# Urban Sprawl Modelling: Combining Models to Make Decision

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## ABSTRACT

Urban sprawl is frequently associated with the idea of an unsuitable development, leading to increasing economic, social and environmental problems. Moreover, its control is difficult because multiple patterns (concerning numerous traditional urban planning fields) overlap. In order to understand the sprawl process and to manage its consequences, it must be simplified. The construction of a decision making tool appears then interesting. The GIS-based tool presented here is being developed in collaboration between the urban planning agency of Belfort and the laboratory of geography of Strasbourg. It requires three steps: 1. quantification of the sprawl (how much areas are involved in the urban sprawl process?); 2. location of the sprawl (where are the areas defined in the first step?); 3. differentiation of the sprawl (what are the areas located in the second step?). Of course, the succession of the three stages makes the use of the complete model more complex. So, a global ergonomic user interface is being developed within the GIS, allowing to modify each parameter and to play easily numerous simulations.

## 1 INTRODUCTION

Two years ago, the French Ministry of Equipment (*Direction Départementale de l'Equipement 90*), responsible for planning affairs in the city of Belfort, focused on the urban sprawl problem. They asked the University of Strasbourg for constructing a tool allowing to understand the underlying processes and control the consequences of urban sprawl. As regard the sprawl, the situation of Belfort (North-East of France, about 80000 inhabitants in 1999) cannot be compared with the evolution of bigger French cities, as Paris (exceptional), Lyon, Marseille or Strasbourg: the size and the growth are not the same, and Belfort is not so concerned with urban sprawl. But the processes leading to possible unsuitable developments are probably already acting in the urban area (see figure 2). Discussions quickly led to a three-year collaboration between the *Agence d'Urbanisme du Territoire de Belfort* and the Laboratory *Image et Ville* (University Louis Pasteur, Strasbourg): from the material, the data and the experience of the urban planners, a tool is now being developed. It takes the form of a global model relying on classical models in geography, a new conceptual approach issued from Artificial Distributed Intelligence and Geographic Information Systems (GIS) technology. Allying urban planners and geographers knowledge, the goal of this tool is to produce a means for understanding, predicting and simulating the future expansion of the city of Belfort. It has to be simple, easily usable and

clearly understandable for all planning or politic users. The aim of this paper is to present the methodological approach to construct this decision making tool. The presented results are communicated as examples and do not correspond to any realistic simulation.
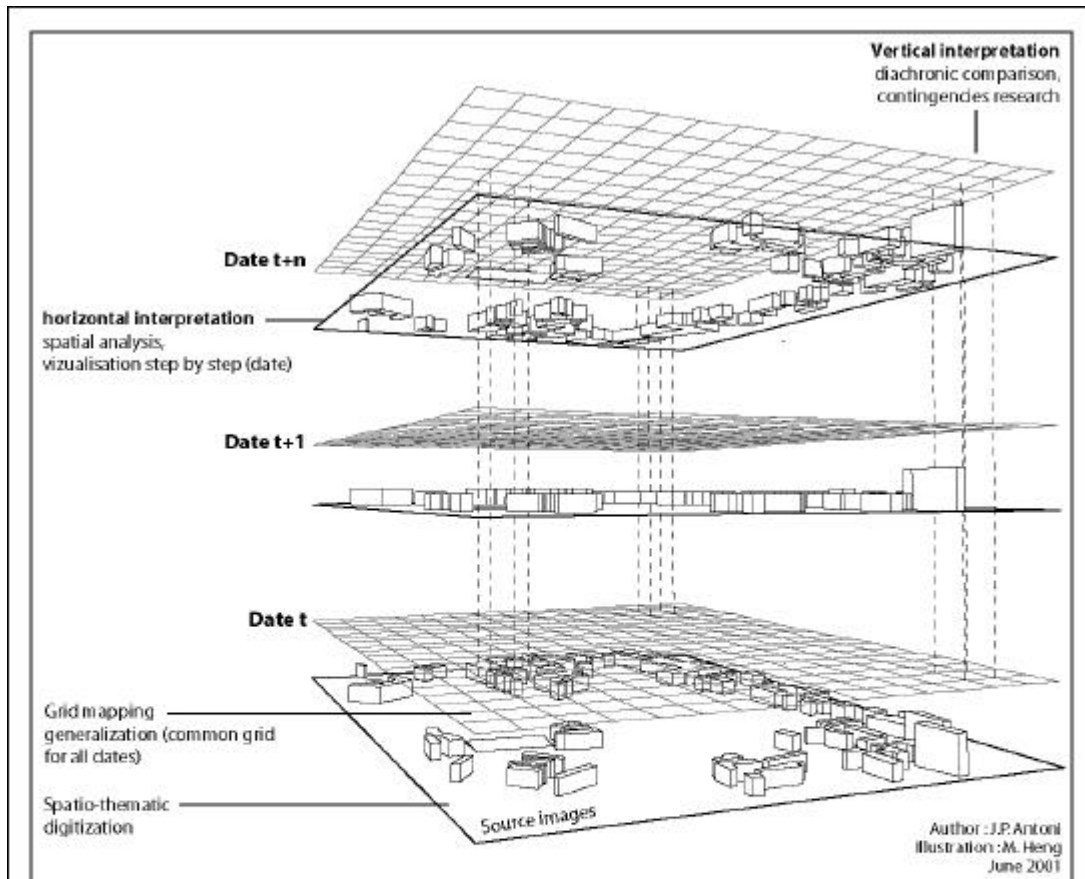

## 2 MODELS: SIMPLIFIED VERSION OF REALITY

In accordance with P. Haggett, a model can be defined as a "simplified version of reality, built in order to demonstrate certain of the properties of reality" (Haggett, 1965). That means that it does not reflect the totality of a phenomenon or a process, but that it only focuses on a part of it. In our case (urban sprawl modelling), this simplification appears both in the consideration of the sprawl phenomena itself and in the data used to process.

### 2.1. **Complexity reduction**

For the urban planners of Belfort, urban sprawl is considered as a spatial expansion of a city through time. It also leads to urban problems, which belong to different fields of urban planning. As regards transportations, it leads to the increase of roads infrastructure, atmospheric pollutions, environmental deteriorations, peak-hour congestions, etc. As regards settlements, it leads to urban spill over pushing away the limits of the city, breaking the frontier between urban and rural areas, creating a new dichotomy between dense centres and diluted outskirts, etc. As regards housing, it leads to new kinds of behaviours (neo-rural or rurban realm) and socio-spatial segregations (districts exclusively built-up with individual houses), etc. As regards economics, it leads to increasing costs for equipping peri-urban areas with the needed facilities and services, and to connect them to water, gas, electric or phone networks, etc. As regards environment, it leads to break up the peri-urban farming activities by influencing the prices of agricultural terrains, etc. And, as regard modelling, it leads to so many complex and numerous ways that it cannot be modelled without being simplified.

To reduce this complexity, the urban sprawl process will then only be considered through its visible aspect, that means through the changes of the city's shape over time, as shown on maps. Modelling will then concern the spatial expansion of the urban built areas, compared with the decrease of rural non-built areas. Such a built / non-built dichotomy can be justified by the fact that it characterizes the first manifestation of the urban sprawl process, from which other phenomena follow. A good characterization of the dichotomy's evolution will then be a first approach of the sprawl, allowing to parameter others existing models, which will take over from it and study precisely the consequences on the economic, social, housing, (etc.) fields. This goal implies the construction of a solid database for considering correctly the changes within the dichotomy.

Figure 1: **Spatio-temporal data generalization**

The figure contains the following labels:

**Vertical interpretation**
diachronic comparison,
contingencies research

Date t+n

**horizontal interpretation**
spatial analysis,
vizualisation step by step (date)

Date t+1

Date t

Grid mapping
generalization (common grid
for all dates)

Spatio-thematic
digitization

Source images

Author : J.P. Antoni
Illustration :M. Heng
June 2001

**Spatial resolution:**
Each cell is a fifty-meters wide square (0.25 hectares). The 300x300 grid is composed of 90000 cells and covers a 15 kilometers wide study area (22500 hectares).

**Contained land use categories**
1.Open areas (fallow land); 2.Forests; 3.Water surfaces; 4.Individual houses; 5.Buildings ; 6.Estate housing; 7.Facilities; 8.Public buildings; 9.Industrial and commercial units; 10.*Routes Départementales*; 10. *Routes Nationales*; 11.Highway nodes; 12.Railway stations.

## 2.2. **Data generalization**

Urban sprawl has to be considered within a temporal dimension to be understood as a process. Considering the rural depopulation (1954-1968) and the massive peri-urbanization (1968-1999) statistically measured by the French statistics Institute (INSEE), it could be interesting to study it from the 50's. Information is then needed for describing the morphologic urban area at different dates and measuring the changes. Moreover, measuring the urban sprawl requires to consider space at the urban-block scale or at the individual house scale, and not at the community scale as in the available censuses: the land use changes introduced by peri-urbanization cannot by visualized at a small scale and demand to use precise indicators. We must be able to visualize thin land use transformations of urban and peri-urban areas, and compare these transformations from one location to another and from one date to another. So, the problem is how to harmonize this disparate raw data for obtaining comparable information in space and time. Using a tessellation appears an interesting solution for collecting and storing the information. In our case it consists in transforming continuous original mapped data into discreet spatial data within regular square polygons of a fifty-meters spatial resolution (0.25 hectares). Tessellation produces then a grid that makes it possible to consider the geographical information inside its cells, whatever the date and the source of information (figure 1).

## 2.3. **A spatio-temporal lattice**

As satellite images do not exist before the late 70's and aerial photographs are not sufficiently numerous on the study area, the more complete sources of information for considering urban sprawl trough time seem to be the different maps produced at three dates (1955, 1975 and 1995) by the French national geographic institute (IGN). These maps (scale 1/25000) cover regularly the study area: one map a twenty-year period. Nevertheless, they strongly determine the discrimination of the land use categories related to the urban sprawl process. All categories must be represented on each map so as to be regularly considered for the encoding. According to the map keys, thirteen categories only appear systematically for the three dates: 1.Open areas (fallow land); 2.Forests; 3.Water surfaces; 4.Individual houses; 5.Buildings; 6.Estate housing; 7.Facilities; 8.Public buildings; 9.Industrial and commercial units; 10.*Routes Départementales*; 10. *Routes Nationales*; 11.Highway nodes; 12.Railway stations. The whole information will be queried trough a spatio-temporal database relaying on Geographical Information Systems, considered as a generic tool for using it (see Batty, 1998). The vector structure of the GIS groups the spatio-temporal data into 90000 polygons. For each polygon, a table of attributes describes the land use in 1955, 1975 and 1995. The database allows then to map the built / non-built dichotomy between the three dates and its evolution for the two periods (1955-1975 and 1975-1995) as a first representation of the urban sprawl process (figure 2).
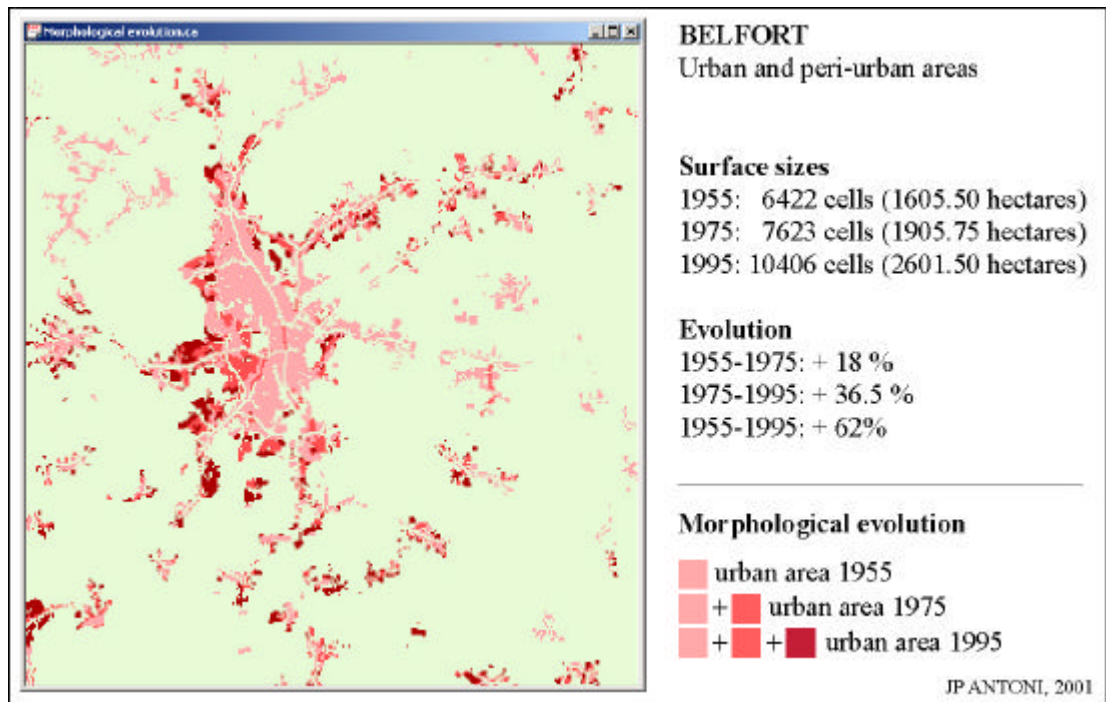
BELFORT
Urban and peri-urban areas

Surface sizes
1955:   6422 cells (1605.50 hectares)
1975:   7623 cells (1905.75 hectares)
1995: 10406 cells (2601.50 hectares)

Evolution
1955-1975: + 18 %
1975-1995: + 36.5 %
1955-1995: + 62%

Morphological evolution

| | urban area 1955 |
| + | urban area 1975 |
| + + | urban area 1995 |

JP ANTONI, 2001

Figure 2: **A first approach to measure the urban sprawl**



Model :
Transition model, Markov chains

Calibrating:
The state of 2015 is estimated from the state of 1995. The homogeneous transition matrix is the sum of the two transition matrices (for the two studied periods) weigthed by their effective on each line.

Results:
The 1768 cells determined by the model correspond to the cells which will change from a non-built to a built category. At this step, these cells are not located. They are represented in black, in the upper-left corner of the map.
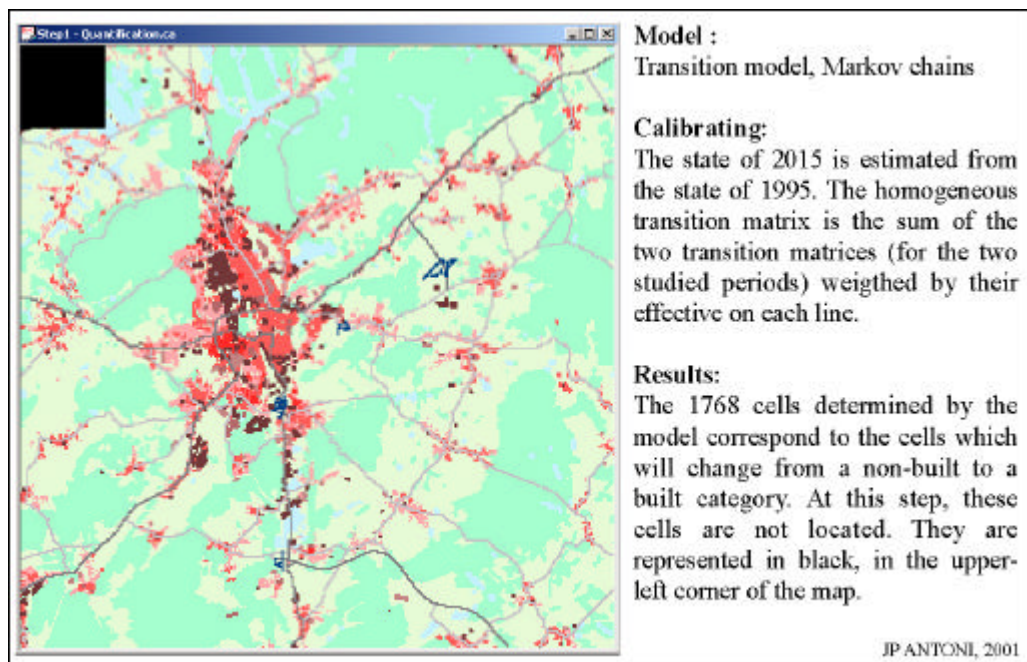
JP ANTONI, 2001

Figure 3: **First step of the modeling – Quantification of the urban sprawl**

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# 3 MODELLING BY DECOMPOSING COMPLEXITY

Phenomena as complex as urban sprawl can probably be better considered if decomposed into different parts, corresponding to a particular aspect of the phenomenon. Firstly, such decomposition allows to discern correctly the meaning of this modelling. Secondly, it appears a necessity to construct simple models, that means models which are not *ad hoc* designed and finally too complex to be clearly understood by non-specialist users. Urban sprawl will then be decomposed into three parts, leading to the construction of three combined models. Each one corresponds to a step for global modelling: quantification (step 1), location (step 2) and differentiation (step 3) of the sprawl.

## 3.1. **Quantification of the sprawl**

Quantifying the sprawl over time corresponds to measure the spatial expansion of urban built area. The spatio-temporal database can be queried to appreciate the numeral values of this expansion. It leads to a first answer to the question "how much?" for each past known date, obtained by measuring the growth of the city of Belfort. The last map shows that the city grows constantly since the 50's. By counting the cells, the precision of the fifty-meters grid allows to approximate the surface sizes (converted into hectares) built between 1955 and 1975 and between 1975 and 1995, and to calculate the importance of the evolution (figure 2). Moreover, it shows that the importance of the evolution has increased during the second period. But, this answer has been processed through a dichotomist approach, separating built and non-built areas. It can be improved by considering the same kind of evolutions for all land use categories stored in the grid database. The method consists then in constructing a table of contingency for each period, relating the numbers of cells, which moved from all categories to all others. These tables can quickly be turned into transitions matrices if transforming the numbers of movements into probabilities of occurrence. It allows to know the probability of a cell to move to a given "arrival category", according to its known "departure category". These two matrices correspond the a second answer for the question "how much?", teaching that probabilities of changes are more important in the first period than in the second one. By considering the important assumptions that the changes follow a trend which is similar through time (1955-2015), and that it can be determined from the two known periods (1955-1975, 1975-1995), a stochastic model can be constructed from these results. It consists in creating a general homogeneous transition matrix, taking into account the probabilities contained in the both matrices. Such a goal relies then on Markov chains (see Collins, 1975), and can be simply calculated by summing up the two transition matrices weighted by their effective on each line (see Berchtold, 1998). Then, considering the land use in 1995 as a "departure state" and the homogeneous matrix as a global transition function, we can estimate the numbers of cells affected to each land use category at the "arrival state" in 2015 (figure 3).
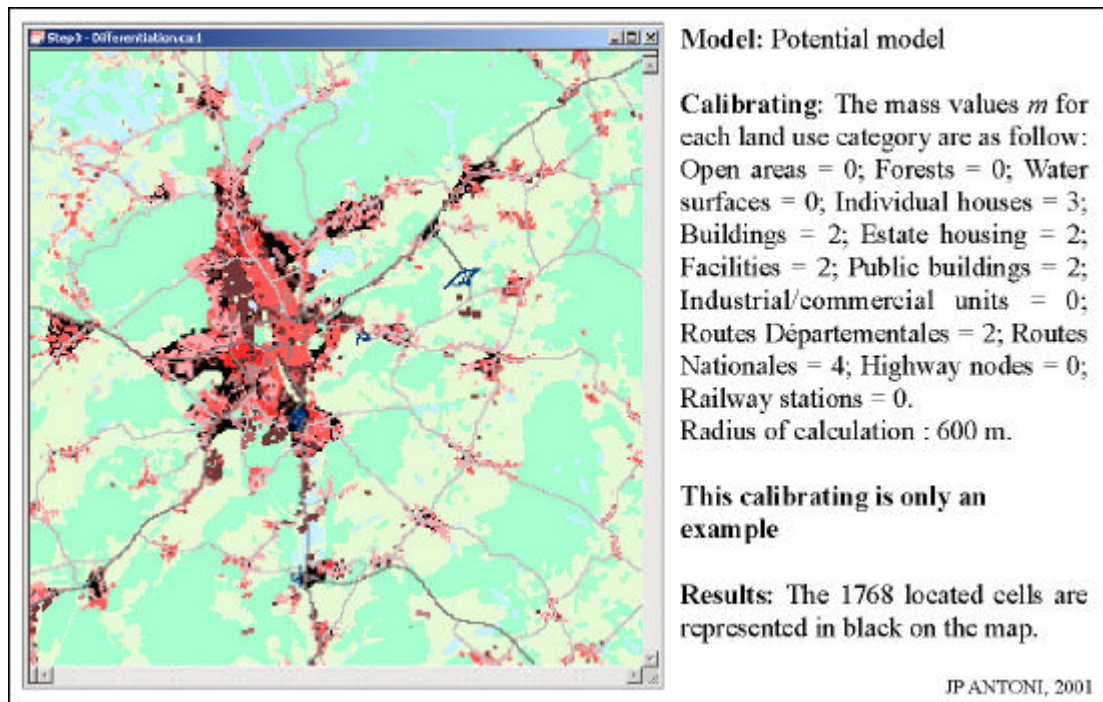
**Model:** Potential model

**Calibrating:** The mass values *m* for each land use category are as follow: Open areas = 0; Forests = 0; Water surfaces = 0; Individual houses = 3; Buildings = 2; Estate housing = 2; Facilities = 2; Public buildings = 2; Industrial/commercial units = 0; Routes Départementales = 2; Routes Nationales = 4; Highway nodes = 0; Railway stations = 0.
Radius of calculation : 600 m.

**This calibrating is only an example**

**Results:** The 1768 located cells are represented in black on the map.

JP ANTONI, 2001

Figure 4: **Second step of the modelling – Location of the urban sprawl**



**Model :**
Cellular automata

**Calibrating:**
The transition rules allow to create commercial / industrial units within the cells surrounded with a highway node and other commercial / industrial units, to create facilities within the cells exclusively surrounded with residential buildings, etc.

**Results:**
Most of the 1768 cells (located with the potential model) are now affected in a land use category. This third step allows to differentiate the areas involved in the urban sprawl process.
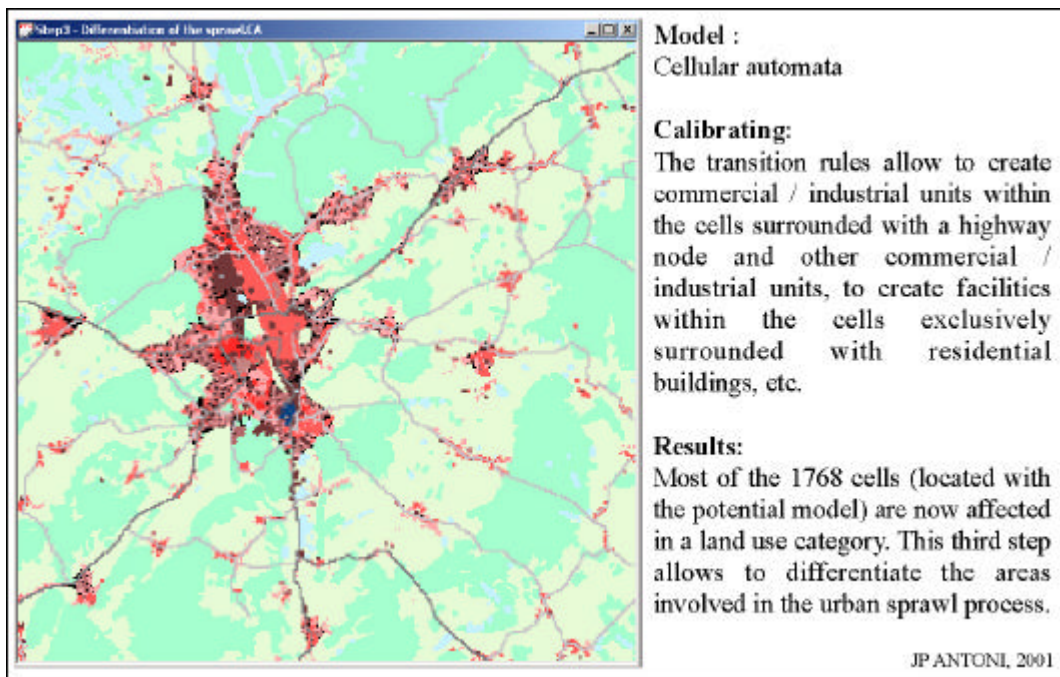
JP ANTONI, 2001

Figure 5: **Third step of the modelling – Differentiation of the urban sprawl**

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## 3.2. **Location of the sprawl**

The first step (quantification of the urban sprawl) is interesting to estimate the proportion of each land use category in the future. But this estimation is not really usable for urban planning without any information about its geographical location. A second step is then required; it should answer to the question "where?". Different spatial models can be used to locate the $n$ cells that will be built in 2015 ($n$ being defined in the first step). For instance, we can choose to use a potential model (see Donnay, 1992; Weber, 1997; Weber, 1998). It takes simultaneously into account the complementarities between each cell and the rest, their respective distances, and the intervening opportunities existing on the study area, as it usually appears in spatial interaction models (see Warntz, 1958; Abler et al., 1972). This way, the potential model assumes that: 1. urban expansion creates an interaction between new and old urban spaces which can be considered as complementary spaces; 2. urban expansion is based on the minimization of the mathematical distances between the concerned cells; 3. urban expansion favors the best solutions by testing all the possibilities of complementarities and distances. In order to better explain, we will take an example using one of the most simple equations of the potential model, and will consider only the open space cells:

$$P_i = \sum_{\substack{j=1 \\ i \neq j}}^{n} \frac{m_j}{d_{ij}}$$

$P_i$ = potential value of the cell I; $m_j$ = mass value of the cell j; $d_{ij}$ = distance from i to j

The potential values calculated for the open cells on the study area are represented on a potential map. Calibrating such a model means defining the mass values $m$ corresponding to each land use categories. Empirically, these values are defined according to the presumed attractiveness (by the experience of the urban planners) of each category and can be validated by running the model on the known past periods: from the initial state 1975, we tried to find the initial state 1995. The results were quite relevant: about 25% of the simulated cells were located in the same location as observed cells, and about 90% were located within a radius of 200 meters. Then, we can reproduce the same exercise for the next period in order to locate the 1768 most important values, theoretically corresponding to the cells that will be built in 2015. So, the next map shows the results. These 1768 cells should correspond to the ones which will be built during the 1995-2015 period. A method based on principal components analysis (see Sanders, 1989) is currently under development to measure the land use of neighbor cells around the cells built between 1955 and 1975, and between 1975 and 1995, within different radii. This should help to determine the mass values $m$, according to statistical measurement and not to any personal experience.

## 3.3. **Differentiation of the sprawl**

At this stage, the modelling approach allows to locate the *n* cells that should change from a non-built to a built category, but it cannot describe more precisely the nature of these changes. For instance, it does not allow to know if the *n* (step 1) located (step 2) cells involved in urban sprawl will be residential, industrial units or facilities. This discrimination remains to be done in the third step. The recent works in urban geography, using techniques issued from Artificial Distributed Intelligence, offer a new conceptual framework to treat this kind of problems (see White, 1994; Langlois, 1997; Batty, 1999). Here, cellular automata seem an interesting tool to determine the land use category of the cells located in the second step. Cellular automata should assume that the category of the cells is determined by its neighborhood, actually by the categories of the neighbor cells:

$$ s_{it+1} = f( \ s_{it} \ , I_{it}^{h}) $$

$s_i$ = land use of a given cell I; f( ) = functional relationship
$I_i$ = neighborhood of the cell I; h = size of the neighborhood; t = time

In fact, the analysis of the neighborhood should allow to define some transition rules that could be applied to the non-defined cells to choose their category (figure 5). Of course, the biggest problem is the definition of pertinent rules. At first, they can be determined by empirical tests, according to the users' estimation. Then, a statistical method should be developed to construct a set of rules firmly relying on quantified observations (it could be quite similar to the method developed for the calibration of the potential model, cf. section 2.2). Finally, it will be interesting to integrate administrative information or legislation (that means information not directly concerning the land use) so as to refine the transition rules.

## 4 COMBINATION OF MODELS TO SIMULATE COMPLEXITY

By associating these three steps, the methodological approach presented here can be associated to a combination of models. The final global model corresponds to an interesting solution for understanding the urban sprawl and the role of the neighborhood (and its attractiveness) in the process. It should allow to run simulations easily. Nevertheless, if the overlapped approach is satisfactory in a theoretical way, it is technically more complex and requires the use of a real modeling tool (for example, GIMS; see Laaribi, 2000).

## 4.1. **Towards Geographical Information Modelling System (GIMS)**

In fact, the models described at each step are not very complex and the global approach is easy to understand. It does not require any important theoretical or mathematical training.But, the links between the models, and the related hypotheses, have to be correctly proceed. The outputs of the firsts models are the inputs of the last ones. Moreover, the approach presented here uses a vector GIS as a generic tool for handling spatialized database at every steps. But, GIS is unable to run the three models and to calculate any complex result: it is a poor tool for advanced spatial analysis (Laaribi, 2000). Some "home-made" software or developments have then been needed to achieve the global process. At last, the final model appears a succession of different tools which must be well connected to be really useful. This connexion can be processed within an ergonomic user-friendly interface in order to be easily and quickly handled by planners. Such an interface, fast and convivial, should allow to increase the number of uses and the numbers of scenarios tested in a short time. For the moment, it appears a condition *sine qua non* to assure of its real efficiency and to avoid the tool to be forgiven by planners. Such an interfacing may finally correspond to turn the GIS database into a GIMS global tool. At the moment, the three models compose the first stage of a GIMS construction: the different software are not used successively in a disconnected way (first stage of a GIMS construction), but can be launched from an initial computer window which links and combines the steps. Forward, the GIS developed interface will be used to manage every step, from the storage of the data to the calculation of each model and to the different links allowing to feed each model with the results of the others (figure 6).

## 4.2. **Simulations**

The modelling of a process should lead to possible simulations, teaching how it will change in the future (see Dauphiné, 1987). But, of course, the relevance and the soundness of the simulations are strongly reduced by the simplification and the generalization used for modelling. Then, the users must be conscious of the hypotheses and the conditions involved in the modelling approach before coming to any conclusion. Every step of the global model embodies several hypotheses and coefficients which have a concrete signification. This signification must be clearly understood before simulating urban scenarios.

Thus, two ways seem suitable for using the model as a decision-making tool: 1.continue the mainstream or 2.supervise each step within planning sketches. In the first case, the model runs using the default parameters determined by studying the known past periods (1955-1975 and 1975-1995). In the second case, the parameters needed for these simulations can be modified at each step, according to the assumptions associated with the tested scenarios: modification of the general trend (step 1), of the global attractiveness (step 2), of the neighborhood's role (step 3). In the first step for example, the modification of the

probabilities values for each land use leads to a new calculation, bringing to a new numeral description of the simulated area.
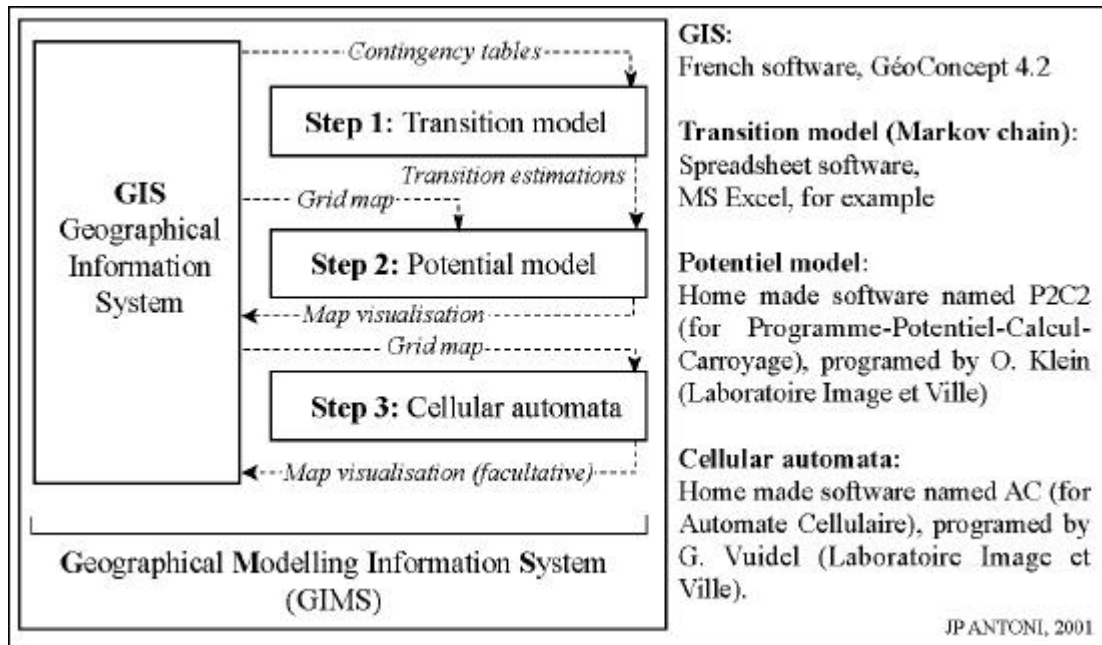


Figure 6: **From GIS to GIMS**

What could the study area be if forest modification is strictly forbidden? What could it be if, in a local zone, industrial implantations in agricultural lands are encouraged? The homogeneous transition matrix can conscientiously be modified to reply to these questions and simulate the possibilities related to each scenario. In the second step, the attractiveness of every object (through its land use category) can be modified. It allows to measure the influence of each one on the study area and to calculate a new global attractiveness according to the thematic goals of the tested scenario. For example, what could be the potential of a precise local zone if the attractiveness of rail station is more important than the actual roads and subways' one? What could the new urban morphology be if public rail transportation services overtake individual automobiles utilization? At last, in the third step, the modification of the transition rules used by the cellular automata allows to introduce elements of scenarios for better understanding the role of neighbourhood and refining the responses answered in the previous steps. Numerous developments are possible. Some could concern the land use changes; some others could offer general estimations, concerning the costs of urbanisation for example. This work presents a decision support tool, which is not yet totally achieved. The methodological approach is quite complete and seems efficient, but the calibrating and the interfacing remain to be improved. Statistical methods and

technical means are under construction to reach this double goal. In fact, the most important question is probably what is the best way to finish the tool construction? Should we determine immovable coefficients or focus on the possibility of sketches simulations? In the both cases, the signification of the assumptions associated with the models must be most clearly considered and the project must allow to follow up any continuation for the modelling, according to the perspectives of urban planning.

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