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ADOPTION AND DIFFUSION OF INNOVATIONS

AND

EVOLUTION OF SPATIAL SYSTEMS

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**VRIJE UNIVERSITEIT
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A M S T E R D A M**

ADOPTION AND DIFFUSION OF INNOVATIONS

AND

EVOLUTION OF SPATIAL SYSTEMS

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1. INTRODUCTION

Technology and (spatial-)economic dynamics are closely intertwined phenomena, and therefore it is no surprise that the current economic stagnation has led to an increased interest in innovation as one of the driving forces for structural change (see for instance, Klein-knecht, 1986). The role of innovation has become a central piece of current economic research, witness a great many debates on the validity of concepts like 'depression trigger', 'demand pull' and 'technology push'. In this context, Stoneman (1983) has made a useful distinction of this research area into the following parts: the generation of new technology, the diffusion pattern of new technology (including the adoption of innovations), and the socio-economic impacts of these processes. These three elements will briefly be discussed.

First, the way new technologies and innovations are being induced has been studied quite extensively in the recent literature, in the context of both the 'long waves' discussion and the 'product cycle' theory. Also the spatial framework of technological innovation has received a great deal of attention, inter alia in the field of the 'urban incubator' hypothesis (see for an extensive review Davelaar and Nijkamp, 1986).

The second element, viz. the dispersion of technological innovations, has also received much attention in the past years (see among others Brown, 1981), following the earlier attempts made among others by Hagerstrand (1967). Despite path-breaking work in this field, the behavioural and quantitative-analytical background of many contributions to innovation diffusion has not always been impressive, one of the main reasons being that in several cases a behavioural (especially a micro-economic based) choice theory was lacking. An interesting exception in this field is a recent publication of Sonis (1986) on the relationship between innovation diffusion and spatial change in the framework of ecological dynamics.

Our paper will make a modest attempt at revisiting and extending some essential elements of structural spatial changes caused by technology diffusion and adoption. The focus of the present paper will mainly be on the (spatial aspects of the) diffusion of technological innovations (interpreted here as the design, construction and successful introduction of new (or improved) commodities, services, produc-

tion processes or distribution processes; see Dieperink and Nijkamp, 1986). In a broader and more comprehensive context such innovations may occur as clusters, coined 'technological regimes' by Winter (1984). An attempt will be made here at specifying a stochastic model for the adoption of innovations and the pertaining spatial developments.

The third component of technology research, viz. the socio-economic impacts, will be dealt with in a less elaborate manner here, viz. mainly in relation to spatial dynamics. For a more elaborate treatment of this subject, especially as far as the triangular relationship is concerned between technological change, employment and spatial dynamics, the reader is referred to Nijkamp (1986).

The paper is organized as follows. Section 2 contains a first version of a stochastic model for the acceptance of innovations in different sectors and different cities, based on the technological potential for adopting innovations. In a subsequent section, an introductory exposition of non-linear dynamic models of the Verhulst type is given, followed by an application of the Verhulst type of model, in which the impacts of new activities on the urban economies (in different sectors) are related to competition (in terms of differential attractiveness factors) between cities and sectors in a spatial system. Section 4 provides a link between the acceptance of innovations and its impact on the spatial evolution of the multi-sector multi-city system. The paper is concluded with some reflections on the operational mechanism of such a dynamic model.

2. A STOCHASTIC MODEL FOR ADOPTING INNOVATIONS

The model developed in the present paper will be based on a stochastic theory of spatial evolution. An attempt will be made at constructing a simple multi-sector multi-region (or multi-city) model, which is able to describe the impacts of technological innovations in one or more specific sectors on the spatial system concerned. Thus the main focus of the paper will be on the interaction between the evolution of a spatial system and the diffusion of innovation.

Let us assume the following stochastic binary choice model for the adoption of a certain technological innovation (or a technological regime):

$$p(x_i, k, t) = \frac{r_{it}^k}{r_{it}^k + h_{it}^k}, \quad (2.1)$$

where: $p(x_i, k, t)$ = probability that a city i with size x_i will adopt (the generation and implementation of) innovation in sector k at time t

x_i = size of city i (measured in terms of population, e.g.)

r_{it}^k = volume of activities of sector k in the city of size x_i that are able to generate and implement a certain relevant innovation in period t

h_{it}^k = volume of (remaining) activities of sector k that - for technical reasons - are unable to create and realize a certain innovation.

Clearly, $(r_{it}^k + h_{it}^k)$ represent the total volume of activities of sector k in a city of size x_i at time t . It is assumed here that h_{it}^k is independent of city size i , as this limitation is caused by technical reasons, specific for sector k , hence:

$$h_{it}^k = h_t^k \quad (2.2)$$

Here, it is assumed that the volume of activities r_{it}^k can be decomposed into 2 elements, viz. the city size x_i and an innovation acceptance coefficient g_t^k , i.e.,

$$r_{it}^k = g_t^k x_i, \quad (2.3)$$

where g_t^k reflects the fraction of activities of sector k in city i that can technically implement the innovation at hand in this city in period t .

The foregoing model is assumed to have the following properties:

- (1) $x_i, g_t^k, h_t^k \geq 0$
 $0 \leq p(x_i, k, t) \leq 1$ (2.4)
- (2) technical progress implies the following conditions:

$$\dot{g}_t^k > 0; \dot{h}_t^k < 0; \dot{\kappa}_t^k < 0 \quad (2.5)$$

where κ_t^k ($\kappa_t^k \geq 0$) is defined as follows:

$$\kappa_t^k = \frac{h_t^k}{g_t^k}$$

It is assumed in the present paper that long-run technological progress (i.e., when $t \rightarrow \infty$) implies that $\lim_{t \rightarrow \infty} \kappa_t^k = 0$. A reasonable specification fulfilling this condition for the time trajectory

of κ_t^k may be an exponential function:

$$\kappa_t^k = a_0^k \exp(-a_t^k t) \quad (2.7)$$

Clearly, alternative specifications may quite well be possible.

$$(3) \lim_{x_i \rightarrow \infty} p(x_i, k, t) = 1 \quad (2.8)$$

This condition is in agreement with a hierarchical (rank-size) system. It is easily seen that condition (2.8) also holds if $h_t^k = 0$.

$$(4) \lim_{x_i \rightarrow 0} p(x_i, k, t) = 0 \quad (2.9)$$

It is also easy to verify that condition (2.9) holds if $g_t^k = 0$.

The foregoing properties imply that $p(\cdot)$ satisfies the additivity condition and hence may be interpreted as a choice probability, as it is easily seen from the binary choice model (2.1) that:

$$p(\cdot) + (1-p(\cdot)) = 1 \quad (2.10)$$

Furthermore, it is also worth noting that permanent long-run technological progress implies:

$$\lim_{t \rightarrow \infty} p(\cdot) = 1 \quad (2.11)$$

For further expositions on the shape of the adoption curve of innovations the reader is referred to Allen et al. (1978).

Clearly, the degree of acceptance of innovations in a specific city is depending on city size on the one hand and technological progress on the other hand. In the light of these observations, it is an interesting question how the dynamics of the spatial system affects the innovation diffusion and vice versa. Therefore, in the next section a simple model for spatial dynamics based on a Verhulst dynamic model will be developed. Despite its simplicity, the qualitative properties of our model will be shown to be fairly intricate. Only simulation experiments on a computer are then able to reveal the full flavour of such a space-time model. Nevertheless, some basic qualitative properties will be outlined in section 4.

3. A SIMPLE MODEL FOR SPATIAL DYNAMICS

In recent years, a wide variety of dynamic (often non-linear) models has been developed in order to describe the impact of a significant exogenous stimulus (an innovation, e.g.) on the equilibrium pattern of a dynamic system. A usual specification of a general dynamic non-linear model is the Verhulst equation of logistic growth (see Maynard-Smith, 1974):

$$\dot{x} = \alpha x (N-x) - \beta x, \quad (3.1)$$

where α and β are constant parameters, and where N is related to a capacity level (or saturation level) for the systems variable x . The variable x may represent, for instance, the economic performance of the existing system.

Suppose now the introduction of a significant technological innovation (occurring in a clustered manner, e.g.; see Mensch, 1979). This new set of activities may be denoted by y ; it has an impact on the existing economy as follows (see Batten, 1983):

$$\dot{x} = \alpha x (N-x-\gamma y) - \beta x, \quad (3.2)$$

where y may exhibit the same dynamic pattern as x , so that a nested dynamic process may emerge. This variation through innovations (see Nicolis and Prigogine, 1977) evokes the problem of steady-state solutions (see also Allen, 1976). In recent years this problem has been studied quite extensively in the literature, and further contributions to the field of such multi-actor Volterra-Lotka and predator-prey type of models can be found among others in Brouwer and Nijkamp (1985), Casti (1982), Dendrinos and Mullally (1984), Dendrinos and Sonis (1984), Pimm (1982), Ralston (1977), and Samuelson (1971).

The strength of those models is that they are able to generate a great diversity of complex dynamic behaviour while retaining simplicity in model structure, although an apparent drawback is still that most of the models are lacking a testable micro-based behavioural foundation.

In this context, an interesting neoclassical approach to the choice process underlying innovation diffusion can be found in Soete and Turner (1984), who used Nelson and Winter's (1982) evolutionary theory of economic growth to analyze the micro-economic level of the adoption

and diffusion of new technologies. Their analysis is however based on a deterministic approach in which spatial dynamics is not explicitly taken into account; new advances based on stochastic (disaggregate) utility theory can be found in Haag and Weidlich (1984), who tried to develop a probabilistic evolutionary spatial model. A review of such non-linear dynamic modeling efforts can be found in Barentsen and Nijkamp (1986).

Altogether, it can be concluded that there is an increasing tendency toward constructing discrete choice models based on a stochastic acceptance (and diffusion) of innovations.

In the present section an illustrative model based on a Verhulst specification will be used as a framework for treating urban dynamics in a spatial system. The fundamental growth equation for city i is supposed to be:

$$\dot{x}_i = \alpha x_i (N + \sum_k \epsilon^k v_i^k - x_i) - \beta x_i, \quad (3.3)$$

where α is the birth rate of urban activities, β the death rate of existing activities, N the initial physical-economic carrying capacity for economic activities of the city, v_i^k the volume of new activities in sector k generated in city i (measured in appropriate units), and ϵ^k the impact of new activities in sector k on the growth of city i . Thus the expression $\sum_k \epsilon^k v_i^k$ indicates the capacity growth in the original volume N , due to the introduction and implementation of new activities k .

Next, the growth of these new activities in sector k in city i may be represented as follows (see also Allen et al., 1978):

$$\dot{v}_i^k = \eta v_i^k (e_i^k - \delta^k v_i^k), \quad (3.4)$$

where η is the growth rate of these new activities, e_i^k the volume of employment (or, in general terms, production factors) that might potentially be generated in sector k in city i (i.e., a ceiling for new urban activities), and δ^k a market threshold coefficient in sector k .

In addition, one may assume:

$$e_i^k = \mu^k d_i^k, \quad (3.5)$$

where d_i^k is the demand for the products generated by sector k in city i , and μ^k a (constant) parameter linking the effective demand for k to their potential employment opportunities (usually, $\mu^k \geq 1$).

Besides, the total demand in city i generated by residents of other cities j is - in case of absence of spatial competition - equal to:

$$d_{ij}^k = \lambda^k x_j / (p_{ij}^k)^v \quad (3.6)$$

where p_{ij}^k is the c.i.f. price of a unit of products from sector k , produced in i and shipped to residents in j ; λ^k and v are just normal reaction parameters.

Now the price p_{ij}^k is supposed to depend on communication costs between cities i and j as follows:

$$p_{ij}^k = p_i^k + \phi^k d_{ij}, \quad (3.7)$$

where p_i^k is the f.o.b. price, d_{ij} the distance between i and j , and ϕ^k the unit communication cost.

Next, one may introduce spatial competition between cities on the basis of an attractiveness indicator a_{ij}^k for sector k which incorporates urban facilities and price levels of sector k :

$$a_{ij}^k = \rho n_i / (p_{ij}^k)^\theta \quad (3.8)$$

where a_{ij}^k is the relative attractiveness of city i for residents of city j , n_i the share of facilities in city i , while θ and ρ are standardization parameters.

Consequently, the demand in city i generated by households outside city i is co-determined by the relative attractiveness of city i , so that equation (3.6) may be adjusted as follows:

$$d_{ij}^k = \lambda^k x_j a_{ij}^k / (p_{ij}^k)^v = \lambda^k x_j \rho n_i / (p_{ij}^k)^{v+\theta} \quad (3.9)$$

It is easily seen that the total sectoral demand can be directly calculated from (3.9), while also (dis)economies of scale may be incorporated. By substituting now (3.9) into (3.5), followed by a

substitution of (3.5) into (3.4), equations (3.3) and (3.4) describe a highly non-linear dynamic evolution of a spatial system composed of competing regions, which might lead to competitive exclusion (see also Johansson and Nijkamp, 1986). Thus various types of dynamic behaviour may emerge, depending on the initial conditions and the various parameters of the system. As the analytical properties of this model are hard to trace, usually simulation experiments have to be carried out in order to study the stability and equilibrium properties of such a model. Having presented now a model for spatial competitive dynamics, we will in the next section integrate the elements of the innovation diffusion model discussed in section 2.

4. INNOVATION DIFFUSION AND SPATIAL DYNAMICS

As mentioned in section 2, technological progress implies that the ratio of activities which cannot technically implement a certain innovation with respect to those which are actually able to do so is declining (see condition (2.5) and (2.6)). Clearly, an innovation will only be successfully introduced if it creates a decrease in production

costs c_{it}^k , i.e., if

$$\dot{c}_{ij}^k < 0 \rightarrow \dot{c}_{it}^k < 0. \quad (4.1)$$

Clearly, cost savings will lead to a reduction in the f.o.b. price p_i^k in equation (3.7), so that then sector k in city i improves its competitive position, i.e.,

$$\dot{p}_i^k = f(\dot{c}_{it}^k). \quad (4.2)$$

Consequently, once condition (4.1) is fulfilled, the basic model linking acceptance of innovations to spatial dynamics is composed of equations (2.1), (3.3) and (3.4) (after substitution of the pertaining equations).

Now the mechanism of this model and its features may be explained as follows. Suppose a major technological innovation taking place in a cluster-wise manner and penetrating the majority of all sectors k (the informatics revolution, e.g.). The spatial-economic spread effects of such an information wave can then be traced as follows. First, there is an initial diffusion of innovation according to equation (2.1). If

city i is large, it will probably incorporate directly a large share of the innovation (reflected by a high value of $p(\cdot)$), while the (hierarchical) spatial diffusion of the innovation concerned will depend on the size of cities in the spatial system.

Next, the time path (i.e., the adoption rate over time) of the innovation depends on the value of κ_{it}^k and its impact on production costs. Clearly, the combination of both processes may lead to the well-known space-time processes in dynamic geographical systems (see Griffith and Lea, 1984). The way these combined processes affect the spatial system can now be described in a stepwise way.

- (1) Define the existing spatial system with cities i and sector k by means of the abovementioned state variables and related parameters.
- (2) Identify the rate of potential technology acceptance parameters κ_{it}^k for the successive time periods and calculate the corresponding probabilities $p(\cdot)$ for each city i and each sector k .
- (3) If condition (4.1) is fulfilled, one may use (4.2) (as well as the remaining equations) to analyze the impact of a major innovation (accepted in many sectors) on the dynamic evolution of a competitive spatial system. If, for instance, city size x_i increases (see (3.3)), then $p(\cdot)$ will increase (see (2.1)); a higher adoption rate of innovation will decrease production costs and hence the competitive position of city i , so that employment growth will take place, leading to a growth in i , etc.

The dynamic development of such a spatial system might be generated or reproduced by means of simulation experiments. To some extent, the diffusion mechanism of this model is aligned to the Christaller framework, especially because city size plays a major role in the adoption rate of innovations. However, because of the distance decay function for communication costs, the model is also exhibiting a distance-related diffusion pattern. Clearly, technological innovation might also lead to a reduction in communication costs. Given the positive impact of large cities on the acceptance rates of innovations, there is some reason to assume that large cities will become larger in our dynamic system. Consequently, beyond a certain threshold level of city size, it might be important to include a negative externalities factor

in order to allow the model to generate a broad spectrum of different spatial behaviour.

5. CONCLUSION

The approach presented in the previous sections was essentially based on the competitive aspects of spatial dynamics. A proper choice and implementation of new technology in a certain place enhances its efficiency and hence its relative growth chances in a spatial system. This growth was assumed to be caused by a simultaneous occurrence of both producer behaviour and consumer behaviour in the adoption of technological innovations.

It should be added that this model as such is not fully operational (in terms of empirically based quantitative models), although - by means of simulation experiments, e.g. - it may reveal a diversity of space-time patterns, emanating from the interplay of economic and technological key forces (for example, by means of an evolutionary event history analysis).

Our approach emphasizes the impact of technology on production processes and, hence, on growth of cities through multiplier processes emerging from innovations and related agglomeration forces. In an analogous manner, our model might be used to trace the impacts of new information technology (NIT) on city size in a technology-driven spatial system through an analysis of agglomeration forces associated with different kinds of technology. Altogether, the potential of this model can be further explored under different economic-technological regimes.

Finally, it is worth noting that a space-time model like the one considered in this paper, is fairly complex in the sense that it is not possible to represent the content of the model in terms of a few easily tractable qualitative (of quantitative) properties. However, this is the trade off to be faced, if one wants to model the interplay of economic and technical forces in an evolutionary context, whereby a diversity of space-time patterns can be studied.

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