Faculteit der Economische Wetenschappen en Econometrie

ET

05348

Serie Research Memoranda

Impacts of Changing Environmental Conditions on Transport Systems

P. Nijkamp
A. Reggiani

vrije Universiteit   *amsterdam*
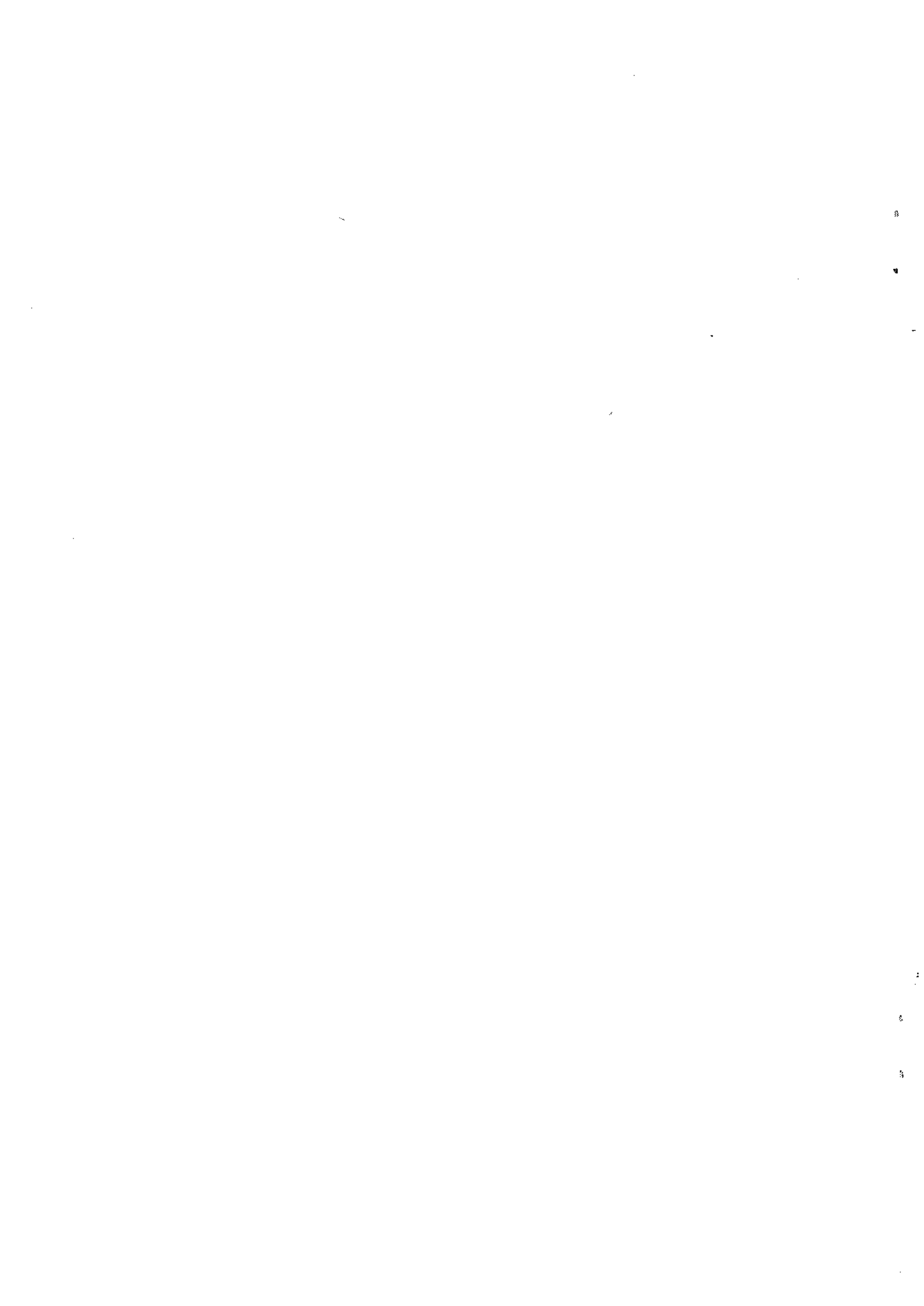
1. MAN AND ENVIRONMENT: A HIERARCHICAL-EVOLUTIONARY APPROACH

"There has been much recent debate concerning the nature of environmental systems. Much of this arises from the recognition of the increased interaction between man and nature, and of the ascendancy of the former leading to the modification of the better" (Bennett and Chorley, 1978, p.xi).

In the context of man-nature interactions, it is clear that the complex interface man-environment poses difficult analytical problems, in particular the question whether man is separate from nature, for instance, by adjusting the natural environment behaviour within constraints of natural lows to his individual goals and purposes. The man-environment interdependence and evolution are also represented in laws from evolutionary theories developed recently in ecology/biology as well as in economics.

Recently, Rosser (1991, 1992) has underlined the dialogue between economic and ecological theories of evolution. In particular, he has pointed out how economics was influenced by ecology in the analysis of complex dynamic phenomena, such as cycles (first analyzed in nature by Lotka, 1920, and Volterra, 1931), and bifurcations and chaos (discovered by May, 1975, in his studies of insect populations). For example, also the vivid debate on the nature of evolution, viz. gradualism (i.e., continuous evolution) advocated by Darwin (1859) vs. saltationism (i.e., discontinuous evolution) advocated e.g., by Wright (1931), was later on followed by economists. On the one hand we may refer to Marshall (1920) as the greatest admirer among economists of Darwin by accepting the proposition that the 'struggle for existence' explains the evolution of market structure and that human society gradually and continuously evolves (gradualism in evolution). On the other hand, we may refer to Schumpeter (1934) for whom the "very essence of economic development lies in the discontinuities engendered by the innovative activities of entrepreneurs" (Rosser, 1991, p. 208). Positioned in between the two streams of theories (for a wider review see again Rosser, 1991), Boulding (1978) argued for a mix of continuous and discontinuous processes in

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which instability - even though rarely - plays a significant role by generating discontinuous events. Starting from these recent discussions this paper will consider the hypothesis that economics and ecology are two evolutionary complex systems, with the possibility of both continuous and discontinuous processes interacting with one another at different levels of structure (or capacities of the system).

In the present paper we will consider, in particular, as an interesting example, the relationships between transport systems and environmental systems, by supposing the following interdependence (see Figure 1) as described by Mesarovic and Pestel (1975).
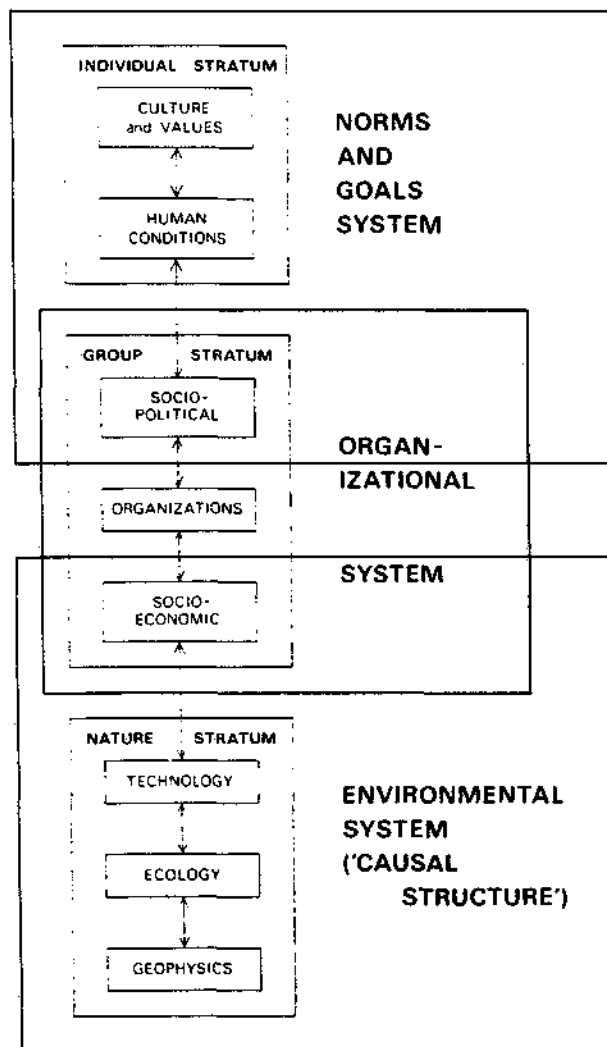

Figure 1. The interfacing of the man and environment systems
(After Bennett and Chorley, 1978, p.506)

The previous interdependent system may lead to interesting dynamic interactions of the potential of these systems. Here we will transfer the previous relationships displayed in Figure 1, in a dynamic context as follows (see Figure 2):
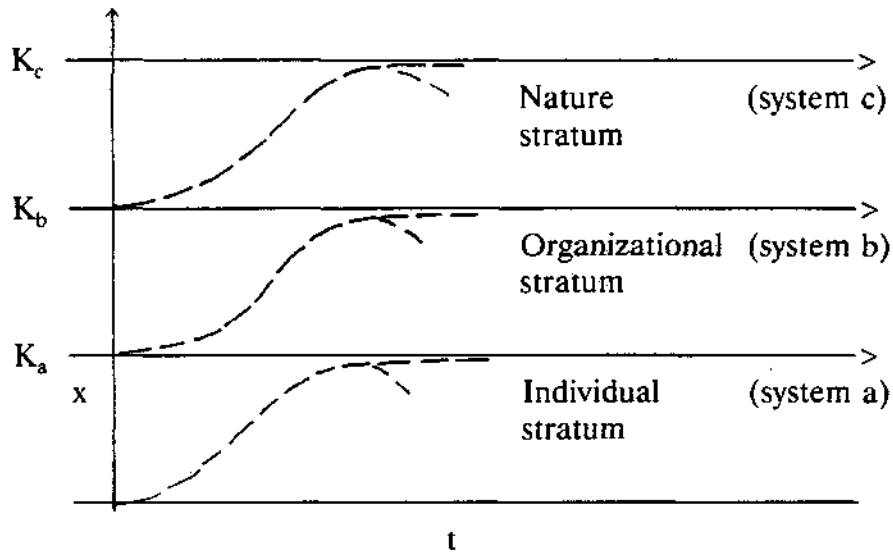

Figure 2. The dynamic relationships 'man-environment'

where the time-dependent variables K_a, K_b, K_c represent the related capacity of the three systems, shown here as logistic functions.

In Figure 2, we suppose the emergence of a higher level of structure which altogether leads to the emergence of greater complexity or to the 'progressiveness' of the evolution. However, it should be noted that in our hypothesis the three capacity levels K_a, K_b, K_c are not fixed, but may vary as state variables over time. This means also the possibility of generative feedback processes or system's overlapping, in other words, the emergence of the possibility of explaining 'devolutionary' dynamic processes.

Then the evolution of each system can be considered as the result of the competition between different subsystems within the main system, leading to a self-organisation process. Such a structure can easily be modelled by means of a recent and increasingly popular approach to competition analysis in ecology and social sciences viz. niche theory (see also Nijkamp and Reggiani, 1992a). This will be dealt with in the next section.

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2. SOME CONCEPTS FROM 'NICHE THEORY'

2.1. Definitions of 'niche' in ecology

The term 'niche' has become a popular concept in ecology and biology. Grinnell (1917) was the first scientist using the term 'niche' in order to describe the 'functional role and position of an organism in its community.' His work was followed by other ecologists such as Elton (1927) who claimed: 'the niche of an animal can be defined to a large extent by its size and food habits' and Clarke (1954) who distinguished between the 'functional niche' and the 'place niche'. Clarke also observed that the same functional niche may be filled by quite different species in different geographical regions. This concept was subsequently more specified by Odum (1959) who considered the habitat as the organism's 'address' and the niche as its 'profession'.

Later, a modern approach was offered by Hutchinson (1957) who defined a niche as 'the total range of conditions under which the individual (or population) lives and replaces itself'. He also made a distinction between the 'fundamental' and the 'realized' niche (see Section 2.2).

It is thus clear that the term 'niche' has been used in a wide variety of different contexts, while it has also met some criticism by a few ecologists (see Pianka, 1976). Following Pianka (1978, p. 238), we will now define here a niche as "the total sum of the adaptations of an organismic unit or as all of the various ways in which a given organismic unit conforms to its particular environment". This definition emphasizes in particular dynamic feedback patterns, which are the subject matter of our paper.

Recently, the niche concept has also been linked to the phenomenon of inter-species competition and to dynamic patterns of resource utilization.

2.2. Formalization of the niche concept

The niche concept deals with optimal adjustment (or survival) processes in dynamic systems with scarce resources. Usually niche relationships among potentially competing species are often visualized by means of bell-shaped

resource utilization curves, starting from Hutchinson's works (1957) on the law of tolerance (or curves of performance - or tolerance curves - analyzed by Shelford, 1913) (see Figure 3).
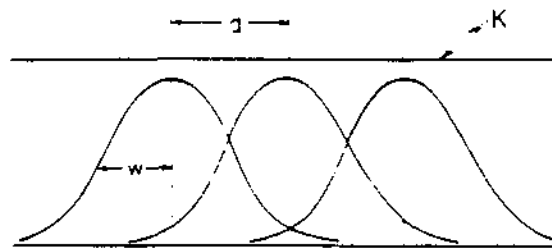

Figure 3. A bell-shaped tolerance curve. The curve labelled K represents some resource continuum, say amount of food as a function of food size, which sustains various species whose utilization functions (characterized by a standard deviation w and a separation d) are as shown). (Source: May, 1973, p. 140)

Tolerance curves are typically bell-shaped and unimodel, with their peaks representing optimal conditions for a particular process and their tails the limits of tolerance. Performance or tolerance curves are often sensitive to environmental variables. Such external conditions may be multidimensional in nature and governed by synergistic linkages. In order to identify optimal adjustment (or survival) patterns of species (i.e., the best fitness), a non-linear programming model would have to be specified, which - in case of multiple objectives for the organisms concerned - might even take the form of a non-linear multi-objective programming model.

Consequently, when tolerance is plotted against a single variable we get the following shape for a chain of niches (see Figure 4).
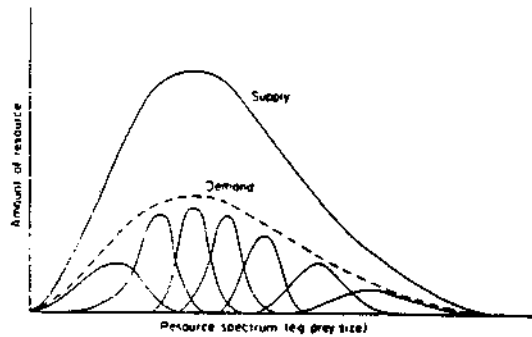
Figure 4. Chain of niches
(Source: Pianka, 1976, p. 117)

In Figure 4 the vertical axis measures the amount of resource available in some time interval. The upper curve represents the supply of resources along a single resource continuum (e.g., prey size or height above ground). The seven lower curves represent seven (hypothetical) species; in particular those with longer tails have broader utilization curves (i.e., broader niches) because their resources are less abundant. Their total sum indicates more or less the envelope curve of their demand.

By adding next new variables to the horizontal axis we get the tolerance curves in a 'more-dimensional' space (see, e.g., Figure 5 for two dimensions).
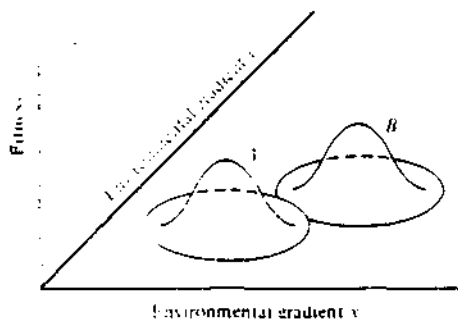

Figure 5. A three-dimensional plot with a fitness axis
(Source: Pianka, 1978, p. 240).

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Besides these concepts of tolerance and fitness, also other concepts are useful in this context such as the concept of niche 'breadth' (or 'width' or 'size') which is simply the total sum of the variety of different resources exploited by an organismic unit (or individual or species).

It is clear that any real organismic unit does not exploit its fundamental niche (or virtual niche, i.e., the idealized niche in which the individual can live and replace itself in the absence of any competitors or other enemies), since its activities are curtailed by its competitors (or its predators). Thus the realized niche (or actual niche) is a subset of the fundamental niche, since the difference between the fundamental and realized niche reflects the effects of interspecific competition.

Another central aspect of niche theory concerns the amount of resource sharing, or niche overlap. Many ecological models (see Pianka, 1976) suggest that the maximum tolerable niche overlap should decrease as the number of competing species increases, where such a decrease in overlap would by approximation be a decaying exponential function. From a mathematical viewpoint measures of niche overlap are often divided by the estimates of the competition coefficients in the usually Lotka-Volterra competition equations (see also the next Section 3). However, it should be noticed that relationships between niche overlap and competition are dubious. For example, "although niche overlap is nearly a prerequisite to exploitative competition overlap need not necessarily lead to competition unless resources are in short supply" (cf. Pianka, 1976, p. 122).

Thus niche overlap is only a necessary but not a sufficient condition for exploitation competition. For instance, in case of complementarity (i.e., joint positive use of a resource) there may often be an inverse relationship between competition and niche overlap, so that extensive overlap might be correlated with reduced competition (see again, Pianka, 1976).

In order to clarify the above concepts but to offer at the same time a framework for confronting ecological concepts with those from the social sciences, we will in the next sections present some formal models on niches and niche chains.

3. EVOLUTION OF A SYSTEM BY MEANS OF 'NICHE' CHAINS

3.1. Introduction

Starting from an analysis carried out by May (1973) we will show here how niche theory can be embedded in standard competition models whose potential has recently been advocated for geography and economics (see Nijkamp and Reggiani, 1992b, 1993).

As a starting point we will analyze here the prototype model of several competing populations studied by Lotka (1925) and Volterra (1926) and interpreted on the basis of niche theory by May (1973):

$$\dot{x}_i = x_i \left(K_i - \sum_{j=1}^{m} \alpha_{ij} x_j \right) \tag{3.1}$$

where x_i is the population of a species i (i = 1,2,...,m), the constant k_i represents the suitability of the environment for the ith species (e.g., carrying capacity) and the competition coefficients α_{ij} measure the overlap in the utilization functions depending via the ratio of d to w (see Fig. 3) on the ith and jth species. In particular May interprets k_i as integrals - with respect to some parameter y - over the product of the resource spectrum (K(y)) and the utilization function $F_i(y)$ of the ith species (depicted in Figure 3) (see 3.2). Furthermore, May defines the competition coefficients α_{ij} essentially as convolution integrals between the utilization functions of the ith and jth species:

$$K_i = \int K(y) \, f_i(y) \, dy \tag{3.2}$$

$$\alpha_{ij} = \int f_i(y) \, f_j(y) \, dy \tag{3.3}$$

Thus model (3.1) is tied now to the underlying 'microscopic' model illustrated by Fig. 3. While first the 'macroscopic' parameters k_i and α_{ij} were phenomenological constants, we have now an explicit interpretation for k_i and α_{ij} in terms of direct biological assumptions (see again May, 1973). This implies also an eventual feedback between the macroscopic structure of the evolutionary process

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described by (3.1) and the related microscopic mechanisms displayed in Fig. 3, so that the macroscopic structures emerging from microscopic events would in turn lead to a modification of the microscopic mechanisms (i.e., niche overlapping). It should also be noted that the extension of the Volterra scheme of type (3.1) based on the Pearl-Reed equation (see, e.g. Sonis, 1991, 1992) is also efficient in this context.

Model (3.1) is not only a standard model in ecology, but has also been applied elsewhere, even without an explicit reference to niche theory. For example, system (3.1), simply interpreted as a competition system, was used by Johansson and Nijkamp (1987) in their study on urban and regional development with competing regions.

It is well-known (see Smith, 1974) that for the system of type (3.1) (for both the continuous and discrete time specification) the equilibrium - if it exists - is either stable or unstable, but in either case non-oscillatory. However, in a recent analysis (see Nijkamp and Reggiani, 1993) the possibility of irregular behaviour emerging in case of the presence of a 'chaotic' evolution in the system has been shown. An interesting step from this latter analysis is consequently the introduction of the niche concept in such a competition system. For this purpose we will analyze in the following subsection the evolution of a competition system on the basis of equation (3.1), where we will analyze the self-organizing potential of a dynamic system with two species.

3.2. Evolution of self-organizing systems

Biological evolution takes normally for granted three determining factors:
a) reproduction, b) selection through competition and c) variation through "mutation" (see Nicolis and Prigogine, 1977). All these factors can be represented by a generalized equation of the type (3.1) (see Nicolis and Prigogine, 1977):

$$\dot{x}_i = N_i x_i [K_i - \sum_j \beta_{ij} x_j] - d_i x_i + F_c(x_j) + F_r(x_j) + F_m \{(x_j, x_j^e)\} \qquad (3.4)$$

where:

N_i = growth rate of species i

K_i = carrying capacity of species i

F_c, F_r, F_m = non-linear functions describing, respectively, the rate of competition other than implied by equation (3.1), the rate of regulation and the rate of migration (or movement), the latter one depending also on external values of x_i.

It is clear that from equation (3.4) many particular cases can arise, for example, the well-known prey-predator system. In this context it is also interesting to observe that from equation (3.4) also the concept of 'ecological evolution' emerges as described by Allen (1988, p. 19) "The important point is that 'evolution' implies some changes of form, character or behavioural strategy, which affects the manner in which individuals perform in capturing prey, reproducing and avoiding death". Thus, in Allen and Nicolis and Prigogine's view a new population type - a mutant or an innovation - leads to evolution as presented in equation (3.4) - evolution interpreted as change of form, and character.

In this framework equation (3.4) may be applied to socio-cultural and economic evolution (where the population dynamics can be extended to urban and regional development, economic activities, diffusion of ideas, transport systems, etc.) in which learning mechanisms, innovations, or technological changes exist. In other words, we are facing a choice situation with different strategies which can be adopted or rejected by surrounding 'populations'.

Equations based on formulation (3.4) have been applied, for example, to urban dynamics (see Allen and Sanglier, 1981 and Camagni et al, 1985) where each center's growth path is subject to successive bifurcations which are linked to the appearance of new economic functions as well as to the pace of general technical progress. According to these authors if the species x_i are interpreted as economic functions, then new species $x_2....x_n$ - with respect to the previous species x_1 - are the new economic functions competing with the previous niche (or niche chain). In particular, an evolutionary model of type (3.4) can be

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interpreted in the framework of the self-organization of systems (i.e., the inner dynamics which drive them to reconstitute themselves in new structures) (see Prigogine, 1976), where the new 'competitors', or new 'species', may be considered in terms of ecological fluctuations. These fluctuations continue and replace the old population when the new species have a better capability of exploiting the same resources, or the 'ecological' niche (see Figure 6).
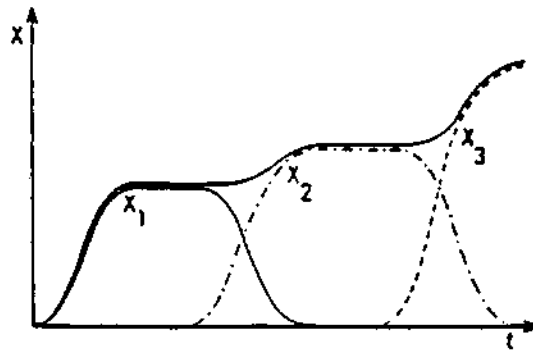

Figure 6. Niches occupied successively by species of increasing effectiveness. (Source: Nicolis and Prigogine, 1977, p. 457)

A further example of the process described in Figure 6 is provided by the evolution of technological innovation, where the new series are represented by new technological products (or in general 'new technological paradigms'). But just like in ecology, each technology which replaces an old one is not capable of doing the same, but generally also generates new opportunities (see Jantsch, 1980). An empirical example of the above process can also be found in the substitution of transport infrastructures (see e.g. Figure 7 related to the U.S. context).
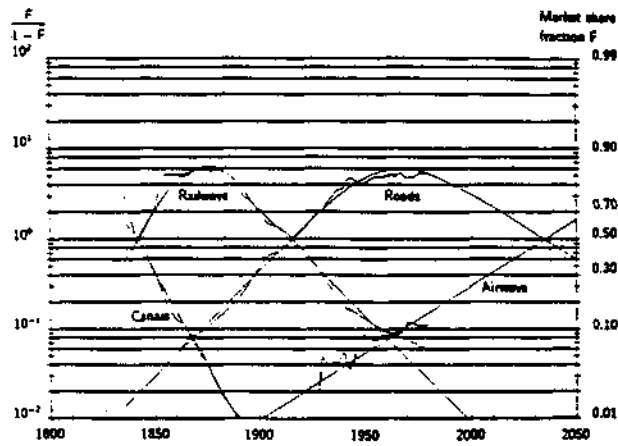
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Figure 7. Substitution of transport infrastructures in the USA; shares in length,
logit transformation.

(Source: Grübler and Nakicénovic, 1991, p. 10)

It is noteworthy that system (3.4) - which represents a hierarchy of levels of self-organisation - is also an autopoiètic system, i.e. a system whose function is primarily geared to self-renewal (or self-production) (see, for the concept of autopoièsis Maturana, 1970, and Maturana and Varela, 1975).

It is thus clear now that, from a modelling point of view, the competition coefficient $ß_{ij}$ in (3.4) which represents the measure of niche overlap, plays a fundamental role in the evolution of a 'self-organizing' system, since its value generates the possibility of extinction or co-existence of species. In the next section we will consider the indigenous dynamics of such a system by examining the particular case of the evolution of two species, focusing the attention on the role played by the competition coefficient $ß_{ji}$.

4. A TRANSPORT/ENVIRONMENT MODEL FOR THE COMMODITIES SECTOR

4.1 Introduction

In this section we will analyze the specific case of three competing niches in transport systems behaviour, starting from the theoretical analysis developed in the previous sections.

The above niche methodology can be applied to each type of transport

network where the competing species can be <u>arcs</u> or <u>nodes</u> to be chosen in a network, or the <u>modes</u> to be chosen in a segment with one origin and one destination, or-given a certain mode - different infrastructural opportunities to be chosen.

We will consider in our model the case of three competing modes (roads, railways and inland waterways) with reference to commodity flows. We will specify formulation (3.1) in a discrete time version, since the relevant types of data are often discrete in nature.

4.2 A two-layer model

For the case of three competing species, system (3.1) in discrete form can be reduced to (for $x_1 = x$, $x_2 = y$ and $x_3 = z$):

$$x_{t+1} = x_t \, (K_{1,t} - \alpha_{11} \, x_t - \alpha_{12} \, y_t - \alpha_{13} \, z_t)$$
$$y_{t+1} = y_t \, (K_{2,t} - \alpha_{21} \, x_t - \alpha_{22} \, y_t - \alpha_{23} \, z_t) \qquad (4.1)$$
$$z_{t+1} = z_t \, (K_{3,t} - \alpha_{31} \, x_t - \alpha_{21} \, y_t - \alpha_{33} \, z_t)$$

where x represents the mode <u>road</u>, y the mode <u>inland waterways</u> and z the mode <u>railways.</u> The variable k refers to the total capacity of the mode in a given period, including the addition in the relevant period as a result of new investments. This means essentially that the capacity variable can be influenced by the investments as a control variable; clearly, this has implications for the competitive position of each of these modes.

The competition coefficients α_{ij} represent, in a 'niche' interpretation, the measure of niche overlap over time. We will assume for the sake of simplicity that $\alpha_{12} = \alpha_{21} = a$; $\alpha_{13} = \alpha_{31} = b$; $\alpha_{23} = \alpha_{32} = c$; $\alpha_{11} = \alpha_1$; $\alpha_{22} = \alpha_2$; $\alpha_{33} = \alpha_3$. It is noteworthy in particular that, when the competition coefficient α_{ij} is equal to zero, we have no competition (or no common resources), while for $\alpha_{ij} = 1$ x_i and x_j completely overlap. Partial overlap is consequently expressed by the condition $o < \alpha_{ij} < 1$.

Thus our competition system (4.1) can then easily be rewritten as follows:

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$$x_{t+1} = x_t (K_{1,t} - \alpha_1 x_t - a y_t - b z_t)$$

$$y_{t+1} = y_t (K_{2,t} - a x_t - \alpha_2 y_t - c z_t) \qquad (4.2)$$

$$z_{t+1} = z_t (K_{3,t} - b x_t - c y_t - \alpha_3 z_t)$$

Next we assume - as indicated in Section 1 - that the effective capacity of the three modes may be actually constrained by the external environmental costs of transport, not only by the social costs of their own mode but also by the social costs of competing modes (all of them are competing in terms of use of scarce environmental resources). Thus the actual capacity of all modes may be varying over time until a threshold level is reached determined by the environmental costs constraint for each transport mode.

Consequently, by taking into consideration the principles of Figure 1, condensed in a two-layer model, we will assume a new level of organization in which the capacities K_1, K_2 K_3 of the three modes are also competing for scarce environmental amenities. The relating model reads than as follows:

$$K_{1,t+1} = K_{1,t} (C_1 - \beta_1 K_{1,t} - e K_{2,t} - f K_{3,t})$$

$$K_{2,t+1} = K_{2,t} (C_2 - e K_{1,t} - \beta_2 K_{2,t} - g K_{3,t}) \qquad (4.3)$$

$$K_{3,t+1} = K_{3,t} (C_3 - f K_{1,t} - g K_{2,t} - \beta_3 K_{3,t})$$

where C_i is the maximum threshold level of environmental costs for each mode i (i = 1,2,3,).

The next step is now to test by means of simulation experiments the sensitivity and the stability of this two-layer environment transport mode model.

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4.3 Simulation experiments

In this sub Section we will investigate the behaviour of the nested model (4.2)-(4.3) by regarding in particular the conditions and relationships causing (in)stability between the variables K_1, K_2, K_3, x, y, t and C_1, C_2, C_3.

We will first start our presentation of simulation experiments for stable behaviour, i.e., for values of C_i that lead to stability of the model results. We will use the following starting values:

$$C_1 = 2.9 \quad C_2 = 3 \quad C_3 = 2.5$$

with the following values for the competition coefficients:

$$\alpha_1 = 0.05 \quad \alpha_2 = 0.05 \quad \alpha_3 = 0.05$$
$$a = 0.01 \quad b = 0.05 \quad c = 0.05$$
$$e = 0.1 \quad f = 0.5 \quad g = 0.3$$
$$\beta_1 = 1 \quad \beta_2 = 1 \quad \beta_3 = 1$$

The related simulation experiments have been carried out by means of the well-known STELLA simulation programme for dynamic systems. The results show the following stable diagrams for both the three modes and the three capacities (see Figures 8 and 9).

In particular it can be seen from Figure 9 that the above parameter values lead to a stable configuration in which the modes 'roads' and 'railways' turn out to become the winner in the long run, followed by the mode 'inland waterways'.

By increasing now the values of C_i as follows:

$$C_1 = 3.5 \quad C_2 = 3.8 \quad C_3 = 3$$

and by keeping the other parameters equal, we can next observe the emergence of a 'chaotic' behaviour for the capacities (see Figure 10) which correspond to oscillations in the mode choice (see Figure 11).
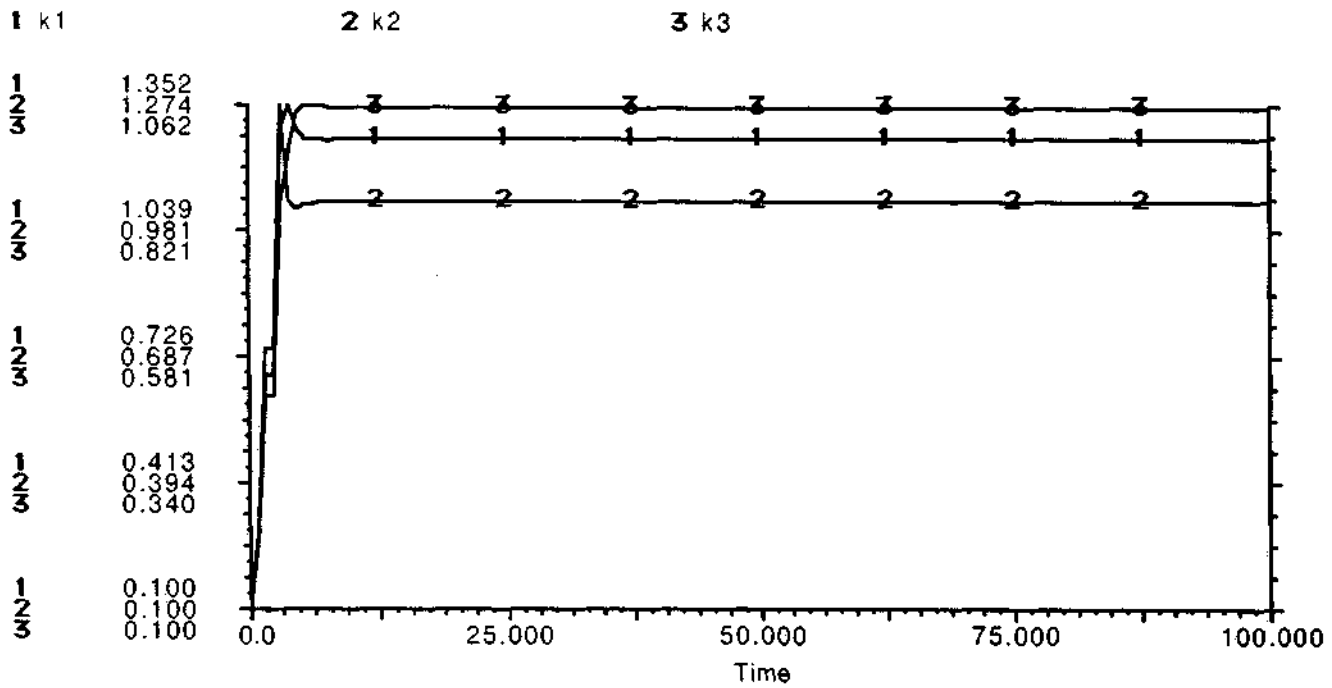
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1      1.352
2      1.274
3      1.062

1      1.039
2      0.981
3      0.821

1      0.726
2      0.687
3      0.581

1      0.413
2      0.394
3      0.340

1      0.100
2      0.100
3      0.100
```

Figure 8. Stable behaviour for the capacities of the three modes

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1      0.530
2      0.100
3      0.103

1      0.398
2      0.0753
3      0.0773

1      0.266
2      0.0507
3      0.0518

1      0.133
2      0.0260
3      0.0263

1      0.000810
2      0.00139
3      0.000847
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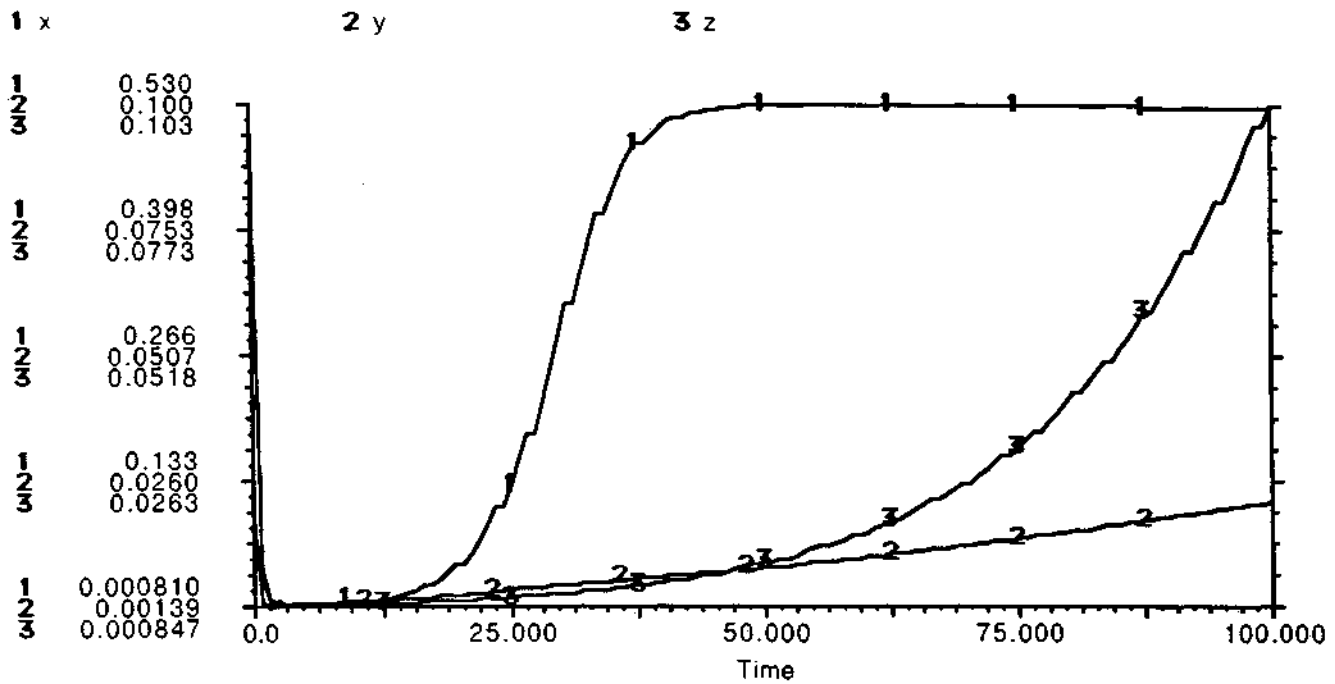
Figure 9. Stable behaviour for the three modes choice (roads, inland
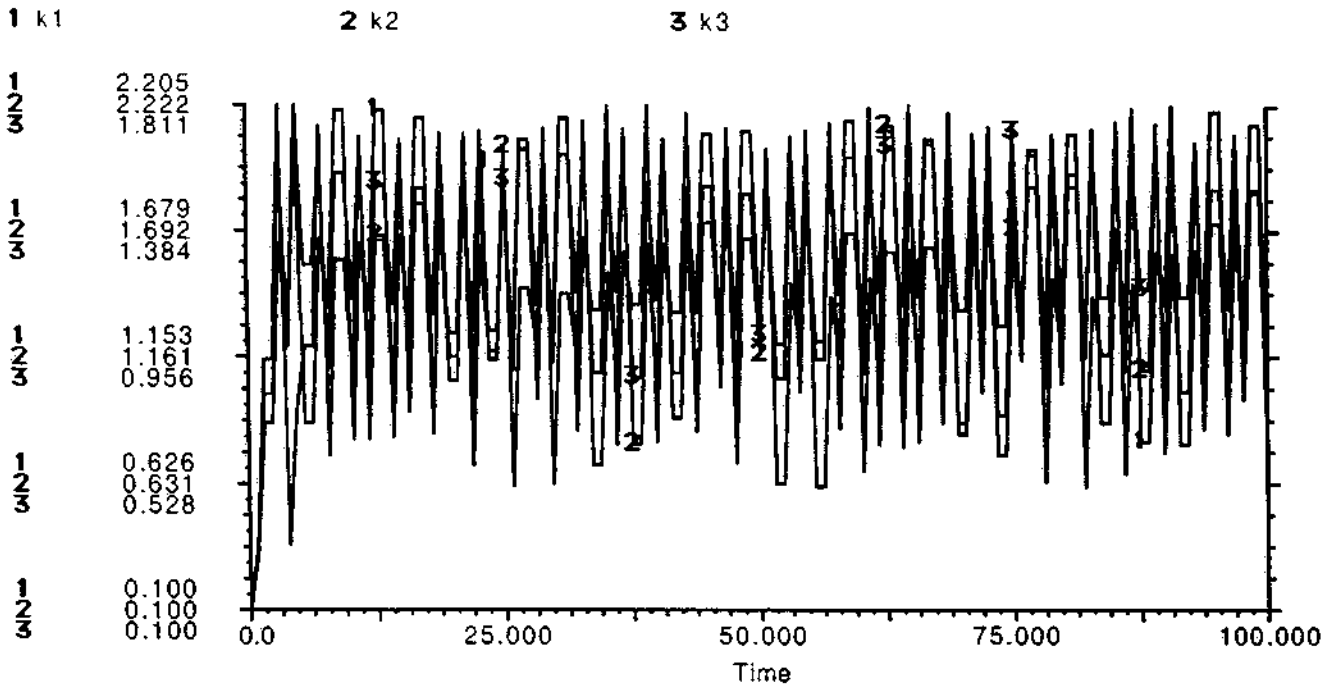waterways, railways)

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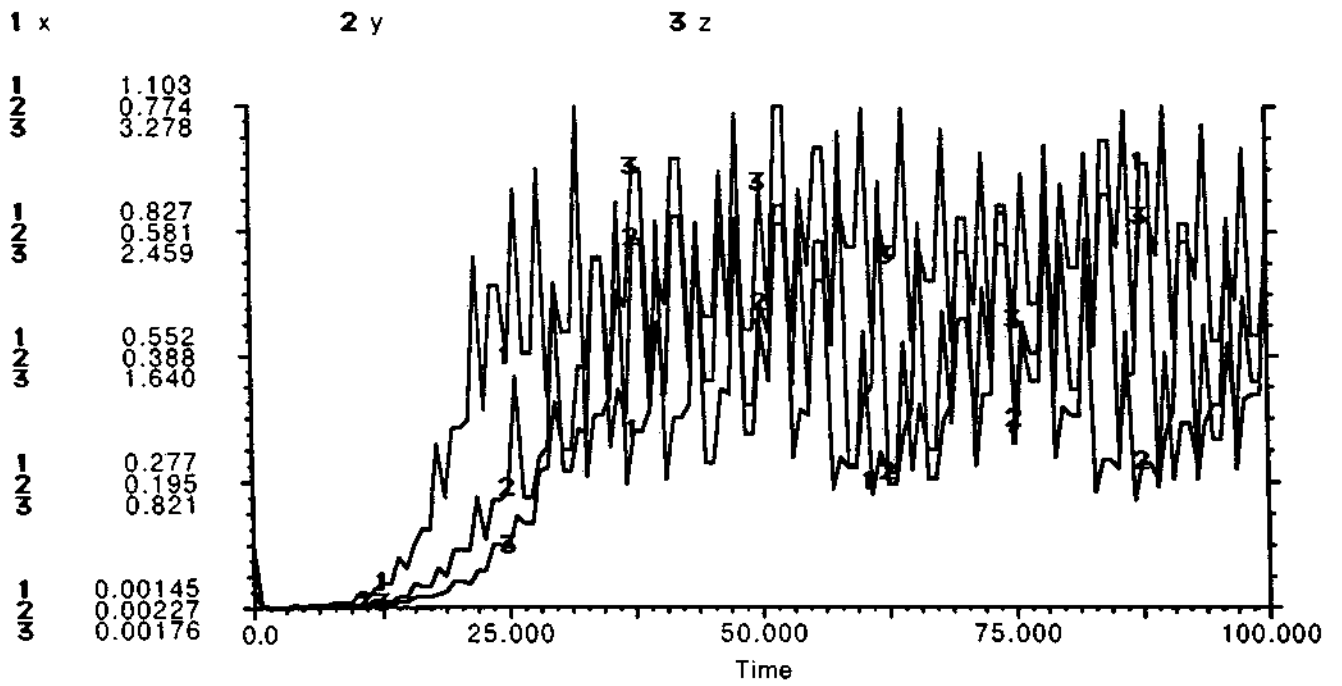
Figure 10. Oscillating behaviour for the mode capacity

Figure 11. Oscillating behaviour for the three-mode choice (roads, inland waterways, railways)

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5. CONCLUDING REMARKS

In the present paper we have identified a conceptual - theoretical framework for describing the dynamic man-environment relationships.In particular, we defined a two-layer model based on niche theory approach constrained by the capacity (varying over time) of the two-layer system. The model was - for the freight sector - simulated for the particular case of three competing modes (roads, inland waterways, railways), that were nested with respect to the competition of the three related capacities and limited by a final threshold determined by environmental costs (or social costs in general).

Simulation experiments showed the direct link - in terms of (in)stability - between the nested variables, so that (un)stable values for the choices of the modes correspond to (un)stable values of capacities. The model, in this two-layer niche formulation, also shows an extreme sensitivity to parameter values, notably competition coefficients and carrying capacities.

The present example represents a first step toward a broader research direction in which further layers of capacity may be identified within these two principal layers in a network-tree structure. A first new step in this context would be a subdivision, on the one hand, of the first layer into two levels of choice (micro-macro) determined respectively by the carrying (technical) capacity of the modes and by the investment capacities determined by modal decision makers.

On the other hand also the 'cost-capacity' level can be subdivided into three further sub-levels (safety costs, 'purely' environmental costs and operating costs), whose hierarchy is also varying over time.

Obviously, this multi-layer model may lead to further n hierarchical levels interacting with one another in a nested-parallel form. Consequently, also the formulation of the model in n layers may lead to more difficult research issues, such as computational problems, scale problems, stability analysis, etc. In this framework a parallel computing approach or a neural network approach would certainly be useful.

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BIBLIOGRAPHY

Allen, P. and Sanglier, M., Urban Evolution, Self-Organization, and Decision-Making, Environment and Planning A, vol. 13, 1981, pp. 167-183.

Allen, P., Evolution: Why the Whole is Greater than the Sum of the Parts?, Ecodynamics (Wolff, W., C.-J. Soeder and F.R. Drepper, eds.), Springer-Verlag, Berlin, 1988, pp. 3-30.

Bennett, R.J. and Chorley, R.J., Environmental System, Methuen, London, 1978.

Boulding, K.E., Ecodynamics: A New Theory of Social Evolution, Sage, Beverly Hills, 1978.

Camagni, R., Diappi L. and Leonardi, G., Urban Growth and Decline in a Hierarchical System, Regional Science and Urban Economics, 1986, vol. 15, pp. 145-160.

Clarke, G.L., Elements of Ecology, Wiley, New York, 1954.

Darwin, C., On the Origin of Species by Means of Natural Selection of the Preservation of Favoured Races in the Struggle for Life, John Murray, London, 1958.

Elton, C.S., Animal Ecology, Sidgwick and Jackson, London, 1927.

Grinnel, J., The Niche Relationship of the California Trasher, AUK, vol. 21, 1917, pp. 364-382.

Grübler, A. and Nakićenović, Evolution of Transport Systems: Past and Future, RR-91-8, International Institute For Applied Systems Analysis, Laxenburg, 1991.

Hutchinson, G.E., Concluding Remarks, Cold Spring Harbor Symp. Quant. Biol., vol. 22, 1957, pp. 415-427.

Jantsch, E., The Self-Organizing Universe, Pergamon Press, Oxford, 1980.

Lotka, A., Analytical Notes on Certain Rhythmic Relation in Organic Systems, Proceedings of the National Academy of Sciences, United States, vol. 6, 1920, pp. 410-415.

Lotka, A., Elements of Physical Biology, Williams and Wilkins, Baltimore, 1925.

Marshall, A., Principles of Economics, Macmillan, London, 1920.

Maturana, H.R., Biology of Cognition, Report Biological Computer Laboratory 9.0., University of Illinois, Urbana, 1970.

Maturana, H. and Varela, F., Autopoietic Systems, Report Biological Computer Laboratory 9.4., University of Illinois, Urbana, 1975.

May, R.M., Stability and Complexity in Model Ecosystems, Princeton University Press, Princeton, 1973.

May R., Simple Mathematical Models with Very Complicated Dynamics, Nature, vol. 261, 1976, pp. 459-467.

Mesarovic, M. and Pestel, E., Mankind at the Turning Point: The Second Report to the Club of Rome, Hutchinson, London, 1975.

Nicolis, G. and I. Prigogine, Self-Organization in Nonequilibrium Systems, Wiley, New York, 1977.

Nijkamp, P. and A. Reggiani, Spatial Competition and Ecologically Based Socio-Economic Models, Researsch Memorandum, Department of Economics, Free University, Amsterdam, 1992a.

Nijkamp, P. and A. Reggiani, Interaction, Evolution and Chaos in Space, Springer Verlag, Berlin, 1992b.

Nijkamp, P. and Reggiani, A., Space-Time Dynamics, Spatial Competition and the Theory of Chaos, Structure and Change in the Space-Economy (Lakshmanan, T.R. and P. Nijkamp, eds.), Springer, Berlin 1993 (forthcoming).

Odum, E.P., Fundamentals of Ecology, Saunders, Philadelphia, 1954.

Pianka, E.R., Competition and Niche Theory, Theoretical Ecology (May, R.M., ed.), Blackwell Scientific Publications, Oxford, 1976, pp. 114-141.

Pianka, E.R., Evolutionary Ecology, Harper & Row, New York, 1978.

Prigogine, I., Order through Fluctuation: Self-Organization and Social System, Evolution and Consciousness (Jantsch, E. and C.H. Waddington, eds.), Addison-Wesley, Reading, Mass., 1976.

20

Rosser, J.B., *From Catastrophe to Chaos: A General Theory of Economic Discontinuities*, Kluwer Academic Publishers, Dordrecht, 1991.

Schumpeter, J.A., *The Theory of Economic Development*, Harvard University Press, Cambridge, Mass., 1934.

Shelford, V.E., The Reactions of Certain Animals to Gradients of Evaporating Power and Air, *Biological Bulletin*, vol. 25, 1913, pp. 79-120.

Smith, M.J., *Models in Ecology*, Cambridge University Press, London, 1974.

Sonis, M., Territorial Socio-Ecological Approach in Innovation Diffusion, *Sistemi Urbani*, Vol. 1-2, 1991.

Sonis, M., Innovation Diffusion, Schumpeterian Competition and Dynamic Choice: A New Synthesis, *Journal of Scientific and Industrial Research*, Special Issue on Mathematical Modelling of Innovation Diffusion and Technological Change, Vol. 51, No. 3, 1992, pp. 172-186.

Volterra, V., *Leçons sur la théorie mathématique de la lutte pour la vie*, Gauthier-Villars, Paris, 1931.

Wright, S., Evolution in Mendelian Population, *Genetics*, vol. 16, 1931, pp. 97-189.

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