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EVOLUTIONARY PATTERNS OF URBAN PRODUCTION SYSTEMS

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ABSTRACT

In this paper long-term (structural) changes in urban systems are analyzed from the viewpoint of the dynamics of the production systems concerned. On the basis of some simple assumptions a discrete dynamic model is derived, which has a structure similar to the well-known May type of models in population dynamics. This model appears to be able to generate a diversity of evolutionary paths ranging from stable to chaotic patterns. Next, this basic model is extended by means of endogenous R & D investments and mutual exclusion phenomena between different competitive urban production systems. It is essentially demonstrated that regular urban life cycles are not necessarily a plausible phenomenon in urban dynamics, but that irregular fluctuations may equally well occur, depending on the initial conditions, the production structure, and the various feedbacks incorporated in the model.

1. Introduction

Urban growth patterns have in the past decades been marked by dramatic changes, in both developed and developing countries. Surprisingly enough, however, these changes do not reflect a uniform trend: urban decay in the one country takes at the same time place as rapid urban growth in the other. Therefore, it is extremely relevant to analyze the conditions under which such structural changes may occur, especially because such changes will not only effect the stability of equilibrium points in urban systems, but also lead to a new topology of systems trajectories (see Dendrinos, 1982, Nijkamp, 1982, Nijkamp and Schubert, 1983, and Wilson, 1981).

A basic feature of current urban dynamics is its complex,multidimensional and nested structure. Due to large fluctuations caused by dissipative structures affecting the homogeneity and isotropy of space and time, the geographical structure of cities may become unstable and even exhibit bifurcations (see Turner, 1980). In particular, if various subsystems within a city (for instance, industry, infrastructure, etc.) are intertwined in a non-linear dynamic way (sometimes even with differences in the successive rates of change), unexpected switches in the evolutionary pattern of a city may take place (see also Haag and Weidlich, 1983). Consequently, agglomeration economies in a city may exhibit complex non-linear patterns, caused by the existence of technological, social or environmental limits to scale-dependent increases of productivity (see Wibe, 1982). In addition, it is worth noting that agglomeration economies may also induce a certain degree of exclusion of different activities competing for the same inputs within the urban territory (for instance, specific types of labour force, land, infrastructure facilities etc.). This competitive interaction may be modelled as an endogenous process within the frames of a product cycle theory (see Andersson and Johansson, 1984). Further contributions to the issue of structural changes in spatial systems can be found in Nijkamp (1986).

In the present paper, the notion of structural dynamics for an urban system will be illustrated by means of a simple dynamic model reflecting the production structure of an urban economy. It will be shown that structural changes - caused *inter alia* by technological innovation and by capacity limits of the urban system at hand - may lead to various kinds of dynamic behaviour of the urban economy. Spatial competition and exclusion will finally also be dealt with.

2. Structural Urban Change: A Preamble

Especially in recent years, several geographers have claimed that various urban growth patterns exhibit a clean break with the past (see among others, Berry and Dahmann, 1977; Vining and Kontuly, 1977; and Vining and Strauss, 1977), though this reversal of past trends has been questioned by others (see Gordon, 1982). Clearly, various countries have to a certain extent demonstrated a pattern of spatial and urban fluctuations in the post-war period. It appears that external economies and diseconomies have successively had a deep impact on urban systems in the Western world. Several theories have emphasized the close linkage between economic and urban developments (see Nijkamp, 1984) such as: economic-base/multiplier models, (inter)regional input-output models, gravity and income potential models, growth pole models, center-periphery models , unbalanced growth models and development potential models.

In the past years, a wide variety of dynamic urban analyses and models has been developed. Surprisingly enough, only a limited number of these studies exhibited structural dynamics (see for a survey Nijkamp et al., 1985). A major analytical problem in this respect is the question whether structural changes are due to intra-urban endogenous developments or exogenous forces (external to the city). This problem runs parallel to the current scientific debate on the existence of long waves in economics, where especially the Schumpeterian viewpoint regarding the endogeneity of Kondratieff cycles is being tested (see also Kleinknecht, 1985). Kondratieff's original theory made a distinction between five stages in a long-term (cyclical) pattern of a free enterprise economy: take-off, rapid growth, maturation, saturation and decline. Due to lack of long time series data this proposition is hard to validate, especially if each new phase of a cycle has to be explained from <u>endogenous</u> forces taking place in previous stages.

In line with the foregoing remarks, a meaningful model for analyzing structural urban dynamics should be able to generate various trajectories for the evolution of the city, in which both endogenous and exogenous cyclical patterns may play a role. Furthermore, such a model may lead to testable hypotheses in order to explore under which conditions a certain stable or unstable growth path for an urban system may emerge.

The approach adopted in the present paper is mainly supply-oriented, as it is taken for granted that the supply side of the urban market (including infrastructure and R&D capital) is mainly responsible for the long-term evolution of an urban agglomeration. Furthermore, it is assumed - in agreement with the Schumpeterian view on economic dynamics - that industrial innovations (either basic or process innovations) are the driving forces of structural changes in the urban economy. In this context, the so-called 'depression-trigger' hypothesis is regarded as extremely relevant, as this hypothesis indicates that a down-swing phase will induce the invention and implementation of radically new (often clustered) technologies (see also Mensch, 1979). The demand side of the market can in this framework be included by means of the so-called demand-pull hypothesis (see Clark et al., 1981, Mowery and Rosenberg, 1979, and Norton, 1979).

The 'depression-trigger' hypothesis is extremely relevant for the urban economy, as it states that a stimulus to new economic growth can only be given, if the necessary basic innovations in the productive sector - either private or public - are taking place. Private basic innovations would require the production of new commodities and/or the location of new firms within the urban territory. Public basic changes would require the implementation of new urban infrastructure investments that act as stimuli for mutation in the urban economy. In this respect, the notion of infrastructure indicates all public overhead capital that is necessary for the take-off or growth of private activities. Examples of infrastructure categories are: streets, highways, medical, socio-cultural and educational facilities, housing, recreational and "quality of life" capital, and so forth.

Thus, the combination of R&D capital, productive capital, public overhead capital and new markets is a necessary condition for creating radical technological changes (cf. Schmookler, 1966). Such changes are essentially the propulsive factors behind the process of structural urban economic developments.

The presence of a satisfactory urban infrastructure is thus a necessary condition for making a city a breeding place for new activities (cf. Rosenberg, 1976). This requires, in general, favorable educational facilities, communication possibilities, market entrance, good environmental conditions and agglomeration favoring innovative activities. This may also explain why monopoly situations and industrial concentrations (including patent systems) often have greater technological and innovative opportunities. Although the data on innovations are in general poor (cf. Terlecky, 1980), there is a certain empirical evidence that only a limited number of industrial sectors account for the majority of innovations (electronics, petrochemics and aircraft, for example), although in various cases small firms may also be a source of major innovations (micro-processors, for example) (see also Rothwell, 1979, and Thomas, 1981). This also implies that sectoral specialisation and urban fluctuations may go hand in hand. In this context, it is often claimed that city size favors innovative ability (cf. Alonso, 1971; Bluestone and Harrison, 1982; Carlino, 1977; Dunn, 1982; Jacobs, 1977; Kawashima, 1981; Pred, 1966; Richardson, 1973; and Thompson, 1977). It should be added, however, that the innovative potential in the U.S. which was traditionally concentrated in large urban agglomerations, is showing a declining trend, especially in the largest urban concentrations (see Malecki, 1979; Nelson and Winter, 1973; Norton, 1979; and Sveikauskas, 1979).

After the previous remarks on urban evolution, in the next section a model describing structural urban dynamics will be presented.

3. A Simple Model for Structural Urban Dynamics

The growth pattern of a city may exhibit fluctuations, unbalanced growth processes and perturbations, depending on the rate of change and on the qualitative pattern of the urban economy and its underlying explanatory variables.

It is evident that in case of qualitative changes in a non-linear dynamic system several shocks and perturbations may emerge (see also Allen and Sanglier, 1979; Batten, 1981; Casetti, 1981; Dendrinos, 1981; Isard and Liosattos, 1979; and Wilson, 1981). A simple mathematical representation of the driving forces of such a system can be found in Nijkamp (1983, 1984). This simplified model was based on a so-called quasi-production function (including productive capital, infrastructure and R&D capital as arguments). The dynamics of the system was described by motion equations for productive investments, infrastructure investments and R&D investments. Several constraints were also added, for instance, due to maximum congestion effects and maximum consumption rates. Equilibrium solutions of the model were obtained by using optimal control theory. In the present paper a simple dynamic neo-classical production function will be used as the starting point of a more formal analysis of growth patterns of a city. The assumption is made that urban output is generated by a mix of productive capital K, public overhead capital P (or infrastructure), R&D capital R (including education, information and communication technology), and remaining production factors L (land, labour, etc.)

Hence, the following generalized production function may be assumed for the (closed) urban economic system:

$$Y = f(K, P, R, L,) \qquad (3.1)$$

The parameters of the urban production technology depend on the general state of technology and on specific local conditions (agglomeration economies, innovation intensity etc.). If a normal Cobb-Douglas specification is assumed, one may write (3.1.) as follows:

$$Y = \alpha\, K^{\beta}\, P^{\gamma}\, R^{\delta}\, L^{\varepsilon} \qquad (3.2)$$

where the parameters $\beta,\ldots,\varepsilon$ reflect the production elasticities concerned.

It should be noted that, if instead of R&D capital an exponential growth rate of technological progress would have been included in (3.2.), the resulting Cobb-Douglas production function would have been at the same time Harrod-, Hicks- and Solow-neutral, provided the technical change concerned would have been disembodied (see Stoneman , 1983).

Production function (3.2.) is assumed to be a reasonable approximation of the underlying production technology within the range (Y_{min}, Y_{max}). Only on this range the production elasticities are assumed to be strictly positive. Beyond the minimum threshold level Y_{min}, the city size may be too small for agglomeration economies, so that then a marginal increase in one of the production factors may have a negligible impact on the urban production output. This situation indicates that a city needs a minimum endowment with production factors before it reaches a self-sustained growth path.

Besides,beyond a certain maximum capacity level Y_{max} of urban size, bottleneck phenomena (congestion, e.g.) - caused by a high concentration of capital K - may lead to a negative marginal product of productive capital or other production factors. Then any further increase in productive capital may affect urban output, unless this situation of a negative marginal product of capital is compensated and corrected by the implementation of new public overhead and R&D investments (the depression trigger phenomenon).

If model (3.2.) is explicitly put in a dynamic form, then within the relevant range (Y_{min}, Y_{max}) the changes in urban output in a certain period of time may be approximated by means of the following discrete time version of (3.2.):

$$\Delta Y_t = (\beta k_t + \gamma p_t + \delta r_t + \varepsilon l_t) Y_{t-1} \quad , \tag{3.3}$$

with:

$$\Delta Y_t = Y_t - Y_{t-1} \tag{3.4}$$

and :

$$k_t = (K_t - K_{t-1}) / K_{t-1} \tag{3.5}$$

while p_t , r_t and l_t are defined in a way analogous to (3.5). Thus the production factors are included as relative changes in the dynamic model (3.2). Such a discrete approximation of a model with a continous time trajectory is valid within the range for which the structure of the system is stable. Within this range the urban system will exhibit a non-cyclical growth. This self-sustained growth path may be drawing to a close due to two causes:

- external: scarcity of production factors or lack of demand
- internal: emergence of congestion effects leading to negative marginal products.

External factors will only imply that the system will move toward an upper limit set by the constraint concerned. Internal factors may lead to perturbations and qualitative changes in systemic behaviour. Suppose for instance, a congestion effect caused by too high a concentration of capital in an urban agglomeration. Then each additional increase in productive capital will have a negative impact on the urban production level. This implies that the production elasticity has become a negative time-dependent variable. In other words, beyond the capacity limit Y_{max} an auxiliary relationship reflecting a negative marginal capital product may be assumed:

$$\beta_t = \hat{\beta}\ (Y_{max} - \kappa Y_{t-1}) / Y_{max} \tag{3.6}$$

Analogous relationships indicating a negative marginal product for the remaining production factors L and R&D capital R may also be assumed. Substitution of all these relationships into (3.3) leads to the following adjusted dynamic urban production function:

$$\Delta Y_t = (\hat{\beta} k_t + \hat{\delta} r_t + \hat{\varepsilon} l_t)\ (Y_{max} - \kappa Y_{t-1}) Y_{t-1} / Y_{max} + \gamma p_t Y_{t-1} \tag{3.7}$$

This is seemingly a fairly simple non-stochastic dynamic relationship, but it can be shown that this equation is able to generate unstable and even erratic behaviour leading to a-periodic fluctuations. The standard format of (3.7) can be written as follows:

$$\Delta Y_t = v_t \, (Y_{max} - \kappa Y_{t-1}) Y_{t-1} / Y_{max} + \gamma p_t Y_{t-1} \tag{3.8}$$

with:

$$v_t = \hat{\beta} k_t + \hat{\delta} r_t + \hat{\varepsilon} l_t \tag{3.9}$$

The latter relationship is essentially nothing else but the relative change in urban output generated by the new technological conditions reflected in the production elasticities marked by the ∧-symbol. Usually such a relative change is positive but smaller than 1. This statement can also be justified on the basis of the expression at the right-hand side of (3.9), where the new production elasticities $\hat{\beta}$, $\hat{\delta}$ and $\hat{\varepsilon}$ may be interpreted as weights attached to k_t, r_t and l_t, respectively. If the Cobb-Douglas function is homogeneous of degree one, it is also plausible to stipulate that only in case of drastic or structural changes v_t is larger than 1. But even if the degree of homogeneity would be higher than 1, the expression at the right-hand side of (3.9) is in case of incremental changes smaller than 1, as in case of a normal evolutionary pattern the relative changes in production factors will not be excessively high.

Equation (3.8) is essentially a part of a Volterra-Lotka type model which has in recent years often been used for modelling predator-prey relationships in population biology (see also Goh and Jennings, 1977; Jeffries, 1979; Pimm, 1982; and Wilson, 1981). This model in difference equation form has been dealt with among others by May (1974), Li and Yorke (1975) and Yorke and Yorke (1975). Applications in a geographical setting can be found in Brouwer and Nijkamp (1985) and Dendrinos and Mullally (1983, 1984) among others. In the present context, the dynamic trajectory of the urban economy can be studied more precisely by rewriting (3. 8) as:

$$\Delta Y_t = v_t \, (1 - \kappa Y_{t-1} / Y_{max}) Y_{t-1} + \gamma p_t Y_{t-1} \tag{3.10}$$

Equation (3.10) is a standard equation from population dynamics. It should be noted that logistic evolutionary patterns may also be approximated by a (slightly more flexible) Ricker curve (see May, 1974). In that case, the exponential specification precludes the generation of negative values for the Y variables in simulation experiments, a situation that may emerge in relation to equation (3.10). Model (3.10) has some very unusual properties. On the basis of numerical experiments, it has been demonstrated by May (1974) that this model may exhibit a remarkable spectrum of dynamical behaviour, such as stable equilibrium points, stable cyclic oscillations, stable cycles, and chaotic regimes with a-periodic but bounded fluctuations. Two major elements determine the stability properties of (3.10), viz. the initial values of Y_t and the growth rate for the urban system (which is depending on v_t). Simulation experiments indicated that especially the growth rate has a major impact on the emergence of cyclic or a-periodic fluctuations.

Clearly, in our case there is a difference with respect to May's model. In May's model, v is a constant, whereas in our case v is endogenously determined by the evolution of the urban system (see equation (3.9)). This has clearly an effect on the trajectory of urban growth, but - given the conditions on v_t - this does not affect the main conclusions regarding the stability of the system, though it has to be realized that drastic changes in a previous period are likely to generate perturbations in the next period.

May (1974) has demonstrated that a stable equilibrium may emerge if the growth rate satisfies the condition: $0 \leq v_t \leq 2$; otherwise stable cyclic and unstable fluctuations may be generated. Li and Yorke (1975) have later developed a set of sufficient conditions for the emergence of chaotic behaviour for general continuous difference equations. Clearly, in a discrete model the potential chaotic behaviour depends on the value of v_t. As indicated above, especially in case of incremental changes $v_t \leq 1$, so that then a stable equilibrium is assured; otherwise many alternative evolutionary patterns of the city concerned may emerge.

Consequently, the conclusion may be drawn that - due to the presence of a capacity limit Y_{max} - a city may exhibit a wide variety of dynamical of even cyclical growth patterns. A long wave pattern of an urban economy is compatible with the abovementioned urban production technology, but this is only a specific case. A wide variety of other dynamic (and sometimes unstable) trajectories may arise as well. This heterogeneity in urban development patterns is also reflected in current trends of cities all over the world. The shape of urban fluctuation curves is determined by the initial city size and by the growth rate of the urban production system. This growth rate is a weighted average of the individual growth rates of the urban production factors.

In contrast with many biological growth functions, however, the growth rate v_t is not necessarily a constant, but it may become an endogenous variable. Consequently, it may be used as a control variable in order to generate a more stable urban growth path. In this respect, relationship (3.8) may be used in the context of an optimal control approach. It should be noted that equation (3.8) is essentially a signomial specification, for which in the framework of geometric programming analysis appropriate solution algorithms have been developed (see among others Duffin and Peterson, 1973; and Nijkamp, 1972).

The general problem of discrete versus continuous model specification is very intriguing. Though time is essentially a continuum, for practical reasons (data availability, observations, sampling) a discretization is usually necessary. Clearly, in a space-time context this may lead to specification errors in a way analogous to the scale and aggregation problem in geography. Thus the formulation of appropriate discrete-time analogues for continuous processes is far from easy (see also Sonis, 1983).

In order to show the possible varieties of system's behaviour of the above mentioned model, we will present the results of two simple simulation experiments. The first simulation will be based on very modest growth rates of our dynamic system which will lead to stable equilibrium (see Figure 1).
The second run takes for granted extremely high growth rates so that system's boundaries are rapidly reached. In that case wild fluctuations may occur which are of a chaotic type (see Figure 2).
It is evident that the plausibility of such results depends on the specification of the model, the initial conditions of the variables and the critical values of model parameters. This is of course a matter of further empirical tests of our model in a real world situation.

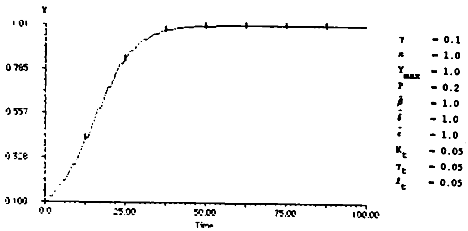

Figure 1. Results of a simulation run for stable growth.

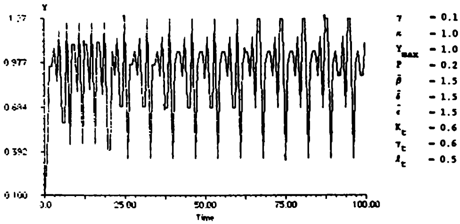

Figure 2. Results of a simulation run for unstable growth.

4. Generalizations of the Basic Dynamic Model

The basic model from section 3 can be extended in various ways. In the present section, two kinds of extensions will successively be presented, viz. endogenous R&D investments and exclusion constraints associated with diffusion of innovation.

4.1. Endogenous R&D investments

It is plausible to introduce an auxiliary relationship for R&D investments, if technological progress is regarded as one of the tools to cope with urban capacity constraints (the so-called depression-trigger hypothesis). This implies that the efforts to be made in the R&D sector have to increase as a city is surpassing its critical upper limit. Thus R&D investments can be used to improve the locational profile of a city, for both entrepreneurs (e.g., by improving accessibility) and residents (e.g., by improving urban quality of life). Then the following auxiliary relationship may be assumed:

$$r_t = \lambda(Y_{t-1} - \pi Y_{max})/Y_{max} \tag{4.1}$$

Substitution of (4.1) into (3.8) yields the following result:

$$\Delta Y_t = \{v_t^* + \hat{\delta}\gamma\ (Y_{t-1} - \pi Y_{max})/Y_{max}\}(Y_{max} - \kappa Y_{t-1})Y_{t-1}/Y_{max} + \gamma p_t Y_{t-1} \tag{4.2}$$

where:

$$v_t^* = \hat{\beta} k_t + \hat{\varepsilon} l_t$$

Relationship (4.1) may also be related to a vintage view of urban capital. If after some time periods the existing capital becomes less efficient (including a decline in urban development), R&D capital may be used to compensate for this decline. This implies that - after the implementation of a new technology - an upswing may take place based on a more efficient capital stock. It is of course a major problem to start R&D activities in the right time period so as to achieve a balanced growth path. Due to lack of insight and monopoly tendencies (innovations may be monopolized through patent systems), a fine tuning is not likely to take place. This may of course lead to various fluctuations in the urban system, which are determined by initial conditions and the various growth rates of congestion and/or production efficiency.

Relationship (4.2) is essentially a nested dynamic difference equation. The perturbation caused by the congestion effects may be neutralized or enforced by the R&D investments in the city, depending on the fine tuning of innovations to urban fuctuations. Thus the ultimate growth path may be a superimposition of two dynamic structures. Clearly, the above-mentioned fine tuning might again be achieved by an optimal control approach. In that case, however, one has to include additional constraints, as the amounts of money spent for productive investments, labor, energy, materials, public overhead investments and R&D investments have to be reserved from savings emerging from the income generated by the urban production value (see also Nijkamp, 1982). In addition, the 'demand-pull' hypothesis states that a balanced urban growth will also require that a substantial amount of the urban production value is earmarked for private and public consumption purposes.

4.2. Exclusion constraints

In this subsection a situation of spatial competition among cities will be dealt with based on a simple model for spatial spillover effects caused inter alia by diffusion of innovation (see also Pred, 1977, and Ralston, 1983).

Innovation diffusion has been the subject of geographic research for quite some time (see Brown, 1982). In a spatial context, especially the notions of hierarchy effects (spread of innovations from large to small places) and of neighbourhood effects (contagious wave-like shapes of diffusion processes) are extremely relevant. Spatiotemporal patterns of innovation diffusion can be represented by means of mixed logistic-gravity models.

It wil be assumed here that innovation of diffusion may create a situation of either spatial-economic dominance of a certain city or a decay, depending on the extent to which the city at hand is able to generate or to adopt - by means of new R&D investments - more efficient production technologies.

The model presented in (3.8) can now be extended as follows:

$$\Delta Y_{it} = v_{it} \{Y_{i\,max} - \kappa_i Y_{i\,t-1} - \mu_{ij} Y_{j\,t-1} \exp(-\nu d_{ij})\} Y_{i\,t-1} / Y_{i\,max} + \gamma_i P_{it} Y_{i\,t-1} \qquad (4.4)$$

where the subscript i refers to city i and the subscript j to an other city j in the spatial system at hand. This model is already closer to the standard specification of a Volterra-Lotka population dynamics model, as it includes a competition among city i and j. The distance friction between i and j is represented by the exponential function $\exp(-\nu d_{ij})$, while the competitive friction between i and j is reflected by the parameter μ_{ij} (see also Batten, 1983; Johansson and Nijkamp, 1984 and Sonis, 1983). Two situations may now be distinguished:

(a) $\mu_{ij} > 0$

This case reflects a purely competitive system in which any increase of the urban output of city j will have a negative effect on city i. This situation may be due to the fact that city j is adopting innovations easier or more efficiciently than city i, so that R&D investments in city j stimulate a higher technological progress than in city i. This implies an exclusion of city i through competition with j. It is worth noting however that this exclusion relationship will only hold true if the analogous equation of output of city j has a negative value for the competition parameter μ_{ji}; otherwise a synergistic decay of both cities will occur.

(b) $\mu_{ij} < 0$

This situation reflects a complementarity relationship between city i and j, as an increase in the output of city j will induce a growth in city i. This means that innovations in city j have positive transmission effects upon city i. If the analogous parameter value μ_{ji} for city j is positive, city i will dominate in the long run city j. However, if both values μ_{ij} and μ_{ji} are negative, a situation of synergistic reinforcement can be observed.

It is clear that the abovementioned competitive situations can easily be extended to multiple cities, so that then the stability conditions of a whole spatial system can be analysed in greater detail.

5. Conclusion

The model described in this paper provides a simplified picture of a complex urban system driven by production and innovation effects. Despite its simplicity , it is able to encompass various mechanisms that act as driving forces for structural changes of a dynamic urban system. In addition, it also sets out the conditions under which stable or non-stable urban growth patterns may emerge. Various alternative ways are open to extend the model presented above, such as the introduction of multiple conflicting objective functions for urban development policy, the introduction of spatial spillover effects in an open urban system so as to include also top-down impacts from a regional or national level (or central city-hinterland interactions), or the introduction of a set of separate difference (or differential) equations for specific urban sectors or markets (employment, housing, transportation, facilities, etc.).

In conclusion, the model presented in this paper has tried to make plausible that the qualitative position of a city (*inter alia* its breeding place function) is co-determinded by its internal policy (infra-structure, R&D capital, and technology) and its external competitive power.

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