SPATIAL MODELING OF URBAN DYNAMICS

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1. Introduction

Nowadays, one of the basic conceptual tools for analyzing the economic, ecological and social aspects of urban dynamics, is the paradigm of sustainable development (Giaoutzi and Nikamp 1989, 1993; Nijkamp 1990; van den Bergh, 1991;). The basic tool on the other hand, which has been extensively used to analyze spatio-temporal aspects of urban dynamics, during the last decade is the Geographical Information Systems (GIS) (Burrough 1983, 1991; Dangermond 1990, Despotakis, 1991a,b). These two approaches can be linked into an integrated tool which aims to sustainability to GIS.

Spatial non-dynamic dispersion and spatial diffusion models have previously been constructed by various researchers, such as in the Hägerstrand model (Morril et al., 1988), gravity models (Haynes and Fotheringham, 1988; Trevor and Munford, 1991), transportation models (Wemer, 1988; Hagishima et al., 1987) etc. In all these models the development process is regarded in a non-dynamic perspective and the object propagation in space due to this development is calculated by the deterministic models at any specific time point. Spatial flow models that used only the distance as a spatial parameter indicated strong spatial correlation of the model residuals (Baxter, 1987). Therefore, model misspecification may occur when not all spatial registrations (e.g., a 3-D local or national reference coordinate system) are properly taken into account. On the other hand, several studies using GIS for monitoring (mainly urban) development have also been carried out in the past (Méaille and Wald, 1990; Lo and Shipman, 1990). These approaches, despite the fact that they give very useful results for monitoring urban development, do not incorporate scenario generation techniques, so that the regional sustainability criteria can be applied, not only in an "external event" scenario mode but also in a "policy" and "behaviourial" scenario mode. Finally, pioneering studies in applying GIS to "conservation databases generation" (a concept that is close to Spatial Dynamics considerations) have also been conducted in the past (see, e.g., Ahearn et al., 1990), but again the spatial dynamics have not been considered. From the above discussion follows that a missing node exists between the field of geographical information systems (GIS) modeling and the non-spatial SD modeling which will integrate both fields in a dynamic sense. In this paper the aim has been to provide this link in both a theoretical and practical sense.

2. Spatial Dynamic Modeling

After the above considerations, our generalized spatial model of dynamic phenomena takes the mathematical form:

$$dS_i / dt = f_i(t,x,y,z\,;\; S_i\,;\; F_i\,;\; C_i),\; i = 1,2,..,r \qquad (1)$$

where:

S_i are the components of the social phenomena under investigation (e.g. urban population), treated as "Stocks" of a dynamic model (Richmond, et al., 1987),

F_i and C_i are the "Flows" and "Converters" of each stock, determining the mathematical way these stocks are changing, by interacting with other stocks, and variable or constant quantities of the general model.

t,x,y,z are the four physical dimensions of the phenomenon under investigation, subjected to temporal (t) and spatial (x,y,z) variations.

with the initial conditions:

$$S_i(t_0, x_0, y_0, z_0) = INIT(Si), i = 1,2,..,r \qquad (2)$$

Then the sustainable development considerations can be embedded in (2) and in each integration step dt by:
1) imposing the necessary conditions that stocks S_i should fulfill,
2) defining and examining the values of the indicators (but also the stocks, flows and converters themselves) as functions of the stocks, flows, and converters, and
3) defining and examining alternative scenarios which, in our system, can be of any kind: no-policy (external events) scenarios (natural progress of the eco-system), external policies (influence totally or partially one or more functions of the eco-system) and behavioral scenarios (creating and monitoring spatial dynamic behavioral patterns such as migration, urban growth, etc.)

The rules of motion have to govern the propagation of the stock changes that will result from the dynamics on time solution to the spatial geographic system. Such rules can be built in a raster (or quadtree) format and will reflect the spatial reality of the region. For example, if the dynamic solution gives an increase in "urban stock" of the land-use layer of $10000m^2$, then the spatial model can equally (this can be an assumption, and unequal changes in x and y can be treated as well) increase the x and y dimension of this class by the square root of 10000=100m. The "candidate" squares in the geographic layer that can accommodate this expansion will be determined by overlaying the land-use layer with other layers that can influence this expansion: the layer of slopes, aspects, elevation, transportation, etc. (see also Méaille and Wald, 1990). This way we create what we call "suitability layers" to govern the stock motion. After all the "motion" assignments have been completed into the geographic system in a hybrid user-computer manner, then the results (maps, reports, etc.) for this time stage will be written on disk, and numerical integration will proceed to the next step. The proposed system is shown in Figure 1: sustainable development constraints can be entered at the "expansion rules formation" stage, after each integration circle has been completed. These constraints can be in the form of:

$$G_{SD}(S_1,\ S_2,..,\ S_r) = 0 \tag{3}$$

or the form:

$$G_{SD}(S_1,\ S_2,..,\ S_r) \geq 0 \tag{4}$$
$$G_{SD}(S_1,\ S_2,..,\ S_r) \leq 0$$

All the above modeling concepts have been implemented using mainly FORTRAN coding and GIS and SD numerical tools. In the next chapter we provide some numerical results from the model as it was applied on the island of Alonissos, Sporades, Greece.

3. Numerical Results

An integrated ecological, economic and geographical model for the area of Sporades islands, Greece, has been constructed, in conjunction with infrastructure maps of the region, such as land use maps. Starting from the year T=1985, the model runs for a period of fifteen years and computes the land use changes that result from the application of the above model for the Alonnisos island, with an emphasis on the urban expansion (Map 1).

The urban area (marked in red in the above maps) is expanded in selected sites of the island, subjected to natural and man-made sustainability constraints. For example, a natural constraint is that no urban expansion is performed on sea, or on the north-west part of the island where the terrain is very steep. A man-made constraint is that buildings are prohibited within a zone surrounding the forest areas of the island (marked in magenta). All the non-spatial interactions between the various quantities of the model (food chain, tourism, enterprises, economic growth) are taken into account by means of sets of first-order differential equations which transmit the outcomes of the integration for each time step to

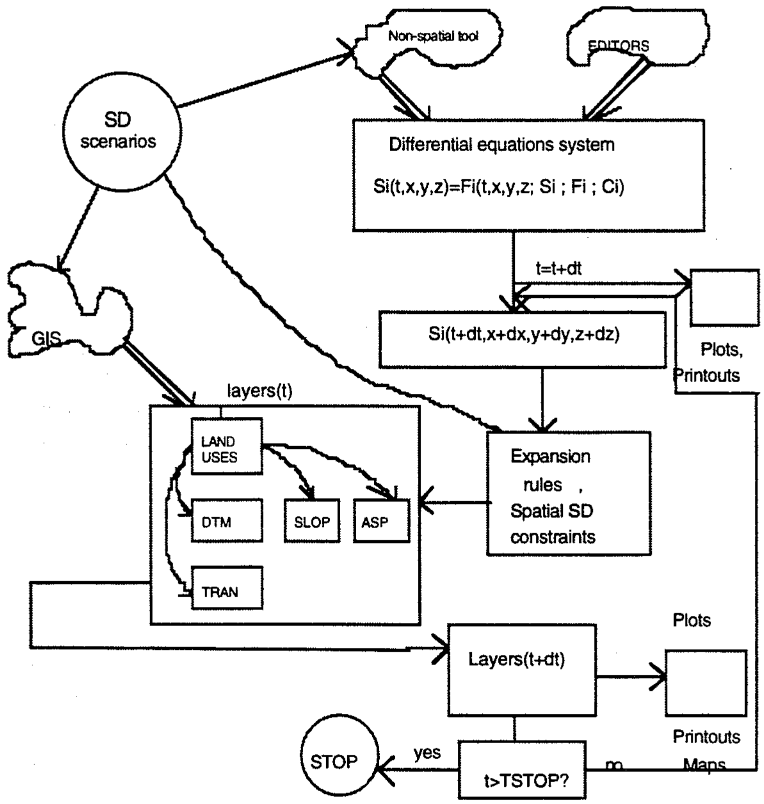
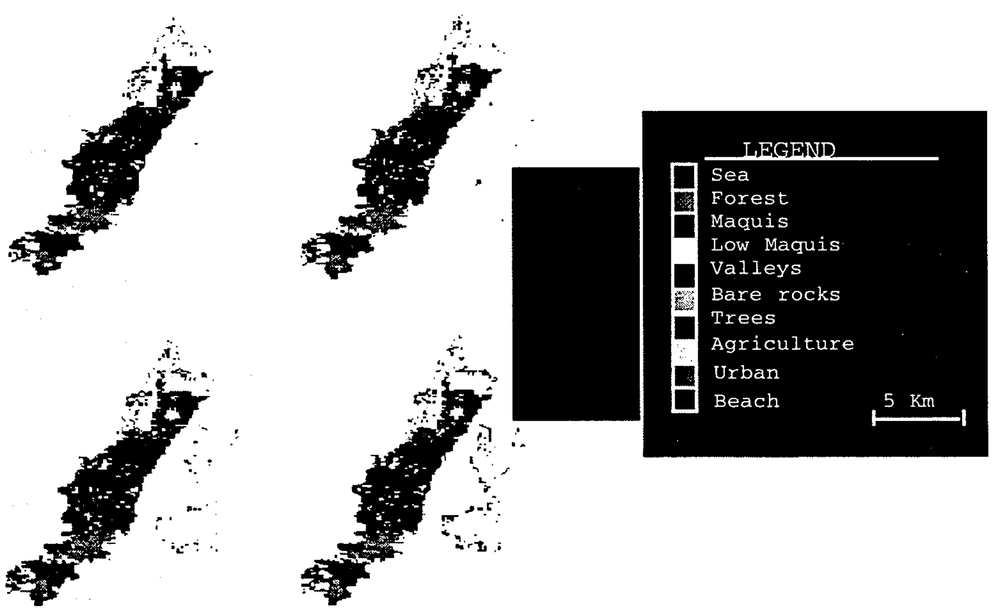


Figure 1: The link between non-spatial and spatial dynamic modeling.



Map 1. The dynamic land use changes scenarios in Alonnisos

the general 4-D model. The user may change almost every parameter of the model, initial values, variables, constraints, geographical parameters, specific close-range models (e.g. forest fires etc.).
It is thus remaining the incorporation of such dynamic models into well-established GIS (e.g Arc/Info), so that the modelers may be armed with a valuable, general-purpose spatio-temporal GIS tool tailored to meet their specific needs.

4. Conclusions

Social-economic and ecological spatio-temporal phenomena may be efficiently modeled by means of traditional GIS and SD systems, enhanced with user-supplied modules, describing the reality and how it is changed. In this study, an example was provided, on how we can model the urban expansion (or shrinkage) for a selected region in a rigorous and concise way. Similar natural or man-made processes may be efficiently modeled by using the concepts presented in this study. We only need to model the "change" process by means of a set of differential equations, and, subsequently, link these changes to the area under consideration by allocating the new values for each time step to the geographical 3-D area. Thus, this study has approached the 3-D dynamic modeling in a concise way and has provided the modelers with some standards for using the existing GIS tailored to their needs. It is expected that these novelties will be incorporated in the existing systems in the near future.

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