COMPLEXITY AND SPATIAL DYNAMICS MODELLING. FROM CATASTROPHE THEORY TO SELF-ORGANIZING PROCESS: A REVIEW OF THE LITERATURE

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Abstract

This paper is a survey of the spatial dynamics models found within systematic approaches to evolution which are based upon the paradigm of complexity. It includes a deterministic analysis of structural stability and spaces morphogenesis as proposed by the catastrophe theory and mathematical ecology, as well as an outline of those stochastic approaches which consider self-organizing spaces according to various principles (order through fluctuations or complexity through noise).

1. Introduction

Seventeen years ago a survey of the applications of systemism and cybernetics to regional and urban research was published [137]. Since then, the development of the systemic approach and its application to urban analysis and regional science have been oriented towards the modelling of discontinuities phenomena in the catastrophe and bifurcation theories, as well as towards the integration of the concept of autonomy through the process of self-organization. Such developments both contribute to a renewal of spatial dynamics analysis [65, 118] and offer a suitable way for an analytic approach to the evolution of economic areas. The objective of this paper is to survey the applications of such analytical methods to regional and urban morphogenesis.

1.1. From Differential Formalism to Bifurcation Theory

Although Forrester's dynamic is one of the most general systemic approaches to urban and regional problems [92], its numerous applications will not be analyzed because such an approach is more pragmatic than analytical. Accordingly, the survey will be limited to the applications of differential equations formalism [190] to urban and regional dynamics. In that way, one of

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the main hypotheses of the dynamic analysis is the distinction between state variables x and control variables or parameters u [81, 111, 160]. These variables are related through the operator M:

$$M(x,u) = 0 \qquad (1.1) \qquad x \in X^n, u \in U^m$$

Such a distinction specifies different temporalities for each kind of variable: a fast dynamic for state variables which can be quickly adjusted, and a slow dynamic for parameters whose changes correspond to structural transformations of the system [223]. Considering that the historical dimension which appears through such structural change is produced by the variation of parameters, whereas a time-sequential dynamic (cinetics) is temporal but non-historical [120], this distinction may be associated with the synchrony/diachrony duality [123] which corresponds to two different forms of stability: local stability and structural stability [47]. The following characteristics are associated with the two types of variable:

$x \in X^n$	state variable	fast dynamic	synchrony	local stability
$u \in U^m$	parameter	slow dynamic	diachrony	structural stability

Local stability is studied in the neighborhood of a fixed point x*, a steady-state for a given parameter sector $u = u_o$, as defined by:

$$\dot{x} = dx/dt = F(x^*,u) = 0 \qquad (1.2)$$

From initial conditions x_o, equation (1.2) defines a trajectory f on interval I given by:

$$x(t) = f(u_o,x_o, t) \qquad t \in I \qquad (1.3)$$

with:

$$d f(u_o,x_o,t)/dt = F(x, u_o) \qquad (1.4)$$

The evolution of the system along such a trajectory when a slight perturbation v is introduced (x = x* + v) is analyzed through local stability. Will the system return to the previous state, or will it move away? Its behaviour may be specified by analyzing the differential equation

$$dv/dt = F(x^*+v,u) - F(x^*,u) = f(v,u) \qquad (1.5)$$

Near such a fixed point, approximation of this equation through linearization [101] leads to the decomposition of the variation into two different terms given by:

$$f(v,u) = D_x f(x^*,u) + N(x^*,u) \qquad (1.6)$$

where $D_x f(x^*,u)$ —noted $D_x f$—is the transposed Jacobian matrix at the equilibrium x* $\| \partial f / \partial x$ with $x = x^* \|$, and where N(x*,u) is the nonlinear term in x. Asymptotic stability, marginal stability (center) or instability of the fixed point x* may be deduced from the roots of the characteristic polynomial associated with the matrix $D_x f$.

A more general study of the stability of the system defined by equation (1.2) corresponds to the analysis of structural stability. This involves perturbations acting not upon the state variables x (along one trajectory), but upon the general design of the trajectories through a variation of the parameters u. Qualitative changes relative to the structural stability of the system (e.g., loss of stability or sudden jumps from one state to another) are studied in bifurcation theory [100, 104, 58]. The set of values of the parameters which produce such sudden changes is the bifurcation set.

These bifurcations may have different forms:

—the solution of the system defined by equation (1.2) keeps its uniqueness but loses its asymptotic stability; i.e., the steady state becomes unstable;

—the solution loses its uniqueness, and then its stability; i.e., new solutions appear locally. Here, the matrix $D_x f$ becomes "degenerated," corresponding to a process of destructuration/restructuation for the system [200];

—taking into consideration the distribution of variables in space, a new term is added corresponding to the diffusion process. Under certain conditions, this term may introduce new bifurcation points. It plays an important role in the theory of nonequilibrium thermodynamics and dissipative structures, where a self-organizing process produced by fluctuations cannot be explained by the deterministic equation (1.2) [146];

—a specific type of bifurcation concerns gradient dynamics, i.e., systems for which the fixed point x* is a local minimum of the potential V defined by:

$$dx/dt = F(x,u) = -\operatorname{grad} V(x,u) = 0 \qquad (1.7)$$

where $-\operatorname{grad} V = (\partial V/\partial x_1, \partial V/\partial x_2, \ldots, \partial V/\partial x_n)$ is a gradient vectors field. These bifurcations are analyzed in the catastrophe theory developed by R. Thom [117, 118] who has proposed a classification of the elementary catastrophes [46, 164, 222].

1.2 From Deterministic to Stochastic Approaches to Spatial Dynamics

Discontinuities in the dynamic of an economic local space—a city or region—mark the evolution of this area. This morphogenesis is governed by changes in its relative situation according to various factors which contribute to its economic development or underdevelopment. The introduction of discontinuities implies the irreversibility of history, as opposed to the Newtonian dynamics, which assumes a harmonious, stable system and reversible trajectories [168, 95]. But the representation of discontinuity may remain entirely deterministic, with different changes and directions adopted at bifurcation points being operated through some objective process, generally an optimization process through the minimization of a potential. Such approaches to spatial dynamics are proposed by applications of catastrophe theory and mathematical ecology to urban and regional problems. They do not necessarily assume that human history is purely deterministic and that observers have a complete knowledge of the local dynamic factors. Rather, they may suppose that knowledge of the dynamic expressed by the potential is not useful in the formalization of spatial catastrophes [55], as Thom suggested, or that simple deterministic models, rather than probabilistic ones, are a satisfactory approximation to a complicated reality [85]. These approaches will be reviewed in Section 2.

The emergence of novelty [56]—that is, the integration of relative autonomy—implies a certain degree of undeterminism. However, the recognized scientific status of undeterminism is stochastic analysis; therefore the formalism of self-organizing processes is more often probabilistic. Such a view point may approach history as a mixture of determinism and hazard, as in the theory of nonequilibrium thermodynamics and dissipative structures developed by Prigogine [170]. In this case, the evolution of a local space is explained by some invariant factors (determinism) whose locally events produce a specific form (probabilistic aspect). But the stochastic approach does not necessarily assume that spatial dynamics is governed partially by chance; it may be justified by the fact that perfect knowledge is impossible and that the stochastic model expresses the observer's partial knowledge, or its ignorance. Hence, the novelty may not be absolute, but relative to the observer's knowledge. From a deterministic representation of a stochastic phenomenon such as in Prigogine's analysis, self-organization concept [89] presupposes a probabilistic representation of spatial dynamics as developed by Atlan in the formalism of the information theory [28, 29]. The processes of spatial self-organization are analyzed in Section 3.

2. Structural Stability and Morphogenesis of Spaces

As nonlinear systems [66], cities and regions imply discontinuities. Their space is neither homogeneous nor continuous: it appears through conflicts and jumps in spatial forms and histories. Such discontinuities may be analyzed as a loss of structural stability in bifurcation theory [222, 203, 167], which specifies both catastrophe theory and mathematical ecology.

2.1. Applications of Catastrophe Theory

For R. Thom, who has developed the catastrophe theory, "modeliser, c'est spatialiser" (modelling is spatializing [199, p. 12]). This explains the swiftness with which it has been applied to urban and regional problems. After developing a catastrophic model of urban civic plasma by analogy with the van der Walls equation [21, 22, 23] (a more economic approach is proposed by Richardson [180, 181]), Amson published a detailed, synthetic paper which presented the principles of the theory of elementary catastrophes, and which proposed to generalize its use in the approach to urban systems [24]. Similarly, Perrin asserted that catastrophe theory must be a basis for a new meso-approach to spatialized analysis [161]. A large controversy evolved about the use of catastrophe theory among English geographers subsequent to the modelling of the evolution of settlement patterns by Wagstaff in 1978 [206] (see [31, 205, 207, 208, 1, 72]). Today this infatuation seems old-fashioned, but for a few years during the seventies, many problems of regional and urban analysis were reexamined in the light of catastrophe theory, either in an analogical way, or in "catastrophic" approaches.

2.1.1. Analogical Applications

Analogical applications start with one of the equations which define elementary catastrophes: the fold, cusp, swallowtail, butterfly, and elliptic, hyperbolic, or parabolic umbilic. With a socioeconomic interpretation of variables and parameters, jumps and breakdowns produced by the equation of an elementary catastrophe are analyzed.

In the case of the cusp catastrophe, the potential

$$V(x,u) = x^4/4 + u_1.x^2/2 + u_2.x \quad (2.1)$$

is assumed to be an economic function like the social welfare function, or the profit and social cost functions if the inverse is taken; i.e., maximizing—V is equivalent to minimizing V. But the potential is not always interpreted and attention is often focused only on the cusp surface. With the economic interpretation of the state variable x (population, density, etc.) and of the parameters u_1 and u_2 (income, productivity, technological level, etc.), the cusp manifold is defined by the equation:

$$dV/dx = x^3 + u_1.x + u_2 = 0 \quad (2.2).$$

When the parameter u_1 (the splitting factor) reaches a critical value, the surface folds ($u_1 < 0$). Then, a continuous change in parameter u_2 (the normal factor) may produce three main catastrophic behaviours of the system (Fig. 1): jumps (a), hysteresis (b), and divergency (c).

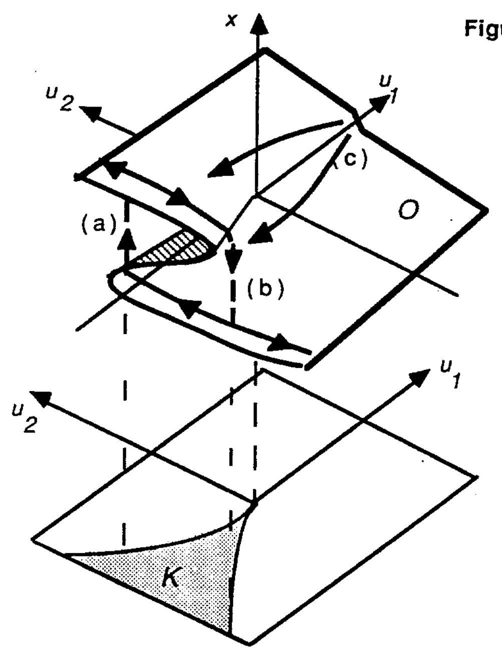


Figure 1 - The Cusp: Catastrophe of Riemann-Hugoniot

O observable behaviour set :
$\{ (x, u_1, u_2) \mid x + u_1 x + u_2 = 0 \}$

K catastrophic set : competition between several attractors

One of the most useful perspectives on spatial systems is the formalization of threshold and inertia effects. The former represents the sudden appearance of a new economic function, activity or equipment when some variable that varies continuously (population, for example) exceeds a critical value. This is equivalent to the bifurcation point in the cusp catastrophe with the perfect delay convention: a sudden jump in the equilibrium value of the state variable results from a continuous change in parameter u_2 when it leaves the catastrophic set. Reversing trajectory in control space (parameters one), the jump will appear for another value of the parameter u_2. This may easily be justified by the inertia of the existing structures which remain in place as long as possible: the threshold of disappearance is lower than the threshold of appearance. Such a hysteresis effect is often observed in many urban and regional problems, and this explains the success of catastrophe theory among specialists in regional science and urban economics.

In that way, the cusp surface formalizes discontinuities in spatial growth which is explained by thresholds in private and public equipments or economic functions [57, 55, 90, 147, 148] and by inertia in the behaviour of the economic agents (energy consumption for Nijkamp [150], and the transportation mode for Wilson [218] in a model calibrated by Blase [44]). Isard and Liossatos have proposed an explicit interpretation of the potential of the cusp catastrophe as a social welfare function which external effects use to define the optimal size of an agglomeration or a growth pole [106, 107, 108, 109].

Some authors have developed the formalization of urban discontinuities through more complicated catastrophes, especially the umbilics which integrate two different state variables. For Dendrinos, the potentials of the umbilics either are analyzed as social cost functions in the study of slums formation and in the evolution of the neighbourhood quality park [73, 76], or they are used to represent the location of economic activities in urban areas [74]. Puu has interpreted the potentials of umbilics as price landscapes in his analysis of the structural stability of exchange flows [175, 176, 177, 178, 39]; he extended his analysis of the stability of interregional trade flows by studying the bifurcations which occur in limit cycles produced by nonlinearities corresponding to multiplier-accelerator models [179]. With the butterfly catastrophe model, already used by Casti and Swain [57] to modellize discontinuities in land price variations, Mees has analyzed the revival of European cities during the medieval period [139, 26]. This author has explored one of the main issues of the "catastrophic" approach: the sudden jump in urbanization during the last two centuries.

2.1.2. "Catastrophic" Approaches

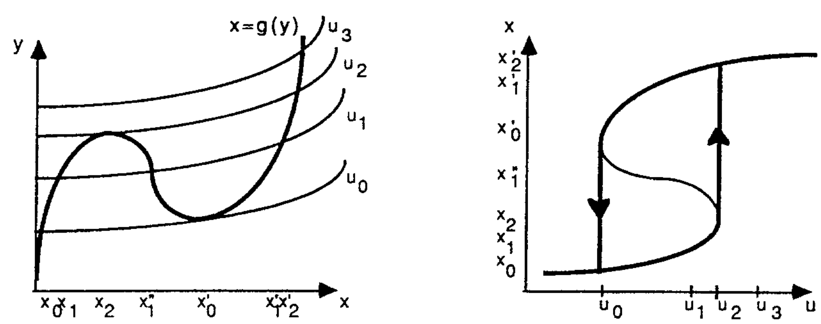
According to the "catastrophic" approaches, catastrophe theory is not a restrictive framework in which the spatial model must be reduced to one of the elementary catastrophe equations. Rather, it becomes a generalization of a socioeconomic argument. Therefore, these approaches are limited to the simplest catastrophes, the fold and the cusp, and their method can be summarized as follows. Two variables x and y are assumed to be related through two functions which are complementary for economic or logical reasons (for example: supply and demand, and rural-urban population balance). These relationships are specified by the parameters (u,v) as follows:

$$x = g(y) = G(y, v) \tag{2.3}$$
$$y = f(x) = F(x,u) \tag{2.4}$$

At the intersection of the two curves defined by equations (2.3) and (2.4), there is an economic equilibrium (x*, y*). When one of the parameters (u or v) changes, the corresponding function (f or g) is modified, the curve moves, and the equilibrium shifts. The change in equilibrium may become discontinuous under economic assumptions that induce curves which may or may not be strictly concave. Such jumps are related to the cusp or the fold catastrophes.

If f(x) is represented by a cross-section or a convex curve, the cusp catastrophe may be obtained if the first equation x = g(y) defines an S-shaped curve (the fold catastrophe appears with a strictly concave curve). Three cases are then possible: one, two, or three equibria, some stable (minimum), others unstable (maximum). If the second function has the form $y = f_u(x) = F(x, u)$ (or $x = G(y,v)$), then a change in the parameter u produces a shift of the curve defined by equation (2.4). This move can induce jumps in the evolution of the value of the state variable equilibrium, and hence, discontinuities in the system behaviour. A jump appears in the variation of x for the critical value of the parameter u_2 and the reversed path produces a jump for another value u_0 (hysteresis). This is a form of the cusp catastrophe (Fig.2).

Figure 2 - An example of the "catastrophic" approach



A continuous change in the parameter u produces a jump and hysteresis in the state variable x

In most applications, the parameter u, which is the factor producing catastrophes in the behaviour of spatial systems, is interpreted as a technological level and its variation as technical progress. Thus, structural instability is a precondition for innovation [25]. An important subject of these applications is the formalization of sudden jumps in urbanization (especially the explosion of urbanization during the last two centuries): the rural-urban population balance analyzed by Simon [187, 189] has been reinterpreted within catastrophic formalism by Casetti [50], Dendrinos [75], and Papageorgiou [155, 156, 157]. Casetti has applied such a formalism to other forms of spatial growth as well as the world economy [51, 52] and regional growth [53, 54]. A more specific application is Smith's model [191], which attributes the overbanking in the U.S.A. during the twenties to a catastrophe produced by the diffusion of cars throughout the population.

Fujita and Ogawa [93] have proposed a "catastrophic" approach of structural transitions in urban morphology and the evolution of land rent (see also [154], and [184] for a survey), but, at the intraurban level, the most important and general research has been developed at Leeds University. Here, A. G. Wilson and co-authors propose a systematic application of catastrophe theory and bifurcation analysis to urban modelling (for a synthesis, see [63, 64]). Formalizing spatial interactions in a Lowry-type model, the Wilson city has catastrophic behaviours resulting from two main factors: interdependency between variables and nonlinearities. The "catastrophic approach" is developed for two subsystems, the retail model and the residential location. For the retail model, Poston and Wilson's exploration of catastrophe theory [166] was extended by Harris and Wilson [98] in a general study of the bifurcation points, i.e., the critical values of the different parameters which lead to a sudden jump in the equilibrium size of the retail center in each urban zone. Such discontinuities are explained by the spatialization of consumer behaviour: the parameters represent economies of scale and inclination to transport. This geometric approach, completed by Harris, Choukroun, and Wilson [99], was analytically generalized [182, 183, 112] and the model was the object of numerical applications [60], computer simulations [61], and calibration on the Rome metropolitan area [124, 43]. The approach was extended to the residential location model [220], where more complicated nonlinearities multiply bifurcation points [62]. The generalization of the method leads to a new central place theory allowing for the analysis of urban morphogenesis [222]. But all these analyses are static or, at best, comparative static. With the introduction of dynamics, new problems appear concerning growth stability which mathematical ecology has studied.

2.2. Implications of Mathematical Ecology

Ecology is concerned with the analysis of population growth in a limited environment. Limited natural resources and interaction between species define the carrying capacity of the environment. A population x leads to an equilibrium size x^*, a process which can be reproduced by the differential equation of the logistic curve (Pearl-Verlhust equation):

$$dx/dt = \alpha.(1 - x/x^*).x \tag{2.5}$$

where α is the "intrinsic" growth rate. Growth is faster for low density and slows down for high density. In the case of a single population, such a dynamic may produce complicated trajectories analyzed by the "chaotic analysis" of local growth. Taking into consideration the interactions between species as in Lotka-Volterra models, spatial dynamics becomes more diversified.

2.2.1. Stability of a Spatial Growth Process: The Chaotic Analysis

Spatial economic growth can be treated as a trajectory towards a steady state. At any time t, the environment (social, technical, and economic conditions) defines an equilibrium location for different economic sectors (industry, services, residential housing) in a limited area (a city or a region). These locations determine local economic potentialities. Effective locations (Y_t) generally differ from potential ones (Z_t) and this difference is the motor of the economic growth. In this fast dynamic (synchrony), growth is an adjustment process of the local economic structure to the steady state equilibrium, an adaptation which is a function of the delay of response of the different agents (β). Such an adjustment process may be represented by the differential equation:

$$dY/dt = \beta \; Y_t \, (Z_t - Y_t) \tag{2.6}$$

Since $dY/dt = Y_{t+1} - Y_t$ and considering that the "ecological niche" is defined by $Z_t = (\alpha - 1)/\beta$, equation (2.6) is equivalent to the difference equation:

$$Y_{t+1} = Y_t \, (\alpha - \beta \cdot Y_t) \tag{2.7}$$

With a variable transformation $X_t = \beta . Y_t / \alpha$, equation (2.7) may be rewritten in the canonical form [221, 222]:

$$X_{t+1} = \alpha X_t \, (1 - X_t) \tag{2.8}$$

Equation (2.8) exhibits discontinuous, "chaotic" behaviour for critical values of the parameter α [122, 134]. The notion of "chaos" is based on the idea that if the system behaviour is strictly deterministic [40], it is unpredictable and appears chaotic for two reasons. First of all, with its extreme sensitivity to initial conditions, a small perturbance may lead to very different trajectories; secondly, aperiodic and interlaced cycles produce very complicated forms. Therefore, under some assumptions, equations of type (2.8) could produce discontinuities in the economic growth of a spatial system depending on the relation between the inertia of local agents (the delay of response to the potentialities given by parameter α) and the economic size of the local space (through the variable X).

Such an analysis has been explored by Wilson and co-authors in their study of the evolution of urban structure through the growth of retail centers. They used computer simulations to specify the effects of the variations of the parameters [37], especially the effects of an increase in energy prices, and the delay in consumer adaptation to such a sudden change [38]. Other "chaotic" approaches to local dynamics have been developed by Rogerson [185], White [213, 214, 215], and Leonardi and Casti who generalize such bifurcation phenomena through mathematical programming [121]. A global application of "chaotic" analysis to socio-spatial dynamics is proposed by Dendrinos and Sonis in their last publications [80].

Ecology is not the only modus for a "chaotic" approach, as suggested in Paelinck's "anti-fickien" diffusion model [152, 153], but it does offer a broader framework for the explicit integration of the environment. This environment could be decomposed into the analysis of the interrelation between populations as in the Lotka-Volterra models.

2.2.2. Utilization of the Lotka-Volterra Models: Toward a New Urban Ecology

An ecological equilibrium is a steady state with no variation in the population size. The stability of such a state may be analyzed through the model:

$$\dot{x} = A \; x = 0 \tag{2.9}$$

where $\dot{x}$ is the n populations growth vector ($\dot{x}_i = dx_i/dt$ for i varying from 1 to n), A is the interaction matrix (n x n), x is the population size vector (1 x n), and 0 is the null vector (1 x n). Considering two populations (n = 2), the model becomes:

$$\dot{x}_1 = dx_1/dt = \tau\ (a_1 + a_{11}.x_1 + a_{12}.x_2)\ x_1$$
$$x_2 = dx_2/dt = s\ (a_2 + a_{21}.x_1 + a_{22}.x_2)\ x_2 \qquad (2.10)$$

where τ and s are the delay of adaptation parameters. These Lotka-Volterra models integrate different forms of interaction between species depending on the signs of the parameters a_{12} and a_{21} (independently of the signs of the other parameters): prey-predator, competition for limited resources, symbiosis, amensal, commensal, and isolative [133, 135]. Mathematical ecology may be applied to urban and regional problems for which it is easy to justify an analogical approach. Therefore, Dendrinos and Mulally have proposed to classify six types of geography according to the forms of interaction between two spatialized variables x_1 and x_2, e.g., the ecological interactions between two species [85]. Bifurcations in the spatial dynamic from one geography to another correspond to the evolution of the local area.

This ecological approach has been used to analyze competition between agents or activities in a limited space, e.g., the spatiotemporal diffusion of innovations [193, 194] and the division of labor [68]. Competition between different areas—central places—has been also analyzed in the same model [113]. This formalism seems particularly adapted to modelize regional or urban cycles, which have been developed by Dendrinos and Mulally from the prey-predator model—Nijkamp [149] reaches the same conclusion with a different approach. In this model, two thresholds appear which can be economically interpreted:

—first, predator density (w) increases if prey population (z) is over the subsistence threshold for the predator (z_0):

$$dw/dt = a(z - z_0)w \qquad (2.11);$$

—second, prey density (z) declines if the predator population becomes too numerous ($w > w_0$):

$$dz/dt = b\ (w_0 - w)\ z \qquad (2.12).$$

For a local area characterized by two variables—the population x (equivalent to the predator) and the income y (prey)—the properties of the model given by equations (2.11) and (2.12) could be transposed to regional and urban analysis.

Note that this model introduces a marginal stability, an orbital cycle around the center (w_0, z_0) [101]. Asymptotic stability of the steady state (Fig. 3) implies that the model integrates a limitation on the population growth imposed by the environment (limited natural resources or limited space). Taking into consideration the effects of congestion and overcrowding, the model can be rewritten to specify the spatial dynamic as:

$$dx/dt = \alpha\ .(y - y_0).x - \beta .x^2$$
$$dy/dt = c.(x_0 - x).y \qquad (2.13)$$

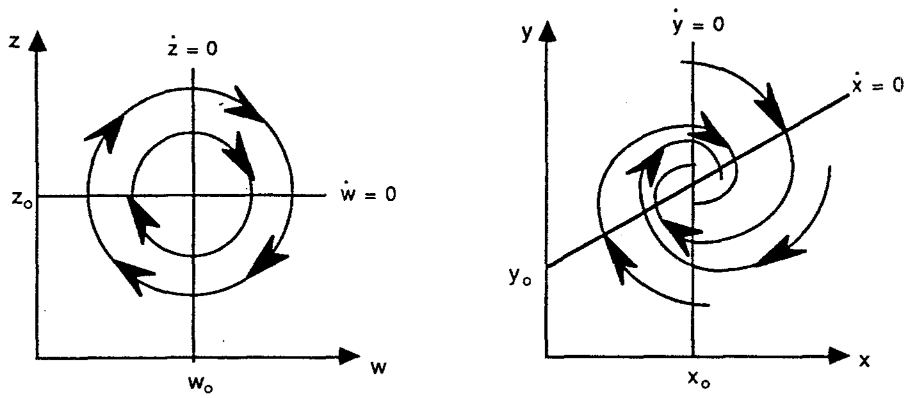
where x is the relative population (local population/national population) and x_0 the equilibrium share,

y is the local per capita income and y_0 the national one,

α and c are the adaptative delay parameters (α, migration speed), and

$-\beta x^2$ corresponds to negative external effects (overcrowding, congestion).

Figure 3 - Stability in the Prey-Predator Model



Marginal stability *Asymptotic stability*

The model explains a very simple spatial dynamic: local (urban or regional) population increases if local per capita income is higher than the national level (i.e., if the local area is attractive for external populations), but local per capita income decreases if the population exceeds a given threshold for which negative externalities become greater than positive externalities.

Dendrinos [77, 78] used this kind of model to formalize the regional dynamics in the U.S.A. during the period 1929-1979. Similarly, analysis of European regional growths has shown the existence of bifurcations in a regional cycle [48] which could be analyzed in the Lotka-Volterra formalism; this is suggested by the model FLEUR interpreted as a Lotka-Volterra model type [151]. Using this formalism, Dendrinos and Mulally [82, 83] have generalized an analysis of the urban cycle explored by catastrophe theory [81]. Even more ambitious is their project to develop a new urban ecology, an extension of the Chicago School through a theory based on applications of the Lotka-Volterra models to the interurban and intraurban dynamics [85]. The interurban dynamic seems stable and may be represented by the prey-predator model for all U.S. metropolitan areas—except for Rochester which exhibits marginal stability [84]. This is also the case for non U.S. cities, as the study of Madrid, Spain, has suggested [79]. On the contrary, the intraurban dynamic is unstable: numerous bifurcation points both between and within the different types of geography are implied by phenomena like gentrification/neighbourhood tipping, suburbanization/centralization, slums formation/historical preservation, and residential/manufacturing locations. Therefore, Dendrinos and Mulally propose a neo-Darwinian interpretation of the evolution of spatial structures according to which an optimization process governs the selection. This approach remains a deterministic one, as opposed to the stochastic analysis of the history of spaces by Allen and the Brussels school. Subjectivity and probability must be introduced to define a self-organizing process in urban and regional structures.

3. Toward a Self-Organizing Space?

At the 19th R.S.A. North American Congress, the presidential address proposed self-organization as the basic concept for a new theory in Regional Science which might resolve the unsolved problems of spatial dynamics [87]. Two main approaches have been applied to regional and urban problems in an attempt to analyze spatial structuration as a self-organizing process. The first, derived from Prigogine's theory of the nonequilibrium thermodynamics and dissipative structures, is a principle of order through fluctuations. The second approach finds its source in the application of information theory to biology, especially by Atlan. Self-organization is explained there by the principle of complexity through noise.

3.1. Spatial Order through Fluctuations

Prigogine has specified conditions necessary both for the maintenance of a system away from thermodynamic equilibrium (homogeneity) and for the production of new local forms of order, counter to the second law of thermodynamics (increase in entropy). Such a system must be open: exchanges of energy and matter with the environment are the permissive factors of self-organization (dissipative structure). Internally, the system must be composed of a great number of interacting elements associated through nonlinearities; the interdependency among elements and the form such interdependency takes, viz., nonlinearity, define a system's capacity for self-organization.

Nonlinearities produce a multiplicity of possible states in the system: with such a choice, the system becomes relatively autonomous with respect to its environment. Near bifurcation points, these nonlinearities induce an amplification of fluctuations (from internal or external sources) which lead the system to a new structure. A system history is then characterized by a sequence of stable periods when the system goes on a deterministic path, and by unstable moments, near bifurcation points, when fluctuations lead the system to a new trajectory. Both determinist and stochastic, history renders each system unique and each state irreversible.

From the Universite Libre de Bruxelles (Belgium), where Prigogine is established, this approach has been generalized in its epistemological aspects [171] and with applications in different sciences [146], especially in human and social sciences [170, 2, 3, 4]. Allen and co-authors have developed an analysis of urban systems from an application of the concept of self-organization at interurban and intraurban levels. These models have been elaborated in different reports to the U.S. Department of Transportation [18] and are summarized in [17].

3.1.1. Regional Space Structuration

Modelling the urbanization process of a region, Allen and Sanglier propose a dynamic version of central place theory based on the principle of order through fluctuations. Since the Christalle 's model is static, therefore the hexagonal structure is of a crystal order type. The introduction of time in either a static comparative [158] or a dynamic way [211, 212] disturbs such order and produces new interurban hierarchical forms. The emergence of such a spatial structure is analyzed as a self-organizing process in the Brussels interurban model in various publications, especially the Journal of Social and Biological Structures [12, 13, 15], and Geographical Analysis [14, 16].

This model considers the urbanization of a region as a successive integration of economic functions, the hierarchy in urban centers (central places) being deduced from the hierarchy in economic functions. The evolution of interurban structure is determined by the different locations of new economic activities which are the result of an innovation appearing when a critical threshold of population size is crossed (the minimum size of the market). Two main nonlinearities are introduced: the urban multiplier, and economies of scale for consumers (cooperation between economic functions). These nonlinear interactions produce instability in the interurban system, whose structure may change with the spatiotemporal diffusion of innovation. Such change occurs with the emergence of a new activity (function) in a central place and its diffusion through the region by imitation. Allen and Sanglier use stochastic laws which produce fluctuations in the population size of central places and these fluctuations lead to the threshold. The model introduces hazard in the emergence of economic functions and, hence, in the urbanization process of a region.

Different numerical simulations of the model by computer will produce different histories of a regional urban system (due to random effects), but permanent characteristics appear in all simulations concerning the evolution process and the urban hierarchy. Firstly, the evolution of an urban structure is always divided into four distinct phases: central urbanization, "growth-plateaux," counterurbanization, and polarization. Secondly, this evolution leads to an interurban hierarchy which verifies the rank-size rule (Zipf law). Some empirical evaluations of the model have also been proposed by its authors.

The model was extended in different papers. Camagni and co-authors [49] generalized the dynamic modelling of hierarchical interurban systems by integrating more specific economic arguments (technical progress, returns of scale, etc.). The model has also been modified to analyze changes in population distribution in a rural region, following the integration of service activities in different central places [88]. The same basic principles of spatial dynamics modelling have been used as well to analyze the evolution of regional growth disparities in the U.S. [5, 6] and regional energy demand in North Holland [7, 8].

Prigogine's research has suggested other applications which do not focus on regional structuration, but rather on the relative position of a region with respect to the global spatial dynamic, and especially on any change in this position. In a transition model of regional accumulation, Isard developed an analogical analysis based on error copying in genetics [105]. This led him to a stochastic approach to structural change so as to formalize such transitions [106]. With Liossatos, Isard has proposed models of transition processes based on the principle of order through fluctuations [107, 109]. One model is a stochastic version of the cusp equation: near the bifurcation set, fluctuations in state variables can produce jumps from one equilibrium state to another. This presupposes that parameters have the critical values necessary for system receptivity to fluctuations. Wilson has developed the same kind of argument, interpreting his model as an extension of Prigogine's work [219]. Another model proposed by Isard and Liossatos analyzes the emergence of economic novelty (innovations, new products, technical change, etc.) as a consequence of fluctuations and studies its effects on a spatial structure. Liossatos, again, has analyzed the Marxist approach of change in regional dynamic in relation with the thermodynamic of nonequilibrium [123].

As with the "catastrophic" approaches to space, technical change is often defined as the main factor in regional transition. Spatial crisis induced by industrial changes are opportunities for some economists to apply, metaphorically, Prigogine's concepts in the description and explanation of actual regional restructuring, especially in France [132, 163]. In a strictly analogical model, Curry applied the Prigogine analysis, formalizing the effects of price variations on the spatial structure [69].

3.1.2. Urban Spatial Dynamics

Mathis developed a metaphorical approach to the city as a dissipative structure in his systemic analysis of urban economics [129]. According to this approach, the basic principle of a city is its openness to an environment: its evolution depends on its ability to draw energy and information from its spatial environment, that is, the negentropy to compensate for the internal production of entropy. This ability is a function of the variety, diversity, and complexity of the urban structure, i.e., information. This type of intraurban dynamic has been modellized by Allen and co-authors [9, 10, 11, 19].

The model describes the locations of different interacting economic activities which compete with one another for the use of the limited space in a city. This competition is concentrated on the bid-rent. The intraurban model develops the same analysis of spatial dynamic, as proposed in the interurban model: the urban multiplier and external effects. Distinction between export-related (basic sector) and local activities is disaggregated into different industrial and service sectors. Alternative locations of manufacturing or residential activities within a city are then a function of the relative local attractiveness for each sector. These can be explained by three factors: attraction or repulsion between different types of agents, vacant land (bid-rent, congestion), and generalized transportation costs.

Such a model analyzes the evolution of a city as a self-organizing process through qualitative changes in the urban structure. The integration of a transportation system—which can be modellized by the principle of order through fluctuations [86]—completes the model, and simulations of metropolitan development are proposed to describe the effects of urban policy decisions. The model is the subject of a global program of empirical calibration on different French cities by Pumain and co-authors [172, 174]. These same authors have emphasized the closeness between Allen's and Wilson's approaches [173], but similarities in formal aspects of modelling must not conceal oppositions in the dynamic processes.

Although the Wilson urban model is a Lowry-type and the Allen one is deduced from the EMPIRIC model, their structures remain very similar, integrating nonlinearities especially through the urban multiplier and external effects. This suggests a general type of spatial dynamics formalization [126]. At a moment in time t, urban space is characterized by the distribution of the economic activities (k) in different zones (i); hence, this space may be represented by a matrix $X = \{x_i^k(t)\}$. In each zone, growth in one economic sector is expressed by the logistic curve (indices i, k and t are omitted for simplification):

$$dx/dt = \tau .(y - x).x \tag{3.1}$$

Growth is thus a function of the difference between the potential location (y) and the actual location (x), taking into account the delay of response of economic agents (τ). Potentialities are determined by the location demand deduced from the urban structure (x) and from external factors (z), with respect to the relative attractivity of the zone considered (A_{rel}):

$$y = f(x,z) \cdot A_{rel} \tag{3.2}$$

This relative attractivity (A_{rel}) is a composite function of the negative and positive external effects (function w) produced by the other sectors (proximity, overcrowding) and of the generalized cost of transport (cost function g and distance d):

$$A_{rel} = w(x)^{\alpha} \cdot \exp(-\beta . g(d)) \tag{3.3}$$

Wilson has pointed out the existence of critical values for the parameters α and β , which produce bifurcations in the urban space morphogenesis. With the instabilities corresponding to the delay of response τ, it could seem that the fluctuations of the "dissipative" city meet the jumps of the "catastrophic" city. But such a view neglects the oppositions within the approach of the spatial dynamic.

Although the Wilson and Allen models are structurally similar, they do not produce the same type of spatial dynamics. This is explained by their opposing epistemological foundations: strict determinism in the Thom approach, which modellizes catastrophes on a trajectory along the equilibrium states; and a mixture of determinism and chance in the Prigogine analysis, wherein dissipative structures lead the evolution away from equilibrium (see the discussion around "Halte au hasard, silence au bruit" (Stop to hazard, Silence to noise) in the French review Le Débat (201, 169). In the Wilson model, the urban dynamic is analyzed mainly through the variation of parameters corresponding to the transformations of economic norms and social praxis. Such variations produce discontinuities in the urban forms which are the results of sudden jumps in the equilibrium state. By contrast, the Allen urban system never reaches equilibrium because interactions between sectors and urban zones lead the system to new trajectories away from equilibrium. According to Allen, the evolution of the urban system is the result of external changes and threshold effects: fluctuations are amplified by the nonlinear interactions (the urban multiplier). Parameters are assumed to be stable as long as there is no change in factors governing the general spatial dynamic.

The principle of order through fluctuations gives a deterministic representation of spatial dynamics (possible states of the urban or regional system are defined by the model's equations) in which stochastic perturbations play an essential role in the choice of one of the predetermined behaviours. But the main structural principles of spatial organization are invariant and the history of the spatial system gives it only a specific—but not a new—configuration. Taking into account the relation between the system and the observer, Atlan proposed a probabilistic representation of the self-organizing process in the formalism of information theory.

3.2. Increasing Spatial Complexity through Noise

Information theory has been used largely by biologists in their systemic approaches to the Living. A living system is the chief example of an open system, which escapes from the second law of thermodynamics by means of its openness to the environment [42]. Biology often tends to assume a leading role as a model for other scientific disciplines; thus, numerous sytemic analyses in urban and regional problems are applications of the results of biologists' research. Although the basic work of Varela on autopoiesis [204] does not seem to be used, despite the potentialities of its application to the social sciences [224, 225], two authors are often mentioned: Atlan, who has developed an analysis of the organizing effects of noise for the living system and the observer [28, 29]; and Laborit, who has emphasized the ideas of different organization levels and information forms, structure-information and circulating-information [116, 117]. The first approach allows for a formalism of spatial organization within the language of information theory, while the second refers to a general systemic modelling of urban or regional dynamics based on a biological metaphor.

3.2.1. Information Theory with Noise and Spatial Organizing Processes

For communication engineers who developed the information theory [186], the problem was to produce a statistical approach to information so as to optimize the communication transfer between a source of information and the destination of a message (independently of its meaning). This takes into consideration the constraints that (1) the maximal capacity of a communication channel limits the quantity of information which can be transmitted, and (2) noise on the channel transforms the information that is transmitted. During the transmission noise destroys information, but it also adds new information.

A message can be interpreted as a sequence of independent signals characterized by their probabilities of occurrence p(i). The representation of a discrete information source as a Markoff process leads Shannon to propose a measure of the quantity of information contained in a message through the equation:

$$H = -k \sum p(i).\log p(i) \tag{3.4}$$

where k is a positive constant. The entropy of a statistical distribution is defined as $H = - \sum p(i).\log p(i)$ which has minimum value (0) when the occurrence of one event is certain ($p(i) = 1$, $p(j) = 0$ for all $j \neq i$) and maximum value ($H_{max} = \log N$) in the equiprobability case ($p(i) = 1/N$ for $i = 1,\ldots,N$). In this context, entropy does not have the same meaning as it does in thermodynamics: rather, it is a measure of uncertainty, of information associated with a stochastic process.

To reduce the effects of noise and increase the quantity of information transmitted, redundancy may be introduced in the message sent by the information source. This redundancy corresponds to the possibility of predicting one signal from another signal. Through relative entropy, i.e., the entropy H proportional to the maximal entropy H_{max}, the measure of redundancy is:

$$R = (H_{max} - H) / H_{max} = 1 - H/H_{max} \tag{3.5}$$

Information theory has received a new interpretation with Brillouin's book [45], which replaces this theory in the process of scientific knowledge. From a subjectivist point of view, entropy is relative to the partial knowledge that an observer may have of the microstates of an observed system: it measures the lack of information on the real structure of the system. Brillouin proposes a new measure of information, whose relations with Shannon's entropy have been studied by Webber [209, 210]. This measure is the main one used in the numerous applications of information theory to urban and regional problems. Most of these applications, especially in the work of Wilson [217], have developed the formalism of maximizing entropy proposed in Jayne's analysis in the field of statistical mechanics [110]: maximizing entropy is a method which estimates the most unbiased statistical distribution, given a state of limited knowledge of the microstates of a system (as an absolute knowledge of such numerous microstates is impossible). The extension of such an approach through the minimum information principle [192] offers new perspectives with the measure of information gain proposed by Kullback [114], especially in the problem of spatial aggregation [35, 36].

Another way of applying information theory to urban and regional analysis is derived from Wiener [216], who interpreted Shannon's entropy as a measure of disorder, i.e., disorganization in a system, and its inverse -H as a measure of system order, organization, or complexity. Such an interpretation is still contested [202]. Some applications have defined entropy as a statistical measure of a spatial system's organization. According to Theil [196], the entropy associated with an observed spatial distribution of a variable is considered to be a concentration ratio: its evolution over time indicates the tendencies of spatial disparities to increase or to decrease (see, for example [78]). In the same way, central place theory is reanalyzed in informational terms: an interurban hierarchy is a form of a spatial order for Berry [41], and Medvedkov identifies the distortions from the theoretical model produced by concrete geographical space as the effects of noise [138]. But this remains a static approach to information theory, while self-organization implies a dynamic approach.

Order appears through regularities, interaction between elements, and the structuration that an observer perceives in a system. Redundancy corresponds to the partial knowledge achieved through the organizational constraints between the elements of the system studied (conditional events). From the definition of redundancy (equation (3.5)), Von Foerster has modellized a self-organizing process as an increase in system order over time ($dR/dt > 0$) which is the result of its relations with the environment [91]:

$$dR/dt = \frac{(H.dH_{max}/dt - H_{max}.dH/dt)}{H_{max}^2} \qquad (3.6).$$

Self-organization is then produced by two factors: the importation of variety (dH_{max}/dt) from outside, and the increase in internal constraints (dH/dt). It is a principle of order from order, an increase in internal order being paid for by a decrease in environmental order (entropy growth). A direct application of this model has been realized by Marchand [128] who considers different scenarii of urban growth given the local social diversity and the intensity of the social constraints. He aplies his models to three different cases: North-American metropolitan areas, European agglomerations, and the city of Algiers. But Von Foerster has proposed an other principle of order through noise, which Atlan has developed and reformulated as complexity through noise.

For Atlan, complexity denies system order as discerned by the observer: it is an ignored order which can be interpreted as disorder. A system's complexity (H) is a lack of observer knowledge of the internal constraints of the system (redundancy R) given by:

$$H = H_{max}.(1 - R) \tag{3.7}$$

where H_{max}, interpreted as a state of complete ignorance, is a function of the number of the possible states of a system, i.e., its variety. The self-organizing process is the increase in complexity over time under the accumulated effects of noise (fluctuations of the environment); that is,

$$dH/dt = -dR/dt.H_{max} + (1 - R).dH_{max}/dt \;>\; 0 \tag{3.8}$$

The first term on the right corresponds to the positive effects of noise, which reduce the quantity of transmitted information through a communication channel by means of the decrease in redundancy ($g(t) = dR/dt < 0$). In the second term appear the negative effects of noise, the loss of information for the observer ($h(t) = dH_{max}/dt < 0$).

Noise produces double effects: both the destruction of information (a tendency towards disorganization) and the production of complexity (making up for the disorganization). The observed system is able to reorganize itself under the effects of environmental fluctuations (hazard to the observer) in spite of information lost between its components. This increases the quantity of information missing for the observer, and then increases the complexity. From the initial variety (H_{max}) and redundancy (R), the reliability of the system, i.e., its resistance to changes produced by noise, must be studied under different assumptions about the functions g(t) and h(t).

The perspectives that such a formalism offers for an analysis of economic evolution, especially the study of the spatiotemporal diffusion of innovation, have been explored by Curry [70]. But the applications of Atlan's principle remain largely metaphoric: the spatial organization is defined by its ability to integrate the effects of environmental fluctuations in a process of destructuring / restructuring of local economic activities (assimilation of noise effects by the spatial system). This analysis results from the approach to the spatial system as a biological organism, i.e., the biological metaphor.

3.2.2. The Biological Metaphor

The systemic approach defines regional or urban development as a process of complexifying of the spatial economic structure. This notion of complexity, between its mathematical definition [94] and the epistemological developments concerning the emergence of a new paradigm [143, 144, 145], remains scientifically ambiguous. Such a cleavage between the Anglo-American approaches and the dialectical discourses of French culture has been emphasized by E. W. Ploman in his introduction to the publication of the minutes of the meeting on "The Science and Praxis of Complexity" organized by the United Nations University at Montpellier (France) in 1984 [103]. However, in regional and urban analyses, the term takes on the meaning proposed by Passet [160]: economic development is a complexifying growth process which integrates not only the accumulation of wealth but also the diversification of economic activities associated through intensified connectivity, that is, through a network of increasingly dense interrelationships.

Such an approach leads to the search for a justification of an economic principle of decentralization. Biology seems to offer a suitable paradigm for this: the organization of living is defined as a system which maintains its structure by means of the relative autonomy of its elements (see, for example, Laborit for the biological paradigm itself [116, 117], and Passet for its application to the economic decentralization problem [159]). Molecular biology proves the necessity of a "system of minimal autonomy" for biological reproduction [102]. The main properties of a living system can be summarized as follows: it is open to its environment and to itself through different levels of organization, and it reproduces its own internal structure by means of this energetic and informational opening. This self-reproduction constitutes its finality and implies a minimum threshold of diversity, a variety necessary for the adaptability of the system to the effects of environmental fluctuations. Openness, multilevel hierarchical structure, finality and diversity are then the main characteristics for a regional or urban spatial system. They are the preconditions for a process of economic development.

The property of openness is obvious for regional and urban spaces: they are influenced by social and technical environment in which dynamics can transform the local economic structure, and they interact with other cities or regions. But the difficulty is to define them as systems. It could seem relatively easy to identify a city through the external effects associated with the proximities between economic agents, and to interpret an agglomeration as a system [140, 41]. But the systemic characterization of a region is less obvious: its openness dilutes its identity. One approach is to define a regional system in light of the local forms, according to the principle of regional unity versus local diversity [71], or in relation to other spatial levels, by means of the notion of "organizational closure" [204].

In that case, the regional system is integrated into a economic space organized into different hierarchical levels [188] that are open to one another [162]. On the basis of the mathematical foundations of the Mesarovic's theory of hierarchical multilevel systems [141, 142], such an approach to the region has been developed to analyze the spatial structuration of the decision process [33, 34, 109]. Although the approach seems to be well adapted to planning questions [136], its possibilities remain analytically limited to a static situation. A dynamic approach still seems impossible, because this formalism cannot integrate the higher levels of complexity of the systemic object: learning, self-organization, and self-finalization [119].

As with all open systems, spatial dynamics may be characterized by the ability of the region or city to integrate environmental fluctuations and external changes. The adaptability of a space is just its ability to compensate for the destructuring effects produced by the environment with a restructuring process which complexifies its organization. Such a phenomenon is a direct function of the system's reliability, redundancy (see Atlan), and variety (see Ashby's law of variety): the diversity of economic activities and agents is necessary for the economic development of the local area, defining its plasticity. Diversification is one form of this complexifying process. By contrast, lack of variety could explain urban and regional crisis [130, 132] or inability to adapt to technical change [164]. In that case, it contradicts the main finality of each system: self-reproduction.

The finality of living systems is often defined as survival, what Laborit calls the permanence of the information-structure [116]. In the same way, the finality of a spatial system may be defined at a general level as the realization of its own reproduction, completed with economic ends [131]. But an overly general application of the finality principle takes away credibility from the systemic approach. Therefore, different authors have proposed a more restricted definition of the spatial system finality. The notion of a "hypo-integrated system," defined as a system that is finalized ambiguously, and that offers much autonomy between subsystems, seems particularly useful for urban and regional analysis [59, 164]. The finality is then not absolute, but rather relative to each space and time: systems are historical forms which must not be considered as definitive. This idea is suggested by Barel, who analyzed the European medieval city as an urban system [32]; however, with the biologist Laborit [115], he denies the status of system for modern cities, inasmuch as they have lost the property of self-reproduction. Auriac has proposed a historical analysis of the viticultural system in the Languedoc region in the south of France [30]. For this author, self-finalization constitutes a self-organizing process in the emergence of the local area as a system: self-organization is spatialization.

4. Conclusion and remarks

The main purpose of the works surveyed in this paper is theoretical: the complexity of social phenomena seems difficult to calibrate in canonical forms corresponding to mathematically sophisticated models. Nonlinearities produce interesting analytical effects but complicated dilemma for empirical adjustments. Some efforts have been achieved in calibrating the Brussels school models and the Dendrinos ecological ones, but a feasible means for testing such adjustments is lacking. Computer simulations of theoretical models are easier than calibration. Therefore, empirical approaches to urban regional problems with new systemic instruments are mainly metaphoric or analogic.

Despite some contradictions and limitations [125, 127], the analytical efficiency of the new systemic instruments, useful for modelling both the formal aspects of spatial dynamics and their theoretical explanations, appears primarily in two main areas: threshold effects and spatiotemporal diffusion of technical change. Using a deterministic approach, catastrophe theory and mathematical ecology consider regional and urban areas in light of two determining factors: their economic environments and spatial hierarchies. The self evolution of social relations and technical system entail the laws of transformation of spatial dynamics. These laws are imposed on local areas which are integrated in a form of spatial organization hierarchized by socioeconomic constraints. Depending on other areas, a city or a region undergoes a global spatial dynamic which it cannot change, but it tries to adapt its socioeconomic structure to the changes imposed exogenously. Such a formalism explains the local dynamic without any reference to a relative autonomy of spaces: rather, it belongs to the approach qualified as "development from above," while self-organizing processes offers new possibilities for modelling "development from below" [195].

Modelling the process of spatial self-development necessitates some undeterminism in the evolution of areas. From this perspective, the analysis of structural stability and morphogenesis is doubly enhanced by the concept of self-organization: first, it formalizes the main role which marginal agents (innovators) can play and which can lead to bifurcations in the history and the future of a city or a region; second, self-organizing processes imply an ability of the local economy to integrate external changes. This ability is determined by the existence of thresholds relative to diversification and structuration. Such an approach gives the most leeway to local economic agents and authorities. In today's historical context of technological and social changes, which produce new forms of spatial dynamics, such a formalization could be particularly helpful to local authorities: through the identification of areas where political intervention is efficient, it could contribute to the elaboration of local policies of development which take advantage of structural instability rather than reproduce obsolete practices.

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