeast area due to cheaper prices and good accessibility, while in the west area industrial uses along with commercial uses, warehouses and small industries are located.

During the same period, scattered residential development takes place, with buildings constructed in plots located outside the city plans. This type of development is favoured by the legislative framework which permits building on all agricultural plots and practically promotes uncoordinated urban land expansion in agricultural and natural areas. Recent sprawl has resulted to an important loss of agricultural land and to environmental problems with a characteristic example being the degradation of the ecosystem of the Koroneia Lake (Lagarias, 2011).

Contrary to previous work (Lagarias, 2012), in the present context we selected a wider surrounding zone for the analysis, reaching to the seaside area of Epanomi on the south, to the agricultural areas surrounding Vasilika on the east, to the city of Lagadas located near the Koroneia Lake on the north and to the important periurban settlements of Halastra and Agios Athanasios on the west. The central zone of the city has also been included in the analysis.

The selected periurban areas are characterized by a maximum time distance of 50 minutes from the CBD, rapid population increases (over 25% during the decade 1991-2001), an important proportion of employers (more than 15%) travelling everyday to the urban center.

Land cover data have been defined through satellite images of circa 1990, 2000 and 2010 (Spot and Landsat images at a resolution 20-25 meters). Essential ancillary data, including 1:50.000 topographic maps, census data at municipality level and shapefiles of protected areas were obtained from local offices. The transportation network, countor lines, land use zones and other necessary data were digitized. All the data layers were registered to the local coordinate system (EGSA87). Statistical data were obtained from the National Statistical Service of Greece (NSSG, 1991; NSSG, 2001).

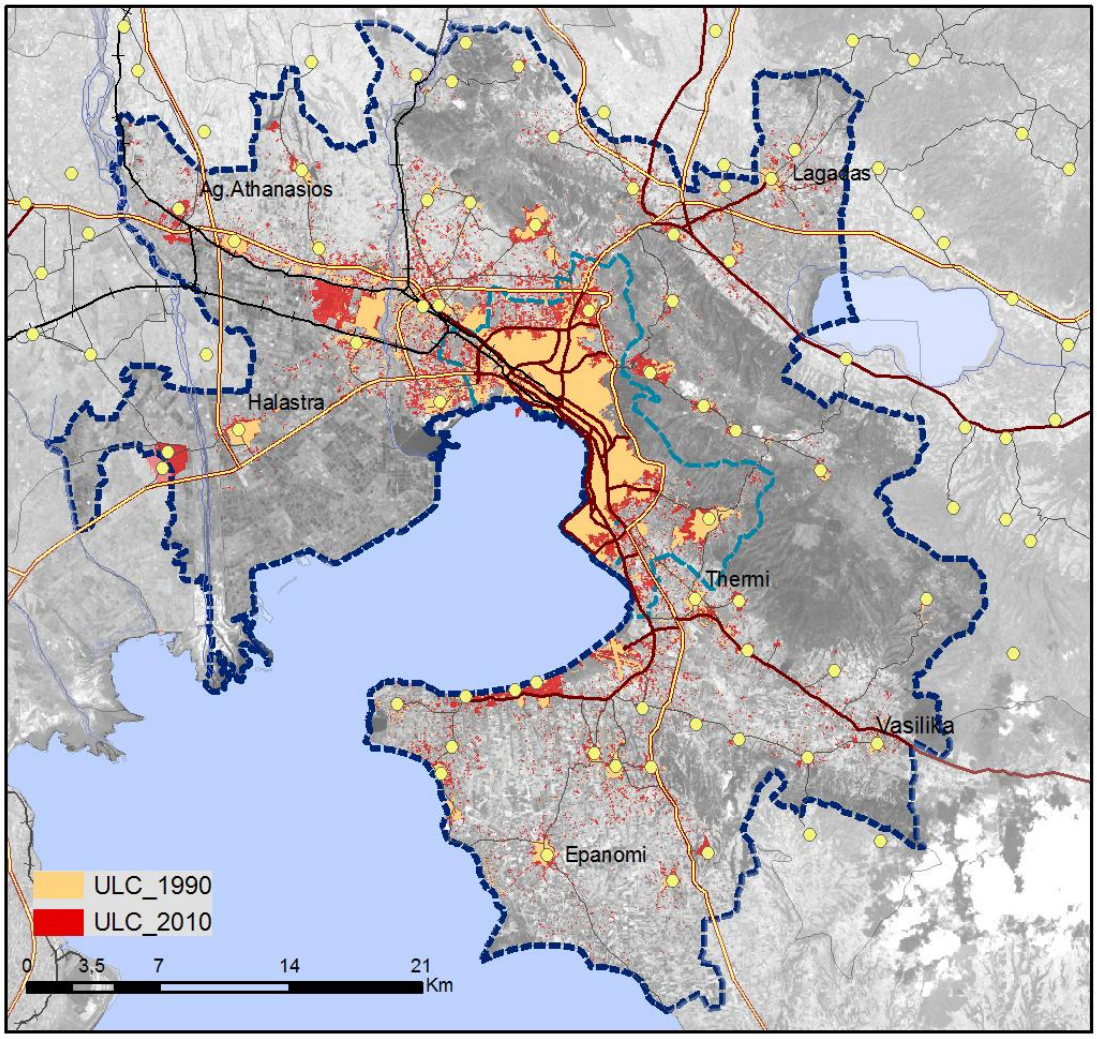


Fig.3 Recent Urban land cover changes in the case study area

The satellite images were classified through supervised and unsupervised classification methods performed in ERDAS IMAGINE suite of software. A maximum of 10 land use classes were used including urban areas, irrigated land, deciduous and evergreen forest, bare

ground, water bodies etc. The classified raster images were georeferenced and vectorized in a GIS database while urban land cover has been extracted and corrected through a hand-editing process based on fieldwork. Next, an algorithm of cartographic generalization was applied where clusters with distances smaller than 50 meters have been united and empty areas smaller than 2 ha surrounded completely by urban development have been reclassified as urban.

The final map presenting the urban land cover changes is presented in fig.3. The results show that the urban land has increased from about 9500 hectares in the period around 1990 to 13.400 ha in 2000 and to almost 15.550 circa 2010. Urban land cover, therefore, has increased between 1990 and 2010 by more than 6.000 ha, growing at a mean overall rate of 2,26% per year, with the majority of new urban land being located in the periurban zone.

3.2. Explanatory factors and model calibration

The relationship between general factors of the urban structure and urban land cover changes on the macroscale level, was investigated using a multiple regression model. As spatial units, the municipality departments, which are the smaller existing administrative units have been used. The dependent variable was defined as the new urban land for the period 1990-2010 in each zone, normalized by the total zone area with exclusion of surfaces covered by water ($ULC_{ch/area}$).

The explanatory factors which are expected to influence the spatial distribution of land use expansion have been organized into seven groups: 1. Population changes: defined as the mean annual population growth rate for each municipality *(POPrat)* and population density change (*PDENch)* 2. Initial land availability *(AVarea)*, estimated as the surface of remaining undeveloped land in each zone in the 1990 period, weighted by the corresponding mean building ratio and normalized by the total zone area 3. Accessibility estimated as the logarithm of mean time distance from each municipality to the centre *(DIS)*. 4. Land use values as defined by the Greek Ministry of Environment. *LVout* describes land values for plots located outside the city plan, *LVin* describes land values for plots incorporated in the city plans 5. Demographic and socioeconomic data: Combined indexes resulting from a principal component analysis were considered. The indexes represent information on population age distribution, population educational level, employment in the primary, secondary and tertiary sector, employment position etc. Three factors have been extracted for the socioeconomic variables (Fsoc1, Fsoc2, Fsoc3) and four for the demographic variables (Fdem1, Fdem2, Fdem3, Fdem4). 6. Urbanization level & services: we consider here the initial population

density for each municipality *(PDEN)* and the ratio of buildings of central use to the total buildings of the municipality *(SERVrat)* 7. Environmental characteristics: we consider here a variable quantifying the environmental quality and suitability for residential development of each zone, estimated as a combination of distance from the industrial areas, altitude and access to the seashore *(ENV).*

The variables are inserted in the model through a hierarchical stepwise process. The results show that six variables define the best explanatory set with an R coefficient equal to 0.889, and therefore the model accounts for 79% of the total variance of urban land cover change. All variables entered are significant at 5% statistical level. The estimated weight scores and significance levels for the explanatory variables are provided in Table 1.

Table 1: Results of regression model

Variable	**Estimate**	**Std-error**	**Sig**
CONSTANT	0,074	0,031	0,021
AVarea	0,762	0,108	0,00
DIS	-0,039	0,010	0,00
POPrat	0,533	0,157	0,001
SERVrat	0,201	0,068	0,005
PDENch	0,002	0,001	0,044
Fdem3	-0,009	0,005	0,045

Results of the statistical analysis show that urban expansion is positively related to available land for urbanization, to rapid population growth and positive population density change, to population in the age between 15–64 years (as expressed by the Fdem3 factor) and to areas with an important concentration of central uses, while it is negatively related to the distance from the city centre.

Following the regression results, estimated land cover change for each zone is estimated as

$$ULC_{ch/area} = 0{,}074 + 0{,}762 \cdot AVarea - 0{,}039 \cdot DIS + 0{,}533 \cdot POPrat + 0{,}201 \cdot SERVrat + 0{,}002 \cdot PDENch - 0{,}009 \cdot Fdem3 \quad (10)$$

The P_{GL} values for each zone as defined in the model were estimated according to expression (2). The results of the macro-scale analysis have been inserted in the model and the estimated P_{GL} values have been assigned to each zone for further calculations.

A radius of 3-cells, corresponding to 300 meters, has been defined for the cell neighborhood. Road network adjacency has been examined in the Von-Neuman neighborhood. The time step has been defined as a half-year which is considered as the mean time needed for the construction of a housing unit. Therefore, the simulation runs in 40 time increments for the simulation of urban expansion during the period 1990-2010.

The resolution of the land cover data has been sampled to the pixel resolution of 100 meters of the model cells. Urban land has increased from 12.100 cells (in 1990) to 22.408 cells in (2010). If we exclude urbanization if special zones (military camps, mining areas, industrial sites), this change corresponds to 241 new urban cells per time step. 24% of new land units are located in low-density areas and contribute to sprawl, while 76% is regarded as compact development. Approximately 21% are incorporated inside the boundaries of the central agglomeration and of the periurban settlements and 64% are located within a radius of 2 km from existing centres. For areas located inside protected areas the PR_i factor is set to 0, while for all the other areas PR_i is set to 1. The sd_{out} factor corresponding to mean building plot ratio for countryside plots was estimated equal to 0.1 (200 sq meters of residential use and 600 sq for commercial uses in a 4.000 sq meter plot).

The model has been calibrated converging to a set of coefficient scores (fig.4). According to the estimated weights, the sprawl coefficient value is relatively high (*sprawl-coef=0.8*) while the compact coefficient score is smaller (*compact-coef=0.2*). The important role of building regulations and plot ratios is reported through the high building ratio coefficient score (*zone-coef=0.2*). Important also is the road-driven development (*road-coef=0.15*) and the role of existing settlement centres (d_p*=0.1*).

The model fits well to the observed changes, as all geometry 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 from their exact location. Moreover, the fractal dimension values of the simulated and observed patterns are very close, as the areal fractal dimension is 1,52 (r=0.999) in the observed pattern and 1,538 in the simulation, while and the fractal boundary dimension is 1.47 (r=0.992) in the observed pattern and 1,499 in the simulation [1].

[1] The fractal dimensions have been estimated using the box-counting method and the software Fractalyse, Version 2.4 This software is developed by Gilles Vuidel at ThéMA (Théoriser et Modéliser pour Aménager) Laboratory, CNRS Universités de France-Compté et De Boulogne.

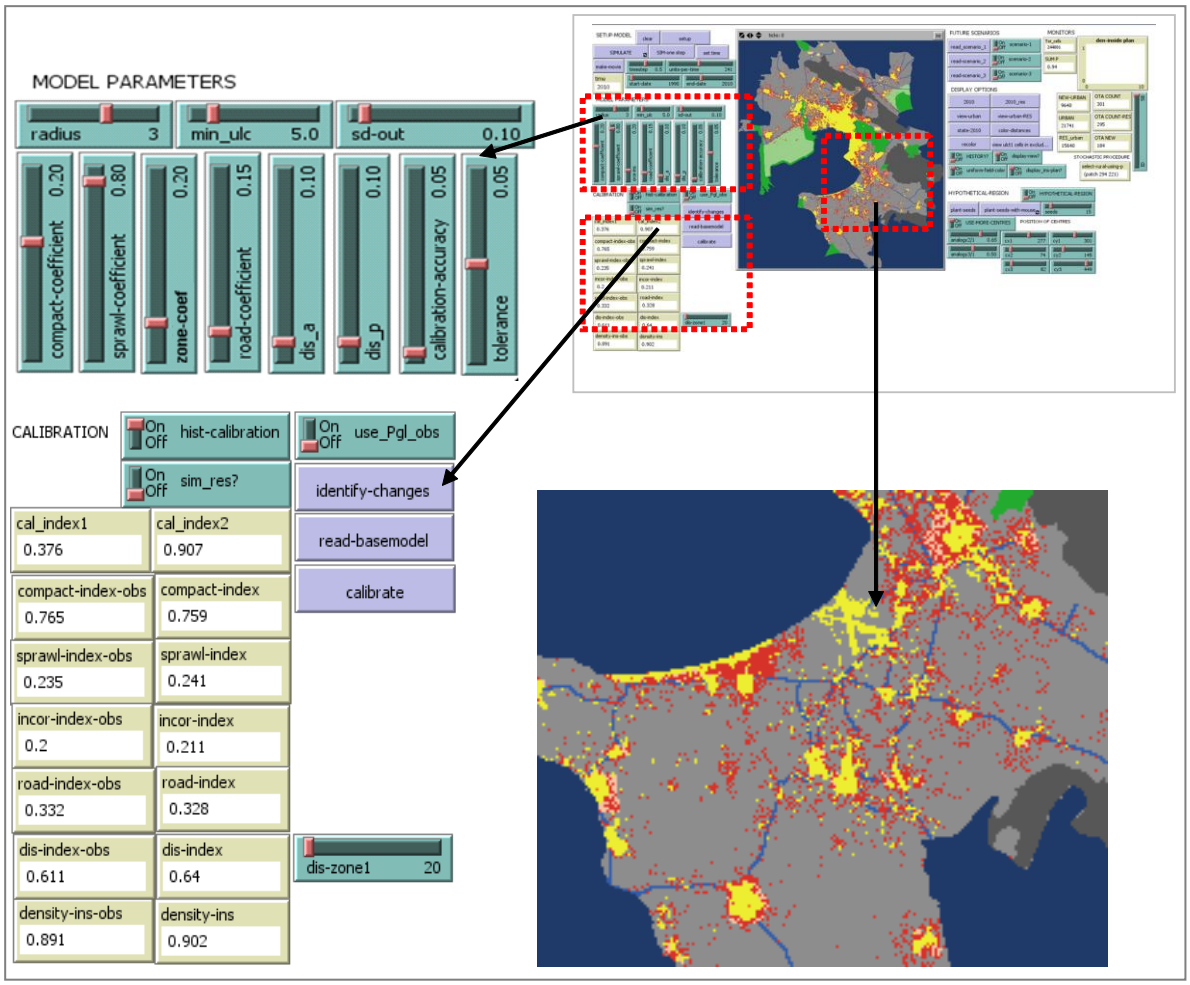


Fig.4 The model platform and the results of the calibration in the case study area

4. Exploration of future development scenarios

4.1. General data and projections

The calibrated model is used to explore two different scenarios of urban development for the next two decades until 2030. The first scenario is based on current trends concerning urban land expansion rates and assumes that protected area policy and land use regulations will remain stable. In the second scenario, we hypothesized a smaller urban land expansion rate and a policy restriction on building in agricultural land, as well as an expansion of existing protected zones.

Both scenarios include the estimation, as a total for the whole area, of population increase and of the corresponding new urban land increase. The population in the study area presents an important increase especially during the second half of the 20th century, while in the period 1991-2011 the population on the prefecture level increased by about 133.000 people at a rate of 13,7%. An important part of this increase can be attributed to immigrants settling in Thessaloniki mainly from the Balkan countries and of countries of the former USSR, which

are estimated at about 55.000 for the period 1991-2001. Internal migration is also important with about 87.000 people moving to Thessaloniki in the period 1995-2001 from other regions of Greece (NSSG, 2001).

For the population projection we used data concerning the aging of population, fertility rates, and immigration trends and estimation based on the data of National Statistical Service of Greece (NSSG). Data shows population aging and a decrease of fertility rates, while immigration slows down during the last years. Specifically, according to NSSG estimations fertility rates of women between the ages 20-24 and 25-29 will decrease in the next decades, while fertility rates of women older than 30 years old will increase. Moreover, foreign population of Greece presented a rapid increase since the mid '90s, but since 2007 slightly decreases.

By using a cohort-survival model to estimate natural decrease in population and hypothesizing that Thessaloniki will be the destination of about 10% of expected foreign immigration on the national level and the destination of about 40.000 people moving from the surrounding regions per decade, we estimated an increase of about 50.000 people until 2030, corresponding to a 0,244% annual increase rate. This estimation fits well to the curve of population growth of the recent period (fig.5).

For the estimation of the corresponding urban land growth we used the concept of the Sprawl Index (EEA, 2006) which is estimated as R_{ULC} / $R_{POP,}$ where R_{ULC} the rate of urban land cover change and R_{POP} the rate of population change. Values higher than 1 are related to a sprawling process while values lower than 1 are related to compact development. According to recent data, in the study area the sprawl index was equal to 3,44 (mean value for the period 1990-2010), reaching 9,87 in the period of the last decade. Based on these data and taking into account a moderate growth scenario as a result to the recent economic recession in Greece, we hypothesized that the Sprawl index in the first scenario will not exceed the value of 6 and in the second scenario the value of 5. These indexes correspond to a 1,46% annual rate of increase of urban land in scenario-1 (5.250 ha of new urban land) and to 1,22% annual rate of increase of urban land in scenario-2 (4.275 ha of new urban land) (fig.5).

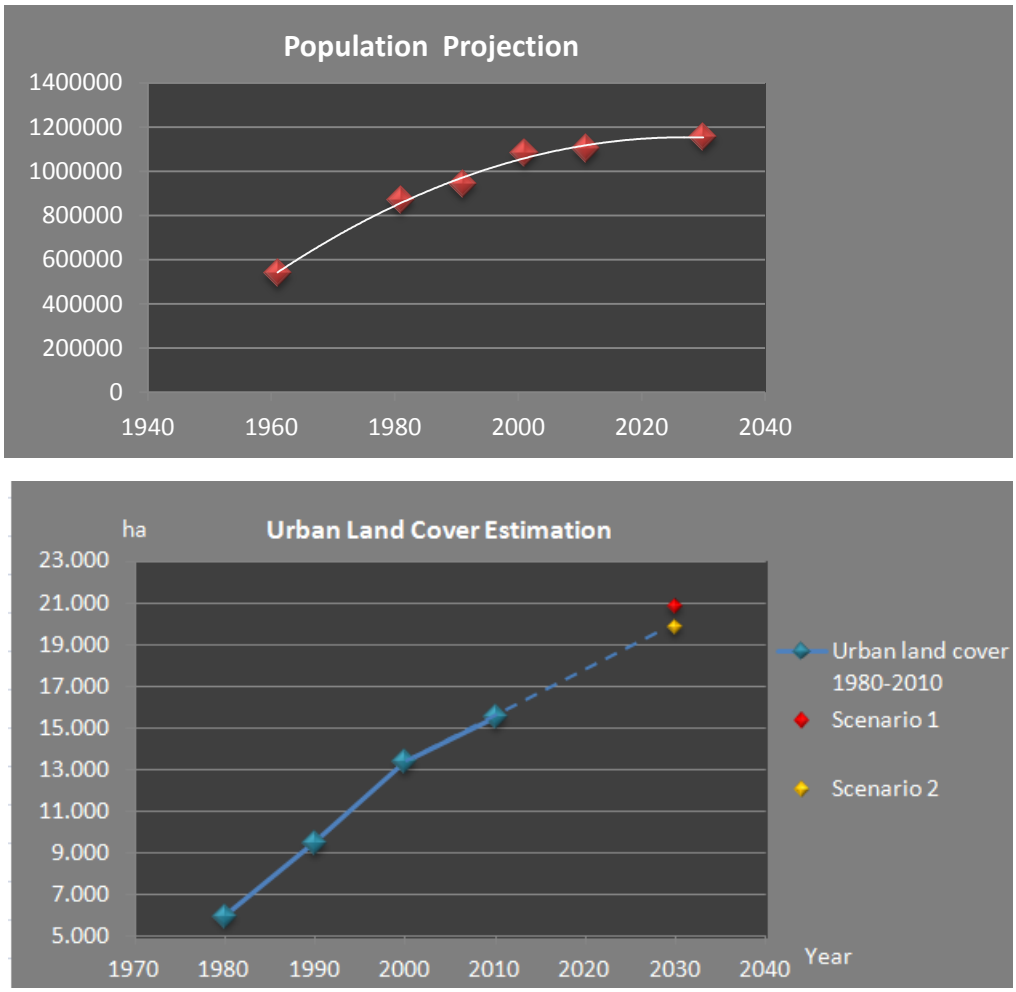


Fig.5 Trajectories of population and urban land cover growth in Thessaloniki.

4.2.Scenarios of urban sprawl

The first step in the exploration of each scenario is the estimation of estimated urban land cover changes (ULC_{ch}) and of the corresponding P_{GL} values for each model zone according to expressions (2) and (10). Hypotheses concerning population changes, land availability, accessibility, concentration of central uses and population age distribution, were formulated for each zone.

Scenario-1 considers current trends. Based on existing trends and the total population estimated for the target year, we hypothesized that the existing rapid population growth of certain periurban zones will continue at a rate between 1% to 2,5% per year, and that the population of the central municipality will continue to decrease by 1% per year. Municipalities located in the out zone of the central agglomeration are expected to present a smaller annual population increase of 0,25% while the more distanced periurban areas are expected to present stability in population terms. Based on these data the POPrat and PDENch indexes were estimated for each zone.

As far as the planning policy is concerned, in scenario-1 we hypothesized: a) that the existing land use regulations concerning the land use regulations for building outside the official settlements' boundaries and protected area policy will remain stable b) expansions of the periurban settlements plan, concerning areas of residential development and commercial-industrial installations, will take place according to the recently completed structural plans.

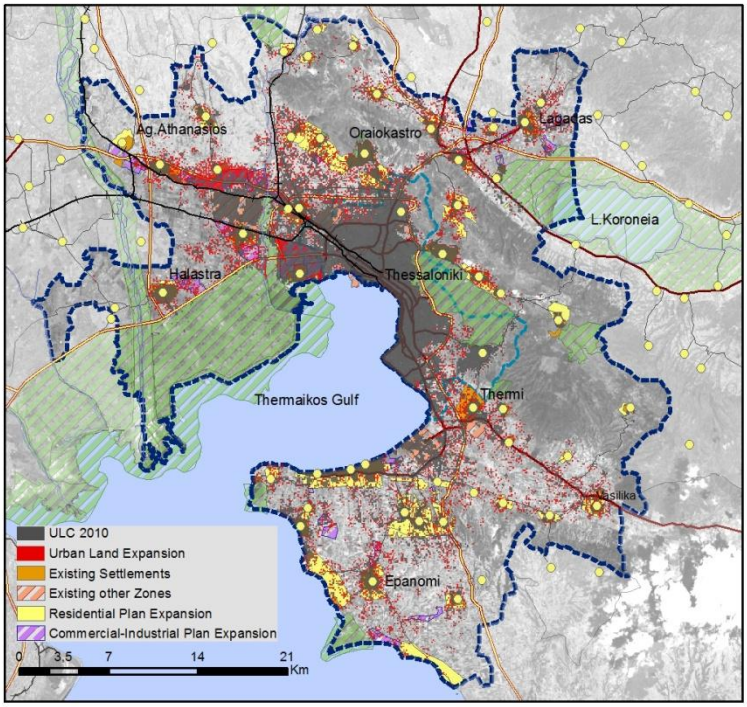
These plans include city plan expansions of about 6.500 ha for residential uses and of about 3.000 ha for other uses. Residential expansion areas are designed as low density development with building ratios (sd_i) ranging between 0,2 and 0,4 in most cases, especially in the south and eastern periurban sector. Based on these data, the AV_area index was estimated for each zone for the period of 2010. The accessibility data were estimated under the hypothesis of construction of new road infrastructure, as described in the recently updated regional plan of Thessaloniki and the relevant traffic and transportation studies. These plans propose the construction of a new external ring highway to the north and of other important transportation axes in the periurban zone. Based on these data, the DIS index was estimated for each zone.

The central uses index was estimated with the hypothesis of a continuation of the installation of commercial, office and entertainment facilities mainly in the southeastern zone and stabilization of the concentration of industrial facilities and wholesale in the west sector. Based on these data the SERVrat index was estimated for each zone. Population age distribution as expressed by the corresponding demographic index was assumed to remain stable. For the local coefficients, the values of the calibrated model were used, while the urban land cover data of the period of 2010 was inserted as an input to the model.

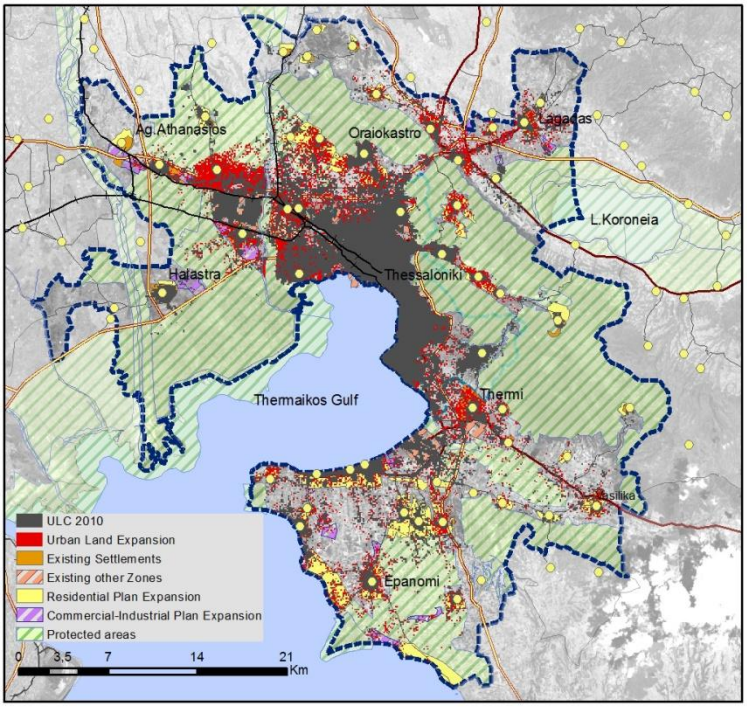
The mapping of the scenario results is presented in fig.6. Results show that in scenario-1 urban sprawl process will continue with rapid rates, with only 35,5% of new urban land located in areas incorporated in the city plan and with the other 64,5% located in agricultural land and the countryside. 22,4% of new urban areas are located in low density neighborhoods and 30,9% adjacent to road network, while 64,6% is located within a distance of 2 km from the periurban settlement centers.

In the second scenario, the same hypotheses concerning population distribution, accessibility and central uses were used, while a different planning policy concerning building in agricultural land and natural areas protection was assumed. The scenario involves restrictions on building regulations concerning the outside-of the plan areas, with the corresponding mean building plot ratio (sd_{out}) being reduced to 0,05 (200 sq meters of permitted residential use or 600 sq for commercial uses, in a 8.000 sq meter plot). Moreover,

the scenario involves the establishment of new protected areas with a total surface of about 64.000 ha. These areas concern high fertility agricultural land mainly in southern periurban zone and in the west periurban zone areas, as well as the mountainous areas in the north. For these areas, a more strict protection status was assumed with the corresponding factor PR being set to 0,5.



Scenario-1



Scenario-2

Fig.6 Scenario results

Taking into account the new data concerning land availability the AVarea factor was re-estimated. Results of scenario-2 show that urban sprawl process will be reduced new urban land located in areas incorporated in the city plan increasing to 44,6%. In this case, 17,3% of new urban areas are located in low density neighborhoods and 32,5% adjacent to road network, while 64,4% is located within a distance of 2 km from the periurban settlement centers.

5. Results and Discussion

Spatially explicit urban expansion models can effectively trace the urban development in the past and predict the possible expansion scenarios and can be regarded as important tools in urban sprawl analysis. The present work acknowledges that further development in existing CA models should focus on a closer connection to urban planning theory, on the need to link macro-scale processes and microdynamics and on the incorporation of data concerning building regulations land use policy, population and socioeconomic characteristics.

In the present context a CA-based model of urban sprawl was used to explore two future development scenarios in the area of Thessaloniki, the first based on current trends and the second examining a planning policy against urban sprawl. From the comparison of the results, we observe that in scenario-1 urban sprawl characterized by leapfrog development in the periurban zone is accelerated and that despite large area expansions of the settlement plans in the settlements surrounding the city, the expansion of urban land uses in the agricultural and countryside land remains intense. On the other hand, in scenario-2 although the urban land cover increase remains important, a large part is incorporated inside existing boundaries and urban sprawl in environmentally important areas and fertile agricultural land in reduced.

The conclusions force us to recognize that CA-based integrated modeling could act as a land use policy development tool, targeting the evaluation of policies against sprawl.

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