SPATIAL INTERACTION IN DYNAMIC URBAN SYSTEMS

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FOREWORD

Declining rates of national population growth, continuing differential levels of regional economic activity, and shifts in the migration patterns of people and jobs are characteristic empirical aspects of many developed countries. In some regions they have combined to bring about relative (and in some cases absolute) population decline of highly urbanized areas, in others they have brought about rapid metropolitan growth.

The objective of the Urban Change Task in IIASA's Human Settlements and Services Area is to bring together and synthesize available empirical and theoretical information on the principal determinants and consequences of such urban growth and decline.

This paper by Eric Sheppard, a visiting Research Scholar in the Urban Change Task, discusses the role of spatial interaction in models of change in inter-urban systems. A general methodological framework for incorporating spatial interaction is laid out and used to review the literature on city size distributions and on the diffusion of short-term economic cycles between cities. A model of patterns of metropolitan concentration and deconcentration is then provided as an application of this framework.

A list of publications in the Urban Change Series appears at the end of this paper.

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ABSTRACT

It seems contradictory to model urban system change without considering changes in inter-urban interaction patterns, but this has frequently been the case in the urban literature. Consideration and explanation of changing interaction patterns is an area to which the "geographer's perspective" has much to contribute. Most explanations of city size distributions have ignored interactions and thus seem to be fundamentally in error. Short-term responses of cities to economic cycles may be identified and understood better by considering the inter-urban space-time diffusion pattern of economic impulses. Long-term changes such as urban concentration and deconcentration can also be modeled with dynamic interactions. Among other conclusions it can be shown that unequal urban, and regional, growth rates are probable if interaction patterns are dynamic, even in the absence of economies of scale.

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I shall concentrate on economic and demographic interactions, many of the same conclusions hold for other types of contacts between cities, such as flows of information. A series of sections will illustrate how interactions play an important role in many of the issues of interest to issues of urban change, as raised by Korcelli (1980).

The first section constructs the argument that theories of how interaction patterns respond to spatial configurations of opportunities are essential in dynamic modeling of multi-locational systems. This is an issue particularly, although not exclusively, studied by geographers, who can thus provide a complementary perspective to that of other social scientists in studying cities. The second section considers theories of urban size distributions, and concludes that, virtually without exception, the role of inter-urban links is ignored. It is suggested that such a neglect is only valid in the unlikely event that a theory can be developed showing that interactions are irrelevant to size distributions.

Section 3 argues for the importance of studying short-run urban responses to economic cycles. Such crises are as important in trying to improve urban living conditions as are long-run trends. A body of literature which has provided insight into such issues is then examined from the perspective of the spatial interaction paradigm. Finally, section 4 applies this paradigm to a long-run problem, that of urban concentration and dispersal. While no definitive theory results, it is demonstrated how many of the ideas put forward by others may together be incorporated into a common model with dynamic interactions. Dynamic interactions can also easily allow for the type of unbalanced spatial growth patterns that fundamentally underlie this phenomenon. Some data needs are also indicated.

One question of terminology should be discussed at the outset. The expression "configuration" will be used to describe the geographical distribution of some phenomenon, instead of the more customary "spatial structure". The term structure and

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INTRODUCTION

Despite the long history of research into inter-urban systems, questions of temporal change have been somewhat neglected. This is particularly true with regard to the development of well-specified theories, since much of the work has been of a very empirical and exploratory nature. Furthermore, there is a curious contrast in approaches taken in different disciplines. Comparing the work of economists and geographers, the two most active groups in this area, the former concentrate on ascribing the causes of change in a city, to variables representing its internal structure. Geographers, on the other hand, have performed a number of studies isolating the importance of inter-urban flows of technology, labor, and commodities, while showing a persistent failure to incorporate such considerations into the appropriate sociological and economic theory. If good theory is necessary to both understand and change urban systems, then a strong case exists for integrating these two approaches together into a coherent conceptual framework.

The major theme of this paper is a plea for greater consideration of changing inter-urban spatial interaction patterns in our theories of urban system development. The argument is phrased primarily for inter-urban systems although similar points could be made at other spatial scales. Similarly, although region of current residence, then a model of spatial savings dynamics would be:

$$\underline{y}'_{t+\delta t} = \underline{x}'_{kt} \cdot M_t \cdot S^d_t \tag{2}$$

where M_t is a matrix of migration rates at time t, and S^d_t is a diagonal matrix of savings propensities, s_{it}, in region i at time t.

Two comments should be made regarding this model. First, it has a simple Markovian time structure which cannot allow cyclical change without special assumptions about M_t. More generally we can write:

$$\underline{y}'_t = \sum_k \sum_{s=0}^{T} \underline{x}'_{k,t-s} \cdot M^k_{t-s} \cdot S^d_{kt} \tag{3}$$

In (3), time lagged dependency or multiplier effects have been incorporated into the interaction terms of M rather than in the response factors S^d. This allows application of general potential theoretic equations to describe spatio-temporal multiplier effects (Sheppard 1979a,b). This choice, however, will depend on circumstances.

Second, the separation made in (3), if appropriate, allows one to distinguish the "geographer's story", in specifying M, from that of (in this case) the economist who would suggest the choice of variables in (3). The fact that these two questions are difficult to isolate from one another points to the necessity for interdisciplinary work, to which each specialist will contribute his or her specific expertise (Sheppard 1979c). It goes without saying that replacing M by an identity matrix is as likely to produce incorrect results as is any model which incorrectly chooses $\underline{x}_k$ and $\underline{y}$, or neglects S^d (cf. Rogers and Philipov 1979). An interdisciplinary approach is thus essential.

its adjectives will be reserved to discuss non-spatial distributions; such as the mix of secondary versus tertiary industry in a city.

1. A METHODOLOGY FOR DYNAMIC SPATIAL MODELING

The aim of a dynamic spatial theory is to replicate the changes that occur in the phenomenon under study. Taking a discrete space-time representation let the vector $\underline{y}_t' = (y_{1t}, \ldots, y_{nt})$ represent the levels or stocks of variable y in each region i at time t. The prime indicates transposition of a vector or matrix, and the n regions are assumed to represent a mutually exclusive, collectively exhaustive partition of the study area. Describing the spatial configuration in vector terms is not sufficient, however, to represent a conception of the spatial dynamics, as the links between regions form a necessary component. Thus we must define an interaction matrix showing the influence of factors in i at time t on region j at time $t + \delta t$. Generally:

$$\underline{y}_{t+\delta t}' = \sum_k \underline{x}_{kt}' \cdot C_{kt} \qquad (1)$$

where $\underline{x}_{kt}' = (x_{1t}^k, \ldots, x_{nt}^k)$ is a vector of values for variable x_k at each location i, time t, and C_{kt} is a matrix with entries (c_{ijt}^k) representing the effect of one unit of variable x_{it}^k on $y_{j,t+\delta t}$. Obviously, each x_k is assumed to have an additive effect on $\underline{y}_t$.

C_{kt} is a matrix of spatial interactions and thus is a function of the spatial structure of the system. In certain cases, C_{kt} may be partitioned into two matrices, one representing the level of spatial interaction and the other representing *in situ* behavioral responses linking x_{ik} and y_i. Thus, for example, if y_i represents incomes saved in region i, x_{ik} represents the population in i, and c_{ij}^k is the migration rate between i and j, and people are assumed to save all their money in their

At first glance an equation such as (1) or (3) seems to represent a linear system thus being subject to the conventional analysis of such models. For example, one might anticipate assuming the composite matrix $M \cdot S^d$ to be constant over time which would allow statistical estimation of its values as parameters from time series data. However, geographic theory tells us that such an assumption is a simplification that is so inaccurate that its use for descriptive purposes must be rejected. The terms (m_{ij}) of M, for example, represent the proportion of trips from i that terminate at j. This is a function both of the pattern of the configuration of opportunities and of communications in the system. In our expenditure example [equation (2)]

$$M_t = M(\underline{x}_{kt}, F) \qquad (4)$$

where F is a matrix of distance friction effects. Thus, if d_{ij} is the distance from i to j we would expect $\partial f_{ij}/\partial d_{ij} < 0$, where f_{ij} is an arbitrary element of F. As a simple example, we might expect migration to be approximated by a "gravity" model:

$$M_t = F \cdot \underline{x}_{kt}^d \qquad (5)$$

where $\underline{x}_{kt}^d$ is a diagonal square matrix with x_{it}^k occupying the position of the i-th diagonal element.

Substitution of (5) into (2) readily demonstrates that the proper model is quadratic rather than linear, suggesting how grossly inaccurate any assumption of linearity can be. Conceptually speaking, the evolution of spatial configurations is a function of interaction patterns, which themselves are generated by past configurations. There is an "interaction feedback" model with a theory of interaction dependent on a theory of configurational change and vice versa. Thus the geographer has much to contribute to any dynamic urban systems theory by increasing our understanding of the laws of motion of interaction patterns. It is unfortunate, then, that geographical research in this direction has not provided a coherent body of convincing theory (Sheppard 1979d).

In modeling those components of urban system change that are amenable to quantitative approaches, the above interaction feedback framework provides a general methodological foundation. Then locations of equations (3) and (4) may be chosen to represent cities or urban regions, together with those non-metropolitan rural regions that are important. Further, the model may be readily disaggregated, to allow for incorporation of theoretical relations and accounting identities that allow for the differential structural components of change. Thus economic variables may be disaggregated by activity type (Leontief 1951), demographic variables split into age and sex groups (Willekens and Rogers 1978), and social and political variables distinguished by occupation, social class, preferences and power relations (Friedman 1972). Such disaggregations represent increases in computational rather than theoretical complexity, but at the same time represent vital considerations if structual causes of change are to be separated from changes in the "laws of motion" of urban systems. The following sections, it is hoped, will aid in illustrating how the general methodlogical framework outlined above is applicable to problems of interest in understanding urban systems dynamics.

2. CITY SIZE DISTRIBUTIONS

Richardson (1973) has provided a review and classification of explanations for the so-called "rank-size rule", describing the regularity that has been observed to exist in many urban systems between the size of a city and its ordinal rank in terms of size with respect to the other members of the system. Since more recent papers (Dacey 1979, Parr and Suzuki 1973) have added no new dimensions to this typology, it is perhaps useful to review it here as follows:

a) explanations generating city size distributions from assumptions about city growth rates and population reallocations as functions of city size
b) explanations deducing population sizes from employment multipliers generated by assuming some type of central place system
c) explanations deduced from economic models specifying growth rates and economies of scale as a function of city size
d) explanations based on allometric relations between city size and growth rates

The rank size rule itself says nothing about the relative locations of the cities in the system, and indeed from the spatial analyst's point of view the concept says little. The conceptualization of equations (3) and (4) would suggest, considering $\underline{y}_t$ as a vector of populations, that urban growth trends are strongly related to past spatial configurations, and interaction patterns. However, it is of interest to note that none of the types of explanations reviewed by Richardson incorporate this. In each case growth rates are independent of the size of other cities in the system, and of the configuration of cities.

Since the rank size rule is simply a picture of current population patterns, which themselves are the result of past interdependent growth relations, it is strange indeed that no explanations have taken this into account. Such factors are recognized among less quantitatively oriented urban analysts. For example, the existence of primate distributions in former colonies has been frequently, and plausibly, explained by the dualistic development of the country, with the major port being linked into the world economy whereas other cities, with poorly developed links with this port, stagnate. Okabe (1979) and Sheppard (1976) show how, with a "gravity" theory of interactions, an interaction feedback model can easily generate this type of polarized growth theoretically. Okabe also shows its application to the Japanese urban system. I know, however, of no other attempts to theoretically substantiate these issues.

For the explanations reviewed by Richardson to be convincing, it must be shown that the matrices M_t, driving population change through their impact on migration and birth and death rates, can be approximated by a diagonal matrix. There has been no attempt to show this, and in fact common sense would suggest that such a reduction would be unlikely. The conclusion then follows that the geographer's story is not being told here, and that without this the validity of our explanations is likely to be limited.

It is curious, given this, that the rank size rule is such a common phenomenon in urban systems. If the geography of the system is important we might expect each different geography to produce a distinctive urban size graph. On the other hand, however, there are almost as many explanations of this phenomenon as there are examples of its existence, suggesting the many ways by which a rank size curve can be reached. Allowance of urban interdependencies can only increase the number of possible explanations. This suggests the conclusion that the rank size rule is an over-identified concept. There are, perhaps, so many ways of reaching it that a general theory should not be sought. Instead it should be accepted as a fact of life. In this sense one is reminded of the negative binomial distribution in point pattern analysis and the central limit theorem in statistics.

This does not imply that the rank size distribution is an irrelevant concept. It may be useful to identify certain situations, such as that of excessive primacy, which are generally agreed to be undesirable. In addition, the size distributions generated by dynamic models can be indicative of their descriptive accuracy. As regards the use of city distributions in evaluating the social desirability of an urban system, there seems to be no agreement on what is an "optimal" distribution. Indeed this in all likelihood depends on the particular economic, social and political system.

Thus I conclude that the size distribution of cities should be regarded as a derivative concept rather than a starting point; as something that is deduced from applying a general urban systems dynamic model to a particular situation. In addition, in evaluating the desirability of a particular type of size distribution, we should not jump to conclude that a rank size pattern is in some sense optimal because we observe it frequently or because we have explanations for it. That would represent the type of capitulation of normative thinking to reality that radical analysts rightly typify as *status quo* maintaining social science (Harvey 1972). Instead, it is necessary to develop rules for evaluating urban system outcomes so that they can be sorted into desirable and undesirable ones. It may well be that urban size distributions turn out to be an important indicator in such a classification, but if so that is something that is to be deduced rather than assumed.

3. SHORT-TERM URBAN CYCLES

The existence of cyclical phenomena seems endemic to the modern economy, giving rise to serious national policy issues related to unemployment, inflation, over-accumulation, and trade imbalances. At present, policies which can effectively mitigate these effects are not widely agreed on by economists, but nevertheless it is essential to at least attempt to predict the timing and severity of such cycles in order to try and understand this source of short-term economic crisis. A similar argument exists at the urban scale, where such cycles cause major problems for cities. Indeed, national cyclic behavior is just the sum of urban and regional oscillations. The existence and importance of this phenomenon in western countries has already been documented, and it is likely to exist also in Eastern European countries. This suggests that counter-cyclic policies with a specific urban dimension represent a topic of transnational interest, and worthy of study. If such policies could be made effective they could only have a positive effect on the national economic picture.

Three ways of looking at this question can be identified with the aid of the methodological framework suggested in section 1. First, if economic change diffuses through the urban system it may be possible to identify cities that are the first to show economic upturns and downturns. Such cities could then be used as leading indicators; sub-economies that foreshadow economic cycles. Second, the different structural mix of the urban economy in different cities implies that cycles will be more damaging in some cities than others. Examination of structural effects will both indicate what types of urban economies seem more desirable, and also pinpoint cities that need most immediate attention. Finally, if it is possible to understand the spatial interaction mechanisms which propagate the diffusion of economic fluctuations between cities, and to isolate such external agents of change from internal factors, then it is possible to talk of the possibilities of controlling cycles by erecting barriers in the way of the diffusion process.

Of these three questions--the time-space lags in cycles, structural effects, and understanding the diffusion mechanism--the most work has been done on the first problem. The second one has also received some attention, but from a different point of view. The third issue, however, has received little notice. To illustrate this, I shall describe past work on urban cyclic behavior, thus indicating the areas needing most work.

Research on identifying the temporal and spatial leads and lags between cities of an urban system has been largely the domain of geographers. The earliest work concentrated on collecting monthly data, on unemployment rates, employment rates, or wages, for a number of cities, subjecting the data of each city to a time series analysis, and then comparing the time series to identify the sequence of temporal leads and lags exhibited by cities. This was done by comparing the timing of upturns and downturns in different cities (Bassett and Haggett 1971), by correlating the time series with one another at various leads and lags and selecting that lag at which the correlation was highest (Casetti et al. 1971, Jeffrey 1970), and, most rigorously, by cross-spectral analysis (Hepple 1975). The results were then either mapped to indicate space-time lags (Figure 1), or subjected to multivariate analysis

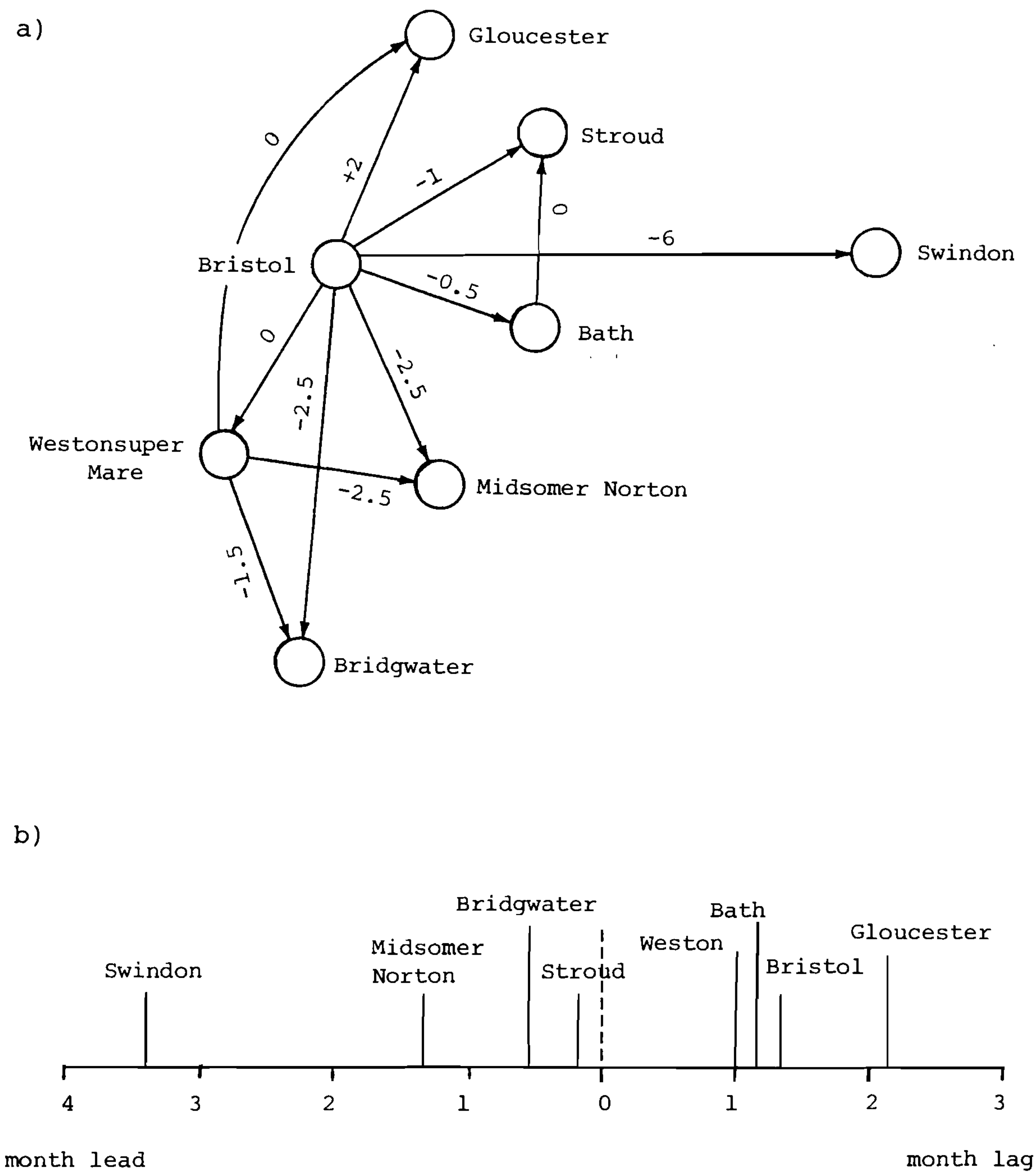

Figure 1. (a) Inter-urban lead-lag feedbacks (months) between unemployment levels in Southwest England. (b) Average lead or lag of each district with all others.

Source: Bennett (1979:444). See also Haggett (1971).

to identify common trends in the diffusion process (Jeffrey et al. 1969).

In terms of equation (3) above, these approaches simplify it to the univariate and non-interdependent model:

$$\underline{y}'_t = \sum_{s=0}^{R} \underline{y}'_{t-s} \cdot S_s^d \tag{6}$$

with the relations between places only considered informally. More recently this has been extended to an interdependent approach incorporating spatial interactions that allow the influence of one place on another in a univariate setting (Bartels 1977, Bennett 1975a):

$$\underline{y}'_t = \sum_{s=0}^{R} \underline{y}'_{t-s} \cdot M_s \tag{7}$$

The interaction components are then statistically estimated: directly by auto-regressive moving average (ARMA) approaches, or less directly by spectral analysis (Bennett 1979, Rayner 1971).

The goal of using these models to identify cities that are always leading indicators, and to show that the structure of leads and lags between cities is persistent, has only met with mixed success. The results often vary over time and also differ depending on the wavelength of cycles, and no general results relating these patterns to other observable features of the urban system have been forthcoming. I can suggest two constructive reasons for this. First, the cities are linked in a highly interdependent manner, with most entries in M_t being positive. As a result the initial diffusion of one cyclical effect generates many secondary, tertiary, and higher order cycles in various directions that take time to work themselves out (Sheppard 1979a). Indeed these may overlap with the initial shocks from the next cycle. As a result it is hardly surprising that leads and lags are complex phenomena; one could only expect them to be easily identified if the structure of interactions in M_s reduced to a directional network with few cycles. Second, models such as (6) and (7) ignore exogenous explanatory variables incorporated into (3). In general, it is reasonable to expect forecasts to be better with a properly specified model which predicts unemployment and other variables from a set of simultaneous space-time equations (King et al. 1969):

$$\underline{Y}'_t = \sum_s \underline{X}'_{t-s} \cdot M^*_s \tag{8}$$

where $\underline{Y}' = (\underline{y}'_t, \underline{x}'_{1t}, \ldots, \underline{x}'_{kt})$ is a $(1 \times kn)$ vector;

$\underline{X}'_{t-s} = (\underline{y}'_{t-s}, \underline{x}'_{1,t-s}, \ldots, \underline{x}'_{m,t-s})$ is a $(1 \times mn)$ vector,

M^*_s is a $(mn \times kn)$ vector of spatio-temporal autoregressive moving average coefficients incorporating the effects of a set of exogenous variables $(x_{k+1}, \ldots, x_m)$

This "STARMAX" model has been represented as a linear model, where M^*_s is estimated as a large autocorrelated regression. Estimation theory for such models has only recently been developed (Hepple 1976, Bennett 1979), and practical experience is limited to one regional case study (Bennett 1975b), so we know little of their predictive success.

If a suitable disaggregation of equations such as (8) into economic sectors is carried out, it is possible to use this conception for modeling the effects of urban economic structure on cyclical behavior. We should expect economic structure to affect the timing and severity of cyclical behavior, perhaps influencing some indicators more than others. This would be reflected in the estimated coefficients. There has been very little research at all rigorously modeling the effects of structural mix on a sub-national economy and trying to design specific counter-cyclic policies (Engerman 1965, L'Esperence 1977). Only L'Esperence's study of Ohio concentrates on this issue, and he uses an econometric export-base model aggregated into two locations: Ohio and the rest of the world. This econometric approach introduces structural disaggregation at the expense of extreme spatial aggregation. One question which becomes particularly acute with disaggregated models is manageability. There is a real danger in this type of model that data needs, computational requirements, and even the requirements made of investigators trying to understand and interpret results, will all get out of hand. This will be addressed below.

The third issue identified, that of trying to understand the interaction mechanisms governing the diffusion of cyclical behavior, has not been researched. All the models discussed above treat the urban system model as one which is linear in its parameters. Even in equations (6), (7) and (8) the coefficients are dependent on the lags, but not the observed time period t. Thus they are held constant over time in order to provide degrees of freedom for estimation purposes. However, it was argued in section 1 that such a conception is fundamentally misleading, as these represent spatial interaction terms, and will thus change over time as the configuration of opportunities varies. Bennett (1975c) has allowed for time varying parameters, using Kalman filters for statistical estimation. However, this problem is fundamentally theoretical rather than statistical, since for a well specified method we must be able to understand what the interactions are, and how they change. It is by introducing more theory into our models in this manner that we can hope to reduce the number of unknowns to be estimated without sacrificing the dynamic properties of these models (Bannister 1976).

Summarizing, a certain amount of basic empirical research has been performed on the subject of short run cyclical crises in urban systems. As the above outline shows in comparison to the scheme of section 1, there is still much to be done in formulating adequate theories of cyclical responses and of their spatial diffusion. These must, of course, include demographic, social and political factors in addition to economic ones. It should be remembered how easily any resulting model can grow to an impossible size. In order to develop a manageable approach some severe simplifications will be necessary to concentrate on major factors. I would argue, however, that the essence of a systems approach should be holistic; initially laying out the entire scheme before reduction of the model on pragmatic grounds.

4. A NAIVE MODEL OF URBAN DECONCENTRATION

There has been a recent upsurge of interest in the so-called process of "deconcentration", whereby former trends toward increasing population agglomeration in the largest urban areas are weakening (Korcelli 1980). Research on this question has involved primarily empirical analysis of the data (Morrill 1980, Bourne 1980) and the conclusions are at best,mixed (Gordon 1979). The aim in this section is to counter-balance such work by providing a simple theory of urban change that allows for deconcentration. The resulting model is naive in the sense that only some obvious relationships are included, with no attempt at a comprehensive framework. Only a relatively limited aim is sought, that of demonstrating an application of the general methodological structure outlined in section 1.

From a theoretical point of view, it would be unsatisfactory to ascribe the deconcentration to a "clean break" from past trends. Instead of relying on some such structural instability, it would seem better to explain how a break might occur. In a general sense this can be achieved by having a theory where forces pulling in opposite directions (in this case towards concentration and deconcentration) are always present, but with the relative weight ascribed to each changing over time. Further, an explanation would be needed which accounts for such changes, and shows how an increase in the weight applied to one set of forces leads to a decrease in the importance of the other. In short, the weights should be related to one another.

The theory to be developed here is for a society where economic efficiency is the prime motivating force of production. Thus certain types of activities by central authorities are not incorporated, and government is seen as reflecting, rather than inducing, change. In addition, I should say something about the underlying conception of spatial economic growth in the model. Two general explanations of deconcentration are possible. On the one hand, it has been regarded as a readjustment of the economy towards balanced growth in all regions (Weinstein 1980). This position, based on neo-classical economics, is countered by the argument that deconcentration is a reversal in the dynamics of polarized growth with the roles of the fast and slow growing regions being reversed. The ideas presented below come closer to the latter position.

At a conceptual level two stories of growth could be told. The story of concentration argues that the market orientation of industry, and migration in response to economic opportunity form a self-reinforcing cycle of spatially concentrated growth. The urbanization economies resulting from this situation stimulate further cost savings, technological advances and birth of new industries, and large urban areas grow at a rate consistently faster than that of smaller cities. At a regional level, this has been well summarized by the "Verdoorn Law" (Dixon and Thirlwall 1975; Ledent and Gordon 1980). This growth is possible with adequate population increases (Hicks 1950) which in the case of large cities has been facilitated by drawing on a pool of labor from smaller cities, rural areas, and peripheral regions. Further, with scale economies there is relatively little reason for capital disinvestment to slower growing places to help them catch up in a neo-classical sense.

A tale of deconcentration reflects the increased movement of industry and population out of the largest cities. In the case of industry this can be related to diseconomies of large scale urbanization, to the higher wages and unionization in metropolitan centers, to a fall in communication costs making industry more footloose, and to the structural shift in the economy towards market oriented service activities which follow the deurbanizing population. Other factors include a rise in demand for certain resource industries, particularly coal (Markusen 1979), and a decreased need for scale economies within individual plants as they become part of larger corporate structures. All this adds up to capital disinvestment on a large scale, but without necessarily implying equilibration (Bluestone and Harrison 1980). In the case of population, the shift out of cities can be explained by stronger preferences for rural areas, by migration for retirement purposes, and by the increasing number of jobs available outside the largest cities.

None of the factors discussed with respect to deconcentration represent both necessary and sufficient conditions accounting for the rise of this phenomenon, so obviously the process is complex. Indeed there is little in the above accounts that will explain why a shift might occur. However, it can be seen how a process of cumulative de-urbanization can be deduced once the shift does occur.

A Production-oriented Demo-economic Model

The model developed below is designed to be descriptive and to be able to account for both types of processes outlined above given the appropriate conditions. It is within such a framework that one can look for explanations of the existence of trend reversal. It is a demo-economic model in that population and production are included. Rates of capital accumulation in a city depend on the competitiveness of its industries in the national market, which in turn is based on prices and delivery costs. Growth is constrained by the availability of, and wages negotiated by, labor, and unemployment is a result of capital accumulation at a rate lower than that of population growth. The distinctive factor is that this is linked together by dynamic interactions. Inter-urban commodity flows depend on inter-urban purchases, which in turn depend on the prices at any one point in time. This is converted into spatial variations in the accumulation of capital, determined by a strong tendency to equalize rates of profits everywhere. Migration depends on economic opportunities and preferences, with certain segments of the population more able to respond to different pull factors.

Neglected components in this initial treatment include natural increase, population aging, the role of corporate structure and oligopoly, fixed capital underutilization, and links outside the urban system, although each should be incorporated.

Price Determination

In this model, market prices are determined primarily by production costs, plus a mark-up representing the profit rate. The rationale for this conception is that in modern economies the less-than-competitive nature of most production processes implies that supply factors are relatively more important than demand factors in the market. Alternatively, such production prices can be regarded as the minimum price at which firms will produce. Prices falling below these levels would imply a combination of disinvestment from that location, and a tendency to reduce production by not using all capital resources in an attempt to push up prices. We shall also assume an equal rate of profit in all industries in all cities. Then prices are determined by:

$$p_{it}^{k} = (1 + \pi)\left(\sum_{m=1}^{M} \sum_{j=1}^{N} a_{jit}^{mk} \cdot p_{jit}^{m} + w_{it}^{B} \cdot L_{iB}^{k} + w_{it}^{W} \cdot L_{iW}^{k}\right) \quad (9)$$

In general, superscripts represent the M industrial sectors, and subscripts represent the N locations (cities) and time periods. Here:

p_{it}^{k} is the production price for good k in city i, time t

a_{jit}^{mk} is the amount of good m shipped from j to i that is used to produce there one unit of k at time t

$\sum_{j} a_{jit}^{mk} = a_{.it}^{mk}$ is the technological input-output coefficient in region i, time t

p_{jit}^{m} is the delivered price at i for one unit of good m produced in j at time t. In general, we shall assume $p_{jit}^{m} = p_{jt}^{m} + c_{jit}^{m}$, where c_{jit}^{m} is the per unit transport cost of m at time t

w_{it}^{B}, w_{it}^{W} are the wage rates in city i for blue and white collar workers, respectively

L_{iB}^{k}, L_{iW}^{k} are the hours of blue and white collar labor necessary to produce one unit of k, in region i

π is the rate of profit

These equations are an element of the Cambridge (England) conception of economic growth (Abraham-Frois and Berrebi 1979, Pasinetti 1977, Morishima 1973) translated into spatial terms. In matrix form:

$$\underline{p}_t' = (1 + \pi)[i' \cdot P_t' \otimes A_t + \sum_{\ell=B}^{W} \underline{L}_\ell' \cdot \underline{w}_{\ell t}] \quad (10)$$

where:

$\underline{p}_t' = [p_{1t}', \ldots, p_{1t}^{M}, \ldots, p_{Nt}', \ldots, p_{Nt}^{M}]$

A_t is a MN by MN matrix of elements a_{ijt}^{km} arranged, as for $\underline{p}_t$, with N^2 blocks, each M × M, representing intra-urban input-output coefficients (in the blocks on the main diagonal), and inter-urban blocks linking each pair of N cities

P_t is a similar NM by MN matrix of elements p_{ijt}^{km}

$\underline{L}_\ell' = [L_{1\ell}', \ldots, L_N^M]$ is a 1 × MN vector

$\underline{w}_{\ell t}$ is a MN by MN diagonal matrix with the first M-elements equal to w_{1t}^{ℓ}, the second M-elements equal to w_{2t}^{ℓ}, etc.

$\underline{i}'$ is an appropriately dimensioned vector of ones, and the symbol $\otimes$ refers to an unorthodox matrix multiplication: $B = A \otimes C$ implies $b_{ij} = a_{ij} \cdot c_{ij}$, $\forall i,j$.

If we assume $p_{ijt}^{k} = p_i^k + c_{ijt}^{k}$, and if transport rates between all cities are known, then in system (10) there are MN + 2N + 1 unknowns, the p_i^k's, w_i's, and π. If the w_i's are taken as exogenous, and if we add another equation to normalize prices:

$$i' \cdot \underline{p}_t = 1 \tag{11}$$

then (11) and (10) may be solved for the relative price levels and for the rate of profit. This is the standard approach based on Sraffa (Pasinetti 1977). Unfortunately, this is not adequate for the spatial case since the relative prices are set [in equation (11)] independently of c^k_{ijt}. Since c^k_{ijt} and p^k_{jt} are both measured in the same monetary units, this is inconsistent. One solution to this problem is to define:

$$c^k_{ijt} = p^c_{it} \cdot g^k_{ij} \tag{12}$$

where p^c_{it} is the price of a "unit" of transportation provided at i, and g^k_{ij} represents the number of units of transportation necessary to ship k from i to j, which we can assume to be given exogenously. Then we can add the following equation to determine p^c_{it}; the price of transportation at i

$$p^c_{it} = (1 + \pi)\left(\sum_{j,m} a^{mc}_{jit} \cdot p^m_{jt} + w^B_{it} \cdot L^{cB}_i + w^W_{it} \cdot L^{cW}_i\right) \quad \forall i \tag{13}$$

In addition, set

$$i' \cdot \underline{p}_t + \sum_i p^c_{it} = 1 \tag{14}$$

Then equations (10), (13) and (14) have MN + N + 1 unknowns in MN + N + 1 equations, if wages and input coefficients are predetermined, and can therefore be solved. This system does, however, neglect the extra time taken to circulate goods, and its effect on the profit rate (Steedman 1977).

Note that prices are assumed to be linearly related to production levels. This could be interpreted to mean that industries have constant returns to scale. However, another less restrictive justification is possible (Kalecki 1971). In industries where there is excess capacity, production increases or decreases are met by increasing or decreasing utilization of the current fixed capital and labor force, rather than by changing the size of the plant. We would thus expect the marginal costs of production to change very little, and a linear price relationship would be a good approximation.

Determining Spatial Interactions

If the flow of good k from i for use in product m in region j at time t is x^{km}_{ijt}, then:

$$a^{km}_{ijt} \cdot x^{m}_{jt} = x^{km}_{ijt} \tag{15}$$

Assume that purchase orders made at time t depend on information gained about prices at time t - 1. Thus the locations from which input goods are bought by each industry will be a function of the previous pattern of prices. Within several regions producing good k and competing for the market represented by the demand by industry m at j, we would expect the market share of this demand commanded by region i to be inversely related to the price p^{k}_{ijt}; for example

$$a^{km}_{ijt} = 1 - p^{k}_{ijt}/p^{k}_{\cdot jt} \tag{16}$$

where $p^{k}_{\cdot jt} = \sum_{i} p^{k}_{ijt}$. In fact, such an equation, although plausible, can be inconsistent since it would be expected that an industry, while varying the relative amounts of input goods purchased from each region, would be expected to keep its overall production technology relatively unchanged. We shall assume that the production technology is independent of location patterns and of time, and is defined in region j by a series of input coefficients $[a^{1k}_{\cdot j}, \ldots, a^{Mk}_{\cdot j}]$, $\forall k,j$. Then:

$$\sum_i a^{lk}_{ijt} = a^{lk}_{\cdot j} \quad , \qquad \forall j,l,k \tag{17}$$

With (18) only limited forms of (labor-saving) technological change are possible. A least biased approximate estimate for flows could then be obtained from information theoretic methods by choosing a^{km}_{ijt} to minimize (Snickars and Weibull 1977):

$$\sum_{i,j,k,m} a^{km}_{ijt} \log a^{km}_{ijt}/(1-p^{k}_{ijt-1}/p^{k}_{\cdot jt-1}) \tag{18}$$

subject to constraint (17). Thus past prices are used to project current interregional flows, which in turn are used to determine current prices. It should be noted that summations in (17) and (18) also incorporate transportation industries.

Capital Accumulation

Define the vector of production at time t: $\underline{x}'_t = [x'_{1t},\ldots, x^M_{Nt}]$ containing MN elements. Then it must be true, if markets are cleared, that demands at t + 1 are met by production at t:

$$\underline{x}_t = A_t \cdot x_{t+1} \tag{19}$$

Morishima (1973) has shown, for a two-sector one-region economy like that of (19), but with interactions constant, that there exists an equilibrium growth ray, but that it is unstable. Similarly, Okabe (1979) has shown how multi-city systems with dynamic interactions exhibit equal growth rates for all cities only under special assumptions. Thus the concept of scale economies is unnecessary in order to account for unstable inter-urban growth patterns with different growth rates in different cities (cf. Ledent and Gordon 1980). This is a very simple model, abstracting from the savings, investment, and consumption behavior of the various actors in the economy. However, together equations (17)-(18), (10), (13), (14) and (19) determine the dynamics of a multi-city production system, solving for interactions, prices, and production levels in turn for each time period.

External Economies and Diseconomies

Since the benefits of urbanization and the costs associated with rents and taxes form a significant factor in production costs within cities it would seem useful to incorporate these. In reality, urbanization economies are a form of technological innovation unevenly available in space. In the short run, they would represent an increase in profits for industries selling at constant prices, but in the long run, they would lead to a decrease in prices as capital flows into these industries in response to the profit differential, increasing production relative to demand (Morishima 1973, Marx 1974). In either event, such locations would be more attractive for production. Similarly, high urban rents and taxes represent a deduction from profit, leading to a price rise as capital flows out. As a simple approximation, these effects will be captured by adjustments to the prices in equation (10).

Define u_{it}^{k} as the proportional decrease in prices due to urbanization economies at location i for industry k. We would expect u_{it}^{k} to be positively related to population size, n_{it}; $\partial u_i^k/\partial n_i > 0$; $\partial^2 u_i^k/\partial n_i^2 < 0$. In addition, u_i^k would vary by industrial type. Industries with strong external economies would have u_i^k more strongly related to n_i, whereas more self-sufficient operations, and those linked into corporate networks which act as a substitute for urbanization economies (Pred 1977) would have a smaller u_{it}^{k}. Similarly, define r_{it}^{k} as being the proportionate increase in prices due to rents and taxes at i. r_{it}^{k} will be related to such factors as the density of the built-up area, the configuration of intra-urban land uses, and the political geography of each city, as well as to city size. Now define vectors:

$$\underline{u}'_t = [u'_{1t}, \ldots, u^M_{Nt}]$$

$$\underline{r}'_t = [r'_{1t}, \ldots, r^M_{Nt}]$$

Then:

$$[i' - \underline{u}'_t + \underline{r}'_t]\underline{p}'_t = (1 + \pi)[i' \cdot P_t \otimes A_t + \sum_{\ell=B}^{W} \underline{L}'_\ell \cdot \underline{w}'_{\ell t}] \quad (20)$$

Incorporating Population

It has been assumed thus far that production is unhindered by limits on the availability of labor and resources as factors of production [capital availability is guaranteed by (19)]. Here, we shall concentrate on labor. It is immediately obvious that, with no inter-urban commuting, the following constraints must hold:

$$\underline{L}'_{iB} \cdot \underline{x}_{it} \leq e^B_{it} \quad , \quad \forall i,t \quad (21a)$$

$$\underline{L}'_{iW} \cdot \underline{x}_{it} \leq e^W_{it} \quad , \quad \forall i,t \quad (21b)$$

Here $\underline{L}'_{i\ell}$ is the subvector of $\underline{L}'_\ell$ incorporating $[L'_{iB}, \ldots, L^M_{iB}]$; and $\underline{x}'_{it}$ is the subvector $[x'_{it}, \ldots, x^M_{it}]$ of $\underline{x}'_t$. e^ℓ_{it} is the total employable labor force of type ℓ in region i. Once again these constraints are not automatically satisfied by (19). Instead they represent a full employment ceiling which when approached would sharply limit growth in region i. I shall not attempt here to model the effects of such a stagnation, nor try and incorporate a Hicksian cycle (Hicks 1950). Rather (21a) and (21b) should be seen as relations to be computed to check the validity of our modeled projections.

It is therefore important to model demographic change. For this purpose the population will be split by age into retired and non-retired and by occupation into blue and white collar workers. Of course, much finer disaggregations can be conceived of, for example, to capture the age selectivity of migration. Since migration is partly in response to economic opportunities it is necessary, for non-retired groups, to determine relevant economic factors. This will be done here with reference to the relatively competitive labor market of Western countries with which I am more familiar. Equations (22) and (23) determine wages and unemployment rates:

$$\Delta w^{\ell}_{it} = f[\tilde{g}_i(t), \Delta v^{\ell}_{it}, U^{\ell}_{it}] \quad , \quad \forall \ell = W,B; \; i = 1,\ldots,N \tag{22}$$

where $\Delta x_t = (x_t - x_{t-1})/x_{t-1}$; $\tilde{g}_i(t)$ is a time trend representing "cultural and historical" factors, affecting the trend of wages, that are independent of current economic conditions. v^{ℓ}_{it} is the unemployment rate in occupation ℓ, location t. U^{ℓ}_{it} is the rate of unionization in occupation type ℓ, time t. Unemployment is determined from:

$$\begin{aligned} v^{\ell}_{it} &= [e^{\ell}_{it} - \underline{L}'_{i\ell} \cdot \underline{x}_{it}](e^{\ell}_{it})^{-1} \\ &= 1 - \underline{L}'_{i\ell} \cdot \underline{x}_{it}(e^{\ell}_{it})^{-1} \end{aligned} \tag{23}$$

Migration patterns are assumed to be somewhat different for blue and white collar workers. For white collar workers two groups of factors are assumed to influence migration: economic conditions and residential preferences. The former fluctuate as the urban system develops, whereas the latter are assumed to be a relatively constant migration "wind", dependent more on the environment and other "quality of life" indices. Define f^{ℓ}_{ijt} as the probability that a migrant of type ℓ, moving from i for economic purposes, goes to j. Then:

$$f^W_{ijt} = f(d_{ij},\ n_{jt},\ w^W_{jt} - w^W_{it},\ v^W_{it} - v^W_{jt}) \tag{24}$$

where d_{ij} is the distance between i and j, and n_{jt} is included in (24) in order to capture the attractive effect of destination size, since this is related to the number of job vacancies, the probability that information about the city is available, and the likelihood that previous migrants from i have moved to j.

Define also h_{ij}, given exogenously, as the probability that a migrant leaving i for non-economic reasons, will migrate to j. Then, in a manner similar to Cordey-Hayes and Gleave (1974), assume that outmigration from i depends on job turnover and on how long a migrant has lived in i. Thus if we define g^W_{it} as the number of white collar workers in i who choose to migrate during time period t;

$$g^W_{it} = f(\sum_s a^W_s\ m^W_{.i,t-s};\ v^W_{it}) \tag{25}$$

A variety of sets of weights a^W_s, given exogenously, are possible and could be incorporated into migration projections by developing a semi-Markov model (Ginsberg 1980). $m^W_{.i,t-s}$ is the number of inmigrants to i at time t from all other regions.

Then white collar migration may be determined by:

$$M^W_t = [\alpha_t\ F^W_t + (1 - \alpha_t)\ H]\underline{G}^{Wd}_t \tag{26}$$

where M^W_t is a N × N matrix of gross migrations, F^W_t and H are N × N matrices containing elements f^W_{ijt} and h_{ij} respectively, and $\underline{G}^d_t$ is a diagonal matrix with its i-th element equal to g^W_{it}. α_t is a relative weighting factor.

For blue collar workers I assume that, because of lower wages and the nature of their occupation, they are more tied to the opportunities provided by the job market, and less able to exert their preferences independently of this. Thus, for example, one might expect that blue collar workers currently being put out of work in the north-eastern United States will find it harder to move to the south than will white collar workers. This may be partly due to the wage differential between the two occupational classes, but other factors are probably equally important. Blue collar workers are less flexible in the types of jobs they can take since they have been unable to acquire a range of skills to match those of white collar workers. Thus they are more tied to traditional job opportunities. Similarly, employers in newly industrializing, rural, and often less unionized areas will be reluctant to hire workers accustomed to higher wages and amenable to joining a union. In a crude effort to capture these differentials, I assume:

$$M_t^B = F_t^B \cdot \underline{G}_t^{Bd} \tag{27}$$

$$f_{ijt}^B = f(d_{ij}, w_{jt}^B - w_{it}^B, v_{it}^B - v_{jt}^B, n_{jt}) \tag{28}$$

$$g_{it}^B = f(\sum_s a_s^B m^B_{.i,t-s}, v_{it}^B, e_{it}^B) \tag{29}$$

where definitions are as before. e_{it}^B is included in (29) because outmigration of blue collar workers, being less apt to change their jobs rapidly, may be more related to total residents than to past migration history.

For retired people migration is for reasons of preference. If we assume that retired people have the same desires with respect to a general living environment as white collar workers, then H may be used to approximate their migration patterns;

$$M_t^R = H \cdot \underline{G}_t^{Rd} \tag{30}$$

where the superscript R refers to "retired". $\underline{G}_t^{Rd}$ could be determined from:

$$g_{it}^{R} = f(\gamma_B \cdot n_{it}^{BR} + \gamma_W \cdot n_{it}^{WR}) \quad , \quad \forall i \qquad (31)$$

where $n_{it}^{\ell R}$ is the number of retired people, formerly of occupation ℓ, in i at time t, and γ_ℓ is the migration propensity of retired people of type ℓ. We would expect $\gamma_W > \gamma_B$ because of income differentials.

To complete the population component we should account for employable people and total population:

$$\underline{e}_t^{\ell'} = i' \cdot M_{t-1}^{\ell} \qquad \ell = W,B \qquad (32)$$

where $\underline{e}_t^{\ell'} = [e_{1t}^{\ell}, \ldots, e_{Nt}^{\ell}]$

$$\underline{n}_t' = \eta^B \cdot \underline{e}_t^{B'} + \eta^W \cdot \underline{e}_t^{W'} + \underline{n}_t^{R'} \qquad (33)$$

η^B, η^W are multipliers converting employable people into population numbers, and $\underline{n}_t' = [n_{1t}, \ldots, n_{Nt}]$; $\underline{n}_t^{R'} = [n_{1t}^{BR} + n_{1t}^{WR}, \ldots, n_{Nt}^{BR} + n_{Nt}^{WR}]$. Equations (22)-(33) determine populations, but treat categories W, B, and R as independent of one another. In fact, of course, they represent occupational states between which it is possible to move. So in practice there should be a probabilistic transition matrix describing occupational mobility and aging in each region. This has been left out for reasons of conceptual clarity.

The above analysis completes a dynamic demo-economic model with interaction feedback included as an inherent component. The entire system can be simulated recursively (Figure 2) to generate urban population and employment distributions through time.

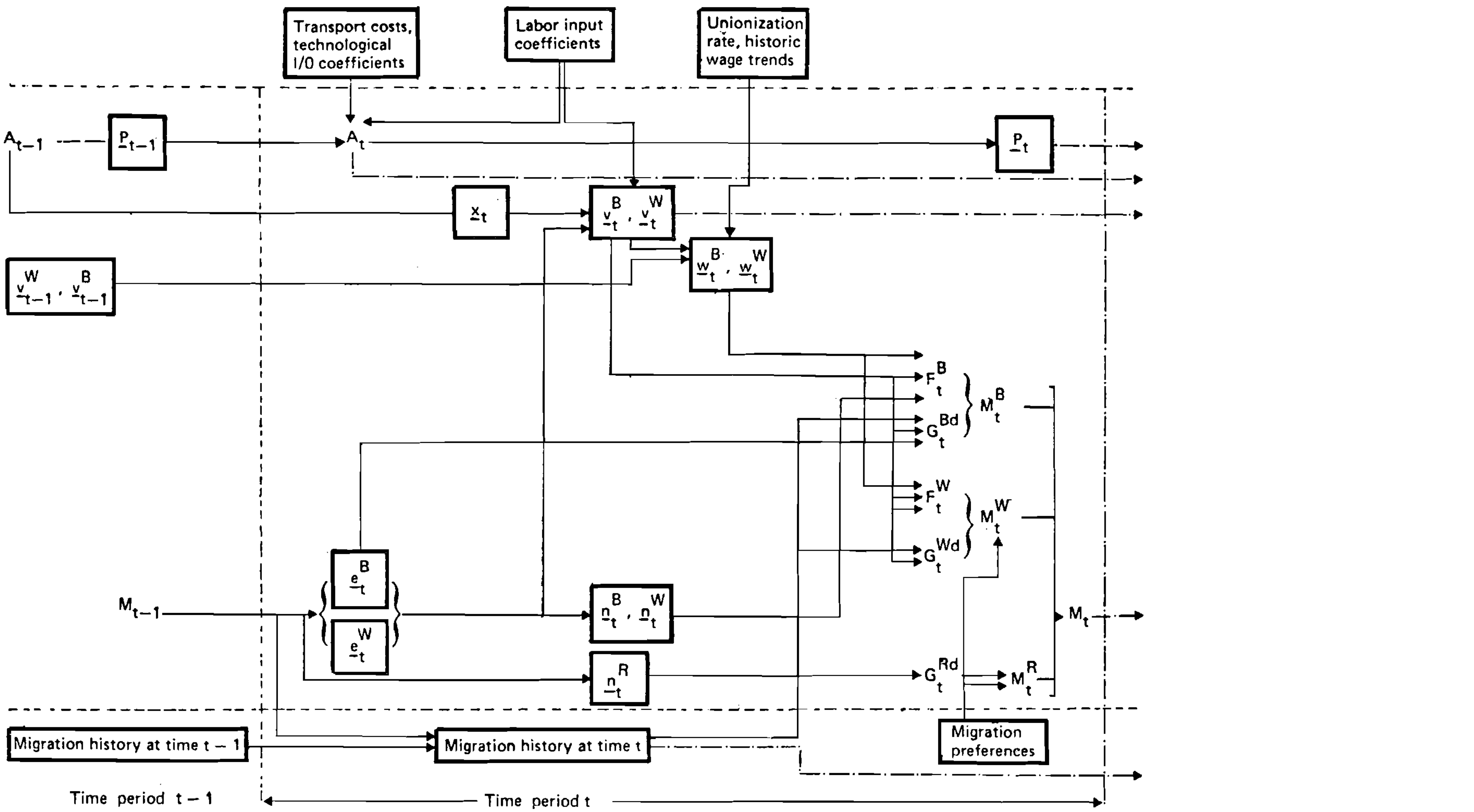

Figure 2. A recursive urban systems model.

An Urban System Model

The model of Figure 2 could be operationalized on a manageable scale as follows. Industrial sectors could be simplified into mineral resources, agriculture, heavy and light manufacturing, services and quaternary activities. Each sector has broadly different input and labor requirements, and relies in different degrees on urbanization economies. These would be defined for each city in the urban system, with cities perhaps best defined as functional urban regions. Finally, non-metropolitan regions should also be introduced. Any simulation experiment should include cities of all sizes and also various types of non-metropolitan regions; one with an exploitable resource base, a rich agricultural region, an underdeveloped peripheral region, and a "retirement" region with a pleasant environment.

The plausibility of this model can be demonstrated informally by considering some of the explanations for deconcentration outlined earlier. Suitable values for $\underline{u}_t$ and $\underline{r}_t$ in (20) will certainly generate investment in urban areas that will increase and then decrease for larger and larger cities. Similarly, as transport costs decrease, the competitiveness of regions further from the market will increase and production that formerly concentrated in metropolises can shift there. Factors encouraging this will be higher wages in large urban areas, increased exogenous demands for resources (such as coal) available in rural areas, as well as decreases in the importance of urbanization economies.

It is also seen that, since H will in all likelihood to be biased toward rural areas, increases in white collar employment or wages, and in retirees will generate a shift of emphasis in population movements from concentration to deconcentration. Once industry and/or population starts to deconcentrate the process is cumulative. Service industries needing to be close to their markets will follow the population, if the range of their market areas is not dramatically altered by lower transport costs. Similarly, people follow industrial employment and the "economic" migration pattern shifts to a position more in conformity with the non-economic pattern, H. Meanwhile, blue collar workers may well be left behind in the metropolises as they are less able to compete with indigenous non-metropolitan populations for unskilled jobs. Wages may persist in being high in the cities due to the importance of cultural, historical, and trade union factors, further accelerating the change by providing more motivation for capital disinvestment.

Another element in the population dynamics of urban systems suggested by Korcelli (1980) can also be captured. As rural areas lose population, cities start to compete more and more for a fixed pool of inter-urban migrants. This will make urban growth patterns less stable, unless a pool of foreign migrant workers can be drawn on to support the cities. This last feature may be happening in several Western European countries, and could easily be modeled.

The true ability of a model such as this to capture significant shifts in population and employment trends endogenously, without resorting to external *ad hoc* factors, remains to be seen. Indeed the model is still insufficient in some respects. For instance, negative capital accumulation in a city is impossible unless population declines. However, it does, perhaps, capture something of the dialectical nature of a system in which trends in one direction at the same time reinforce those influences that eventually push it in a reverse direction. This is the major theoretical challenge.

With the help of this model, some contribution can also be made to the practical problem of identifying necessary data for modeling deconcentration. On the side of industry, it is necessary to reevaluate the comparative costs of different locations. In particular, it is necessary to know the costs and benefits of urban size for industries of different types, and the degree to which service industries will follow inter-regional population shifts, as compared to other sectors. Such questions are particularly pertinent for industries with lower relocation costs. The whole nature of capital disinvestment from less attractive cities is only now being studied

(Bluestone and Harrison 1980). The responses of industry to spatial differences in unionization has also not been carefully studied. Technological change must be studied since long-run shifts toward tertiary and quaternary employment have clearly contributed to the ease of industrial deconcentration in response to population deconcentration. A final area where we have little geographical knowledge is the spread of corporate control in all economic sectors. The spatial impact of this upon differential growth rates, on the degree to which small firms can free themselves of urban ties, and on the economic links between cities has been little studied (Holland 1976). However, the little evidence available does suggest that conventional growth pole conceptions of the diffusion of growth are seriously challenged by the data on corporate linkages (Pred 1977). Such questions are amenable to contributions from the regional development and management-of-technological-change activities at IIASA.

With population, the experience of the Human Settlements and Services Area can be drawn on to look at two possibly significant questions; the possibility of separating, and comparing, non-economic and economic components of migration patterns, and the role of socio-economic position of the migrants in influencing both the resources and migration opportunities available to them when the decision to move is made. Another area of increasing importance is the role of migrant labor within the urban system. With the depletion of other cheap sources of labor in many Western economies, this is likely to become increasingly important.

CONCLUSIONS

The question of urban system change is tremendously important from a policy point of view. The fact that economic infrastructure has typically been much faster in adapting to new trends than has society as a whole has led to conflicts in many countries between economic and social goals, as well as between national and regional goals. One necessary, although not sufficient, step in successful public intervention is a development of adequate descriptive theories, so that we can better understand the impact of various policy instruments. This paper has been addressed to this question, and has argued that a necessary prerequisite for properly specified theories is an inclusion of endogenous changes in interaction patterns. Such changes help explain instabilities in growth rates and may contribute to understanding the sources of such fundamental trend reversals as urban deconcentration. It is to be hoped that the examples presented give some illustration of the importance of spatial interaction in understanding urban systems and in developing better theories of their development than have existed in urban research to date.

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