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TECHNOLOGICAL CHANGE, POLICY RESPONSE AND SPATIAL DYNAMICS*

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PREFACE

Regional and urban systems appear to pass through complicated development processes caused by structural dynamics and urban-regional-national interrelationships. Such turbulent movements reflect in each stage the interactions of different dynamics with both multiplying and dampering effects, as well as thresholds of system responses. The identification of key variables and regularities in complex dynamic spatial systems is essential for planning and adaptive management.

The present paper, written by Peter Nijkamp (Free University, Amsterdam) as a visiting scholar at IIASA, is an attempt at analyzing the impacts of innovations on spatial systems. It provides a survey of the current literature, while it also aims at designing a dynamic model for studying the impacts of (public) policies on the stability of a dynamic spatial system characterized by innovations. In this regard, this paper reflects one of the new research directions in the Integrated Regional and Urban Development Programme.

Börje Johansson
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Regional Development
Group

Laxenburg, October 1982

1. Long-term Cyclical Economic Dynamics

The eighties seem to be marked by a situation of structural economic change and - in a geographical context - a reorientation of cities, regions and countries all over the world. Such perturbations are no new phenomena in the history of the world: economic cycles (especially long wave patterns) have always drawn a great deal of attention in the history of economics (see, for instance, Adelman, 1965, and Schumpeter, 1939).

Especially in recent years many economists have concentrated their efforts on providing contemporary explanations for the emergence of drastic shifts in economic conditions in the Western world. The persistent and deeply-rooted economic recession, the future uncertainties regarding energy and raw materials supply, the divergent development patterns between the developed world and the developing world, and the inability of government policies to control the present unstable economic and technological process have led to a revival of theories and methods aiming at analyzing long-term economic developments. The issue of long waves (including perturbations, balanced growth, stable equilibria, international and geographical discrepancies, and multi-actor conflicts) has become a favourite topic in recent economic literature.

It is no surprise that Kondratieff's theory on long cycles has come to the fore in recent years (see also, Clark et al, 1981, Delbeke, 1981, Van Duyn, 1979, Freeman et al., 1982, Mandel, 1980, and Rostow, 1978). In his view, the long-run development pattern of a free enterprise economy is normally characterized by cyclical processes including 5 stages: take-off, rapid growth, maturation, saturation and decline.
It is true that the existence of such long-term cyclical patterns is hard to demonstrate due to lack of historical data. It is also a pity that - apart from Schumpeter (1939) - too many economists have regarded the Kondratieff cycle mainly as an economic curiosity that was only reflected in price changes (cf. Mass, 1980). Fortunately, recently many efforts have been undertaken to provide the long wave hypothesis with a more substantial empirical foundation (see Clark et al., 1981, Kleinknecht, 1981, and Mensch, 1979).

A fascinating problem is whether a long-term cyclical pattern is an endogenous phenomenon in Western countries. This requires a theory explaining the rise of each new stage of a cycle (such as prosperity, recession, depression and recovery) from the economic and technological developments during previous stages. In this respect one may, for instance, try to answer the question whether economic recovery would require much emphasis on technological progress and innovation during the preceding 'downswing' of the economy.

A basic problem in research on cyclical economic movements is evidently the length of the time horizon. In the literature, several kinds of distinctions have been made: Kondratieff cycles (40 to 50 years), Kuznets (15 to 25 years), Juglar cycles (5 to 15 years) and business cycles (up to 5 years). Clearly, one may also ~~observe~~ in reality a super-imposition of these different cycles. At present, following Schumpeter much attention is being paid to the Kondratieff cycles, as they may reflect the structural economic changes in the Western world. This also explains why almost all authors use Schumpeter as a main source of reference (though his writings on innovations, market structure and industrial concentration are not always clear; see Dasgupta, 1982, Futia, 1980, Loury, 1980 , Rosenberg, 1976 and Von Weizsäcker, 1980).

Various theoretical explanations - not always firmly supported by empirical evidence - have been given to the presence of long-term dynamic and cyclical movements of the economy:

- <u>monetary theories</u>. These were mainly based on the naive quantity theory by assuming an inverse relationship between price level and gold stock (cf. Dupriez, 1947).
- <u>bottleneck theories</u>. Due to production rigidities in the primary sector a continuing rise in the industry will be hampered, so that excess demand - and consequently higher profits - take place in the primary sector. Then more resources flow to the primary sector, so that the bottlenecks in this sector are removed leading to overproduction and finally reduced profits in the primary sector. Then in turn it is again more profitable to invest in the industrial sector, and so forth (cf. Delbeke, 1981).
- <u>profit rate theories</u>. In a competitive situation, profit rates are related to an acceleration and deceleration of capital accumulation. This will lead, in a free-enterprise economy, to varying profit rates. In a downswing of a cycle, profit rates

tend to decline until a depression has been reached. Countermovements may however lead to a reverse development, so that a cyclical pattern may emerge (cf. Mandel, 1980). These countermovements may be caused by a more efficient technological capital composition, capital saving innovations or a wage decline.

- investment and capital theories. The demand for productive capital is usually unstable: a rapid expansion during a period of economic growth leading to high capital costs will be followed by a decline in the production of capital goods leading to low capital costs (cf. Graham and Senge, 1980, and Heertje, 1981). Various reasons may be mentioned for this cyclical pattern. First, due to indivisibilities in capital stocks an overcapacity may emerge leading to fluctuations in the rate of use of existing capital. Secondly, it may be argued that the translation of final demand impulses into new productive investments is characterized by threshold effects (an entrepreneur can only decide whether or not to invest), so that a wave like development may take place. And thirdly, the long gestation period of productive capacities may cause the emergence of long waves in economic life; when new investments come into operation, an entirely different economic situation may already exist, so that an unstable and cyclical growth pattern may be induced. In conclusion, the investment and capital theories take for granted the existence of successive stages of over- and underinvestments due to inertia and rigidity in economic behaviour. This is essentially described in vintage and puttyclay models (cf. Clark,1980).
- systems dynamic theories. Multiplier and accelerator mechanisms lead to fluctuations throughout the economy. Smooth adjustments are disrupted by discontinuous capital stock adjustments: there is normally too much capital expansion in an upswing stage with favourable prospects and too much contraction in a downswing stage with less favourable prospects (see Forrester, 1977).
- resource theories. These theories argue that - from a global viewpoint - long-term international fluctuations may emerge due to variations in the supply of food stuff and raw materials (accompanied by corresponding price patterns) (see Rostow, 1978).
- innovation theories. Lack of innovation (or of diffusion of innovation) is often considered as a source of cyclical economic patterns (see, among others, Clark et al., 1981, Kleinknecht, 1981, and Mensch, 1979). Some aspects of innovation theories will be discussed in greater detail in the next section, as these elements will play an important role in our own contribution to dynamic and geographical aspects of long-term economic growth patterns.

2. Innovation and Economic Dynamics

Innovation will be regarded as a process of research, development, application and exploitation of a technology (see Haustein et al., 1981). A distinction of these stages is meaningful, as very often a certain new invention does not (directly) lead to an application or exploitation of such new findings (due to market structures, patent systems etc.). Also the diffusion of innovation is often hampered by many bottlenecks (due to monopoly situations, lack of information etc.) (cf. Brown, 1981, Davies, 1979, and Rosegger, 1980).

Innovations can be analyzed at two different levels:

- macro; what are the aggregate implications of innovations (e.g., the impacts on labour-saving and capital-saving technological progress; cf. Kennedy, 1964)?
- micro and meso; which factors are the driving motives of innovations at the level of firms or of the industry (cf. Kamien and Schwartz, 1975)?

The orientation toward the micro or meso level is certainly justified, as innovations are not spread uniformly over all sectors of the economy, but usually only in a limited number of key sectors (cf. Kleinknecht, 1981, and Mahdavi, 1972). The growth pattern of individual economic sectors or firms is normally also characterized by a cyclical pattern.

At the level of industries (or sectors) and firms it is usual to make a distinction between two kinds of innovation:

- basic innovations (leading to new products or even new industrial sectors);
- process innovations (leading to new industrial processes in existing or basic sectors).

Momentarily, much attention is oriented toward basic innovations, as they are assumed to take place periodically and in clusters leading to economic fluctuations (in contrast with process innovations). In the literature on basic innovations, it is usually assumed that after a period of growth a period of saturation may take place leading to a recession. Then the struggle for survival will induce entrepreneurs to search for basic changes leading to radical innovations. This so-called 'depression-trigger' hypothesis has been strongly supported by Mensch (1979). Clark et al.(1981) and Freeman et al. (1982), however, have questioned Mensch's hypothesis, as in their view Mensch has failed to demonstrate that in a phase of an economic 'downswing' innovation investments are not too risky. In a further contribution to this debate, Kleinknecht (1981) has claimed that only relative risks (in relation to competitors) are important, so that in a struggle for survival risk-taking via radical innovation may be a rational behaviour.

It is self-evident that the 'depression-trigger' hypothesis will only be valid, if the products from the related basic innovations can be sold on the market (the demand pull hypothesis). Furthermore, it should be noticed that basic innovations may also be caused by intersectoral linkages (e.g., in an input-output framework).

In any case, innovation processes can usually be described by means of a logistic (S-shaped) curve implying the following phases: introduction, growth, maturity, saturation (and eventually decline). Normally, an economic 'upswing' of a certain sector or firm requires the fulfilment of the following conditions:

- a sufficient (potential) demand for the product at hand (Mowery and Rosenberg, 1979);
- a technological innovation inducing the demand for the new product;
- an availability of sufficient resources to finance new investments;
- a satisfactory endowment of public capital favouring the innovation and investment process.

Thus, the combination of R&D capital, productive capital and public capital is a necessary condition to fulfil the (potential) demand for new products and to create radical technological changes (cf. Schmookler, 1966). These changes may be regarded as propulsive factors behind the process of structural economic growth. This emphasis on 'supply side economics' (Giersch, 1979) explains also the revival of growth pole theory, as this theory also claims that polarization phenomena (scale advantages, intersectoral linkages and technological innovation) shape the necessary conditions for a rapid economic growth process characterized by a diffusion of growth impulses from propulsive sectors to other sectors (cf. Nijkamp and Paelinck, 1976, Ch. 7).

There is however a basic difference between the Schumpeterian view of innovation and its usual interpretation in growth pole theory. Schumpeter regards innovation as an endogenous instrument in a profit-maximizing economy, so that cyclical economic patterns may be expected. These cyclical movements are not necessarily smooth and continuous growth processes, as inertia in adopting innovations, rigidities and bottlenecks in exploiting innovations, and indivisibilities at the supply side may cause shocks, perturbations or catastrophes in an economic system. In growth pole theory, innovations are mainly regarded as an exogenous instrument in order to set the stage for a take-off of less developed areas. Clearly, in a short- or medium-term perspective the resulting economic growth pattern may be the same. In any case, dynamic evolutionary models may be used as meaningful operational tools for describing and analyzing innovation and diffusion processes (cf. Nelson and Winter, 1977).

In both the 'depression-trigger' and the 'demand-pull' hypothesis, innovation plays a crucial role, though it may be induced by different sources. A prerequisite for innovation to take place is sufficient effort in R&D sectors; there is a strong positive correlation between R&D efforts and innovative output (see Mansfield, 1968).

Another necessary condition for innovations is the presence of a satisfactory breeding place, characterized by educational facilities (cf. Rosenberg, 1976), communication possibilities and market entrance, good environmental conditions, and agglomeration favouring innovative activities. This also may explain why monopoly situations and industrial concentrations (including patent systems) often face greater technological and innovative opportunities. In conclusion, the availability of a satisfactory public infrastructure capital stock (in its broadest sense) shapes the necessary conditions for innovative capacities in an area (see Nijkamp, 1982a).

The transmission of innovative efforts to other firms or other sectors of the economy is often hampered by barriers emerging from monopoly situations or patent systems. In the short run, such conditions may protect new inventions and even stimulate innovation, but in the medium- and long-term they may lead to rigidities precluding new developments (cf. Mansfield et al., 1981).

Two conclusions may be drawn from the abovementioned studies on spatial dynamics.

- innovation may be regarded as a necessary condition (and thus an instrument) for economic growth;
- R&D activities and public infrastructure capital are necessary conditions for innovative opportunities.

One important aspect of innovation still remains to be discussed, viz. its precise definition and measurement. We have regarded innovation as a process related to structural sectoral changes, technological progress in production processes, adoption of new products or adoption of new marketing strategies. Consequently, a precise measurement of innovation that would allow a cross-sectoral or cross-national comparison is very difficult (though it is clear that significant sectoral and national differences in innovative efforts may exist (see Van Bochove, 1982, and Dasgupta and Stiglitz, 1980)). Therefore, usually only indirect measurements of innovation are used, such as:

- the relative growth rates of (clusters of) key sectors in relation to other sectors (cf. Mensch, 1979);
- the relative sectoral profit rates in relation to other sectors (cf. Brinner and Alexander, 1979);
- the relative amount of money spent on R&D activities in each sector (cf. Haustein et al., 1981);
- the number of (requested or granted) patents on new industrial processes or products (cf. Kleinknecht, 1982, and Thomas, 1981).

Thus, in general, the data on innovations are fairly weak (see also Terleckyj, 1980). Despite these uncertainties however, there is a certain evidence that only a limited number of industrial sectors account for the major share of expenditures in innovative activities (electronics, petrochemics and aircraft, e.g.), although in various cases also small firms may be a source of major innovations, for instance, in the area of micro-processors (cf. Rothwell, 1979, and Thomas, 1981).

3. Spatial Aspects of Economic Dynamics and Innovation

After the previous discussion on economic dynamics and innovation, it may be interesting to examine some spatial aspects of these developments. It goes without saying that spatial systems have also displayed dynamic evolution processes during the last decade. Although spatial systems have never been static, but always in a state of flux, it is interesting to observe that in recent years several geographers have suggested the existence of a clean break with the past (see among others, Berry and Dahmann, 1977, Vining and Kontuly, 1977, and Vining and Strauss, 1977). Clearly, this reversal of past spatial trends has been questioned by others (see Gordon, 1982), but it is a fact that in many countries waves of urban centralization and decentralization can be observed. It seems as though cities are key factors in generating spatial dynamics.

Usually the following phases can be distinguished in urban development patterns (see also Nijkamp and Rietveld, 1981, Van Lierop and Nijkamp, 1981, and Chatterjee and Nijkamp, 1981):

- urbanization: a growth of cities in an economic and demographic respect implying strong agglomeration forces and innovative efforts.
- suburbanization: a further economic growth of cities (especially in the tertiary sector) accompanied by a flight of population to the suburbs; in this stage the city is still the heart of innovative opportunities.
- des-urbanization: a decline of cities from both an economic and demographic point of view, so that also the innovative power of cities may be decreasing; this may even lead to a decline of whole metropolitan areas (see for a further explanation van den Berg et al., 1982).
- reurbanization: a process of urban revitalization and urban renewal, so that cities become again attractive nuclei for residential and (some) commercial purposes.

Several countries in the Western world (Germany, The Netherlands, U.S.A.) have to a certain extent demonstrated in the post-war period such a pattern of spatial fluctuations. Historically, there is a close connection between innovative activities and spatial dynamics. On the one hand, innovation may cause spatial development processes; for instance, the invention of steam engines in the last century or the exploitation of mass transit systems in our era have had drastic repercussions for regional and urban growth processes. On the other hand, geographical concentrations and the availability of good spatial communication systems may imply a better information on new inventions and lead to a geographical diffusion and adoption of innovations, and in turn cause growth and new developments (e.g., in the chemical, aircraft, electronic and microprocessing industry). This altogether suggests that spatial dynamics, public infrastructure in large agglomerations, innovation potential and R&D activities are strongly interrelated, so that product cycles, regional and urban cycles and innovation cycles display parallel patterns (cf. Nijkamp, 1982b). In this respect, it may be worthwhile to draw the attention to the successive phases of innovation processes: new inventions may take place in major agglomerations, while the actual exploitation of these inventions (e.g., the production of new commodities) may be located in low-wage peripheral areas (especially when standardized products are involved). In this respect, locational conditions, agglomeration economies, infrastructure policy, R&D policy and economic developments are closely linked phenomena.

The parallels between dynamics in economic space and geographical space are also reflected in the notions of a growth pole (as a purely economic concept characterized by propulsive intersectoral growth effects) and a growth centre (as a purely geographical concept characterized by centrifugal spatial diffusion processes). External economies are also reflected in large-scale agglomerations, while external diseconomies may lead to locational congestion phenomena. Several theories have emphasized this close connection between economic and spatial developments (see Nijkamp, 1982b), such as: economic base-multiplier models, (inter)regional input-output models, gravity and income potential models, growth pole models, centre-periphery models, unbalanced growth models and development potential models.

The market extension following many innovations has caused the emergence of large scale operations leading to geographical concentration and specialization, inducing in turn innovations and so forth. Conventional wisdom suggests that city size favours innovative ability (cf. Alonso, 1971, Nijkamp, 1981, Pred, 1966, Richardson, 1973, and Thompson, 1977), because:

- geographical concentration of economic activities (implying scale advantages) leads to a higher productivity (cf. Kawashima, 1981).
- large urban agglomerations demonstrate a high industrial diversification, and a rich social, cultural and educational infrastructure, through which innovative ability will be supported (cf. Nelson and Norman, 1977).
- large agglomerations induce technological progress (cf. Carlino, 1977).

It should be noticed however, that the innovative potential in the U.S. which was traditionally concentrated in urban areas, is showing a declining trend, especially in the largest urban concentrations (see Malecki, 1979). This implies that the innovative activity may be suffering from diseconomies of size (cf. also Sveikauskas, 1979).

Such dynamic processes are in agreement with geographical spill-over-effects known as spread and backwash effects (cf. Myrdal, 1957); migration, input-output flows, capital and commodity flows are media through which cumulative spatial processes evolve via multiplier effects. Due to filtering down effects caused by agglomeration diseconomies, the innovative capacity of economic centres may shift to other areas, as soon as a critical congestion effect in the initial centre has been reached.

The latter observation once more demonstrates that innovative potential as a source of regional and/or urban development requires a minimum sustainable threshold of infrastructure endowment, while - beyond a certain critical upper level - (negative) congestion effects may take place. Depending on locational conditions, sectoral structures, infrastructure equipment, R&D capital and the tuning of private and public capital, regions or cities may be able to benefit from innovative activities.

4. A Catastrophe Model for Spatiotemporal Growth Processes

It has been indicated in the previous sections that the evolution of a spatial system may demonstrate unbalanced growth processes with many shocks and perturbations. Several models describing the spatiotemporal dynamics of a systems of regions have been developed in the past (see among others, Allen and Sanglier, 1979, Andersson, 1981, Batten, 1981, Casetti, 1981, Dendrinos, 1981, Van Duijn, 1972, Isard and Liossatos, 1979, and Nijkamp, 1982b). Such models may be helpful in analyzing the evolution and fluctuations of a spatial system. As current spatial systems demonstrate rather drastic changes, it may be meaningful to call attention for models describing discontinuous growth paths characterized by 'bang-bang' switches, bifurcations or perturbations.

In the present paper, spatiotemporal dynamics will be formalized by means of a model that is able to take into account threshold and congestion effects, so that the phenomenon of spatial waves can be related to the endogenous growth pattern of a spatial system. In this model, social overhead capital and R & D capital play a crucial role. A catastrophe-type approach will be employed to construct a discontinuous spatiotemporal model that is able to generate shocks in a dynamic spatial system. This model does not necessarily guarantee a stable equilibrium path, but it sets out the conditions under which various growth paths may evolve.

The key relationship of this model is formed by a generalized production function (a so-called quasi-production function; see Biehl, 1980, and Nijkamp, 1982a). This production function includes - in addition to traditional production factors - also infrastructure capital and R&D capital. Infrastructure serves as the necessary public capital that is a complement to private productive capital; R&D capital (both private and public) serves to generate innovation processes.

Thus the following production function may be assumed:

$$Y = f\ (K, I, R), \tag{1}$$

with:

Y = income (or product) per capita
K = directly productive capital per capita
I = infrastructure capital per capita
R = research and development capital per capita.

Labour has not been included, as all variables are defined in units per capita. The following assumptions are made regarding this production function:

$$\frac{\partial Y}{\partial K} \begin{array}{ll} \geq 0 & K \leq K^* \\ < 0 & K > K^* \end{array} \Bigg\} \tag{2}$$

The condition indicates a positive marginal product of productive capital during a first stage of economic growth. Beyond a certain bottleneck level K^*, diseconomies of scale (high density, congestion, environmental decay etc.) may occur, so that a negative marginal product results. This is reflected in Fig. 1.

It should be noticed that the curve in Fig. 1 is not necessarily the same for a downward movement; usually a production system is not symmetric in a period of expansions and of contraction. This may give rise to an adjusted curve (see Fig. 2.). This curve reflects a situation where inertia in economic and technological behavior may lead to discontinuous growth processes in dynamic systems.

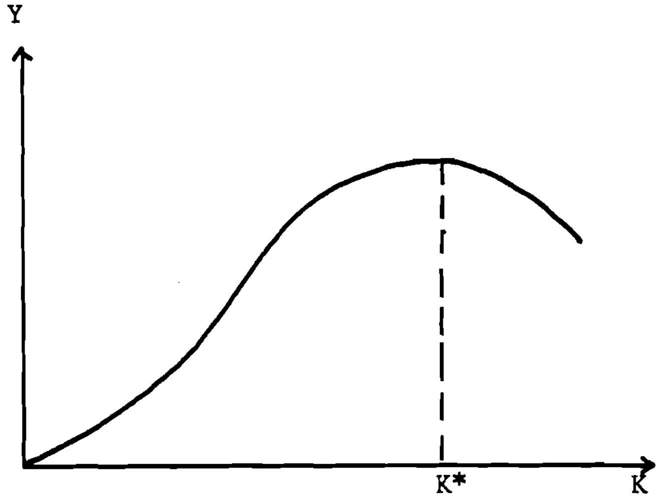

Fig. 1. The partial relationship between product and capital.

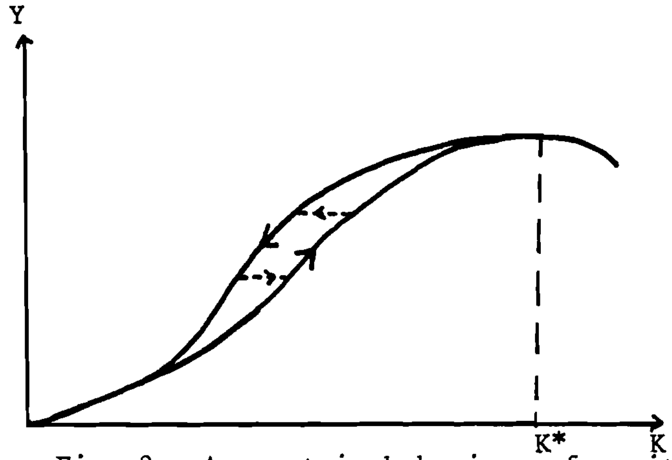

Fig. 2. Asymmetric behaviour of capital in a production function.

This asymmetric behaviour may lead to various kinds of so-called catastrophes (see the dashed lines of Fig. 2), that preclude a smooth transition.

Next, it is assumed that infrastructure investments and R&D investments can be used to cope with negative externalities, so that the level beyond which external diseconomies emerge can be shifted up. Examples of such investments are: water sewage plants, communication infrastructure, and energy envronmental research institutions etc. This leads us to the following relationship:

$$K^* = f(I,R), \tag{3}$$

with the following conditions:

$$\left.\begin{aligned} \frac{\partial K^*}{\partial I} &> 0 \\ \frac{\partial K^*}{\partial R} &> 0 \end{aligned}\right\} \tag{4}$$

Relationships (2) - (4) lead to the following three-dimensional picture:

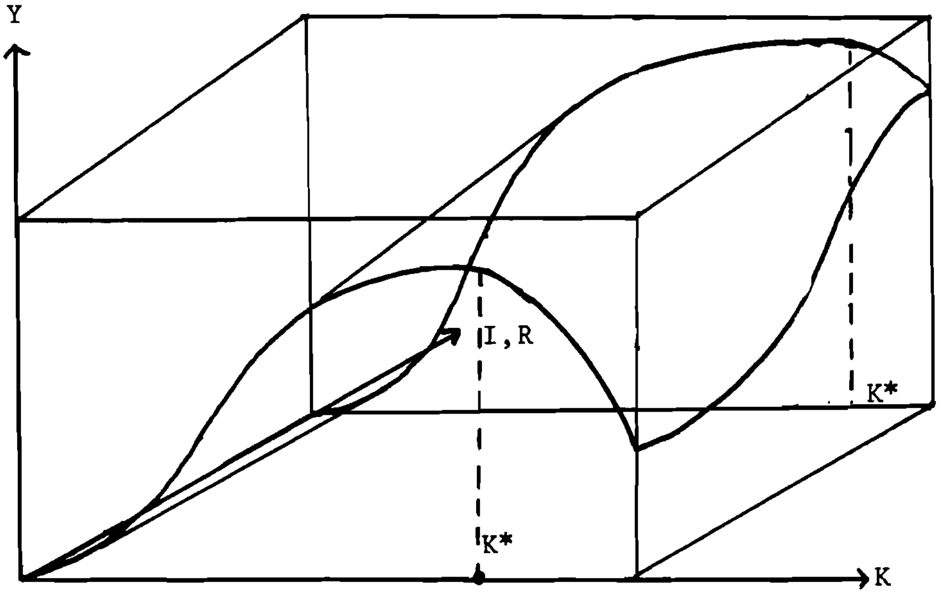

Fig. 3. External diseconomies and infrastructure and R&D capital in a production function.

As far as infrastructure itself is concerned, the production function satisfies the following condition:

$$\frac{\partial Y}{\partial I} \geq 0 \qquad I \geq I^{*}$$
$$= 0 \qquad I < I^{*} \tag{5}$$

This condition states that a city of regions needs a minimum endowment of infrastructure in order to reach a self-sustained growth. In this sense is infrastructure a prerequisite for regional development processes. Thus, the following picture may be assumed for the relationship between infrastructure and production:

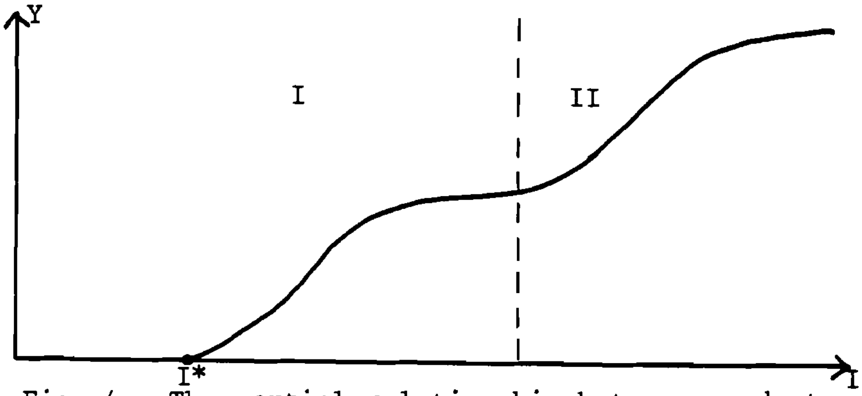

Fig. 4. The partial relationship between product and infrastructure for different levels of capital equipment (domain I: original capital stock; domain II: extended capital stock).

This figure reflects a series of logistic growth paths. This is due to the indivisibility of infrastructure capital, so that only beyond a considerable amount of infrastructure investments significant growth effects may be observed. In a period of contraction again an asymmetric pattern may emerge due to inertia in infrastructure policy and indivisibilities in infrastructure endowment (see Fig. 5). Clearly, in Fig. 5 again various kinds of shocks may be observed in case of a reversed growth path (leading to various catastrophes). This phenomenon is similar to the one described in Fig. 2.

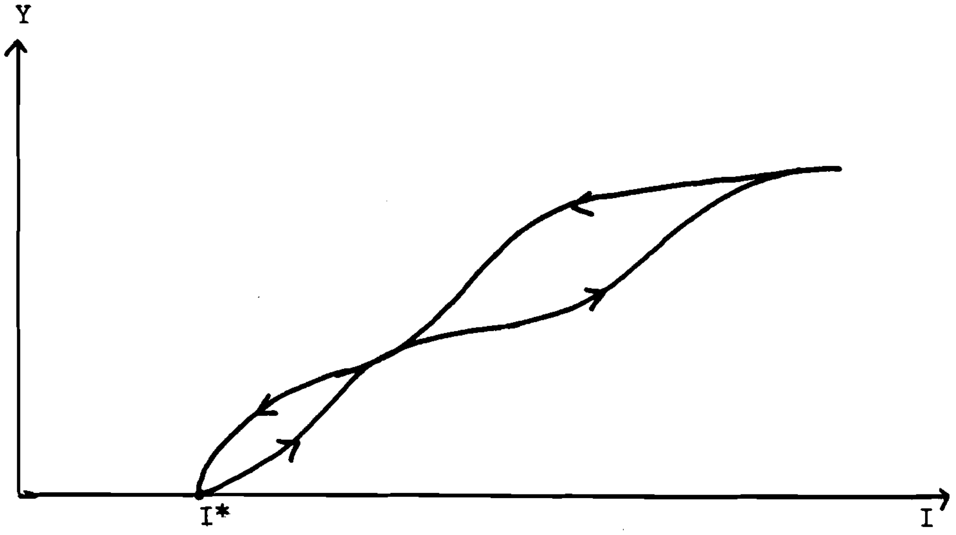

Fig. 5. Asymmetric behaviour of infrastructure in a production function.

Finally, the impact of R&D capital in the production function is assumed to be as follows:

$$\frac{\partial Y}{\partial R} \geq 0 \qquad (6)$$

This partial relationship may be presented in the following figure:

Fig. 6. The partial relationship between product and R&D capital.

Finally, the synergetic effects between K, I and R can be assessed by means of the following second-order derivatives:

$$\frac{\partial^2 Y}{\partial K\,\partial I} \geq 0 \qquad \frac{\partial^2 Y}{\partial K\,\partial R} \geq 0 \qquad \frac{\partial^2 Y}{\partial I\,\partial R} \geq 0 \qquad (7)$$

These cross impacts once more illustrate the necessity of a fine tuning in planning direct productive capital, infrastructure capital and R&D capital. In case of a lack of coordination various jumps in the system may occur leading to various kinds of catastrophes, as can easily be seen from Fig. 3. Such catastrophes can also be depicted in a three-dimensional space as topological singularities in the form of geometrical projections. In this way one gets more insight into the conditions under which equilibrium states of a system display shocks or smooth transitions. Especially if one value of a control variable produces multiple equilibrium values of endogenous variables, a smooth change of a control variable may cause a sudden jump of the endogenous variable (leading to a new value of the latter variable across the fold of the equilibrium surface). Depending on the nature of the equilibrium surface, various kinds of catastrophes may be distinguished, such as cusps, butterflies etc. (see also Nijkamp, 1982a).

Having discussed now the relevant aspects of the production system, we will now describe some motion equations describing the evolution of the system. The following equation for productive investments will be assumed:

$$\dot{K} = \kappa_1 Y - \delta_1 K \qquad (8)$$

with :

$\dot{K}$ = change in capital (= $\frac{\partial K}{\partial t}$)

κ_1 = rate of investment in directly productive activities

δ_1 = depreciation rate for directly productive capital.

A similar equation may be assumed for infrastructure :

$$\dot{I} = \kappa_2 Y - \delta_2 I \qquad (9)$$

with:

κ_2 = rate of investment in infrastructure capital

δ_2 = depreciation rate for infrastructure capital.

Finally, the R&D investment equation reads as:

$$\dot{R} = \kappa_3 Y - \delta_3 R \tag{10}$$

with:

κ_3 = rate of investment in R&D capital

δ_3 = depreciation rate for R&D capital.

The parameter κ_3 deserves a closer attention, as it may be related to the debate on the so-called 'demand-pull' versus 'depression-trigger' hypothesis. If the depression-trigger hypothesis were valid, κ_3 would be higher in case of a decline in Y. On the other hand, if the demand-pull hypothesis were valid, κ_3 would be higher in case of a growth in Y. If we assume for the moment no prior information on κ_3 (nor on the validity of the 'demand-pull' versus 'depression-trigger' hypothesis), it is more appropriate to consider κ_3 as an unknown dynamic control variable whose time path may be assessed on the basis of reasonable assumptions regarding economic behaviour of the system in question. Before doing so however, some more relationships have to be introduced; viz. a consumption equation and some necessary constraints. The following consumption model is assumed:

$$C = (1 - \kappa_1 - \kappa_2 - \kappa_3) Y \tag{11}$$

with:

C = consumption per capita.

Evidently, the following condition holds:

$$\left.\begin{array}{l} \kappa_1 + \kappa_2 + \kappa_3 \leq 1 \\ \kappa_1 , \kappa_2 , \kappa_3 \geq 0 \end{array}\right\} \tag{12}$$

The parameters κ_1 , κ_2 and κ_3 will now be regarded as control parameters. Suppose for instance that consumption is receiving a higher priority, then κ_1 , κ_2 and κ_3 are to be very low. In that case however, productive capital, infrastructure and R&D will be fairly low, so that after some time the productive potential is affected and hence in turn the consumption level. Therefore, a more balanced situation has to be found which guarantees a compromise between short-term desires and a long-term stable growth. In regard to the analysis of a long-term growth path for the system at hand, it is meaningful to use optimal control theory as a mathematical tool. The use of optimal control theory requires the specification of a multi-temporal objective function. Let us assume the following social welfare function:

$$\max \omega = \int_0^T \varphi\,(C,K)\,e^{-rt}\,dt\,, \tag{13}$$

where r is a discount rate for a planning period with time horizon T . The preference function $\varphi = \varphi\,(C,K)$ reflects a compromise between consumption activities C and production activities K . Now the following Hamiltonian H for this optimal control model can be specified:

$$H = \varphi e^{-rt} + \lambda_1\,(\kappa_1 Y-\delta_1 K) + \lambda_2(\kappa_2 Y-\delta_2 I) + \lambda_3(\kappa_3 Y-\delta_3 R) \quad , \tag{14}$$

where:

λ_1 , λ_2 and λ_3 are the costate variables (Lagrangean multipliers).

If κ_1, κ_2 and κ_3 are considered to be control variables, the following first-order conditions for an interior optimal solution for the motion of the system can be formulated by means of optimal control theory analysis:

$$\frac{\partial H}{\partial \kappa_i} = 0 \quad , \quad i=1,2,3 \tag{15}$$

The first order conditions for the adjoint system are:

$$\left.\begin{aligned} \dot{\lambda}_1 &= -\frac{\partial H}{\partial K} \\ \dot{\lambda}_2 &= -\frac{\partial H}{\partial I} \\ \dot{\lambda}_3 &= -\frac{\partial H}{\partial R} \end{aligned}\right\} \tag{16}$$

The conditions for an interior solution of system (14) can be written as follows (see (15)):

$$\left.\begin{aligned} e^{-rt}\,\frac{\partial\varphi}{\partial C} &= \lambda_1 \\ e^{-rt}\,\frac{\partial\varphi}{\partial C} &= \lambda_2 \\ e^{-rt}\,\frac{\partial\varphi}{\partial C} &= \lambda_3 \end{aligned}\right\} \qquad (17)$$

As the λ_i's $(i=1,2,3)$ may be regarded as the shadow prices of productive capital, infrastructure capital and R&D capital, respectively, condition (17) states that the categories of capital have to be utilized in such a way that the shadow prices of all categories are equal. Each of these shadow prices should be equal to the discounted value of the marginal contribution of consumption to social welfare. Thus this condition quarantees a compromise between productive and consumptive activities.

There is however, also a problem related to the foregoing analysis: the control variables are linear in the state space, so that most probably corner solutions will occur (see Nijkamp and Paelinck, 1973). The feasible control space is based on conditions (12) and is represented in Fig. 7.

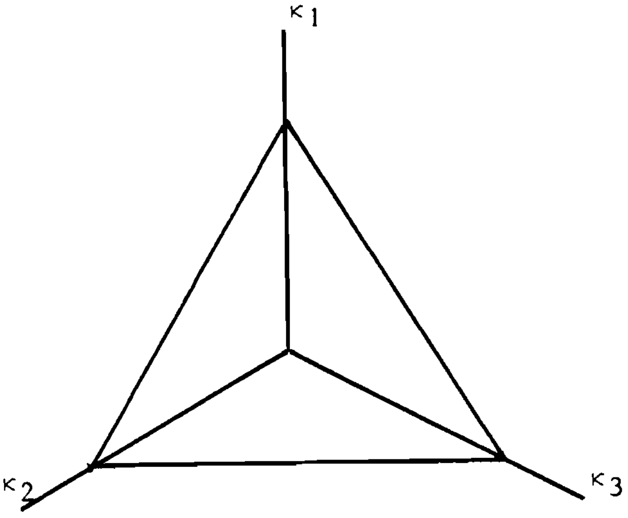

Fig. 7. The feasible control space.

Suppose now, for instance, that the gradient of H with respect to κ_1 is larger than that with respect to κ_2, while the latter is in turn larger than the gradient of H with respect to κ_3 :

$$\frac{\partial H}{\partial \kappa_1} > \frac{\partial H}{\partial \kappa_2} > \frac{\partial H}{\partial \kappa_3} \qquad (18)$$

This implies evidently:

$$\lambda_1 > \lambda_2 > \lambda_3 \quad , \qquad (19)$$

so that the dual price of capital is larger than that of infrastructure, which is in turn larger than that of R&D capital. Then the evident optimal control is:

$$\left.\begin{aligned} \kappa_1 &= 1 \\ \kappa_2 &= 0 \\ \kappa_3 &= 0 \end{aligned}\right\} \qquad (20)$$

Evidently, such extreme controls will - after some time - affect the spending capacity for consumption, so that after some periods a shift toward another control is possible (either another corner solution or an interior solution). In an analogous way all other corner solutions may be analyzed. It is clear that the presence of corner solutions may lead to so-called 'bang-bang' strategies which cause permanent shocks in the behaviour of the system.

Thus, in conclusion, catastrophes and perturbations in the abovementioned system may be caused by two sources:

- the asymmetric behaviour of the dynamic system reflected by the complex production function;
- the corner solutions of policy strategies governing the state of the system at hand.

The foregoing analysis can be extended in two ways, viz. by introducing multiple objective functions (leading to multicriteria optimal control models; see Nijkamp, 1979) and spatial interaction (or spill-over) effects. The first approach is especially relevant in an interactive framework between experts and decision-makers; shifts in policy priorities may here lead to shocks in the outcomes of the system concerned. The second phenomenon is particularly relevant in case of diffusion of innovation or of interregional spill-overs from infrastructure endowment. By introducing such spatial interaction effects, a fully integrated spatial system may emerge that is capable to describe to spatial dynamics in an interwoven spatial system. Clearly, more analytical and empirical work has to be done before such approaches are operational and suitable for practical policy situations.

5. Conclusion

The abovementioned analysis has demonstrated various interesting features. In the first place, it turns out that inertia in a dynamic spatial system can be reflected by means of non-linear dynamic models that may generate various fluctuations. Thus the phenomenon of spatiotemporal waves emerging from recent literature on economic dynamics can be provided with a firm theoretical basis that is in agreement with current economic research in the area of long waves. In the second place, the subdivision of regional capital equipment into productive capital, social overhead capital and R & D capital appears to yield a meaningful framework for analyzing the differential impact of various capital categories on regional growth phenomena. This also offers a possibility for including retardation effects, congestion effects and threshold effects, so that various kinds of catastrophes can be described. Finally, this analysis is extremely important, as it is able to study the conditions under which the demand-pull hypothesis and the depression-trigger hypothesis may have a validity. In this respect, again a close link with current economic studies in the area of innovation and economic growth does exist.

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