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### ► To cite this version:

Jean-Philippe Antoni, Pierre Frankhauser, Cécile Tannier, Samy Youssefi. Simulating and assessing prospective scenarios: A comparative approach in urban planning. Eindhoven University of Technology - Faculty of Architecture, Building, and Planning. 9th International Conference on Design & Decision Support Systems in Architecture and Urban Planning, Jul 2008, Eindhoven, Netherlands. pp.16, 2008. <halshs-00461620>

**HAL Id: halshs-00461620**

**<https://halshs.archives-ouvertes.fr/halshs-00461620>**

Submitted on 5 Mar 2010

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# Simulating and assessing prospective scenarios

## *A comparative approach in urban planning*

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**Key words:** urban sprawl, sustainable development, fractals, cellular automata, spatial interaction models

**Abstract:** The first part of the paper is centred on the phenomena of urban growth, in order to set the rules for a sustainable scenario of urban development. Then we enter the core of the paper that is the comparison of models. For each of the three compared models, we describe its main theoretical characteristics, the chosen parameters, and the obtained results. In section 6, heterogeneity of the produced results is discussed, and we highlight the points of interest and the lacks of the three models. Here we show that results we obtained feed debates about urban growth management. Finally, concluding remarks at the end of the paper address the general topic of the evaluation of the quality of simulation results.

## 1. INTRODUCTION

Managing urban growth and sprawl is currently a crucial issue all around the world. Very often, urban planners use a variety of technical tools such as Geographic information systems (SIG) or Computer aided drafting (CAD) software. Nevertheless, these “traditional” tools have a reduced capability of simulation and since about 20 years, researchers try to develop computer-based modeling approaches allowing to improve describing and forecasting urban growth and its spatial consequences.

However, the underlying hypothesis of the models developed are not always explicit. In best cases, main assumptions are explicitly laid down, but others are leaved in shadow. Consequently, results obtained are hardly

interpreted; misunderstandings and oversimplifications are frequent. A fact is that different models give rise to different simulation results. Moreover, results obtained with the same model are different according to the values chosen for parameters.

Hence, even before the development of computer-based models, I.S. Lowry put forward the need for comparing models: “The model-builders - a group that overlaps but doesn't coincide with the planning profession - claim that their brain-children have present or potential value as planning aids. One of the frustrations of the planner as client is that he doesn't usually find it easy to judge these claims or to choose among the many alternatives now available for his consideration” (Lowry, 1967). Considering more specifically spatial models for simulation of land use changes, authors underlined that the assessment of the validity of the model simulations has become one of the priorities in land use modeling (Verburg & Veldkamp, 2005).

The aim of this paper is to contribute to this field of research by comparing simulation results obtained with three different modeling tools, relying on different theories. We developed the studied models own self and we usually use it for projects which aim is to support spatial decisions in urban planning. Thus, models considered in this paper are in current use for planning purpose in France.

## **2. PRINCIPLES FOR A SUSTAINABLE URBAN GROWTH**

The problem of urban growth and sprawl is currently very crucial for public actors. Principles of urban planning have been proposed in order to offer alternatives to sprawl, in accordance with the principles of sustainable development (Frankhauser et al. 2007).

### **2.1 Alternatives to urban sprawl**

Several studies have already shown that urban sprawl usually leads to numerous kinds of problems. As regards transportations, urban sprawl leads to the increase of road infrastructures, atmospheric pollutions, environmental deteriorations and peak-hour congestions (Handy 1996). As regards settlements (Banister 1992), it leads to urban spill over that pushes away the limits of the city and breaks the frontiers between urban and rural areas, creating a new dichotomy between dense centers and diluted outskirts. As regards housing, it leads to new kinds of behaviors (neo-rural or rurban realm) and socio-spatial segregations. As regards facilities, urban sprawl

leads to increasing costs for the accompaniment of periurban areas with the needed services, and to connect new settlements to water, gas, electric or phone networks, etc. Finally, as regards environment, uncontrolled urban sprawl leads to a major perturbation in the ecosystems of the periurban belt and breaks up the periurban farming activities by influencing the price of terrains, etc.

It does not seem possible, however, to stop radically urban growth. On a quantitative point of view, the increase of the number of households (because of the decrease of their size) contributes to the increase of the housing demand that can not be only satisfied by the occupation of vacant flats and houses. On a qualitative point of view, the residential location, the comfort level and the quality of life associated with available housing do not completely respond to the social wishes. In this context, building new housing is required. Two options exist: 1. Urban renewal consists in transforming old farms and buildings in apartments ; 2. Urbanization of open spaces leads to new sub- or peri-urban settlements. The first option offers the advantage to revitalize peri-central abandoned areas and to increase the housing offer without any sprawl effect. But it will probably not allow to satisfy the whole housing demand. The second option increases *de facto* the consumption of new residential spaces, in favor of urban sprawl.

Nevertheless, fatality of the second option may not be if new urban developments are in accordance with principles of sustainable development. This supposes that new built-up spaces do not: 1. increase the number and/or the length of daily motorized commuting; 2. compromise the economic viability of agricultural spaces ; 3. compromise the landscape quality; 4. compromise the ventilation of urban centers; and 5. compromise the ecological quality of natural areas. This point of view is currently strengthened by several authors noticing that the principles of a compact city do not necessarily present specific advantages any more (e.g. Breheny, 1997).

## **2.2 A sustainable scenario of urban development**

Such considerations lead to the idea that space could be “better consumed” which means that urban growth should be canalized but not forbidden (Beaucire et al., 1999). Considering that little modifications of the urban structure can lead to strong modifications of the urban functioning (Batty, 2001), our aim is to identify relevant locations for new urban developments that lead to a decrease of the global number of trips (and distances travelled, especially by car), which are required to join the different spatial components of the urban fabric. Thus, we want to act on the urban form to influence the urban processes. Following this logic, Frankhauser et

al. (2007) have proposed to base the orientations of urban growth and planning on four principles.

1. Ensure a good accessibility to the various amenities (urban and rural). Urban amenities are retail and service centers of different orders; rural amenities are open spaces of different sizes and functions (small squares, parks, periurban forests...) (Cavailhès et al., 2004).

2. Avoid fragmentation of built-up, natural or agricultural areas in order to protect the ecological environments, to maintain agricultural activities in the urban peripheries, to preserve the landscapes quality (Maruani and Amit-Cohen, 2007), and to develop profitable and effective public transports. Obviously, urbanization rule that favors the development of compact built-up patterns favors in turn compact non built-up patterns.

3. Reduce the decrease of percentage of open spaces (e.g. parks and gardens, outdoor recreational areas, farmlands, forests or nature reserves). Indeed, a rather high percentage of land consumption for non natural purposes is due to the creation of new roads (Tourneux, 2006). The aim is then to limit the creation of new roads.

4. Preserve or develop penetration of green alleys into the built-up areas, in order to ensure a good ventilation of dense central spaces.

These four principles can be translated into related geographical questions: where could we propose new urban developments? Which locations could be relevant for the creation of new centralities or reinforcement of existing ones?

### **2.3 Simulating a single scenario with three models**

In this paper, the term scenario refers to a set of ideas or principles leading to a concrete proposition of land planning or design. A scenario is implemented in a model via a calibration (i.e. choice of parameters or choice of semantic rules values) and an initial state (describing the initial spatial configuration of the test field and the initial values of the variables).

The term simulation is defined as following: simulation = scenario + model. Hence, different simulations may result either from different scenarios applied with the same model, or from the application of a single scenario with different models. In this paper, we consider only one scenario, described in 1.2, which has been tested using three different models. Each model is relevant for urban planning issues. The first model is a potential model (see section 3), the second one relies on cellular automata (see section 4), and the third one on a fractal approach (see section 5).

The test field is the municipality of Saône, located in the urban area of Besançon (East of France, between Strasbourg and Lyon). Saône is a typical example of the French villages located just around the main city (about 15 minutes by car far away) strongly concerned with the periurban growth. To be able to compare the different simulations performed, the studied area has been decomposed into regular cells. Each cell has a dimension of 80 meters.

### 3. A SIMULATION BASED ON A POTENTIAL MODEL

The first spatial simulation uses a potential model. Potential models belong to the main family of spatial interaction models. Based on the well-known Newton's formula, the intensity of the interactions among two places is considered to be proportional to the product of the respective masses  $M_i$  and  $M_j$  of these two points, and inversely proportional to the  $d_{ij}$  distance (i.e. the straight line distance between  $i$  and  $j$ ).

#### 3.1 Specification of the model

Potential models offer the particularity to model the interactions between all the locations of a studied area (and not only two points), by defining complementarities between all of them. They formalize the famous law expressed by W. Tobler: "Everything is related to everything, but near things are more related than distant things" (Miller, 2004). A potential value  $P_i$  is calculated for each location  $i$  regarding the masses  $M_j$  of all the other locations  $j$ . This value can be interpreted as the influence, the accessibility or the attraction between the places. The potential  $P_i$  can be defined as :

$$P_i = \sum_j \frac{M_j}{d_{ij}^b}$$

where  $M_j$  is the mass of the cells depending on the land-use categories and  $b$  is the exponent of distance (here  $b = 1$ ). Hence the influences issued from different places add simply one to the other without explicit interactions.

As noticed by Nadasdi et al. (1991) and Weber (2003), interaction models, and especially potential model, are often used for demographic or

social purposes (so as to assess the relationships between population, services and locations, or between users and services, but more rarely to study the evolution of land use. White and Engelen have also introduced the notion of potential in their CA-model, but without referring to the usual distance deterrence term (White and Engelen, 1993).

In our case, a potential value is calculated for each cell of the studied area and must be interpreted as a potential for future urbanization, produced by the accumulation of all the attractiveness masses  $M$  of the neighbouring cells  $j$ . One interest of this methodology is the surface of interaction that can be associated to the location of each potential value. When all the places getting approximately the same potential values are joined, a map can be designed that represents the reciprocal influence (or force) of each point located in the studied area. These forces might be considered as a gradient decreasing from high potential values to low potential values. Future urbanisation should then take place in the highest potential values cells.

### 3.2 Choice of the model's parameters

Each potential value appears strongly determined by the mass values  $M_j$  associated with the cells of the studied area. These values can be associated with landscape objects, natural or urban amenities that are considered weakly or strongly attractive for future urbanisation, i.e. for each future house or building. Landscapes and amenities are determined by the land-use category of each cell ; the attractiveness (mass value  $M$  theoretically defined between 0 and 10) of each land-use is “man-made” defined regarding the scenario (see section 1.2) and summarized on the following table 2 :

<b>Land-use category</b>	<b>Mass value M</b>	<b>Weighting</b>
Open spaces	5	1
Built-up spaces	5	1
Services	10	5
Roads	10	1

A symmetric mass value ( $M=5$ ) is associated to the built-up areas and the non built-up (open spaces supposed natural) areas. This allows to take into account the fact that urban areas are considered as attractive as natural area. Such a calibration answers the idea that the interface between built-up and non-built-up areas must be privileged (first principle of the sustainable scenario). The strongest mass value ( $M=10$ ) is affected to the services, which should also allow to respect the first principle of the sustainable scenario we want to simulate. The roads are very important too: the associated mass

value ( $M=10$ ) relies on the idea that the global accessibility (i.e. the possibilities of movement between all kinds of spaces) is an absolute necessity (principle 2), but that no new network must be created to accompany new constructions (principle 4).

### 3.3 Results

The potential model reveals a very controversial spatial configuration: on the one hand new built spaces increase the density of the old ones in the centre of the community (north-west sector); on the other hand they take the shape of urban lots in the periphery (east and the south sector) that correspond to sprawl (Figure 1).

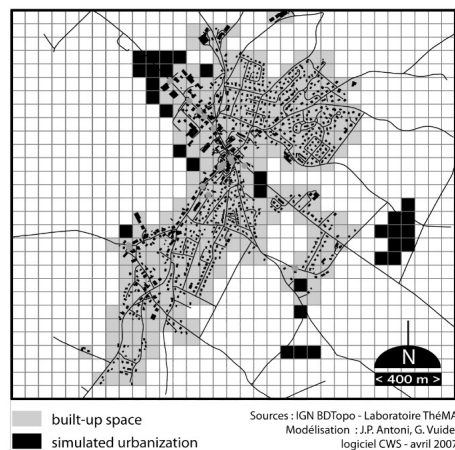


Figure 1. Simulation of extension based on a potential model

## 4. A SIMULATION BASED ON CELLULAR AUTOMATA

The second spatial simulation is based on cellular automata. A cellular automaton is a discrete model in which space is represented as a number of identical cells arranged in a regular grid. Each cell is defined by a limited number of states. Time is also discrete and the state of a cell at time  $t$  depends on the states of a limited number of cells in its neighbourhood (i.e. a selection surrounding cells) at time  $t - 1$ .



## 4.1 Specification of the model

Cellular automata operate on a regular grid of cells in which every cell contains a single value that represents its state at time  $t$ . The state of cell  $i$  at time  $t + 1$  can be defined as :

$$S_i^{(t+1)} = f (S_i^t, \Omega_i^t)$$

where  $S_i^t$  represents the state of cell  $i$  at time  $t$ , and  $\Omega_i^t$  represents the state of neighbouring cell  $i$  at time  $t$ . A cell  $i$  can be defined with two kinds of neighbourhood : 1. the Von Neumann neighbourhood corresponds to the four cardinal cells around cell  $i$ ; the Moore neighbourhood corresponds to the eight first adjacent cells around cell  $i$ .

The transition of a cell's state is rule-based and looks like the form of "if...then" statements, such that if the neighbourhood  $\Omega_i$  of cell  $i$  shows a specific pattern at time  $t$ , then the state  $S_i^t$  of cell  $i$  at time  $t$  will change at time  $t + 1$ , according to a set of rules.

## 4.2 Choice of the model's parameters

In this paper, each cell of the cellular automaton model is defined by its state, that is to say by one of the four land-use categories (open space, built-up area, services, roads) of the municipality of Saône (Figure 1). According to the scenario we want to simulate, the cellular automaton is calibrated according to a single rule allowing the cells to move from the "open-space" category at time  $t$  to the "built-up space" category at time  $t + 1$ . This transition occurs for a cell  $i$  only if: its "3-cells extended" Moore neighbourhood (i.e. in a radius of 240 meters; Figure 3.b) contains more than 35 % of built-up cells (that is to say at least 17 built-up cells among its 48 surrounding cells); and its "3-cells extended" Moore neighbourhood contains more than 35 % of open-space cells (that is to say at least 17 non built-up cells among its 48 surrounding cells ); and its "6-cells extended" Moore neighbourhood (i.e. in a radius of 480 meters) contains at least 1 service among its 168 surrounding cells; and its "3-cells extended" Moore neighbourhood contains at least 1 road among its 48 surrounding cells.

### 4.3 Results

Simulation allows the identification of thirty one cells (about twenty hectares) corresponding to the different criteria (figure 2). It presents a particular spatial configuration, in which the new built-up cells are located around the existing built shape, except in the north-east and the south. In particular, the simulation shows the creation of twelve urban aggregates with a medium size of 1,65 ha. Only one is a little bit more important with about 4,48 ha (south-west).

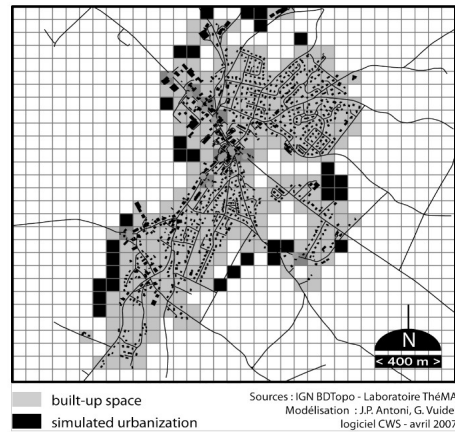


Figure 2. Simulation of extension based on a potential model

## 5. A SIMULATION BASED ON A FRACTAL MODEL

The third simulation is based on a fractal model. Fractal models in geography are defined in several works till the early 90's (see White and Engelen, 1993; Batty and Longley, 1994; Tannier and Pumain, 2005). The fractal model we present here is recent: it has been developed in the framework of a research project funded by the French Ministry of Transport and Public Works (research program PREDIT) and directed by P. Frankhauser. It consists in using fractal geometry to define urbanisation rules, and to apply these rules at different scales, by means of a fractal decomposition of the studied area. The model follows an iterative multi-scale logic. In this paper, however, we only study simulation results at one scale.

## 5.1 Specifications of the model

Fractal geometry allows to generate hierarchical multi-scale structures. This property can be used to enlarge Christaller's central places theory (Christaller, 1933) which introduces a hierarchy of services, but within a uniform spatial distribution of the localization of settlements. Frankhauser et al. (2007) proposed a fractal model for urbanization applying a hierarchical principle also for the spatial distribution of services and other facilities. Residential areas are grouped around first importance shops and services (daily used), whereas larger non-urbanized areas separate locations of the second order (weekly used) and the third order (monthly used) shops and services. Hence large interstitial and non urbanized areas are introduced into the city's shape, while build spaces are moved closer to the main transportation networks (Figure 4.a).

For real world patterns, the presence of such spatial hierarchies can be measured by the fractal dimension. In the model, we wanted to make graphically evident the presence or absence of a fractal hierarchy. For that, a method called fractal decomposition has been developed. It is based on covering progressively the urban pattern by cells of nested size according to different scales of analysis. In the first step, the complete studied area is covered by a system of  $v.v = v^2$  quadratic  $l_1$  size cells called « first order cells ». In the second step, each first order cell is decomposed into  $v.v$  cells of a  $l_2 = (1/v) l_1$  reduced size, called « second order cells ». The decomposition is repeated until the size of the smallest cells reaches the size of the buildings, and allows to calculate the fractal dimension of the built-up space. At each stage of decomposition, the number  $N_i$  of built-up cells is counted. The geometric mean  $N$  through all steps of decomposition allows computing (approximately) fractal dimension :

$$N = \sqrt[k]{\prod_{i=1}^k N(i)}$$

The fractal dimension  $D$  can then be introduced within the standard relation:

$$D = - \frac{\log(N)}{\log(r)}$$

where  $r$  is the decomposition factor.

## 5.2 Choice of the model's parameters

Firstly the area of Saône has been transformed into a multi-scalar grid according to the principles of fractal decomposition. A decomposition factor  $r = 1/3$  as been chosen. Three steps of decomposition are sufficient to highlight the multi-scalar organization of the built-up shape. Results of the decomposition are presented on Figure 4.b where the scale of each cell is given by the thickness of its outline.

Simple urbanization rules have been defined according to the objectives of the sustainable scenario (see 1.2), determining the capacity of each cell to be urbanized. These rules are organized according to their order of priority.

Four rules are considered as first priority rules and are imperatively applied: 1. The total number of built-up cells in each larger cell, etc. must not exceed the  $N$  number determined by the fractal dimension (defined by the fractal decomposition); 2. The priority for urbanization is given to the cells located in the areas characterized by a good accessibility to shops and services; the access to shops and services must not exceed a distance defined by the user. Two orders of retail and services centers are considered. First order centers correspond to a daily (or almost daily) recourse; second order centers correspond to a weekly recourse; 3. New urbanized cells must be contiguous to an existing built-up cell; 4. The contiguity of non built-up areas must be preserved.

Two second priority rules are applied as often as possible: 1. A new urbanized cell must be crossed by a road; 2. A new urbanized cell must border an open space cell. This rule applies only if the new urban developments do not hamper the access to non built-up areas of previously urbanized cells.

The iterative application of these rules on cells of different sizes, resulting from the fractal decomposition, allows to identify the cells that could be built-up in the future.

## 5.3 Results

The simulation (figure 3) shows that urbanization will take place in the east of the village, and take two complementary forms: 1. agglomerated near the existing built-up spaces; 2. scattered into existing interstitial spaces. Finally, urban sprawl is mainly located in the immediate periphery of the municipality, around the main road axis.

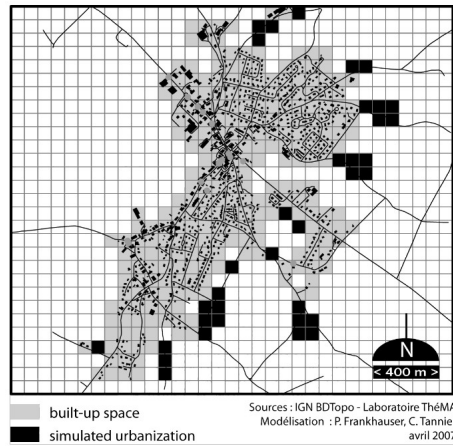


Figure 3. Simulation of extension based on cellular automata

## 6. DISCUSSION

A comparison of the results of the three models shows that there is no actual correspondence or convergence between the results. Each model focuses on cells located in coherence with the sustainable principles declined into rules or parameters, but these cells do not overlap. Although each model has been conceived to meet the four objectives of the sustainable scenario, the comparison of the results shows that no potentially constructable cells are common to the three models. Several reasons may be found for explaining these differences; they are synthesized in the following tables.

Sustainable urban development: principle n°1 Ensure a good accessibility to the various (urban and rural) amenities		
Model	Corresponding rule(s)	Characteristics of the results given by the model
Potential model	Number of cells characterized by a "retail and services" land use in relation to their distance to the evaluated cell Number of cells characterized by a "non built-up" land use in relation to their distance to the evaluated cell	The existence of retail and services centers of different orders is not taken into account. The existence of different types of open spaces is not taken into account. => The model considers only the presence of amenities, but not their variety. The model considers a partial compensation between the amenities (the service centers have a strongest weight in the evaluation than the open spaces).
CA model	Number of cells characterized by a "retail and services" land use in a given neighborhood around the evaluated cell Number of cells characterized by a non built-up" in a given neighborhood around the evaluated cell	The existence of retail and services centers of different orders is not taken into account. The existence of different types of open spaces is not taken into account. => The model considers only the presence of amenities, but not their variety. The model does not consider any compensation between the amenities. A cell is urbanized only if urban and rural amenities exist in the neighborhood.
Fractal model with accessibility constraints	Multi-scale distance to retail and services centers of different orders Urbanized cell must border an open space cell. This rule applies only if the new urban developments do not hamper the access to non built-up areas of previously urbanized cells.	The model considers two types of retail and service centers.  The model tends to increase the length of the urban border. At least, it preserves the number of contacts between built-up and non built-up cells already existing. Due to its multi-scale nature, the model considers different sizes of open spaces, that can be considered as a quite good indicator of their types (or functions).

Neither the potential model nor the cellular automata model takes into account the decline of accessibility to open space for already urbanized cells since rules refer only to non built-up cells and consider their potential for urbanization. The fractal model requires on the contrary that the environment of existing built-up cells is not affected by new urban developments. Moreover the fractal model strictly avoids to destroy the contiguity of open space. Both these restrictions leads automatically to more fingering patterns. This shows that supplementary rules referring to open space and to cells already urbanized should be integrated in the cellular automata model and the potential model in order to obtain comparable results. The preservation of green alleys is also only allowed by the fractal model.

Sustainable urban development: principle n°2 Avoid fragmentation of built-up, natural, and agricultural areas		
Model	Corresponding rule(s)	Characteristics of the results obtained
Potential model	Number of built-up and non built-up cells in relation to their distance to the evaluated cell	Fragmentation can not be avoid by the model because it does not take into account the built-up (respectively non built-up) spatial structures. Moreover, the model considers a perfect substitutability between a certain type of urban amenities (proximity to built-up cells) and rural amenities (proximity to open space).
CA model	Percentage of built-up and non built-up cells in a given neighborhood	Fragmentation can not be avoid by the model because it does not take into account the built-up (respectively non built-up) spatial structures.
Fractal model with accessibility constraints	Multi-scale built-up continuity	Fragmentation of built-up areas is avoided. In turn, fragmentation of open spaces (natural or agricultural) is also avoided. The rule increases the heterogeneity of urban forms through the scales. It avoids the development of large areas characterized by uniform housings (that could lead to the homogenization of the social patterns of the population, and then to possible segregation processes).

Important differences exist also between the potential model and the CA model. Firstly, in the potential model distances are weighted by an inverse power law, and thus influence declines continuously, whereas in the used CA model criteria introduce a strong cut-off: dynamics are conditioned just by the absence or presence of a phenomena (roads, amenities) within a predefined distance range, and out of this range the influence drops immediately down to zero. The same kind of argument holds for the factors  $M_i$  which attribute different weights to the diverse types of amenities in the potential model what is not the case in CA. Finally the first and the second models try to simulate each of the four principles, but do not really succeed. They only offer an approximation of the scenario. It seems that only the third model allows the simulation of all the aspects of the sustainable scenario, due to its underlying assumptions.

Sustainable urban development: principle n°3 Reduce the decrease of percentage of open spaces		
Model	Corresponding rule(s)	Characteristics of the results obtained
Potential model	roads	The model increases the potential value of the cells located near a road, but cannot ensure that the highest values cells are located near a road.
CA model	roads	The model takes into account the presence of a road in a specific distance from the evaluated cell.
Fractal model with accessibility constraints	If possible the urbanized cell must be crossed by a road	The model takes into account the presence of a road near to the evaluated cell as an additional criterion.

Independently of the used model, all the produced simulations can be considered as “good” planning solutions, responding to the goals determined by the choice of parameters. These solutions appear equivalent, but obviously not equal. Their differences depend on the intrinsic specification of each model and the manner they manage different important notions, as neighborhood, distance, attractiveness, etc. The potential model, for example, “automatically” includes a distance weighting that clearly corresponds to the spatial repartition of many observed phenomena (first law of Tobler). It also allows to detect “intervening opportunities” in the whole studied area, by testing every possibilities of mass and distance combinations. In the cellular automata, the friction of the distance is not directly taken into account, but the nature of each neighboring land use strongly determines the possibility of a cell to be built-up, while the potential model only considers it as a kind of mean.

Sustainable urban development: principle n°4 Preserve or develop penetration of green alleys into the built-up areas		
Model	Corresponding rule(s)	Characteristics of the results obtained
Potential model	none	The model does not take into account the local spatial organization of the cells. It only calculates a synthetic measure qualifying the composition of the global environment of each cell.
CA model	none	Transition rules from one state to another only considers the composition of the environment of each cell and not its spatial structure.
Fractal model with accessibility constraints	Fractal logic of urban growth: a non built-up cell at a given (large) scale can not be built at a finer scale	The fractal logic of urbanization allows to preserve nested and connected open spaces.

## 7. CONCLUSION

Finally, this paper suggests the need for a new reading of the simulation results, including a more sensitive approach. The results show the interest of comparing diverse modelling approaches in order to test the influence of underlying assumptions on simulations. Indeed, the concepts traduce different hypotheses concerning spatial interaction and refer, in some sense, to different approaches of perceiving distances. This helps to understand how distance perception may act on urban dynamics. On the other hand, considering planning purposes, the different concepts may be associated to different kinds of constraints for accessibility in order to manage urban sprawl. Such an approach should associate different actors (concerned with the urban sprawl problem and its consequences on social and environmental aspects) and confront different points of view, so as to open discussions and envisage suitable futures for urban areas expansion .

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