SIMPOP: a multi-agent system for the study of urbanism

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Abstract. SIMPOP is a knowledge-based simulation system for the description of the evolution of settlement patterns over long time periods. Rules and parameters are introduced into a multiagent systems formalism where each settlement is considered as a separate entity interacting with the others and transforming itself. The rules may allow for the simulation of the 'urban transition' from a set of homogeneous, agriculture-oriented, and scattered villages into a complex system of functionally diverse, competing, and hierarchised urban settlements. In this paper we show how several modifications of rules and parameters alter further the spatial and hierarchical structure of the simulated urban system.

1 Introduction

Simulation games are popular, even for dealing with important urban problems, as shown by the success of a software package such as SIMCITY[1]. Simulation models are also very useful tools for urban research because they are the only possible means by which theoretical hypotheses can be tested through 'experiments'.

For physical planning, at the geographical level of a single urban area, the interacting strategies of urban actors of different types are the main variables to consider in order to explain and to predict the evolution of the morphological, functional, or residential structure. At a broader spatial scale, the whole settlement system of a region or a country can also be considered as a self-organised system. At that level, the interacting agents to be modelled are the competing towns and cities which tend to attract population, wealth, and innovation. Even if the 'behaviour' of each urban settlement actually results from the underlying strategies of its individual actors, town and cities have a long-term consistency in their size and functional type, and sufficient regularities in their evolution, thus they may be conceived as relevant global entities in a model.

With the formalism of multiagent systems (MAS), the SIMPOP model includes the main evolutionary rules which transform systems of cities over time. MAS are a type of distributed artificial intelligence procedure. With such a knowledge-based model, it is possible to simulate the development of an urban system and to experiment with the effects of various hypotheses about: initial conditions of the distributions of population and resources; rules for spatial interaction; different values of population growth rates

[1] Maxis, 2 Theatre Square, Orinda, CA 94563-3346, USA.

(for instance, to compare the evolution of urban systems in industrialised and developing countries); and exogeneous perturbations, network effects, etc.

In order to validate the plausibility of the simulated settlement system, global measures of their spatial and hierarchical organisation have been developed. The shape of the size distribution of the cities and its dispersion, which is measured by the slope of the rank–size curve, are the two main results. The maps which are produced, the distribution of settlements among various functional types, and their mean spacing may also be helpful for evaluating the quality of the results and for identifying various types of dynamics of the settlement system.

The main evolutionary rules of systems of towns and cities which have been included in the model will be summarised in section 2 followed by a description of the multiagent procedure in section 3. A few characteristics of SIMPOP will then be described in section 4, and the effect of some modifications of the rules will be tested on a few examples of simulations in section 5.

2 Modelling the dynamics of settlement systems

Settlement systems are produced by human societies to exploit and control their environment. Some very general evolutionary rules can be derived from the empirical observation of settlement systems over a very long term (for a review, see Pumain, 1996). Although most detailed available statistical studies deal with settlement systems of industrialised countries of the ancient world (De Vries, 1984) it is very likely that they allow us to identify general laws in the evolution of systems of settlement (Bairoch, 1985). The main regularities are listed below.

(1) The early emergence (Fletcher, 1986) and long-term persistency of a strong differentiation of settlements by their size according to a regular geometric progression. Hierarchical organisation is indeed a permanent property of settlement systems and the universality of the rank–size rule is understood as an attractor within a dynamic system of cities interacting through migration flows, as demonstrated recently by Haag and Max (1993).

(2) A process of internal speciation occurs over time within the system, differentiating types of settlement according to functional division of labour and social representations. This process is partly sporadic, stemming from newly valorised local resources, and partly systematic, linked with the somewhat cyclical appearance and further hierarchical diffusion of bunches of innovations within the system (Pred, 1977). Some of these functional or symbolic types remain attached to specific places for very long periods of time.

(3) The spatial patterns of settlements is, on the whole, stable so long as a sedentary agrarian economy has been developed within a country: "change must inevitably occur within the structural or locational confines of the system as it has developed to date" (Parr, 1981, page 100). Very few new settlements are created during the life of the system; the same stock of settled locations is used by societies for very long periods of time. However, at every location, each node of the settlement system is subject to deep transformations of its aspect and functions, as it is permanently adapting itself to changes in technology, economy, and society.

(4) The settlement system expands over time by increasing the size, number, and diversity of its elements. After various stages of limited expansion and decline in a mainly agricultural economy, a major bifurcation has been observed during the last two centuries: the industrial revolution has increased dramatically the mean size of settlements as well as the number, complexity, and size of levels within the urban hierarchy, inducing a kind of phase transition from a rural to an urban settlement system. In this evolutionary process, decisive parameters seem to be the pace of demographic and economic growth, which allow a global expansion of the system. During the same time, the increase in the speed of communications contributed to an increase in the contrasts in settlement sizes, inducing a relative loss of importance of the smallest elements in the hierarchy of settlements (Guérin-Pace, 1993).

The historical genesis of urban systems from a scattered pattern of rural settlements may be interpreted by two competing major theoretical explanations. In the first theory it is claimed that towns emerged endogenously, as villages accumulated wealth and developed central functions. In variants of such a 'bottom up' theory, it is suggested that this process is economic in nature and that the emerging towns were at first rural markets exchanging agricultural surplus within small regions (Bairoch, 1985) or that the selection of specific nodes was political, as feudal population groups in a given place followed the artisans they needed for their own convenience (Duby, 1984). According to the second theory, the emergence of towns and cities is linked from the very beginning with the development of long-distance exchanges. Large cities could grow without being locally supported by a rich agricultural production but they required a long-distance trade network (Braudel, 1967; Pirenne, 1925). The very general process of hierarchical diffusion of innovations within urban systems supports the second hypothesis. In fact, the two types of processes, 'bottom up', and 'top down' can be exemplified in the literature about urban history and should be included and tested in our model.

The main hypothesis in this work is about the self-organised character of settlement systems: as open systems, the dynamics of their structure at the macro level are supposed to be generated by interactions of the elements of the system at a mesogeographical level. By simulating the interactions existing between the local units within a set of settlements, we should be able to produce an overall evolution of the whole system which is compatible with the state of our knowledge about settlement systems dynamics, as discussed above. The 'urban transition' at the scale of the whole system is made through local and competitive transformations of elementary settlements.

Despite the irreducible uniqueness in the historical path of development of each human settlement (Arthur, 1988), it is possible to identify a few rules that may characterise the successive transitions leading from a small agricultural settlement to a large multifunctional urban metropolis. Other rules describing the way in which settlements interact during their development are needed.

The main transition within the history of a settlement occurs between villages and towns, which are quite different geographical entities. Villages exploit local renewable resources obtainable on their own site. Their ability to sustain and to develop their wealth and population depends mainly on the quality of the resources available; they are of course affected by events from outside, such as climatic fluctuations or military invasions, but villages have very little power over such perturbations and may thus be considered as external constraints. A kind of Malthusian equilibrium limits the growth of their population according to their agricultural production. However, villages may accumulate the surplus of their production and try to commercialise it.

Some of these settlements then become towns by developing a totally different way of accumulating wealth and sustaining their population. They use their trading ability or political power to capture the wealth produced on distant sites through an unequal exchange. They also diversify their production by inventing new products and skills. Their ability to accumulate wealth no longer depends on their own local resources but on the quality of their situation within communication networks. The constraints on their development depend mainly on a competition process with other towns and cities for sharing markets and obtaining wealth from the other sites. Town markets are first strongly limited to a small neighbouring area by transportation costs but this catchment area grows over time with progress in transportation facilities. The range of market areas is also enlarged as towns grow and create scarce activities that are new urban functions. The 'neighbourhood' is then defined in terms of topological and hierarchical distances, measured on the transportation and information networks between urban centres, instead of consisting of a restricted contiguous market area.

A complete model of settlement dynamics should therefore include in an explicit way at least three kinds of interaction flows between places: wealth, population, and information. This can be done by applying the powerful methodology of multiagent systems. In our model each place, according to its natural resources, its functions, and its position within the system, produces wealth. Differentials of wealth between places and the circulation of wealth through exchanges induce the development of the settlement system. The effect of wealth accumulation on population growth is formulated in a simplified way: the ability of a place to increase its population depends on its own wealth. In order to avoid the deterministic effects of this overly simplistic assumption, population growth rates are computed as stochastic functions of wealth (in the first version of the model, population migrations are not explicitly considered but could be integrated later). The circulation of information is another important component in the dynamic of the multiagent system; information about available production is provided to neighbouring consumers, and information about existing demand is communicated to trading centres. During development, innovations and new economic functions are created, through which places gain a wider range of production means and thus assume a higher value. Such information circulates between towns and cities according to a hierarchical definition of their neighbourhood. Therefore the circulation of information between places allows the circulation of wealth. It also encourages competition for accumulating and producing wealth.

In a subsequent step, population flows could be added to the model, following, for instance, the suggestions made by Huff (1976) or by Fik (1988) and Fik and Mulligan (1990) about the distribution of migration flows within a central place system. A more general synergetic model of interurban migrations could also be included (Frankhauser, 1990; Haag et al, 1992; Sanders, 1992).

3 Dynamic modelling with multiagent systems

Multiagent systems are a part of distributed artificial intelligence. If one considers that the two extremes of this field are (1) the reproduction of a complete set of cognitive capabilities in a single agent, and (2) a strongly interconnected network of agents able to execute only a simple task, then 'multiagent systems' lie between these two approaches. Each agent is autonomous and able to reproduce different kinds of tasks, but its capacity for interaction and for cooperation is the basic advantage of the modelling method (Ferber, 1995).

The concept of an agent can represent a human actor as well as a material entity. In geography, it can be applied at different scales—that of the individuals acting in space and time and that of spatial aggregates at various levels. Each section of a city can be modelled through an agent; this can be done for each city in an urban network. The spatial system is then represented by a set of interacting agents, forming a multiagent system. In this kind of application, the agents have a fixed position in space, which is not the case when they represent actors as in most applications. The properties of an agent used to represent a spatial aggregate in a geographical system are discussed below.

The agent can store information corresponding to the associated spatial entity; a kind of local database is then stored at the level of each agent. This information can be of a quantitative type (number of inhabitants, production, income, etc) or qualitative (administrative status, type of economic activity, etc). The agents have a general property of 'inheritance' which is of methodological and technical help in the modelling process.

Once a class of agents is defined with some general abilities, more specific subclasses will inherit these basic properties, making it possible to build up a hierarchy of types of agents with nested properties. This conception of a system as a hierarchy of classes of objects is of special interest for evolutionary systems, such as settlements, which already have a hierarchical principle of differentiation. The increasing complexity of urban structure and the progressive acquisition of new functions accompanying a growth in size are the strongest processes which differentiate the main types of settlements. Figure 1 shows the attributes tree associated with our application. In this tree, the agent has access to the information stored at the level of other spatial entities in surrounding zones. This ability derives from the complex protocol of communication which is specific to multiagent systems. For example, information flows can be modelled between a city and surrounding villages, describing the city's functions and the goods and the services it supplies. Through this communication process, mechanisms of supply and demand between the different units of the system can be modelled. The range of interactions can vary from one kind of agent to another and integrate the effects of possible discontinuities, physical or social barriers, or, on the other hand, specific facilities between some pairs of spatial entities. To the best of our knowledge, this is the first time that the effect of space–time contraction is introduced explicitly within a model of central place dynamics. As such a parameter may vary according to the size and functions of the towns, it is easier to include it in a cellular type of model than within a set of differential equations. We expect to gain an insight into the importance of this effect on the hierarchisation and on the spatial concentration of the system from the simulations.

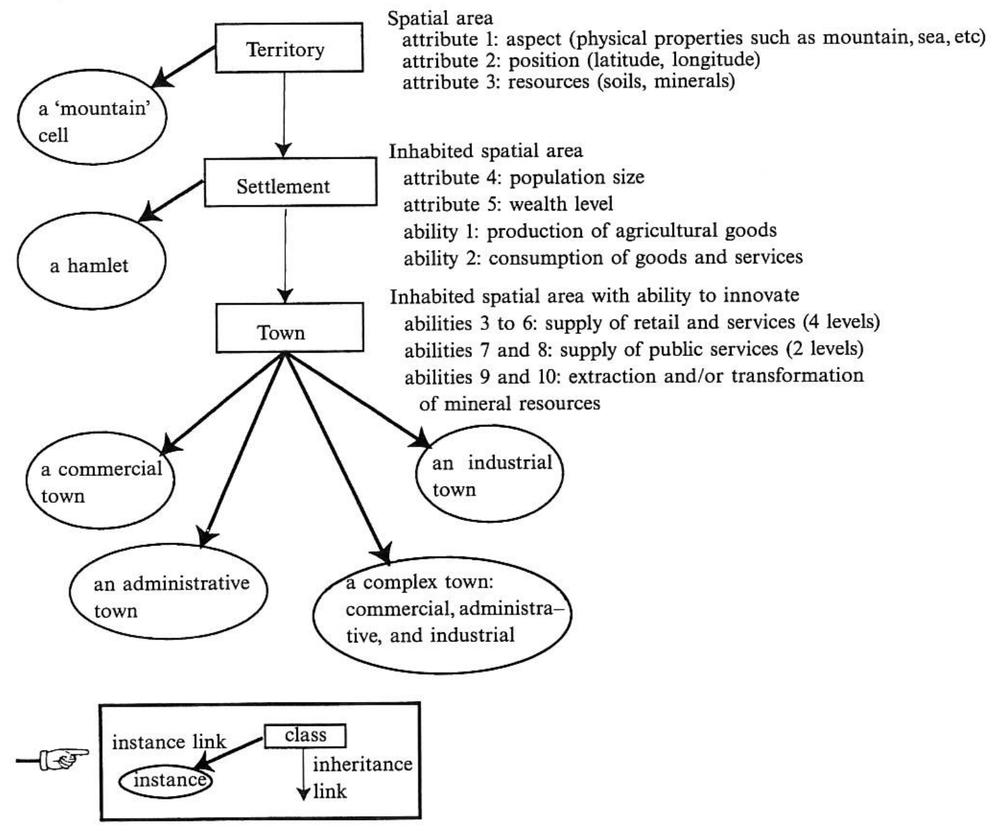

Figure 1. Hierarchy of classes of agents and the property of inheritance.

Further, the agent is able to run locally, at the level of the spatial entity, the rules defined for the class of agents to which it belongs. These rules handle: local information; information concerning the other entities with which the unit is interacting; and mechanisms of interaction between units. The rules are used in order to model the change which will occur at the associated place in a given period. This change can be quantitative (the increase or the decrease in the population) or qualitative (change of status or acquisition of new functions).

This formalism makes it possible to consider the city as an evolutionary system which can receive and diffuse information and can create and innovate. It is able to transform its qualitative functional structure; for instance, a hamlet or a village becomes a city of a higher level in the urban hierarchy. As it competes with others, the reverse change can also occur. In this type of approach, the evolution of each single place is determined from a local point of view. The evolution depends on the specifics of the place, on those of its surroundings, and on the relationships of the place with the rest of the system. Evolution is directed by rules reflecting general mechanisms which are handled locally. For example, the general mechanisms which determine the evolution of two different urban places are of the same type, qualitatively different from those concerning rural units, but the application of the rules of change will differ depending on the local characteristics of each place, in quantitative and qualitative terms. Thus the rules are handled autonomously and independently at the level of each geographical entity but their functioning takes into account the characteristics of the surroundings through the interactions between different spatial units.

A MAS approach differs in many respects from the sets of differential equations often used in dynamic modelling. There are differences both in the treatment of the data and in the working of the model. An example will help us to understand these differences. The negative effect of distance is a component frequently used in spatial interaction models. In a differential equation approach, this effect will appear through a function of distance (such as a negative exponential) inside a global equation which combines many effects and which describes the evolution of various state variables. In a MAS approach, even if the evolutionary rules are the same for all entities of the system, their application is handled locally, at the level of each entity, relative to its state and to the information about neighbouring entities. Instead of a general formula describing the intensity of the spatial interactions, each locality defines its neighbourhood relative to its different activities and their ranges and to the characters of the neighbours which determine the possibilities of exchanges and the eventual existence of competition. In this way, the concept of 'proximity' is not as static as when it is measured by a fixed variable such as the distance between places. From being one variable among others, proximity can be treated in the MAS approach as a dynamic and evolutionary concept which is at the core of the modelling process. The result is a process of self-organisation and the simulations show different kinds of structures which will emerge depending on the rules and the initial values of the variables.

The MAS approach can be compared with cellular automata (CA) techniques as well. In both cases, the evolution of a cell is defined by a set of rules handling local criteria. The rules refer to the state of the cell itself and to the states of the neighbouring cells. The way in which cells are characterised is the major difference between the two approaches. In the MAS approach, each cell may be defined by a potentially large number of qualitative and quantitative variables.

The MAS approach is particularly well adapted to simulate the long-term dynamics of a settlement system. Its properties of self-organisation correspond to a fundamental feature of geographical systems as emphasised in section 2. In addition, the development of a complex protocol of interaction between the agents makes it possible to integrate the phenomena of contraction of space through time. Distances are changing according to the general level of development of the system in terms of technologies and infrastructures. These aspects are particularly important in a long-term approach concerning the emergence of new structures. Attention must then be focused on the phases of transition corresponding to the change from one type of structural organisation to another, for example, as a response to innovations.

4 The SIMPOP model

SIMPOP has been developed with the facilities of an object-oriented computing language (Smalltalk). The multiagent system model is a set of agents interacting through rules which operates at the local level of each agent. According to the principles of self-organisation theory as applied to large-scale geographical systems, the agents have been identified with spatial entities (that is, elementary settlements, in most cases) and the main rules explain how a settlement of a given type may transform itself into another type.

4.1 Initial conditions

The application has been developed on a fictitious territory consisting of a grid of 236 hexagonal cells, each of which represents a district of about 50 km^2. Each cell is called a 'place'. It has a type of natural environment, such as plains, seas, or mountains (figure 2). It may host a settlement and contain a part of various networks, such as a river, road or railway. It receives natural resources (agricultural, mineral, or maritime) which have the potential to be exploited by the population of the settlement. The capacity of each place to improve this potential depends on different factors, including population size, the technological abilities of the time period, and the activities of neighbouring places.

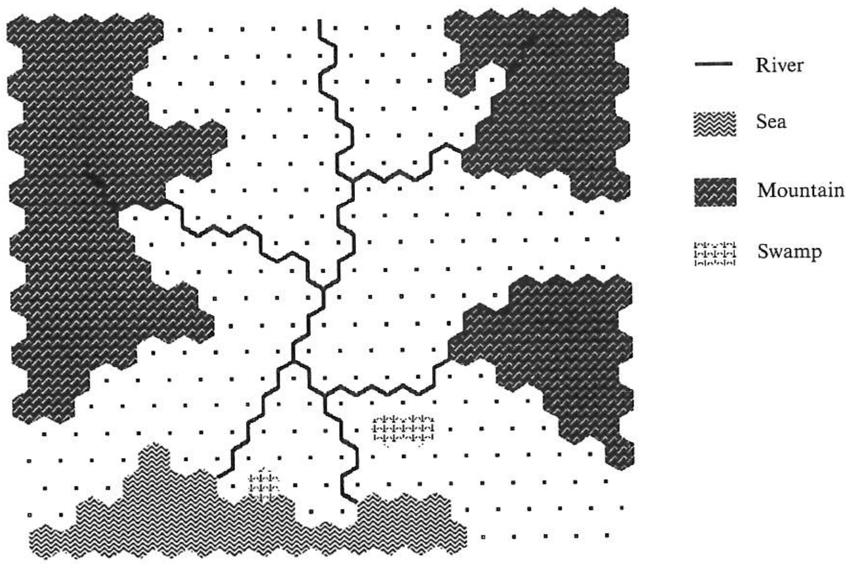

Figure 2. Spatial support for the simulations.

Each simulation starts from an initial configuration of population and natural resources. One of the aims of the model is to test the effects of different initial conditions on the future development of the system. Table 1 (see over) gives a few examples of the parameter values for random (Gaussian) distributions of resources and population which were used successively in the simulations. Mineral resources are introduced in the initial conditions but they can start being exploited only from year 1800. They are attributed randomly to ten places.

Table 1. Examples of variations in the initial conditions.

Experiment number[a]	Population	Agricultural resources
1	N(180, 30)	no restriction
7	maximum [N(180, 100); 50]	no restriction
9	maximum [N(180, 180); 10]	no restriction
11	maximum [N(180, 180); 10]	maximum [N(200, 100); 10]
12	maximum [N(180, 180); 10]	maximum [N(400, 200); 10]
16	maximum [N(180, 180); 4]	maximum [N(400, 200); 10]
25	maximum [N(180, 360); 4]	maximum [N(400, 200); 10]
26	maximum [N(90, 90); 4]	maximum [N(400, 200); 10]
30	maximum [N(180, 90); 4]	maximum [N(400, 200); 10]

[a] In experiment 7, for example, the population is distributed according to a normal distribution with an average of 180 inhabitants and a standard deviation of 100 inhabitants but the minimum cannot be fewer than 50 inhabitants [N(180, 100); 50]. The agricultural resources are unlimited and, consequently, the potential wealth produced depends only on the productivity of the population working in the agricultural sector.

4.2 Settlement types

The settlements are characterised by types of economic functions. These describe the means of production which will enable the settlements to produce wealth, maintain themselves, and increase their population. At the beginning of a simulation, all settlements have the same agricultural production function. A place with only this function is a rural settlement. Three other types of functions may be acquired by the settlements: the commercial function, with four hierarchised levels; an administrative function, with two hierarchised levels; and two types of industrial functions (extraction and transformation) which appear at the beginning of the industrial revolution (year 1800 in our simulations).

The transition from one type of function to another is governed by a set of rules. These vary according to the types of transition. The acquisition of the different levels of commercial functions is linked to increasing population size whereas the attribution of administrative status is assumed to depend also on a threshold of accumulated wealth, which in turn implies perhaps a higher probability of capturing political power. To illustrate this acquisition process we have summarised in table 2 the rules and parameter values which are necessary to obtain each level of economic function. For instance, in experiment 24 the fourth level of commercial function is obtained if a city possesses the third level and reaches a population threshold of 3500 inhabitants, whereas the first administrative level can be attributed only to settlements which already possess at least the second level of commercial function, a population of 1500 inhabitants, and accumulated wealth of 1500 units.

Table 2. Criteria for acquiring a new function (experiment 24).

Function	Previous situation	Population threshold	Wealth threshold
commercial 1	agricultural	1000	na
commercial 2	commercial 1	1500	na
commercial 3	commercial 2	2000	na
commercial 4	commercial 3	3500	na
administrative 1	at least commercial 2	1500	1500
administrative 2	administrative 1	3000	3000
industrial 1	presence of mineral resources	na	na
industrial 2		na	>0.1 R

Note: na, not applicable; R is the total wealth of the settlement system.

In the course of time, places may gain or lose their economic activities. The acquisition of a function produces changes in the share of the labour force attributed to the new activity. So long as a city has a proportion of its population working in a given sector, it can retain the corresponding activity.

4.3 Simulation length and iteration time

Every simulation proceeds in a sequence of discrete iterations. Each iteration represents 10 years and each simulation run represents 2000 years.

4.4 Production and consumption

The first step is the computation of wealth produced by the economic functions of each settlement. Each inhabited place produces the maximum that its status allows. The population devoted to a function f has a productivity β_f which determines the value of the supply related to this activity. For instance, the agricultural population P_a is able to transform fully or partly its agricultural resources K_a, with a productivity β_a. The agricultural production R_a is then a function of the share of the population devoted to this activity and it is limited by the yield (γ_a) which increases over time, with technological innovations. The agricultural income can be written as:

$$R_a = \text{minimum}\,(\beta_a P_a ; \gamma_a K_a)\,.$$

The mechanism of production is the same for all the commercial and industrial activities which produce goods or services. Administrative functions are different in the sense that they yield wealth by collecting taxes.

Consumption of various goods and services is a function of population. To maintain itself, the population of a place expresses a demand which is the sum of all individual propensities (δ_f) to consume goods and services supplied by function f. The total demand D of a settlement is then:

$$D = \sum D_f ,$$

where $D_f = \delta_f P$. Each settlement tries first to satisfy its own demand for goods and services with its own production. Supply and demand are then evaluated for each type of economic function. Settlements may have a positive demand for a kind of product and have a supply surplus of goods for another sector.

4.5 Exchanges

Commercial exchanges between settlements represent an important number of interactions which can be treated easily with multiagent systems. Supply and demand for each place are stored and then treated in terms of decreasing importance of demands and decreasing distances between places.

A commercial trade between settlements takes place according to the network defined by the largest spatial range associated with the functions of places. The spatial range associated with each function determines the geographical area where a settlement of a given type is acting and may have interactions with other settlements. It is measured in terms of contiguity and takes into account the physical constraints of the territory. For instance, the presence of a river or mountains will increase the distance between some places. For commercial functions, the spatial range corresponds to the number of cells, from a given settlement, where it may buy or sell goods and services. Prices increase as a function of the distance between places. For administrative functions which do not produce goods, the spatial range indicates the number of places which will pay taxes for administrative services.

Through messages, the 'demanding' places are known by the 'supplying' places. The trade consists in a transfer of wealth from one spatial entity to another, relative to the price of exchanged goods and services between places. Trade goes on until all possible interactions are completed. However, nonsatisfied demand could exist for places with insufficient financial means whereas other places still have some goods or services to offer.

4.6 Population growth

At the end of each time period a kind of balance sheet is produced, giving the state of each place according to its production, the amount of wealth collected from sales and taxes, the possible amount of unsatisfied demand, and unsold goods and services. This balance sheet is then used to determine the growth of each settlement. The growth of a place depends partly on its urban functions, with a mean value proportional to the functional level, partly on the previous economic balance, and partly on the local environment. These different components are combined in the rules which decide the further growth of the population of the settlements. The growth process is stochastic and we assume that the variation rate of the population at each place follows a normal distribution the parameters of which are determined by a combination of criteria (for example, see experiment 24 in table 3). In this way, two places with similar profiles may not have exactly the same evolution. Though the whole system of rules is globally stable through time, some rules intervene only after a predetermined time period. This is true in the case of the rule concerning industrial activities and favouring industrial cities to the detriment of neighbouring settlements. This rule intervenes after year 1800 and simulates the effect of a strong rural outmigration.

Table 3. Rules for population growth (experiment 24): mean and standard deviation of the variation rates according to type of entity and local demand.

Type of entity	Local demand	
	satisfied	not satisfied
Town		
commercial 1	~N(4; 4)	~N(−5; 2)
commercial 2	~N(6; 6)	
commercial 3	~N(8; 8)	
commercial 4	~N(10; 10)	
Hamlet		
in the neighbourhood of a town	~N(−1; 1)	~N(−5; 2)
far from a town	~N(1; 1)	

At the end of each cycle of the simulation, the gain or loss of urban functions is determined and the working population is redistributed among the activities. This last operation depends on the commercial trade balance. If a place still has unsold goods in one economic sector, it is assumed to be overdeveloped and the variation of the commercial population devoted to it will be negative. On the other hand, a place which benefits from one function will increase its population.

Among simulation runs, there are several constant parameters including the type of economic function, the spatial range of activities, the prices of goods and services, taxes, the productivity of the labour force, and the individual demand for the consumption of goods and services. Some of these parameters increase over time, for instance, individual productivity, according to the development of new technologies or the spatial range of functions with the construction of transportation networks. These constant parameters are presented in table 4.

Table 4. Parameters related to the economic functions.

Economic function, f	Spatial range, p	Price, π	Taxes, I	Individual productivity, β	Individual demand, δ
agricultural		$0.5(d+1)$	$-0.1\ R$	$1.01+0.005t$	1
commercial 1	1	$0.25(d+3)$	$-0.1\ R$	1.5	0.25
commercial 2	2	$0.25(d+3)$	$-0.1\ R$	2	0.125
commercial 3	4	$0.25(d+3)$	$-0.1\ R$	2.5	0.0625
commercial 4	8	$0.25(d+3)$	$-0.1\ R$	3	0.03125
administrative 1	3	na	$-0.3\ R+\sum$taxes	na	na
administrative 2	3−6	na	$\sum$taxes	na	na
industrial	3	na	$-0.1\ R$	5	na

Note: d is the distance between the place of production and the place of demand; R is the total wealth of the settlement system; and t is the time period; na, not applicable.

5 Simulation of the emergence and evolution of an urban system

The model was built up progressively, dealing first with agricultural activities and a simple commercial function only. The simulations result in a rather homogeneous pattern of settlement, with growth roughly equal in all settlements. Only the introduction of a limit in the agricultural potential produced differential growth between places. The ability to produce a surplus is a necessary condition for a place to grow and become a real town or city. Although agricultural potential, representative of environmental constraints, is a necessary condition, it is not sufficient to create long-term growth. However, it is necessary to introduce interactions in the system through competition and complementarity in order to simulate different rhythms of growth and to obtain a sufficiently differentiated distribution of town size. This observation was made for every time period in the simulation: the repeated introduction of innovations and of new functions is a necessary condition for reproducing a plausible urban hierarchy.

After the first step of building the model, about thirty simulations have been run in order to test the effects of different hypotheses on the evolution of the system. About half of them are limited to a period of about 1500 years, and only agricultural, commercial, and administrative functions are taken into account. This is the period of emergence of a hierarchical structure. These simulations reproduce a progressive polarisation of space and the establishment of a system of cities. When these simulations are run for a longer period, it appears that the system stabilises after 1500 years and is unable to grow or differentiate internally. Innovations are necessary to stimulate the growth of the system. During the first 1500 years, the driving effects of new innovations were modelled through the progressive acquisition of new higher level commercial or administrative functions. Around year 1500 the effects of these innovations wear away, and the system 'runs out of breath'. The introduction of industrial activities is then necessary to renew the dynamics of the system. The other half of the simulations integrate these new functions and make it possible to analyse the consequences of different hypotheses on the entire period of 2000 years.

5.1 The emergence of a hierarchical structure

On the whole, the simulations showed clearly the essential roles of three main components in obtaining an evolutionary hierarchical system. They refer to three different scales.
(1) The local level: the ability for a place to produce an economic surplus.
(2) The subregional level: the interactions and the process of competition between places.
(3) The level of the system: the ability to adapt to new innovations which create new functions in the cities.
These components are all time dependent. In the model, some of them vary continuously, for instance, the increase in agricultural productivity. Others vary at some fixed steps, such as the exploitation of mining resources which is only possible after year 1800.

When these components are formalised in the model (see section 4), irrespective of the values of the parameters, the simulations produce a settlement system with a hierarchical structure. Depending on the parameters, important differences can appear in the *timing* of the erection of this structure and in its *intensity*. Many sources of variation have been tested (table 5) in relation to the initial conditions or the economic

Table 5. Different sets of initial conditions and acquisition rules.

Criteria	General formulation	Domain of variation of the parameters
Repartition of		
the initial population	$\sim N(P, \sigma_P)$	$P \in \{90; 180; 360\}$ $\sigma_P \in \{90; 180; 360\}$
the initial agricultural resources	$\sim N(R_a, \sigma_{R_a})$	$R_a \in \{200; 400\}$ $\sigma_{R_a} \in \{100; 200\}$
Acquisition of		
the first commercial function	if the population $> S_{p1}$	$S_{p1} \in \{200; 400; 800; 1000; 1600\}$
the second commercial function	if the first commercial function exists, and if the population $> S_{p2}$	$S_{p2} \in \{250; 600; 1200; 1500; 2400\}$
the third commercial function	if the second commercial function exists, and if the population $> S_{p3}$	$S_{p3} \in \{400; 800; 1600; 2000; 3200\}$
the fourth commercial function	if the third commercial function exists, and if the population $> S_{p4}$	$S_{p4} \in \{750; 1000; 2000; 3500; 5000\}$
the first administrative function	if at least the second commercial function exists, if the population $> S_{p5}$, and if the wealth $> S_{w1}$	$S_{p5} \in \{500; 1500\}$ $S_{w1} \in \{500\}$
the second administrative function	if at least the first administrative function exists, if the population $> S_{p6}$, and if the wealth $> S_{w2}$	$S_{p6} \in \{1000; 3000\}$ $S_{w2} \in \{1000\}$

Note: P, R_a represent the population and the agricultural production; σ is the standard deviation of the normal distribution; S_p, S_w are the threshold values for population and wealth.

parameters as well as the threshold of acquisition of new functions or the values of the growth rates. The resulting simulations have been analysed and compared. In order to test the plausibility of the spatial and hierarchical organisation of the simulated settlement and to compare them properly, a series of global indicators have been computed at the end of each time period. Their representation as functions of time reveals the main features of each simulation.

Figures 3 to 7 present an example of outputs for a simulation which will act as a reference when testing different hypotheses.
(1) The total population and quantity of wealth give a measure of the level of development of the system and the general timing of its evolution (figure 3). In the reference simulation, the total population of the system evolves, for example, from a few tens of thousands in year 0 to 6 million in year 2000.
(2) The evolution of the rates of variation of the total population with time (figure 4) shows how the system enters progressively into a growth dynamics marked by more or less periodic fluctuations.

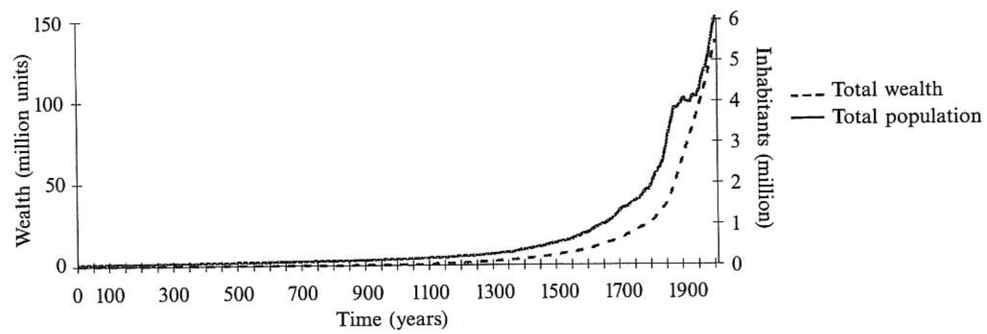

Figure 3. Evolution of population and wealth in the reference simulation.

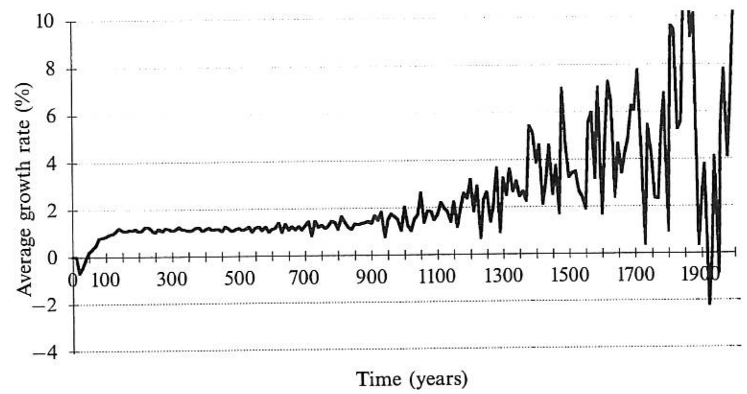

Figure 4. Evolution of the growth rate of the population in the reference simulation.

(3) The bilogarithmic representation of the population of the cities relative to their rank in the urban system helps us to visualise the degree of hierarchical structure of the system. The comparison of the shapes of the size distribution of the settlements at different periods reflects how the process of hierarchy progresses through time (figure 5, see over). The plots of the slopes of these rank–size distributions (figure 6, see over) show how the intensity of the hierarchical organisation is evolving. In the reference simulation, for example, the hierarchical organisation progresses regularly after year 800.

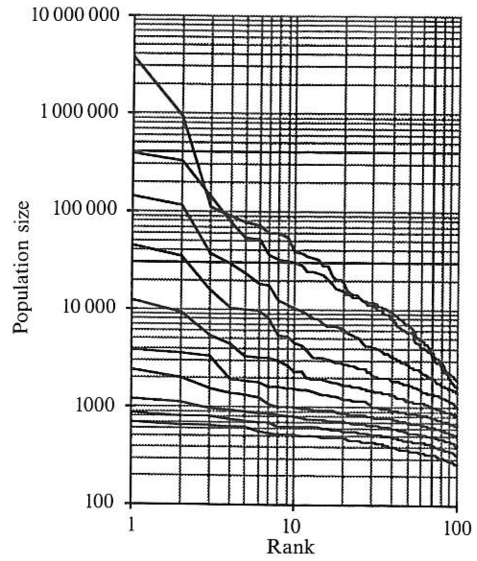

Figure 5. The successive rank – size distributions for years 200, 400, ..., 2000, obtained with the reference simulation.

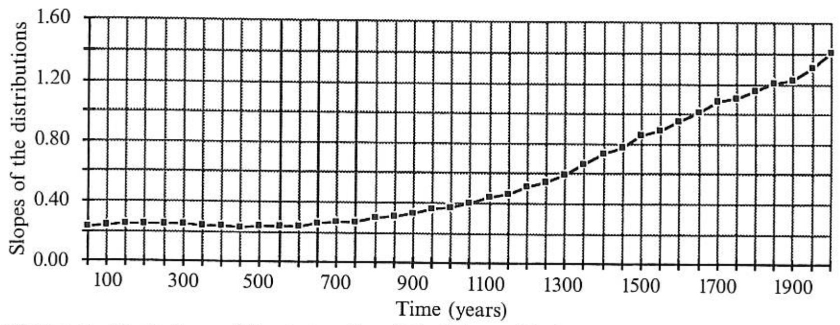

Figure 6. Evolution of the intensity of the hierarchical organisation for the reference simulation.

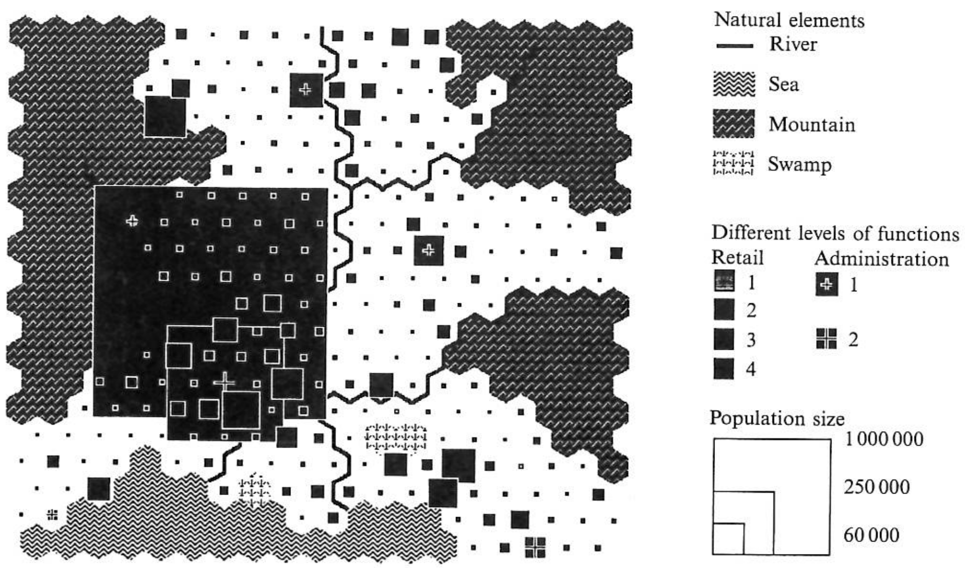

Figure 7. Spatial organisation at the end of the reference simulation.

(4) The proportion of population employed in the different sectors of activity expresses the progressive transition from an agricultural economy to one based on industrial and tertiary activities.

(5) The map (figure 7) gives, at a given time, an idea of the spatial organisation of the settlement system. In this example, the model leads to a concentration of bigger cities in the south western sector; the spacing is more regular otherwise.

5.2 The role of initial conditions

One of the objectives of this work was to determine the relative importance of the initial situation on the future development of the system. What is the degree of inertia of the system? To what extent does the process of establishment of a hierarchical organisation depend on the initial distribution of the population? How is the timing of change in the system affected by the characteristics of the initial situation? Great attention has been given to the hierarchical organisation of the system. Does the settlement become hierarchical at the same period of time? Are the differences between the cities of the same intensity, depending on the initial conditions. The following examples help answer these questions. The effects of three kinds of change in the initial conditions have been tested and compared with the reference simulation: (1) an increase in the degree of heterogeneity of the initial population distribution; (2) a change in the initial total population; and (3) a change in the random seed used for the initial population distribution.

In the first example, the standard deviation of the population in year 0 is doubled. This simulation results in a difference in timing (figure 8) and produces earlier and greater urbanisation of the system. The establishment of the hierarchical organisation is in fact quicker but it remains stable after year 1500; the top of the urban system does not differentiate further and there is a network of large cities of similar size. The increase in the initial heterogeneity of the population distribution leads to a more precocious hierarchical organisation and also to earlier stagnation of the system. It works as the competition between a set of similar cities breaks down the process of hierarchy. The second example produces opposite results. The simulation was started

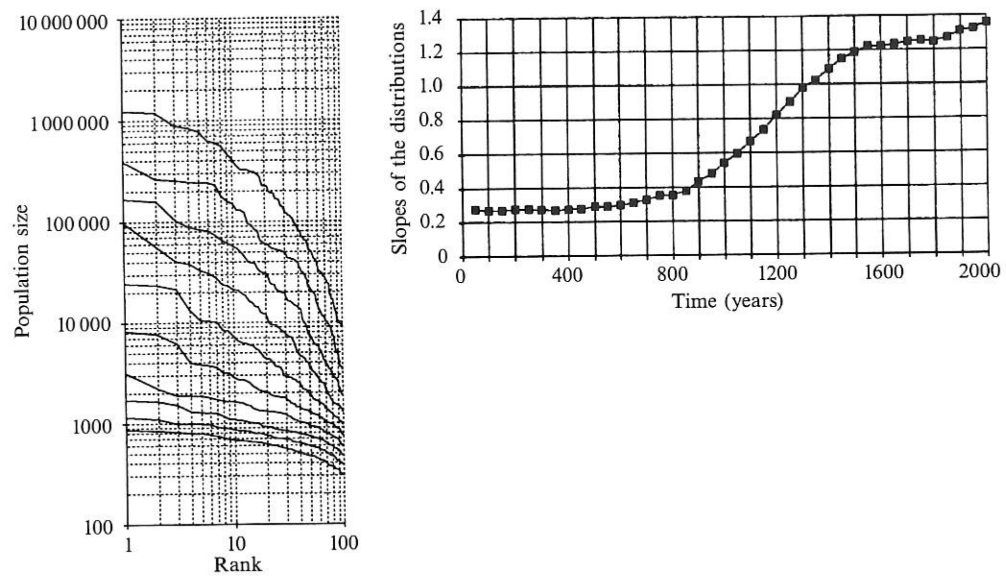

Figure 8. An early process of hierarchical organisation (an increase in the degree of heterogeneity of the initial population distribution).

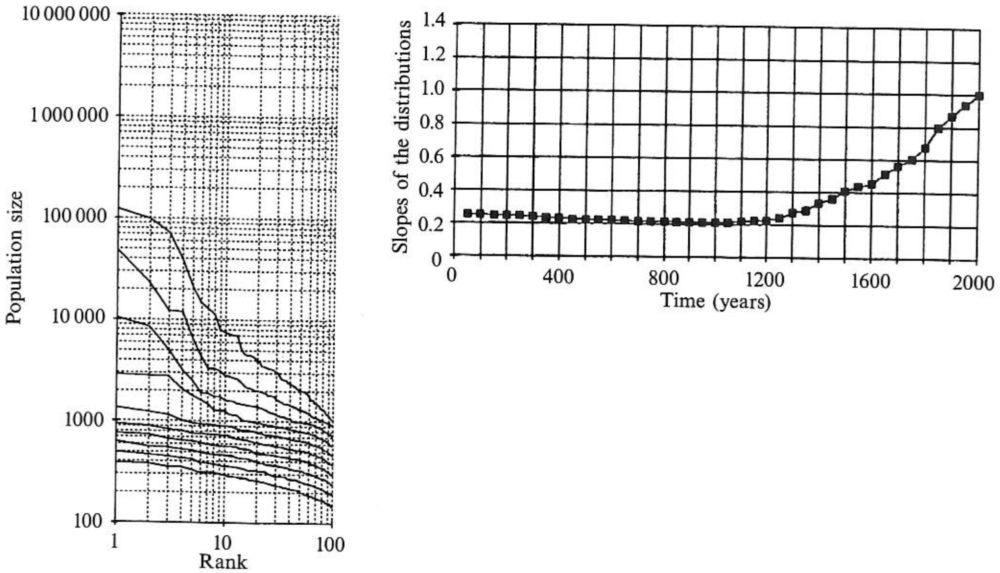

Figure 9. A slow process of hierarchical organisation (a change in the total initial population).

with half the total population as in the reference simulation. The hierarchical structure becomes apparent at a later stage and progresses more slowly, accelerating only after year 1600 (figure 9). The consequences of a significantly smaller initial population are far from linear. The total population remains very small, fewer than one million people, and the largest city is only a tenth of the size attained in the reference simulation. These two examples illustrate the impact of the initial population distribution, in terms of quantities and of spatial patterns, on the future evolution of the system.

The third test of initial conditions relates to the role of randomness. Figure 10 shows the results of a simulation where only the random seed associated with the

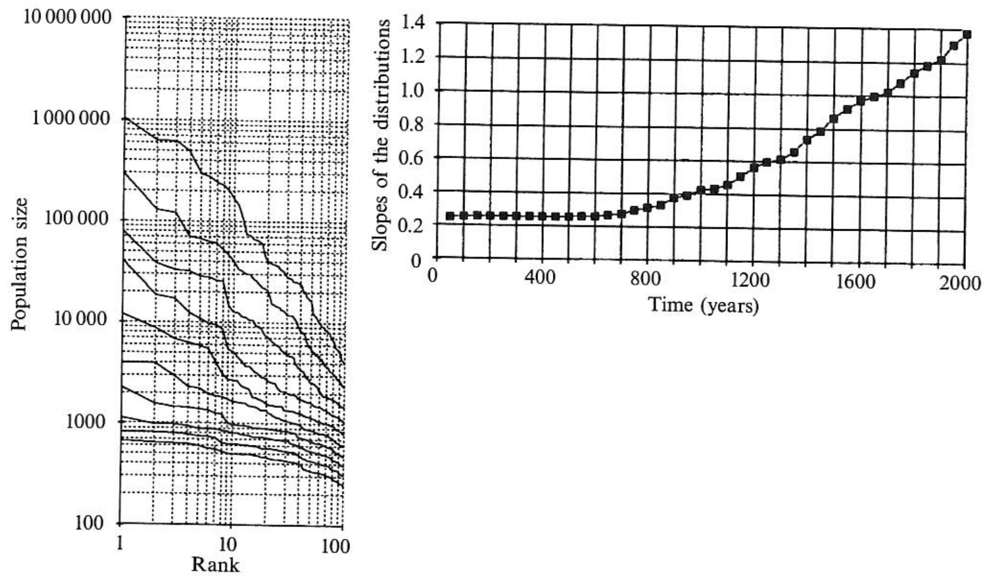

Figure 10. A process of hierarchical organisation similar to the reference simulation (a change of the random seed used for the initial distribution of population).

initial distribution of the population and of the agricultural potentials is different from the one used in the reference simulation. The structure of the results is almost the same; the evolution, the global size of the system, and the degree of differentiation of the hierarchy are very similar. Even the spatial patterns have the same global organisation, as described by the relative positions of the cities, but their absolute locations clearly differ. On the contrary, the shape of the rank–size distribution is qualitatively different, with a concavity for one and a convexity for the other. A few trials have been conducted and this example shows the role of stochasticity in the evolution: the global structure is unaffected, but locally great differences may exist. In this simulation, for example, the largest city is three times larger than in the reference simulation, even if

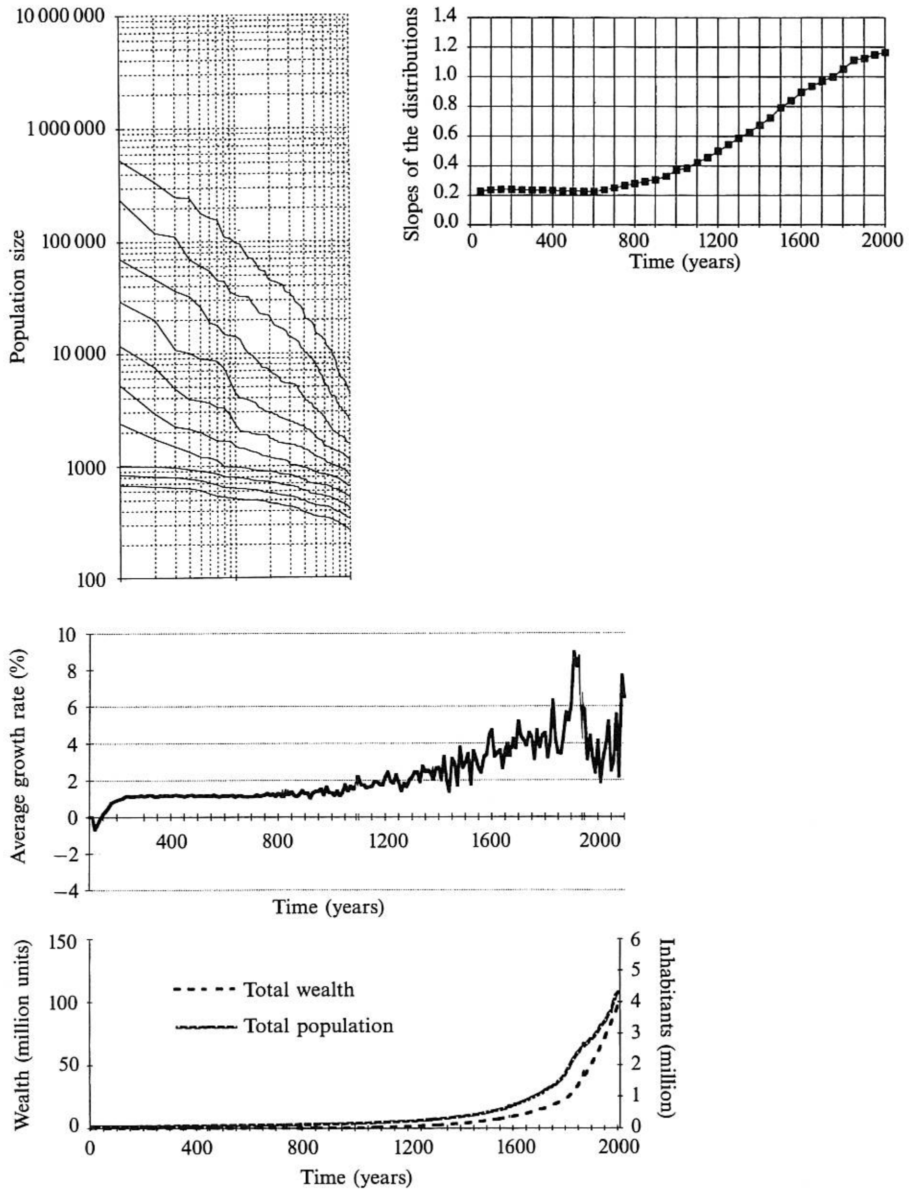

Figure 11. A weaker hierarchical organisation (standard deviation divided by two).

the entire population of the system and its hierarchical structure are very similar. Thus an initial change concerning only the form of the spatial distribution of the population does not affect deeply the structure of the system.

Randomness also intervenes in fixing the values of most of the parameters during the simulation. The model actually integrates many stochastic components and very few rules are fully deterministic. Growth rates, for instance, are dependent on the functional level and on the economic wealth of the settlement, but through the mean and standard deviation of a Gaussian distribution (see table 3). Randomness plays a part in all the more local or specific parameters which do not refer to general mechanisms and which can play an important role in the history of a place. Figure 11 shows an example where the standard deviation of the growth rates is systematically divided by 2 when compared with most other simulations. In this case, the deterministic components of the growth rates are of greater relative importance. Comparing these results with those from the reference simulation, we find that the general growth of the system is then less fluctuating, its total population is just a little smaller at year 2000, and the hierarchical structure is less strong. This example shows the importance of introducing a chance factor in the local dynamics in order to obtain a hierarchical organisation. Some places need a specific advantage at a given period of time to help them to make the difference. If they have the adapted profile, they can then profit from such a forward step and strengthen their relative position in the system.

The results of these simulations are convergent. They express some dynamic features of settlement systems which are in fact very often observed. On the one hand, initial differences have a great chance of being maintained and, more generally, the size differences between the settlements tend to increase over time, reinforcing the hierarchical structure of the system. On the other hand, the inertia of the settlement system increases as the size of its elements increase. It seems that a 'critical mass' of population is needed to develop the hierarchical structure and for the expansion of the system.

6 Discussion

There were two main objectives to this presentation of SIMPOP. The first was to show the methodological potential of this multiagent systems procedure, in particular its great flexibility when compared with systems of differential equations. Threshold and size effects are handled more easily by rules of the 'if ... then' type than by mathematical functions. The connection between changes in the parameter values or in the rules and the resulting settlement patterns is more straightforward than in dynamic models where differential equations are used. Multiagent systems also share with CA the advantage of providing a direct representation of geographical systems. Moreover, they have the additional advantage of allowing for a much larger variety of spatial interactions.

The second objective was to test the possibility of recreating plausible urban systems from rather simple hypotheses about competitive trends in interactions between settlements. In this respect, the model has rather good capabilities, as the major general features of urban settlement systems and of specific spatial or hierarchical organisations can be reproduced.

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