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## **SIMPOP, A MULTI-AGENTS MODEL FOR THE URBAN TRANSITION**

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## **SIMPOP, a multi-agents model for urban transition**

### **Abstract**

In order to simulate the genesis and evolution of a settlement, it is necessary to formalize the process of spatial aggregation of population, the complexification of activities with urbanization and the hierarchization of settlements. Differential equations are too heavy tools for dealing with the multiple spatial interactions which generate and regulate the evolution of the settlement system. Cellular automata, in extended forms such as multi-agents systems, are more promising in this respect. They allow the simulation of a wide complexity of spatial interactions including mechanisms of cooperation and competition between settlements. Using that methodology, SIMPOP has been developed for modelling the transition from an agrarian settlement system to an hierarchical trade- and manufacturing-oriented urban system. Various hypotheses concerning this evolution have been simulated.

**Key-words:** multi-agent systems, settlement systems, dynamic models, cellular automata

### **Introduction**

During the urban transition of the last two centuries, settlement systems have been deeply transformed from rather homogeneous and scattered patterns into much more centralised and hierarchised urban systems. The spatial organization of human activities in agrarian economies was strongly constrained by the resources and the rhythms of the natural environment, whereas during the urbanization process the spatial forms of human communication became the more and more dominant constraint.

The main objective of this paper is to describe a model for simulating the emergence and evolution of systems of cities on a very long time period. The model should include the key parameters of such an evolution, in order to allow the exploration of the conditions which could lead to alternative patterns of settlements. Compared with previous dynamic models of urban systems, a particular attention is devoted to the spatial properties of settlement systems and to their interactions with their environment.

The simulation of the emergent properties of complex systems is a challenge for modelling. Among the several existing methods, the recently developed multi-agent procedure has interesting features for the modelling of spatial dynamics.

### **1 Dynamic modelling and multi-agent systems**

The main philosophy framing dynamic modelling today is the self-organizing paradigm. The structure and the evolution of systems which are observed at a macro-level is depending upon interactions between elements or sub-systems which are described at a micro-or meso-level. Several formalisms have been proposed for simulating the spatial interactions between populations and their effects on the evolution of the whole settlement system.

Most of those models use non linear differential equations. They simulate the evolution of a few state variables describing a spatial system including tens to a few hundreds of geographical units. Such models have very diverse sources of inspiration. Some have transferred to geographical spaces Volterra-Lotka equations (Dendrinos and Mullaly, 1985), others have included the time into the models of central places theory (Allen, Sanglier, 1981, Camagni, Diappi, 1986, Diappi et al., 1990, White, 1978). Master

equations of synergetic theory have been transferred for simulating interregional or interurban migrations (Weidlich, Haag, 1987, Sanders, 1992). Other authors have used catastrophe theory, for instance to explain discontinuities in the history of settlement systems, according to the development of trade (Mees, 1975, Wilson, 1981).

Other technics of modelling are better suited than differential equations for simulating complex spatial interactions between very large numbers of geographical units. They also allow to manipulate qualitative changes in the states of the elements. The Monte Carlo method of simulation first used by Hägerstrand (1952) for simulating the spatial diffusion of innovations was included by Morrill (1962) in a model which simulated the development of a system of central places as induced by population migration flows. More recently, the cellular automata has been acknowledged by geographers as a method especially fruitful for modelling spatial interactions and simulating the evolution of spatial patterns (Tobler, 1979, Couclelis, 1985). R.White (1991) has provided applications of cellular automata to the evolution of retailing systems within cities. The same kind of formalism was used for testing hypothesis of fractal growth in urban systems (Frankhauser, 1993).

Multi-agents systems are part of distributed artificial intelligence methods. An agent is "a real or abstract entity that is able to act on itself and on its environment; which can, in a multi-agent universe, communicate with other agents; and whose behaviour is the result of its observations, its knowledge and its interactions with other agents" (Ferber, 1989).

In most applications, the agents are autonomous and mobile individuals. In geography, it may be interesting to consider, at a given level of abstraction, that some spatial entities like villages or towns have sufficiently permanent properties and a long enough existence to be considered as "agents". They will then have a fixed location. Of course the formalism could be used at another level of resolution. For instance one could consider as agents the various individual actors which are interacting for producing the structure and evolution of a single city. The concept of an "agent" would be directly understood in that case. However, one should not let the applications of the method be limited by the usual connotations of the vocabulary. An "agent" may be a collective entity, its "behaviour" is then defined by the changes in the variables which are usually describing it at its level of aggregation.

We are here concerned by the macroscopic properties of large systems of cities. We assume that they are the result of interactions which can be observed at a meso-scale, between the individual settlements, hamlets, villages, towns and cities which are parts of the system. It is of course a simplifying hypothesis to look at those as individual agents. However, several empirical studies have demonstrated the relevance of such a consideration. The settlements have their names, they keep for very long periods of time their specific features and properties, they also transform themselves with measurable transition probabilities.

The main advantage of the multi-agent formalism is in its local treatment of all evolutions and interactions. To each agent are associated the properties and rules which govern its interactions with the others and its evolution. Even if the rules are common to the entities within the system, they are handled at a local level, according to the state of each entity and to the information it has on its neighbours. For instance, instead of fixing the shape of spatial interactions by a gravity equation for the whole system, each locality defines for itself an interaction zone according to its functions and their spatial range, as well as to the competition with neighbouring localities or local barriers for communication.

In order to simulate efficiently the "urban transition", one has to include within the model the evolutionary properties of the units of settlements and the interacting rules which connect them in a dynamic system. For the sake of simplification, it is assumed

that there is no creation of new settlement units. The initial state is then a region where a well established agrarian economy has already developed. It is first the slow emergence and the persistency of a strong differentiation of cities by their size which has to be simulated, since that hierarchical structure is the main characteristic of urban systems. Second, a major process of urban specialization has to be introduced according to the division of labour and to social representations. This process is partly sporadic, depending upon the location of newly recognised local resources, and partly systematic, including the effects of the more or less hierarchical diffusion of large innovation waves within the system.

In the course of time, the system is expanding by increasing the size and diversity of its elements. Two different stages at least have to be simulated during the same urbanization process: a slow progress with oscillations in a mainly agricultural economy, and then a major bifurcation with the industrial revolution which leads to the urban transition of the last two centuries (Bairoch, 1985). The key parameters are demographic and economic growth rates. Another variable has a very important role: it is the speed of communications which was considerably accelerated during that time. As a result the range and frequency of all spatial interactions increased within the system and the mean spacings between settlements have been enlarged.

If the driving force of the evolution is the continuous creation of innovations and wealth in the system, the main mechanism which controls its structure is the competition between geographical units for capturing and accumulating the product of those resources. This competition is effective through the circulation of informations between the settlements which are then organized in two networks. It is therefore important to define in the model complex spatial interactions whose ranges are increasing over time and are varying according to the acquisition of new functions by towns and cities.

## 2. The model

The computing of a multi-agent system could be done in any language. Meanwhile, when the application is a bit complex and involves many interactions and nestings, an object-oriented language appears indispensable. Their modular structure and their property of inheritance make them flexible and well adapted for a progressive building of the model. The inheritance property of the object-oriented language allows to build in a hierarchic manner sets of more and more complex objects. For instance, a market town, a town and a city are objects of same nature but of increasing complexity.

The area under study is represented as a grid whose cells may have various shapes and sizes. Each cell, that is each spatial unit, defines to an agent. The properties of multi-agent systems allow to stock and to handle at a local level the informations related to each place. In this application three types of information are handled at the level of each cell:

- permanent constraints: the natural environment (plain, mountain, sea...), the resources (agricultural, mineral, position..);
- stock variables, varying in time: population (total population, farmers, commercials..), wealth; growth rates...
- status, that is the qualitative state of the place (agricultural village or a city with a certain functional level).

As agents communicate, the places may have an access to the informations owned by other cells. For instance, the trading or competing relations between neighbouring cells can be modelled for a neighbourhood which depends on the range of their functions. An urban centre receives informations from all cells which are in its market area, an agricultural cell receives informations which are sent out by all the urban centres with which it is connected. Other informations can circulate on a network, from town to town, for instance when a hierarchical diffusion of innovation process is simulated.



The rules determine the nature, the direction and the rythm of the evolution. Change can be qualitative as the acquisition of a higher level function for a city, or quantitative as for example the population growth or the variation of the share of the administrative employees in the labour force.

The evolution of each place is simulated from a set of general rules. The evolution depends on the potential resources of the place, on its productivity which varies according to the technical level of development of the period, and on the balance of its excahnages with surrounding places. Some of these rules are purely deterministic: for example, a city can only acced to a given administrative level if no other city has such a function in a certain neighbourhood; but most of the rules include a stochastic term: for example, if a minimum size is necessary for a village to get the status of town, this transition is not automatic and involves a random term. So, two places belonging to the same hierarchical level, having a similar environment and the same productivity, will not necessarily have the same evolution.

Each simulation develops through many iterations, each corresponding to one time period. At the end of each iteration, a balance of the events and the exchanges is made at the level of each cell of the grid and the new configuration is calculated. Each iteration has several steps:

- evaluation of the economic balance of each place: the exchanges between the spatial units have a central role in the simulation. They represent both the cities levy on the countryside and the effects of the competition between the cities. In each place "i", the population induces a certain demand in goods and services, as a supply. This demand ( $D_i$ ) and this supply ( $S_i$ ) are calculated from the population ( $P_i$ ) of the place and from the parameters which are globally defined: the propensity of the individuals to consume goods and services of type  $f$  ( $\mu_f$ ) and the productivity associated to that product or service ( $\beta_f$ ). The demand  $D_i^f$  and the supply  $S_i^f$  in products or services of type  $f$  which are produced in a place  $i$  are then:

$$D_i = \sum_{f \in F} D_i^f \text{ where } D_i^f = \mu_f P_i$$

where  $F$  represents the set of economical functions.

and 
$$O_i^f = \beta_f P_i^f$$

When the local supply and demand have been estimated for each place, they are confronted between places by the means of message sendings between the agents. The exchanges are modelled by simulating a progressive process of balance between demand and supply. The supply  $S_i$  in a place is first supposed to satisfy the local demand and only the surplus are commercialized towards other destinations. The range of the exchanges varies according to the status and the functions of the place; a regional capital has a greater market area than a small town. Those kinds of spatial interactions are easy to model thanks to the possibilities of "communication" between the agents.

- estimation of the population growth: it depends on the previously described exchange balance and mainly on the resulting profit. To a positive balance, one associates on average a greater growth rate than to a negative one. The local value of each growth rate is drawn from a normal distribution whose mean vary according to the exchange balance. In a further version of the model that procedure will be replaced by a module describing more explicitly the population flows between the places.

- estimation of the composition of the labour force: the active population  $P_i$  of each place  $i$  is distributed between the different sectors of activity which are associated to the functions of the place. Each time a city gets a new function, a part of its active population is assigned to the new activity through a transfer of the old activities to the new ones. The evolution of the relative weight of each industry is estimated through a

similar procedure as for the total population: the activities making profit will have a greater probability to increase their relative weight whereas the losing ones will tend to decrease.

Once these evolutions have been estimated, the status of each place is adjusted: certain functions are acquired or lost according to the population size, the wealth and the functional level of the past period.

The whole complexity of the model is provided by the local management of the multiple interactions between spatial units. At any time, computations made on the global configuration allow for a control a posteriori of the evolution of the macroscopic features of the system.

### 3. The results

To illustrate this description of the model, we propose a synthesis of a few first simulations. For those, we have chosen an hexagonal grid of about four hundred cells. The simulations take place over a period of about a thousand years, divided into periods of ten years. At the end of each period, a balance is done. In order to take into account the emergence of new technics, of the evolution of the communication network..., the values of some parameters are modified every century exogeneously.

The driving force of the evolution is essentially in the acquisition of new urban functions which allow the cities to extend their influence and their trading activities. In this application we introduced a commercial function with four levels (basic goods, high level goods) and an administrative function with two levels. The higher the level of the function, the wider the ranges associated with the function. As time goes by, the agricultural productivity increases with the introduction of new agricultural technics. The ranges of commercial functions increase over time with the development of new transportation networks.

For one simulation to another it is possible to change, the initial conditions (distribution of population and natural resources) as well as the parameters which manage the evolution (thresholds of population, ranges...) or the rules which define the growth rates. Then, we can compare, for different set of parameters, the evolution of the settlement system.

Even with a simplified mechanism of growth and few constraints, almost all simulations show, after one thousand years run, a hierarchized set of cities (for example, see figure 1). Each settlement is represented with a size proportional to the total population and with a symbol corresponding to its functions.

The growth rate of the population is calculated for each period. After a period of fluctuation which corresponds to the emergence of towns in the system, the rates regularly increase around year 600 until they reach about 0.6% per year (figure 2). The joint representation of the evolutions of total wealth and population (figure 3) denotes the existence of a regulation mechanism between those two accumulation processes. One also has to check that the simulated urban hierarchy has the properties which are observed at the macroscopic level in urban systems. A representation of the distribution of the number of places according to their size every hundred years shows that a process of hierarchization starts slowly and takes off after year 400 (figure 4). The level of inequality in the sizes of towns at the end of the period (as measured by the slope of the Pareto distribution) is about the same as what is observed in pre-industrial urban systems (figure 5).

The results of those simulations reinforce some hypotheses about the necessary conditions for the emergence of urban hierarchies. We notice first that the existence of

surplus accumulated from agricultural production is indispensable to the building of a sustainable urban network. On the other hand, the competition between cities is an essential factor of the cities differentiation process. However, the choice of an initial situation or the levels chosen for thresholds allowing to gain new functions, neither the distribution of growth, have any effect on the emergence of towns, they only affect the speed of the hierarchization process. A continuous flow of innovation within the system is nevertheless necessary for simulating the further development of the settlement system. If no new function is introduced in the system, the demographic and economic growth is slowed down, and the urban hierarchies stabilized with less contrasted distributions.

Other simulations are currently run in order to identify the respective effects of each parameter in this hierarchisation process during the urban transition. The model could for instance help to understand the relative role of bottom up (commercialization of agricultural surpluses) and top down (long distance trading) processes in the building of urban networks.

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**captions for the illustrations:**

Figure 1: The settlement system after a 1000 years simulation

Figure 2: Evolution of population growth rates

Figure 3: Growth of wealth and total population

Figure 4: Rank-size distribution of settlements

Figure 5: Slope of a Pareto distribution adjusting rank-sizes

a) for all settlements

b) for the 50 largest cities

# The settlement system after a 1000 years simulation









