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TRANSPORT NETWORK EQUILIBRIUM AND REGIONAL DECONCENTRATION

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TRANSPORT NETWORK EQUILIBRIUM AND REGIONAL DECONCENTRATION

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Abstract. Urban and regional change processes can be classified in terms of their temporal characteristics as fast-adjusting, medium-response, or inert. Based on this classification, a modelling approach is presented that combines (1) a fast-adjusting equilibrium-type transport model, (2) a medium-response residential occupation (housing market) model, and (3) a strongly lagged residential location (housing construction) model. It is suggested that such a model structure takes better account of the range of temporal behaviour observed in metropolitan regions than modelling approaches directed at determining a simultaneous equilibrium of transport and location. Using data of the Dortmund, West Germany, metropolitan region, the model is employed to demonstrate the role of the transport system in the process of regional deconcentration observed in that region.

INTRODUCTION

Regional decentralization has many connotations. In developing countries a regional decentralization policy may seem to be the only way to curb the growth of a burgeoning metropolis. In highly centralized European countries like France, Italy, or Spain, decentralization of selected government functions may be the requisite answer to the growing demand for autonomy and cultural identity expressed by regional constituencies. In a country like West Germany which for historical reasons has a decentralized spatial structure, further decentralization of transport facilities, government agencies, and government-controlled industries, research institutions, or

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military installations is discussed as an instrument to narrow the widening income gap between prosperous agglomerations and economically deficient peripheral regions.

On the urban level, decentralization has also many faces. While in a few highly condensed metropolitan regions such as Tokyo, London, or Paris, planned decentralization has been or still is pursued in an effort to reduce the disutilities of over-agglomeration, today the majority of cities are more concerned about the unfavourable effects of unplanned decentralization such as inner city decline, loss of tax income, and urban sprawl at the periphery. In fact, most large metropolitan areas in the industrialized countries are facing a process of outward movement of population and employment without precedence in their history. Recent attempts to study this phenomenon have identified the now well-known sequence of phases of urban development---urbanization, suburbanization, and deurbanization (van den Berg and Klaassen, 1978; Hall and Hay, 1980)---but have not really been successful in explaining its causes except in the broadest and most qualitative terms (see for instance van den Berg et al., 1982).

So regional decentralization is in some instances a policy goal, or a set of policies to bring it about; and at the same time, at other places, it is a seemingly self-propelled process of spatial restructuring that policy makers may take advantage of, but more often desperately try to avoid.

This paper is concerned with this latter kind of regional decentralization. In particular, it deals with the situation where urban governments in the transition from suburbanization to deurbanization, in their efforts to maintain employment opportunities, a viable city centre, and attractive public services, find themselves fighting against the exodus of people and jobs from their jurisdiction to smaller towns and villages at the fringe of the urban area.

Still more specifically, it looks into the role of the transport infrastructure in this process. That transport technology and supply are among the principal forces shaping the spatial organization of a country or region is one of the basic tenets of Regional Science. Moreover, transport supply can at least in part be influenced by public policies. So if in fact the commonplace hypothesis can be verified that highway construction, increased car availability, or changes in the level of service of public transport have been responsible for the process of regional decentralization in urban regions, policy makers may make more rational judgments about their policy options to slow down, halt, or even reverse the current decentralization trend.

One way of studying the causal mechanisms behind a past or current process is to build a model of its (hypothesized) causal structure, fit it to whatever observables of the process are available, verify that it is capable of reproducing the process as closely as possible, and then to use the model in a contrafactual fashion, i.e. vary its inputs and thus generate different versions of the past based on different constellations of variables of interest. This strategy is followed here.

The model used for this purpose is an urban simulation model linking transport variables such as network structure and capacity, level of service of public transport, car ownership, and transport prices to location variables such as industrial and residential construction and location and relocation of firms, workers, and households. The model differs in a number of aspects from other existing urban models, so first these differences are spelt out. Then the general model structure is briefly discussed giving special emphasis to how the temporal characteristics of the process being modelled are reflected in the model organization. Finally, a model application exemplifying some of the mechanisms behind the process of urban decentralization is presented using data of the Dortmund, West Germany, metropolitan region. In particular, it is asked how much in Dortmund in the past this process was influenced by highway construction, increased car availability, or changes in the level of service of public transport. Based on the results, the potential impacts of future transport policies on the agglomeration-deglomeration process in metropolitan regions are discussed.

1. Existing Urban Models

There exists a long tradition of modelling the spatial development of urban systems as a process of mutual adjustment between agglomerative and deglomerative forces or, using other words, between transport and location. Instead of giving a full account of this tradition, one problem area will be highlighted where the model presented in this paper departs from current mainstream modelling practice.

Urban and regional change processes can be classified in terms of their temporal characteristics as fast-adjusting, medium-response, or inert. Following this distinction by Snickars et al. (1982), urban change processes can be categorized as follows (Wegener et al., 1983):

(1) Fast Processes: Mobility. The most rapid phenomena of urban change refer to the mobility of people and goods within given structures and communication channels. They range from job relocations and moves to daily trips. Relocations, i.e. change of location by firms, change of workplace by workers, and change of residence by households affect workplace and housing occupancy, involve substantial costs, and are therefore normally undertaken every five or more years. Daily trips do not affect workplace and housing occupancy because they start and end at the same place, hence they are more flexible in the short term. However, in particular worktrips are subject to relocation decisions and in the long term cannot change faster than these.

(2) Medium-Speed Processes: Socioeconomic/Technological Change. Relocations and daily movements are embedded in the longer lifecycles of firms, persons, households, products, or technologies. Their speed and direction are either determined by physical or biological laws (e.g. aging) or originate outside of the urban area (e.g. economic cycles), i.e. they may have impacts on but are not affected by what is going on in the region, hence it is hardly possible to reverse their direction. The impacts of socioeconomic and technological change do not change the physical structure of the city, but the activities performed in it.

(3) Slow Processes: Construction. The physical structure of cities displays a remarkable stability over time due to the long lifetime of buildings, the heavy investment involved, and the long delays ocurring between the first decision to invest and completion. So buildings that have become obsolete, uneconomical, or overaged, are usually remodelled or replaced by a similar building, but rarely ever completely removed. The most rigid elements of the urban fabric are transport lines like canals, rails, or major thoroughfares, which normally remain in place over centuries even if the transport equipment using them is replaced several times. Therefore decisions on the location of transport infrastructure may normally be considered as irreversible.

The implications this classification has for the design of urban models is straightforward: Urban change processes are slow in relation to human life and planning perspectives, and therefore urban models intended for planning should take account of the retarding forces, frictions, and delays responsible for their inertia. More specifically, urban models should distinguish between the different levels of change and explicitly recognize their interaction.

Unfortunately, most existing urban models do not pay the requisite attention to the different time scales of urban change. Virtually all urban location models are based on the concept of spatial interaction. The spatial interaction model, used as a transport model, predicts transport flows in equilibrium at a particular point in time. Used as a location model it predicts an equilibrium combination of flows and locations at a particular point in time. In fact the spatial-interaction location model predicts a relatively inert process, location, from a volatile and flexible process, travel, and this arbitrary exchange of cause and effect has been the cornerstone of practically all mainstream urban modelling since the pioneering work of Lowry (1964).

This basic misconception contrasts strangely to the remarkable advances in sophistication and mathematical rigour achieved within the paradigm of the spatial-interaction location model during the last two decades. Starting from its axiomatic formulation by Wilson (1967; 1970), it has undergone several generalizations and refinements. One important line of research has been directed at incorporating zonal or network capacity or supply constraints into the model (Boyce, 1978; 1984; Los, 1978) or by extending it to include more than one urban activity (Coelho and Williams, 1978; Brotchie et al., 1980; Sharpe and Karlqvist, 1980; Leonardi, 1981). These models are equilibrium models where the equilibrium is found by constrained nonlinear optimization, which means that they ignore the lag structure associated with the adjustment processes they assume. A second line of research exploits the difference between a spatial-interaction demand model and supply at the trip ends and interprets the convergence to equilibrium of these two as an adjustment process over time thus arriving at a fully dynamic version of the model (Harris and Wilson, 1978; Beaumont et al., 1981; Allen et al., 1981). This model indeed allows for explicit time delays, but unfortunately it cannot distinguish between growth and decline and produces oscillations in the building stock that have no resemblance with the evolution of real cities (cf. Wegener et al., 1983).

The kind of inconsistencies inextricably linked with the spatial-interaction location model can be illustrated by looking at the familiar four types of spatial-interaction location models suggested by Wilson (1970):

1	unconstrained model	neither residences nor jobs fixed
2	production-constrained model	residences fixed
3	attraction-constrained model	jobs fixed
4	doubly constrained model	residences and jobs fixed

This scheme distinguishes between the different decision situations of new or immigrant households (model type 1), households changing their place of work (model type 2) or place of residence (model type 3), and non-moving households (model type 4), and thus is clearly an improvement over the original Lowry model which allocates all households using model type 3.

However, the models still represent location as a result of and not as the cause of spatial interaction. To predict job locations from worktrips with the production-constrained spatial-interaction model type 2 means in fact to pretend that workers choose their jobs on their morning worktrip, and to predict residential locations using the attraction-constrained model type 3 means that they choose their place of residence on their way back from work. In the real world, however, labour mobility decisions are made in the local labour market and depend on job availability, required skills, salary, and many other aspects which are equally important or even more important than location. Similarly, residential mobility decisions are made in the local housing market and are affected not only by location, but at least equally by housing supply, housing and neighbourhood quality, dwelling price, household characteristics and household budget.

Moreover, model type 4 becomes clearly illogical in a dynamic framework (Wilson adds a footnote to that effect). Model type 4 is supposed to predict worktrips of non-movers, and if indeed they keep their residences and workplaces unchanged during a time interval, their worktrips should remain unchanged, too. Yet the doubly constrained spatial-interaction transport model will only produce identical worktrips if also transport supply and all other trips remain unchanged. In that case the model is redundant, in every other case it is wrong and will infect the other three models. Mackett (1976) has noted this difficulty and suggested a solution that imposes an additional constraint on the individual elements of the model 4 worktrip matrix which ensures that the number of worktrips between any two zones remains unchanged between different points in time, but allows workers to change their mode of travel, which means in effect to abandon the spatial-interaction model altogether.

To summarize, the spatial-interaction location model is inconsistent in a dynamic context. It ignores the costs of relocations and construction and hence the slowness and near irreversibility of urban spatial change. So it tends to overestimate the response of the spatial system to changes of transport supply variables. Even as a transport model, the spatial-interaction model is inappropriate where destination choice is restricted by longer-term constraints such as contracts or habitual patterns.

2. A Model of Urban Change

In this section, an urban model taking account of the above critique of the spatial-interaction location paradigm is presented. It is an extension of a multilevel recursive urban simulation model described elsewhere (Wegener, 1981; 1982a; 1982b), which has been applied to a variety of research problems such as housing choice, intraregional migration, and land-use transport interaction.

The model is composed of seven interlinked submodels which are processed in each simulation period in the following order:

1 transport/car ownership
2 aging of people, households, dwellings, workplaces
3 relocations of firms/redundancies/new jobs
4 nonresidential construction/demolition
5 residential construction/rehabilitation/demolition
6 labour mobility/change of job
7 household mobility/change of residence

Rather than describing each submodel separately, below only those features that distinguish the model from other urban models based on the spatial-interaction paradigm will be presented.

2.1 Model Organization

The first thing to note is that the model has separate submodels for transport and location rather than simultaneously determining locations as trip ends in a unified transport-and-location equilibrium. That means that the transport model predicts car ownership, trips, and destination, mode, and route choice for a given configuration of activities and not the location of these activities.

The spatial distribution of activities in the urban region can change in two ways. One way is through "aging", i.e. through processes which (for the model) depend only on time, but not on endogenously modelled choices--all aging, household formation, deterioration, etc. processes are subsumed under this heading. These changes are performed in the aging submodel (2) having a probabilistic Markov structure (see Wegener, 1982b). All other changes depend on spatial choices generated explicitly in the model. Three levels of choice-dependent spatial change can be distinguished: changes of occupancy (change of workplace and residence), changes of activities (relocations of firms, redundancies and new jobs), and changes of building stock (construction, demolition, etc.). Each of these changes is treated differently in a separate submodel in accordance with its specific time scale, responsiveness, and degree of reversibility.

2.2. The Transport-Location Interface

Except the aging submodel (2), all submodels are consistently designed as spatial choice models having as their basic building blocks multinomial logit models of the following form:

$$p_{ij} = \frac{W_j^{\alpha} \exp(\beta\ u_{ij})}{\sum_i \sum_j W_j^{\alpha} \exp(\beta\ u_{ij})} \qquad (1)$$

where p_{ij} is the marginal probability that a decision maker i, i = 1,...,I selects alternatives j, j = 1,...,J from a choice set of J alternatives. Depending on the context, decision makers may be firms, workers, households, or travellers, and i may represent categories such as industrial sector, skill level, socioeconomic status, or zone. W_j is an attraction term representing the number of units of alternative j. In the case of a firm looking for a site, it might represent the capacity of land of a certain type in zone j, in the case of a household looking for a dwelling, the number of vacant dwellings of type j, in the case of a traveller, the number of suitable destinations in zone j. The u_{ij} are "strict utilities" of alternatives j for decision makers i, i.e. the non-random parts of utility (see Domencich and McFadden, 1975), and α and β, as all lower-case Greek letters in the sequel, are parameters to be estimated (α being equal to one in most cases). The u_{ij} may be aggregated over attributes or over alternatives. Aggregation over attributes occurs additively:

$$u_{ij} = \sum_q w_{iq} \, v_{iq}[f_{jq}(\underset{\sim}{x}_j)] \tag{2}$$

or multiplicatively:

$$u_{ij} = \prod_q \{v_{iq}[f_{jq}(\underset{\sim}{x}_j)]\}^{w_{iq}} \tag{3}$$

where q, q = 1,...,Q indicates attribute q. The w_{iq} are additive or multiplicative importance weights adding up to one, the functions $v_{iq}(.)$ value functions mapping attributes to utility on a standardized utility scale, $0 \leqq v_{iq}(.) \leqq 1$, and the functions $f_{jq}(\underset{\sim}{x}_j)$ generation functions specifying how to calculate attributes from one or more elements of vectors $\underset{\sim}{x}_j$ of raw attributes of alternatives j. Aggregation over alternatives is performed in the nested logit model by replacing u_{ij} in (1) by

$$\overline{u}_{ij} = \frac{1}{\beta} \ln \left[\frac{1}{\sum_k W_k^\alpha} \sum_k W_k^\alpha \exp(\beta \, u_{ij})\right] \tag{4}$$

where k, k = 1,...,K are the alternatives to be subsumed under alternative j. Equation (4) is the "inclusive value" (McFadden, 1978) weighted by the attraction term W_k^α and is very similar to the composite cost formulation suggested by Fisk and Boyce (1984).

This form of the inclusive value is also used in the model to calculate accessibility measures:

$$u^{a}_{iq} = \frac{1}{\beta} \ln \left[\frac{1}{\sum_j W^{\alpha}_{jq}} \sum_j W^{\alpha}_{jq} \exp(\beta \, \bar{u}^{t}_{ij}) \right] \tag{5}$$

Here u^{a}_{iq} is the accessibility of zone i with respect to activities W_{jq} of type n in zones j, and $\bar{u}^{t}_{ij}$ is the composite utility (or disutility) of trips between i and j by modes m, m = 1,...,M with utilities u^{t}_{ijm} (Williams, 1977):

$$\bar{u}^{t}_{ij} = \frac{1}{\lambda} \ln \sum_m \exp(\lambda \, u^{t}_{ijm}) \tag{6}$$

Note that in these as in the following equations an additional subscript indicating socioeconomic status or skill level is omitted, but is present in the actual model implementation.

Accessibility indicators of the form (5) are then included among the attributes of the vectors $\underset{\sim}{x}_j$ of (2) or (3), where they compete with other, non-transport, attributes such as neighbourhood quality, dwelling quality, or land price or rent.

This type of accessibility is used for submodels (3), (4), and (5), i.e. in the choice functions of relocating firms and for nonresidential and residential construction. However, for submodels (6) and (7), which predict labour and household mobility, an additional accessibility measure is used that takes account of the fact that for workers (households) changing their place of work (residence) both, the old and the new workplace (residence) are of importance. So for each pair of zones two spatial utility measures are calculated (for more details see Wegener, 1981):

$$u^{\ell}_{jj'} = \frac{1}{\beta^{\ell}} \ln \left[\frac{1}{\sum_i O_i} \sum_i O_i \exp(\beta^{\ell} \, \bar{u}^{t}_{ij'}) \right] \tag{7}$$

$$u^{m}_{ii'} = \frac{1}{\beta^{m}} \ln \left[\frac{1}{\sum_j D_j} \sum_j D_j \exp(\beta^{m} \, \bar{u}^{t}_{i'j}) \right] \tag{8}$$

The first one, $u^{\ell}_{jj'}$, is the spatial utility of a change of job from zone j to zone j' for workers living in zones i near j, and the second one, $u^{m}_{ii'}$, is the spatial utility of a change of residence from zone i to zone i' for households working in zones j near i. The O_i and D_j are worktrip origins and destinations, respectively. Also this type of accessibility measure is inserted into the vectors $\underset{\sim}{x}_j$ of equations (2) or (3) and in the choice models compete with other transport or non-transport attributes.

Transfer of information from the transport to the location parts of the model is effected once each simulation period, i.e. the transport model is executed at the beginning of each period, and the information it generates (trips, travel times and costs, link loads, accessibilities, etc.) are used unchanged by the location submodels during the whole simulation period. So the location submodels always use lagged information about the transport system. As the model is operated with a simulation period of two years, a perception delay of one year in the average is assumed. However, longer delays are accounted for in some submodels: Changes in the transport submodel will be recognized by the household mobility or housing market submodel only in the period following the change, subsequent changes in housing demand will be visible to the housing supply or residential construction submodel only in the period thereafter, and the new housing thus generated will be put on the market not earlier than three simulation periods or six years after the change in the transport system has occurred.

In summary, the impact of transport on location in this model is much less direct, more aggregate, and more lagged than in the commonly used spatial-interaction location model. Moreover, transport/accessibility variables are not the only determinants of locational change, but are traded off against other non-transport variables, which for many urban activities may have become more important in the past and are likely to become even more important in the future.

2.3. The Location-Transport Interface

The transport submodel consists of 16 interrelated spatial-interaction trip distribution models for four trip purposes (work, shopping, services/ social, and education), four income groups/skill levels, and three modes (car, public transport, walking). For these 16 demand models, the following three steps are performed:

- trip generation and car ownership
- destination and mode choice
- trip assignment and capacity restraint

The trip generation model distinguishes between "obligatory" trips (work, education) and "optional" trips (shopping, services/social). While fixed trip rates are used for the former, the number of "optional" trips is a function of car ownership, travel costs, and travel budgets. Car ownership in turn depends on household travel budgets and travel and car operating costs. The combined destination and mode choice model is a nested logit model taking account of car availability and generalized costs of travel, with mode choice nested into destination choice (Wegener, 1983b). The destination choice level is doubly constrained for "obligatory" trips and production-constrained for "optional" trips, with biproportional adjustment techniques used to calculate the appropriate balancing factors. The trip assignment and capacity restraint step uses standard capacity-flow relationships.

User-optimal, congestion-sensitive equilibrium of trip generation, car ownership, destination, route, and mode choice is approached by applying an extended version of the network equilibrium algorithm by Evans (1976). The extended algorithm proceeds as follows (Wegener, 1983b):

1 Calculate origin and destination activities.
2 Make initial estimates of car ownership and trip rates.
3 Find minimum public transport paths and calculate trip utilities for public transport and walking.
4 Set iteration counter n to zero.
5 Set n to n+1.
6 Find minimum paths and calculate trip utilities for car trips.
7 Solve the 16 trip distribution and mode choice models.
8 Assign car trips of 7 to minimum paths of 6 and calculate new link times and trip utilities for car trips.
9 Recalculate car ownership and trip rates.
10 If $n = 1$, go to 5.
11 Perform line search to find a value θ^n, $0 \leq \theta^n \leq 1$, maximizing the objective function

$$\max_{\theta^n} U^n(\underset{\sim}{t}^n,\underset{\sim}{u}^n) = \sum_h \sum_g \sum_i \sum_j t^n_{hgij}\, \bar{u}^n_{hij} - \sum_h \sum_g \frac{1}{\beta^t_g} \sum_i \sum_j t^n_{hgij} \ln t^n_{hgij} \tag{9}$$

where

$$t^n_{hgij} = (1-\theta^n)\, t^{n-1}_{hgij} + \theta^n\, \hat{t}^n_{hgij} \tag{10}$$

$$\bar{u}^n_{hij} = (1-\theta^n)\, \bar{u}^{n-1}_{hij} + \theta^n\, \hat{\bar{u}}^n_{hij} \tag{11}$$

12 If change of U^n over U^{n-1} is large, go to 5.
13 Stop.

In the above notation, the t^n_{hgij} are trips of household income group/worker skill level h for trip purpose g from zone i to zone j by all modes after iteration n, $\bar{u}^n_{hij}$ is the composite trip utility of such trips as defined in (6), and β^t_g is the parameter of destination choice. The $\hat{t}^n_{hgij}$ and $\hat{\bar{u}}^n_{hij}$ are intermediate estimates of trips and trip utilities, respectively, as calculated in steps 6 to 8 of the algorithm. Thus the algorithm proceeds by repeated averaging between a previous solution and a new all-or-nothing assignment based on that previous solution's trip utilities.

Note that the objective function U, to be consistent, should contain an additional term representing the travel budget constraint (that household's expenditures for cars and for trips must equal their travel budgets). However, car ownership and trip rates quickly stabilize during the iterations, so it is computationally economical to omit the budget term. It is even more economical to avoid the line search altogether by setting $\theta^n = 1/n$, i.e. giving equal weights to all successive solutions. Powell and Sheffi (1982) have proved that even with this approximation the algorithm is certain to converge. After about four iterations, changes of the objective function as well as of car ownership, trip rates, destination and mode choice are sufficiently small for this kind of analysis.

As indicated, the transport model is executed once at the beginning of each simulation period. So it is capable of taking account of all changes either of the transport system itself or of the spatial distribution of activities during the preceding period. Changes of the transport system are exogenous to the model and are fed into it from files specifying transport investments, changes of levels of service of public transport, or changes of transport costs such as car operating costs, petrol prices, or public transport fares. Changes of the distribution of activities are perceived by the transport model as changes in potential trip origins and destinations.

Given these potential trip origins and destinations, plus the information on transport supply, travel budgets, prices, etc., the transport model is free to construct network equilibrium flows using the mechanism described above. But as it has been demonstrated in Section 1 of this paper, this freedom does not exist where destination choice is restricted by more permanent constraints.

This is clearly the case for worktrips. Therefore, for the worktrip part of the model, a different procedure imposing additional constraints on the network equlibrium mechanism was implemented. The idea is to use the complete equilibrium model only for the base year and calibrate it to base year traffic data, but from then on change the worktrip matrix incrementally each simulation period rather than creating it from scratch each time. In other words, the transport model is given a memory which enables it to use its last period's results as a point of departure for this period's solution.

In that sense the procedure is similar to Mackett's (1976) modification of Wilson's model type 4 (see Section 1), but differs from it by having seaparate submodels for labour mobility (change of job) and household mobility (change of residence) rather than using Wilson's model types 1 to 3 as location models. That implies that all changes affecting the association of workers with workplaces occurring in these other submodels are recorded and followed by an appropriate modification of the worktrip table. For instance, a change of job by a worker results in a shift from one column to another in the worktrip matrix (unless the old and new jobs are in the same zone), whereas a moving household produces a shift from one row to another (unless the old and the new dwellings are in the same zone).

Figure 1 illustrates this. Besides the worktrip matrix t, there are two other matrices of the same dimension, $I \times I$, the matrix of intraregional household mobility $\underset{\sim}{m}$ and the matrix of intraregional labour mobility $\underset{\sim}{\ell}$. The broken lines show the flow of information, before the new procedure was implemented: Labour and household mobility resulted in changes of the marginal totals of the worktrip matrix, i.e. trip origins O_i and trip destinations D_j (occupied dwellings and occupied jobs), which in turn served as constraints to the worktrip spatial-interaction model. Now, after the model change, as the solid lines indicate, a change in any element $m_{ii'}$ or $\ell_{jj'}$ affects not only the marginal totals, but also the individual elements t_{ij} of the worktrip matrix. In equation form,

$$\Delta t^{\ell}_{ij'} = -\Delta t^{\ell}_{ij} = \frac{O_i \exp(\beta^{\ell}\, \bar{u}^{t}_{ij'})}{\sum\limits_i O_i \exp(\beta^{\ell}\, \bar{u}^{t}_{ij'})}\, \ell_{jj'} \tag{12}$$

$$\Delta t^{m}_{i'j} = -\Delta t^{m}_{ij} = \frac{D_j \exp(\beta^{m}\, \bar{u}^{t}_{i'j})}{\sum\limits_j D_j \exp(\beta^{m}\, \bar{u}^{t}_{i'j})}\, m_{ii'} \tag{13}$$

are the increments/decrements by which the worktrip matrix has to be updated as a consequence of labour (12) or household (13) mobility.

Of course, changes in location of job and residence are not the only ways the association of workers with workplaces changes during a simulation period. In addition, jobs are created, relocated, or removed, workers are hired, change their skill and income group, are made redundant, or retire. However, most of these other changes can be assumed to be spatially neutral, i.e. to affect the origins and destinations, but not the structure of the worktrip matrix. Therefore these changes can be left to the biproportional adjustment mechanism employed in the transport model.

After all modifications of the worktrip matrix have been made, it is fed into the transport model at the time of its next execution and, having undergone the biproportional adjustment procedure, remains fixed thereafter, except that modal shares are allowed to change in response to changes in demand and supply at each iteration of the network equilibrium algorithm.

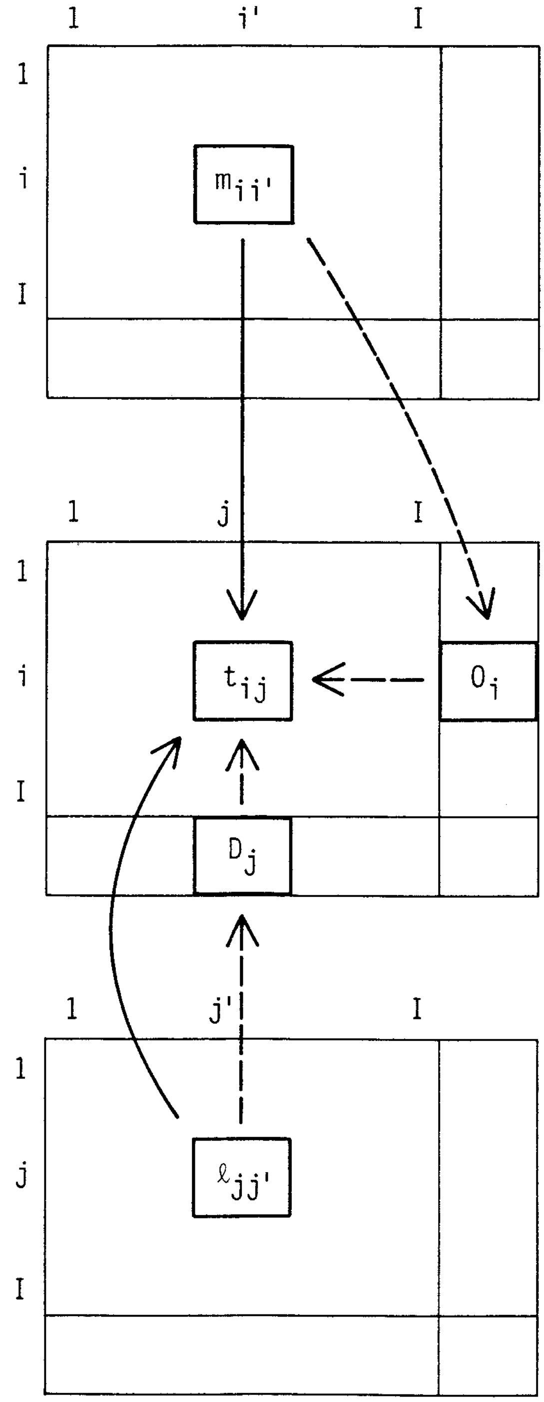

Figure 1. Worktrips, household mobility, and labour mobility.

In the same fashion the resulting worktrip matrix is carried over to the next simulation period; in fact, the actual worktrip distribution model is never executed again after the base year.

3. Regional Deconcentration in the Dortmund Region

The new model version presented in the preceding section has been calibrated and tested with data of the Dortmund, West Germany, metropolitan region and subsequently used to investigate some hypotheses concerning the nature and causes of the spatial deconcentration process observed in the region. In this section, a few results of this work are presented.

3.1 The Study Region

Dortmund (population 600.000) is the most eastern of the large cities in the Ruhr conurbation. It dominates a metropolitan region with a population of about 2.4 million including in its western and southern parts two larger cities, Bochum (population 400.000) and Hagen (population 220.000). However, in its northern and eastern parts, the region is in a transition between rural and suburban consisting of a great number of smaller towns and villages. On the eastern fringe of the region lies Hamm, a more or less self-contained industrial center with a population of 180.000. Figure 2 shows the study region subdivided into 30 zones consisting of Dortmund with its 12 metropolitan districts and 18 municipalities surrounding it.

In the following analysis, Dortmund itself is called the "Core" of the region (zones 1-12), while the open ring of towns and villages stretching around Dortmund from the northwest to the southeast, which are clearly oriented towards Dortmund, are called the "Ring" (zones 13-22). The remaining two parts of the region are treated as external here, although they are not external in the model.

Economically, the region suffers from its unbalanced sectoral composition which is still largely based on coal mining and steel production, both of which sectors have been declining for some time and are almost certain to do so in the future. Total regional employment, after a period of rapid economic reconstruction in the fifties, started to decline in the sixties

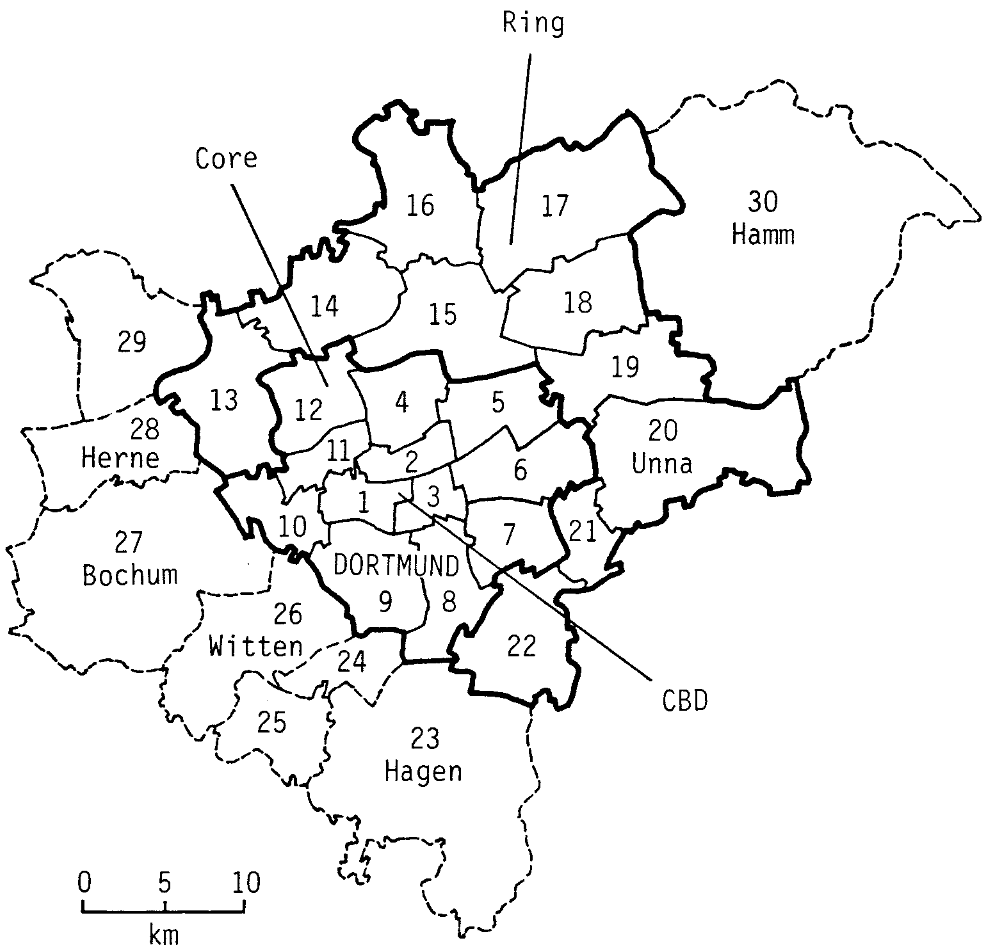

Figure 2. The study region.

with an average annual rate of .4 percent in the seventies, but decline has accelerated in the eighties and is expected to continue by about one percent annually for the rest of the century. As a consequence, unemployment in the region is among the highest in the Federal Republic and would be even higher if the region had not suffered heavy losses of population through outmigration, which together with decreasing birth rates have resulted in a population decline comparable to that of employment. So the region clearly qualifies for being a case of deurbanization.

In parallel and seemingly independently of growth and decline, the region has undergone a process of spatial decentralization. If one plots the relative share of Dortmund (the Core) versus its immediate hinterland (the Ring), as it is done in Figure 3, it becomes apparent that the deconcentration trend is not a recent phenomenon, but started already after the first world war. However, wartime destruction in the second world war accelerated the process both in terms of employment and population, in fact the relative loss of employment and population of the Core has never been fully replaced and was by far more substantial than the gradual decline thereafter. In a long-term perspective, Figure 3 seems to display the typical pattern of spatial substitution between Core and Ring following, like other, nonspatial substitution processes, an S-shaped, logistic-like curve (Batten, 1984). This perspective suggests that also in this region, like in many others, a long-term process of spatial dispersal is at work---a process so fundamental that even a catastrophic physical disruption like the second world war is reduced to an episode from which the spatial system soon recovers to its original trajectory.

3.2 Model Calibration and Validation

During the last years, several progressively elaborated versions of the model presented here have been calibrated using population, housing, employment, worktrip, and migration data for the above 30-zone system. in general, the model parameters were estimated using only data of the base year, 1970, and the time period immediately following it, 1970-1971, in order to reserve all later data for testing the validity of the model. This was done by comparing the model predictions with time series data covering the period between 1972 and the present.

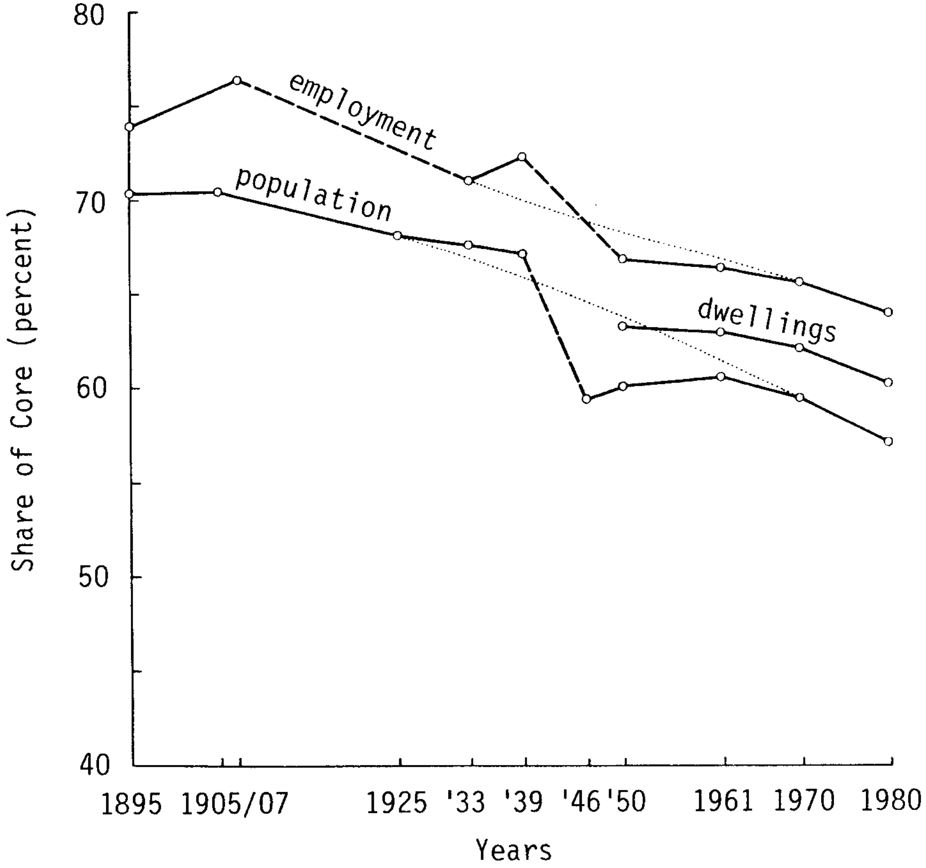

Figure 3. Reality: Employment, dwellings, population of Core in percent of Core+Ring, 1895-1980.

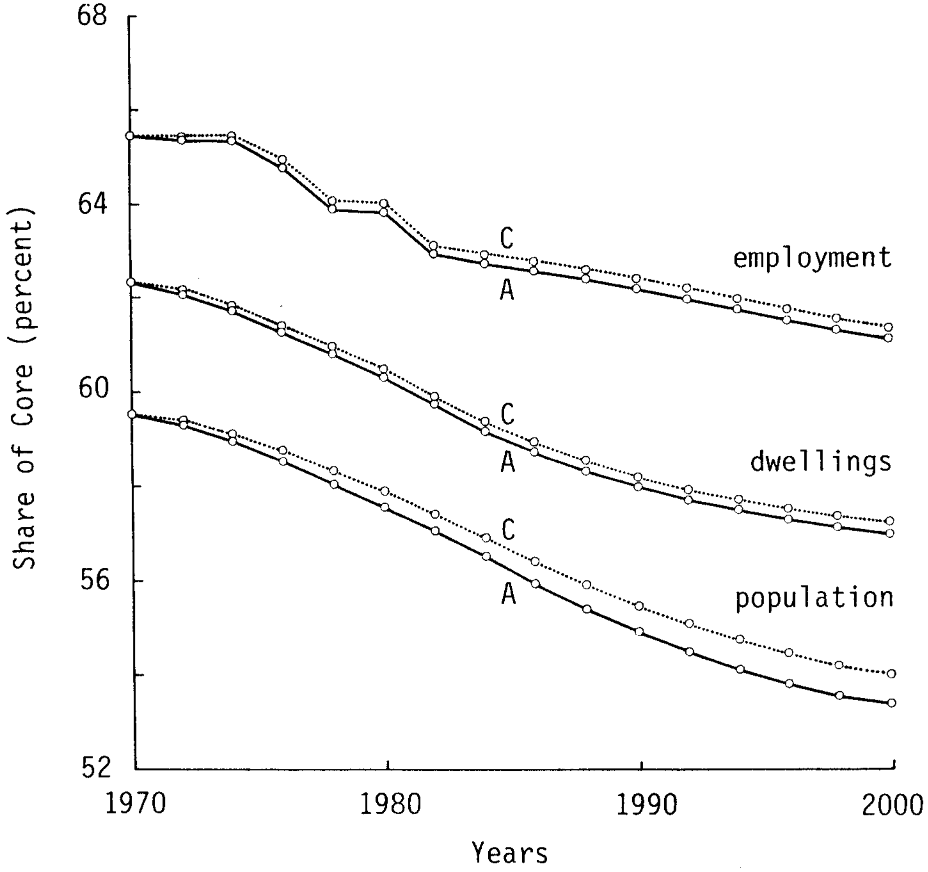

Figure 4. Model results: Employment, dwellings, population of Core in percent of Core+Ring, Scenarios A, C, 1970-2000.

The results of these calibrations and model validity tests have been published elsewhere (Wegener, 1982a; 1983a; 1985) and will only briefly be summarized here.

Base year worktrips are reproduced by the model quite well, with R^2 between predicted and observed trips lying in the range of .98 (n = 900). The corresponding value for migration flows in the two-year period 1970-1971 is only slightly less, .97 (n = 961). Maximum-likelihood estimates of housing choice by household type and zone yielded R^2-values between .77 and .91 (n = 270) and over .98 if aggregated for dwelling types (n = 30).

Test of the predictive capacity of the model consisted mainly of comparisons between predicted and observed zonal values of population, dwellings, and employment for successive years after 1972. Even for 1982, i.e. six simulation periods after the base year, R^2-values for population and dwellings are better than .999 (n = 30) and still over .85 if the rates of change (rather than the absolute values) are compared. The model is equally efficient in predicting employment, with the corresponding R^2-value for 1980 being .92 (n = 30).

Even with the due reservations against the use of R^2 as a goodness-of-fit measure with spatial data, these results must be called excellent. More importantly, it was found that the model reproduces the essential dynamic features of the deconcentration process in the region, in particular the occurrence of trend reversal from growth to decline in the various parts of the region, extremely well. Presently work is underway to extend the model's data base back to the year 1950 in order to test its validity over a still longer time period encompassing the phases of urbanization, suburbanization, and deurbanization in one model run.

3.3 Scenarios

The decentralization trend displayed by Figure 3 gives rise to many questions about the future prospects of urban regions. Here only the role of the transport system as one possible cause of the observed outward movement of urban activities is investigated. In particular, it is asked if highway construction, increased car availability, or changes in the level of public transport have been responsible for the spatial deconcentration in the Dortmund region.

For this purpose, three scenarios were designed and simulated with the model presented in this paper. All simulations started in the year 1970 and went until the year 2000, i.e. covered in part a known period of the past. The three scenarios were defined as follows:

A The Base Scenario. All model parameters were set to reproduce the past as exactly as possible and to make the "most likely" forecast for the rest of the simulation time.

B Like A, but no transport investments are allowed, i.e. transport supply (road and public transport) is kept exactly as in the base year, 1970.

C Like A, but car operating costs and petrol prices are increased incrementally such that car costs are doubled and petrol prices are quadrupled by 1985, etc.

Note that the changes specified for Scenarios B and C become effective immediately after the base year 1970, i.e. only the base run represents the historical development of the region between 1970 and today. In order to study the effects of the new model version, the three scenarios were simulated using both, the new model with constrained worktrip changes (Scenarios A to C) and the previous model version where no such constraints were applied (Scenarios A' to C'). Except for this and the above differences, all six scenarios used exactly the same computer programme, base year data, and model parameters.

3.4 Results

Figure 4 presents summary results for the two Scenarios A and C showing the spatial distribution of the key variables employment, dwellings, and population between Core and Ring over the simulation time 1970-2000 drawn in a manner comparable to Figure 3 (but to a different scale). Each circle in this and the following figures represents the beginning and/or end of a two-year simulation period. The results of Scenario B are not shown; they lie between those of Scenario A and Scenario C, but much closer to A. The alternate Scenarios A' to C' are not significantly different from their respective counterparts A to C.

The three trajectories shown for the base run (Scenario A) are much as one would expect indicating a continuation of the spatial dispersion in the region until the end of the century. With the exception of a small irregularity in the employment curve (due to a minor upswing in the centrally located steel industry befor 1980), all three curves follow the S-shape suggested by the spatial substitution hypothesis, with the flattening at the end indicating a natural end to the spatial substitution process not too far away in the 21st century.

Scenarios B and C both differ from the base run in the direction suggested by theory. Both imply by no means a reversal, but a slowing down of the decentralization proecess. However, the degree of their divergence from the base run may appear to be very small. After all, there are dramatic changes of the transport environment in terms of transport supply and of motorization in the base run, which are not present in the two scenarios. In the base run, 110 km of new motorways are added to the existing 175 km, of which more than 80 are upgraded by adding new lanes; many tramway lines are speeded up by being put on separate or underground tracks and service on most other rail and bus lines is improved several times. All these changes are absent in Scenario B, in which transport supply is kept constant at the base year level. The number of cars in the base run is more than doubled or nearly tripled in terms of cars per capita during the 30-year simulation, while in Scenario C the number of cars per capita remains practically unchanged, which means in effect a reduction of car availability in terms of cars per household. How is it possible that despite these dramatic differences the location of activities in the three scenarios is nearly the same? The answer to this question is connected to the assumptions made in the model about how transport influences location.

This can probably best be discussed by looking at Figures 5 and 6. These two figures use a format suggested by Brotchie (1984) to in a compressed form represent the relationship between spatial interaction and spatial structure in a region: On the abscissa, dispersion of employment in the region is represented by the mean travel distance (Figure 5) or travel time (Figure 6) from the region's centre to all workplaces in the region. On the ordinate, interaction dispersal is represented by mean worktrip travel distance (Figure 5) or travel time (Figure 6). All four measures are calculated using network equilibrium travel distances and times of

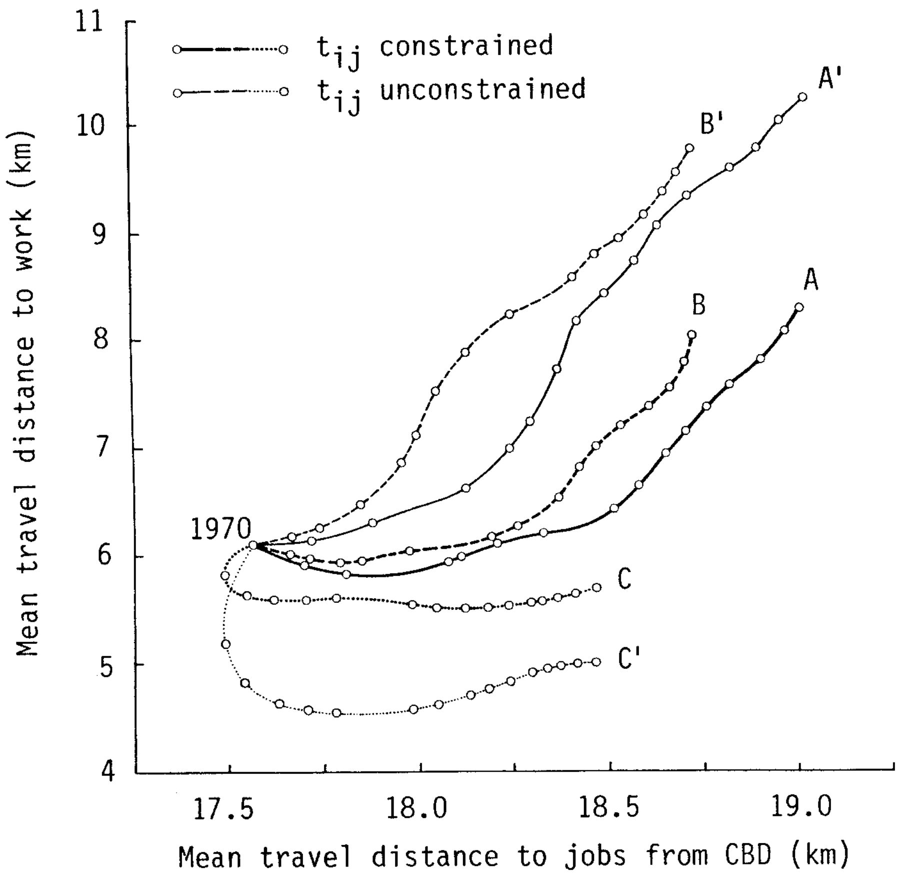

Figure 5. Model results: Spatial interaction versus dispersal of employment by distance, 1970-2000.

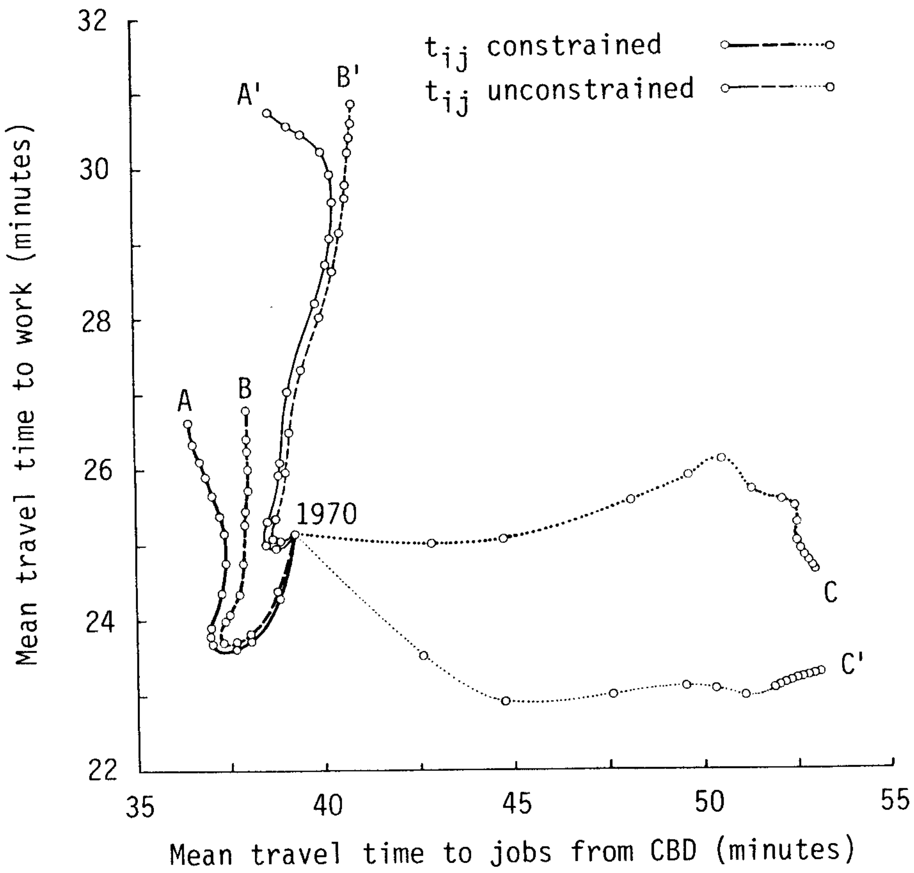

Figure 6. Model results: Spatial interaction versus dispersal of employment by time, 1970-2000.

the whole 30-zone study region as determined in the transport model described in Section 2. The curves in the two figures indicate the path of the spatial system in each simulated scenario from the base year 1970 (the point common to all curves) to the target year 2000 (identified by the respective letter for each scenario), with each circle in between representing the end of a two-year simulation period. The heavier lines belong to the model with constrained worktrip changes, the light lines to the older model version without such constraints.

The first thing to note is that in the base run (Scenario A) the spatial system disperses in terms of distance, but contracts, if only slightly, in terms of time. This is to be expected as it reflects the combined outcome of deconcentration of employment (see Figure 4) and increased car ownership with speeds increasing faster than distances. With increasing car availability, people are able and willing to make longer worktrips; however, initially car availability increases faster than households are able to adjust their residential or job location, so for a transition period worktrips become shorter in terms of time and even somewhat in terms of distance, because car trips are generally more direct than the corresponding public transport trips.

Travel behaviour resulting from Scenario B is not much different from that of Scenario A. As car ownership is as high as in Scenario A, but the highway system is not improved, there is more congestion, so trips are longer in time, but shorter in distance, because trips on city roads are more direct than trips on motorways.

Scenario C leads to much shorter trips in terms of distance, because due to high petrol costs, out-of-pocket costs of trips are much higher, although (see Figure 4) employment continues to decentralize, if only at a slightly lesser rate than in the base run. However, because people have less cars, they make more trips by public transport, accordingly dispersal of employment appears to increase much faster if measured in terms of travel time. Also mean travel time to work increases and would increase much more if it were not constrained by high trip costs, which keep worktrip travel distances down well below the base year level. Note that in this scenario there is one initial period where the spatial system actually contracts even in terms of distance because of the high travel costs.

The results of the alternate Scenarios A' to C' produced with the model without constraints on worktrip change generally display similar patterns, but because of their greater degree of freedom tend to exaggerate the differences between the scenarios. In Scenarios A' and B', without constraints on worktrip change, gains in car availability are immediately converted into longer worktrips both in terms of distance and time. On the other hand, restrictions on car availability and high petrol costs in Scenario C' induce the model to make bizarre attempts to immediately adjust to much lower travel distances and times than would be possible in reality. In other words, the unconstrained model is insensitive to the inertia inherent in location decisions such as residential or job choice, in this case to the restrictions imposed on worktrip destination choice by longer-term housing or employment contracts.

The differences between the two model versions become even more apparent if one compares their convergence behaviour in the network equilibrium algorithm. This is done for Scenarios A and A' in Figures 7 and 8. The two figures show the resultant values of the objective function (9) after the first four iterations and after the final iteration of the algorithm for each time point of the simulation. For intertemporal comparision, all numbers are divided by the current total population of the region.

The shape of the final solution curve reflects the combined effects of spatial deconcentration and changing economic conditions in the region: In the first decade of the simulation, rising household incomes lead to increased car ownership, a higher proportion of car trips and higher trip utilities moving the curve up, except for the short period before 1980 in which the additional worktrips required for the economic upswing pull it down a little. After 1980, car ownership, despite practically stagnant incomes, continues to rise, but for the most part of the eighties and nineties that rise is outweighed by more road congestion and increasing trip lengths. Towards the end of the century, the curve again starts to move up, because worktrips decrease in favour of other, "optional" trips, and this reduces peak-hour congestion.

Figure 7 demonstrates that with the new model version convergence occurs consistently and rapidly. Convergence with the old model version without constraints on worktrip change (Figure 8) is much slower, mostly because that model in each iteration selects a much inferior initial solution, as

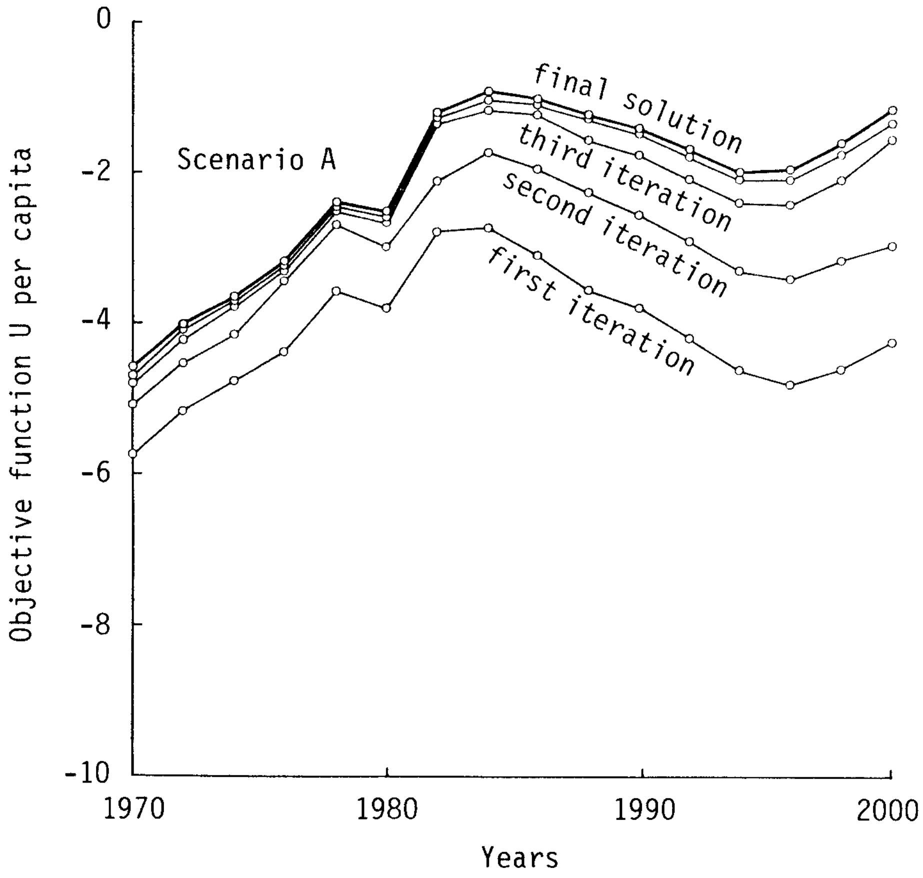

Figure 7. Convergence of the network equilibrium algorithm, Scenario A, 1970-2000.

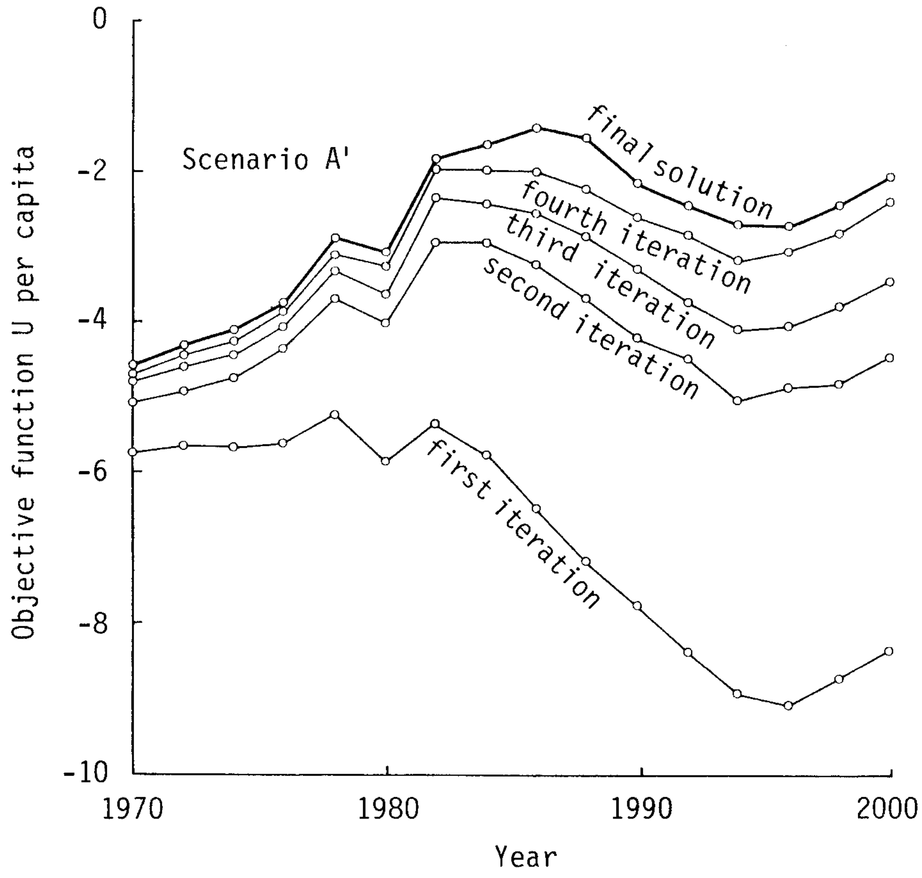

Figure 8. Convergence of the network equilibrium algorithm, Scenario A', 1970-2000.

it lacks the information on likely road congestion available to the newer model version through its "memory" of last period's worktrip pattern. This makes the constrained model not only more realistic, but also more efficient computationally(1).

It is now possible to answer the question why the land-use predictions of Scenarios B and C differ only so little from those of Scenario A. The answer is that in contemporary urban regions the constraints on locational change due to the inertia of the existing building stock as well as through contractual restrictions and habitual patterns are so strong that locational adjustment to changes in the transport environment, unless they are really fundamental, can occur only in an incremental and highly retarded fashion. And, inspected more closely, the changes of the transport environment in Scenarios B and C are not fundamental. Already in 1970 the region had a highly developed hierarchical and well maintained road system and, more importantly, an efficient public transport system, and the level of car ownership of 1970 was more than sufficient to support the suburbanization process, which had been going on already for half a century. So neither the absence of transport investments in Scenario B nor the restrictions on car use imposed in Scenario C make living at the periphery really unfeasible; in fact with time progressing the tension on the time and money budgets of households in peripheral locations lessens due to a variety of reasons such as reduced work hours, substitution of trips by telecommunication and, most importantly, dispersal of employment in parallel with population.

Why then did not the alternate Scenarios B' and C', not constrained as their counterparts B and C, produce substantially different land-use predictions? The answer is that these scenarios are different only in their transport submodel, but employ the same incremental location submodels as Scenarios A to C. If indeed their worktrip predictions as summarized in Figures 5 and 6 would be used to drive singly-constrained spatial-interaction location models of the Wilson type, the resulting land-use predictions would show the same pattern of over-response, i.e would predict spatial shifts of a magni-

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(1) One iteration of the network equilibrium algorithm for the Dortmund region 1,700-link multimodal network requires about 1 second of CPU time on a Siemens 7.890 E (Facom M 380 S) computer, one execution of the whole transport submodel about 10 seconds.

tude never found in reality. It might be argued that such results would represent the equilibrium the system would move to if present conditions prevailed. That is correct, and as such the results would have their own value. But, as the exogenous conditions of the land-use transport interface are always changing, it would be an equilibrium the actual system would never have a chance to arrive at.

4. Conclusions

This paper has had a twofold purpose. First, to communicate a new approach in the direction of developing a dynamic model of urban change. Second, to contribute with this model to answering the yet unsolved question of why cities decentralize.

With respect to the first purpose, a modelling approach has been sketched out that departs in various aspects from current mainstream modelling practice. In particular, it extends the range of subsystems commonly contained in urban models---residential and employment location and transport---by including models of change processes such as relocations of firms, change of job, housing search, and construction, in an effort to capture the different time scales of such processes better than this has been possible with the spatial-interaction location model. Whether this strategy of replacing one simple and relatively well-understood model by several complicated and yet imperfectly known models will be successful is a question that cannot be answered at this time. However, the experiments conducted to compare the performance of the two model types clearly demonstrate that there are substantial differences in model behaviour between the two approaches that are too large to be ignored without careful investigation.

These differences in model behaviour are essential for the second purpose of the paper. They indicate that for modelling the interaction between transport and land use in urban regions it is of crucial importance to take account of the different response times of daily mobility on the one hand and long-term, i.e. residential and labour mobility, on the other. If the assumptions about constraints on residential and labour mobility made in the model are correct, the causal relationship between transport and location in urban areas is not nearly as direct and straightforward as it is commonly perceived and modelled under the spatial interaction paradigm.

At least that is the message coming out of the simulation experiments reported. They clearly demonstrate that the process of spatial deconcentration in the Dortmund region cannot be explained by improvements of the regional transport infrastructure nor bei the increase in car availability experienced in the past decade. The counterevidence is that the core of the Dortmund region continues to decline in employment, housing, and population in all three scenarios, and would probably do that also in even more rigourous transport scenarios.

The conclusion to be drawn out of this is not that accessibility has ceased to be one of the key variables determining location, but that in medium-sized contemporary metropolitan regions with a fully developed transport infrastructure it has become an ubiquitous commodity and hence has lost its bottleneck character. Moreover, changing work patterns and telecommunication will further reduce its importance as a location factor, in particular the importance of the work-to-home relationship. What then will replace accessibility as the major determinant of intraurban location? All evidence suggests that it will be space itself, i.e. the scarce resource land with entirely aspatial characteristics such as environmental quality, closeness to nature, aesthetic pleasantness, and lack of congestion. In the pursuit of these and similar amenities, the deconcentration process in metropolitan regions will continue and is not likely to be slowed down, halted, or even reversed by policies exclusively addressing transport issues.

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Figure Captions

Figure 1. Worktrips, household mobility, and labour mobility.

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