

## **Xplorah Municipio, a Multi Resolution Spatial Decision Support System**

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### **ABSTRACT**

Processes of land use change take place at different spatial scales. Also land use planning takes place at different scales, each scale in proportion to its scope. Subsequently, tools to assist planners should represent the system at the appropriate scale. Local authorities typically use more detail in their spatial planning as compared to regional or national institutions. Xplorah is a spatial decision support system for the three major islands of Puerto Rico. It is equipped with a user friendly interface and runs in a few minutes on an average desktop computer. For this system, models from different disciplines and operating at different levels have been integrated in one single tool. These levels are global, national, regional and local. On the local level, information is represented as a raster at a 240-meter resolution. However, for in-depth analysis of one region, this representation might be too coarse. Xplorah Municipio therefore simulates dynamics at the local level in cells with two different spatial resolutions. In general, the archipelago of Puerto Rico is represented by raster maps at a 240-meter resolution. However, the system has the capability of simultaneously representing any single one or combination of 78 municipal regions at a finer, 60-meter resolution. This paper describes the seamless integration of the two spatial resolutions in one land use model. To do so, the models at local level are applied twice, once at the finer and once at the coarser resolution, while their results are boundary conditions to each other.

**Keywords:** Spatial Decision Support System, Integrated modeling, Land use modeling, Spatial resolution

### **1. INTRODUCTION**

Xplorah is a Spatial Decision Support System (SDSS) that has been developed to support integrated decision making on the three major islands of Puerto Rico. The system comprises several models that are thoroughly integrated, and together represent the main processes at stake. Xplorah allows users to explore the impacts of a range of different policy options and external scenarios on future land use dynamics of Puerto Rico. For this, it simulates developments for periods of 20 to 30 years into the future. Results can be compared and analyzed through a series of spatial and non-spatial indicators.

Real world problems and processes are not limited to a specific sector or domain. Instead there is interaction and interdependency within and throughout different domains. To represent real-world phenomena in their true complexity, Xplorah has been equipped with a fully dynamic model that integrates the economy, demography, transport, and land use and in addition it uses effects of climate change as an input. Xplorah represents these processes at four strongly interlinked spatial levels.

The purpose of Xplorah is to provide policy makers with an instrument that assists in evaluating and formulating land use policies. As such the system permits transparency and provides legitimacy to the politically sensitive process of land use planning. First, the system can address current problems and explore their likely future consequences on the island. Second, Xplorah helps in understanding key

processes that drive these problems and their mutual interaction. Third, it allows assessing the influence of alternative policy measures. Most importantly, Xplorah stimulates discussion among actors involved in the decision making process and improves communication. To support the use for policy analysis, Xplorah is equipped with a user friendly interface and runs as a desktop application in only a few minutes, which facilitates the use of the system by non-scientists.

### **1.1 SDSS Development**

The development of the Xplorah SDSS has been an iterative process with three parties involved: policy makers, scientists and IT specialists. The result of this development process of Xplorah is the integrated system as presented in van Delden et al (2008). More insight in the development process of integrated spatial decision support systems can be obtained from van Delden and Engelen (2006), Rutledge et al. (2007) and Hurkens et al. (2008).

Xplorah is currently being implemented at Puerto Rico's Planning Board. A group of some 50 staff members, ranging from technicians to executives, have undergone a training course of over 150 contact hours to familiarize themselves with the system. Still, expert status will be achieved only through continuous use of the system as it becomes operational. In this process, it is a challenge to create awareness not only on the capabilities of the system, but also on its limitations.

During this implementation phase, the system is also subjected to evaluation on its capabilities for and applicability to the Puerto Rico Planning Board's functions, context, and decision making practices. One of the aspects identified through this process was the need for the system to focus on a specific region in more detail, be it a single municipality or combinations of municipalities. Where the original spatial resolution was sufficient to represent island-wide dynamics, it was felt by municipal planners as too coarse for their perspective.

Xplorah Municipio is the successor of Xplorah that enables simulating land use dynamics simultaneously on two spatial resolutions. Where the whole island is modelled on a raster of 240-meter cells, one selected region (municipality) is simulated using a 60-meter resolution. A higher resolution allows for a more detailed view of local patterns, but requires more precise land use data and requires more computation time.

This paper describes the simulation of land use dynamics on two different spatial resolutions. The next section gives a short overview of the integrated system and the models that are included in Xplorah. Section three focuses on the modelling of land use dynamics at the local level, and particularly, on the seamless integration between the two spatial resolutions simultaneously operating in this model. Finally, section four discusses this integration and points to directions for further research.

## **2. OVERVIEW OF THE INTEGRATED SYSTEM**

The Xplorah SDSS is an integrated system that was built as much as possible from existing models from the respective sectors. It is exactly the integration between these preexisting models that is crucial for effective policy support. Where sector oriented models focus on a detailed representation of a single process, integrated systems include feedback between processes. Xplorah was built within Geonamica, a software environment that is specifically designed for the development of spatial decision support systems (Hurkens et al., 2008).

Xplorah simulates processes in yearly time steps and at four spatial levels: global, national, regional and local. Here global level refers to external influences, such as climate change and external economic influences. The national level represents economic and demographic developments on the whole archipelago. For regional subdivision we use the 78 municipalities of Puerto Rico, of which the larger ones are further subdivided in transport analysis zones for the transport model. Finally, the local level is represented as a land use map with grid cells that measure 240 by 240 meters each.

Although the global and the national level are represented separately, their models both act on the same level. The difference is that global developments are introduced as exogenous factors, while processes at the national level are simulated in Xplorah itself. An overview of the different

components of the integrated system is presented in Figure 1. In the next section all models that are included will be explained shortly. For a more elaborate overview see van Delden et al. (2008).

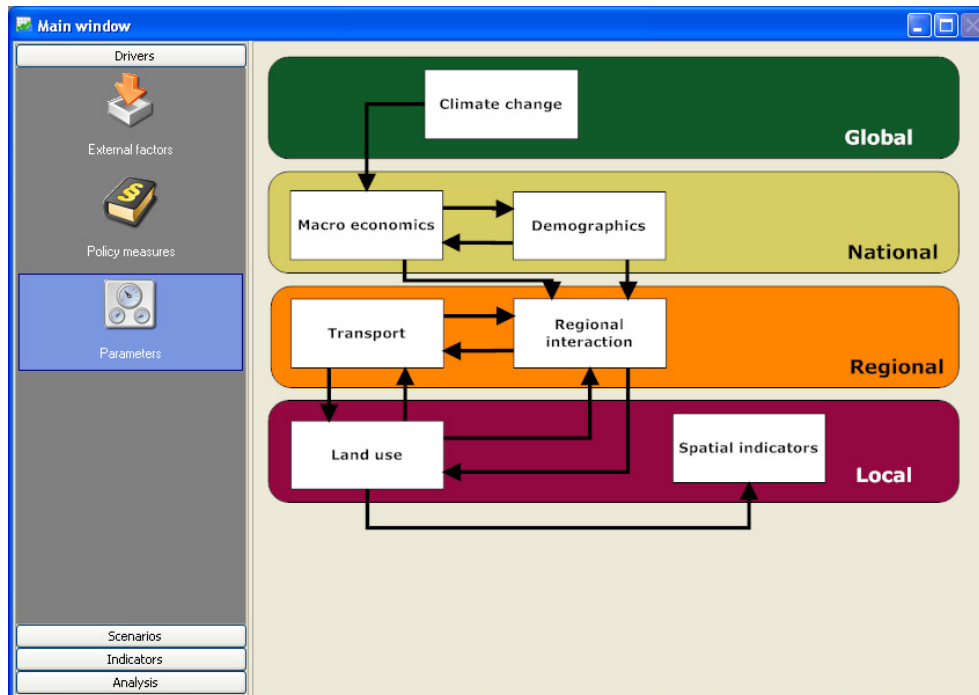


Figure 1: User interface and system diagram of the Xplorah SDSS.

## 2.1 Models at the global level

Xplorah uses climate change scenarios through a set of linked relations that feed to the macro economic model. Hence, climate change is not simulated but the system offers the opportunity to test hypotheses in a relative straightforward way. These relations express the effect of temperature change, through precipitation change and storm frequency on the national production in agriculture and the national demand for tourism.

The other component at the global level is exogenous economic influences. These represent time series for external effects on Puerto Rico such as oil prices and the US transfer payments. These influences feed into the macroeconomic model at the national level. However, since they are exogenous to the island, they are represented separately.

## 2.2 Models at the national level

Macroeconomic activities are modeled by means of an econometric model (Gutiérrez, 2007) that can be updated or changed by the user. The econometric model receives input from the climate change model, the age-cohort model and the external economic scenarios and generates forecasts for the demand and GDP for each of the five aggregated economic sectors: agriculture, construction and mining, manufacturing, trade and services, and public services. Demands are expressed as a number of jobs per economic sector that is later distributed over the municipalities.

On the same level an age cohort model generates the national demographic structure on a yearly basis. The model computes population figures for all ages and both sexes. For this, Xplorah explicitly incorporates legal and illegal migration flows, as well as age-specific fertility and mortality rates. These effects are again influenced by simulated changes in macroeconomic conditions.

### 2.3 Models at regional level

At the regional level three model components are incorporated: a spatial interaction model that distributes national totals for population and jobs over the municipalities, a transport model that simulates congestion and travel times and distances between the different transport analysis zones, and a land use demand component that converts the regional levels of activity in different socio-economic sectors, expressed in number of jobs or people, to land use demands for the local model.

At the regional level, Puerto Rico is subdivided into 78 regions that correspond to the municipalities on the island. The model distributes national totals for population and jobs in each of the five economic sectors over the municipalities based on migration and distribution of national growth. Migration and distribution are computed based on the relative attractiveness of each region using a spatial interaction model or gravity based model (Fotheringham & O'Kelly, 1989, Fotheringham et al., 2000).

The population and numbers of jobs per region that the spatial interaction model computes, are subsequently converted into a number of cells that needs to be allocated. This conversion is done using the cell productivity, which expresses the amount of a specific activity that is located in one cell. Cell productivity is computed as an average for each municipality separately. For land uses that do not have an activity associated with them, such as forests and wetlands, the area demand per municipality is a direct input to the model.

The measure of distance that is used in the spatial interaction model is very important. In fact, it is the determining factor of this model for the accuracy with which migration flows can be modeled. It is known from literature (see for example Fotheringham, et al., 2000) that Euclidian distances are a relatively inappropriate measure of distance for modeling activity migration. Since simulated travel times provide much better results, Xplorah includes a transport model that calculates travel times explicitly, based on activities, travel behavior and the road network.

This transport model is based on a classical four step approach: production-attraction, distribution, modal split, and assignment (see for example Ortuzar and Willumsen, 1994). For the transport model Puerto Rico is subdivided in transport analysis zones. These zones are equal to or smaller than municipalities, depending on the amount of activity within a zone. Trip origins and destinations are generated from the number of inhabitants, jobs and the area of other land uses per transport zone. From this Xplorah calculates travel times between zones and between regions, but also congestion on the transport network and a number of indicators.

### 2.4 Models at the local level

At the local level, Puerto Rico is represented as a grid with cells that show the predominant land use on that location. Changes in land use are driven by demands per land use, as computed on the regional level. Land uses are allocated using a constrained cellular automata (CA) model (White and Engelen, 1993; 2000). This allocation procedure considers several factors that determine land use dynamics. These are the neighboring land uses, the accessibility of a location, the physical suitability, the zoning status and a stochastic perturbation term. The exact allocation procedure is further elaborated in the next section.

Grid cells on the lattice represent an area of 240 by 240 meters. This resolution is sufficient to study land use dynamics for the whole island. However, for studies that focus on smaller regions, a 240-meter resolution might be too coarse. Therefore, we simulate land use changes for one municipality of interest at a 60-meter resolution. In all other aspects this municipality is treated similarly to the remaining 77 municipalities.

## 3. A CELLULAR AUTOMATA MODEL AT TWO SPATIAL RESOLUTIONS

The cellular automata model in Xplorah uses three types of land use classes, named feature, function and vacant classes. Features are those land uses that do not change in a simulation, like water bodies. Functions are those land use functions that are actively allocated with the constrained cellular

automata algorithm. Vacant classes are in fact passively allocated; all cells that are not used by a feature or function land use are assigned a vacant land use.

“Constrained” refers to the notion that the total number of cells per function land use is determined exogenously, while the CA only allocates this land use demand (White et al., 1997). The CA exists on a lattice of regular square cells, which can have one of a finite number of land use classes. Each cell has a neighborhood and there is a set of transition rules to compute land use changes based on this neighborhood. All cell states are updated simultaneously (White and Engelen, 2000). In Xplorah, land use demands are given by the spatial interaction model, or predefined as a number of cells, depending on the particular land use.

Land use is allocated separately for each region; in fact, each municipality acts as an independent CA model. This subdivision allows for the assessment of policy interventions at the local as well as the regional level. Land use from adjacent regions is only incorporated in the neighborhood effect of the cells on the border of adjacent municipalities. Within a region, function land uses are allocated to those cells that have the highest potential for that land use, until the demand is fulfilled. The total potential  $P$  for each land use  $f$  in cell  $i$  at time  $t$  is computed as follows:

$${}^tP_{f,i} = {}^tV_i * S_{f,i} * {}^tZ_{f,i} * {}^tA_{f,i} * {}^tN_{f,i}$$

where:

- ${}^tV_i$  Stochastic perturbation term for cell  $i$  at time  $t$  [-];
- $S_{f,i}$  Suitability of cell  $i$  for land use  $f$  [-];
- ${}^tZ_{f,i}$  Zoning of cell  $i$  for land use  $f$  at time  $t$  [-];
- ${}^tA_{f,i}$  Accessibility of cell  $i$  for land use  $f$  at time  $t$  [-];
- ${}^tN_{f,i}$  Neighborhood effect of cell  $i$  for land use  $f$  at time  $t$  [-];

Generally, land uses that are more distant in the neighborhood will have a smaller effect than land uses that are close by. Thus, each cell in a neighborhood will contribute to the neighborhood effect according to its land use and its distance from the central cell. Specifically, the neighbourhood effect is calculated as:

$${}^tN_{f,i} = \sum_x \sum_l w_{f,l,d} \cdot {}^tI_{x(d),l}$$

where:

- ${}^tI_{x(d),l}$  Kronecker delta function, which has a value 1 if cell  $x$  at a distance  $d$  has land use state  $l$ , other wise the value is 0; [-]
- $w_{f,l,d}$  Weighting parameter expressing the strength of the attraction or repulsion of a cell with land use  $f$  at distance  $d$  on land use  $l$  in the CA-neighborhood; [-]

### 3.1 The Neighborhood effect for two different spatial resolutions

As mentioned in section 2.4, land use changes are simulated at two spatial resolutions; one municipality has a 60-meter resolution, while all other municipalities have a 240-meter resolution.

Since the resolution within one municipality is constant, land use demands from the regional model can easily be transformed in one resolution or the other by multiplying or dividing by a factor of 16.

Then resolution only influences the allocation of land uses within the region. In the computation of the total potential, all effects are strictly local except for the neighborhood effect. Hence suitability, zoning, accessibility and the random perturbation are a function of a cell, but not from adjacent cells. A cell's neighborhood however can include cells of another region and it can therefore contain land use information at two different resolutions.

Consequently we need to aggregate small cells to the coarser resolution and disaggregate large cells to the finer resolution for the computation of the neighborhood effect. To combine two resolutions seamlessly it is essential that the coarser cell size is an exact multiple of the finer one. The neighborhood effect is then computed based on the aggregated or disaggregated cells, as described above.

For the finer resolution, a 240-meter cell is considered as 16 cells of 60-meter each with the same land use. These small virtual cells are considered individually for the calculation of the neighborhood effect in the 60-meter municipality. For the coarser resolution, 16 fine resolution cells are aggregated in one 240-meter cell. However, these 16 cells can have different land uses. The land use that has the majority of the 16 smaller cells is allocated to the larger cell. When two or more land uses have an equal share, that land use which occurs most in the rest of the region is assigned.

#### 4. DISCUSSION AND CONCLUSION

Although the last decade saw a considerable increase in spatial models and their application, the spatial resolution at which they operate has hardly been a topic of discussion. Typically, data availability and time required for computation or storage were constraining. However, for increasingly large areas, especially in the Western Hemisphere, large spatial databases are available. Moreover, the computing power and storage capacity of even the most modest desktop computers are hardly a constraint anymore.

Spatial resolution has a significant influence on the results of CA models as noticed by Menard and Marceau (2005), Jantz and Goetz (2005) and Benenson (2007). Having concluded this neither of them indicates how to determine an appropriate resolution. In Xplorah, spatial resolution was chosen intuitively by considering the processes at stake, that is to say we considered it to be in proportion to the scope of the model. However, the incentive for this study to represent one region on a higher resolution was a request from users rather than for technical or scientific reasons. For users on a national level, the 240-meter resolution was sufficient, while users on a regional level demanded more spatial detail.

A more conceptual issue is the interpretation of cell states, hence land uses, at different resolutions. Since the CA model in each region is in essence a separate model, it is at first sight no problem to represent land use in different resolutions, as long as the resolution is the same within one region. However, since the neighborhood for individual cells can lie outside its own region, regions are in fact each others boundary condition. Therefore, the issue is whether land uses have the same meaning at different resolutions.

From the perspective of the small resolution, we needed to downscale one cell into several cells on the small scale. Since it is not possible to reintroduce additional data, there is only one possibility left which is to reinterpret a large cell as a square of several small cells all having the same land use inherited from the larger cell. Although this is obviously a simplification and a practical rather than a conceptual answer, it is the only option.

From the perspective of the larger cells, however, there are two options. Either land use at the smaller resolutions is combined to a vector with fractions of land uses or we can aggregate them into a cell with one land use. Aggregation into a vector obviously maintains more detailed information; however, it is in violation with the interpretation of a cell's state. In the land use map, the cell state represents the predominant land use. Hence it neglects other land uses that might appear on that location as well. In fact, the land use map is generated using a majority aggregation to aggregate 15-

meter base data into a 60-meter and 240-meter land use maps, respectively. In order to interpret the land use state of a cell in the same way for both normal cells and aggregated cells, we applied a majority aggregation rather than a vector of land uses.

Since data was only available for one moment in time, we could not properly assess the results of the simulation, other than noticing that they match our expectations reasonably well. Therefore this paper only addresses the technical integration of two spatial resolutions in one CA model, but does not yet address the quality model results. It is expected that data for a second point in time becomes available next year, which allows for a better assessment of calibration results.

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