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ENVIRONMENTAL QUALITY AND URBAN DEVELOPMENT:
A SIMULATION APPROACH

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1. Introduction

Numerous recent studies in industrialized countries claim that urban development in the post war years has been characterized by cycles of growth and decline (Norton, 1979; Bradbury, Downs, Small, 1982; van den Berg, et.al., 1982; Friedrichs, 1985; Kawashima, Korcelli, 1982). In the early "urbanization phase" cities attract population from the hinterland, investment in urban infrastructure is substantial and high growth rates of population and income can be observed. In the following "suburbanization phase" population growth in the densely populated cores begins to level off and finally to decline. Ever increasing numbers of urbanites migrate to the periphery of the cities, into newly forming suburbs. Former rural communities come increasingly into the sphere of influence of the city and are finally absorbed. In the "desurbanization phase" the ring of the urban agglomeration begins to stagnate, the urban region as a whole looses population to small and medium sized towns. Whether a new "reurbanization phase", which would logically follow from a wave-like urban development pattern, will lead eventually to a revitalization of the urban cores is still not finally deducible from the small amount of empirical evidence available so far.

From an analytical point of view the question arises which determinants lead to such cyclical behavior as could be observed in the past.

To what extent environmental quality can be one of these determinants of spatial structure and long run time path of urban development is a widely discussed issue in the literature (Portney, Sonstelie, Kneese, 1974; Fishelson, 1975, Schubert, 1979, etc.). Starting point for such analyses is the location decision

by households (maybe also of enterprises), assuming that pollution (as an important negative component of environmental quality) has a negative marginal utility. If pollution levels vary systematically over space the environmental quality of a zone can become an important attribute influencing the location decision.

Note, however, that the multiple feedback chains operating between different components constituting an urban system (such as population, the economy, labor market, land market, city government, etc.) lead to various indirect effects, a fact which considerably aggravates the analytical task of disentangling the impacts of environmental policy. Note further, that the density of land use is itself an important variable in the determination of the intensity of emission of residuals, which after having diffused over the spatial system within a receiving medium determine local residuals' concentration. The existence of such a fundamental feedback chain between the settlement structure and environmental quality must hence be considered explicitly.

It must, however, not be neglected that besides environmental quality, there are other at least equally important variables influencing the settlement pattern and its change. Most of the studies dealing with these problems, are based on static models, thus assuming that all the feedback effects happen rapidly and can thus be viewed as a simultaneous equilibration process. In reality urban development processes are of a long run nature and the settlement structure only changes slowly. An important part of an investigation into urban systems change must hence be to study such long run adjustment processes as well as the effects of policy measures relevant for urban development in the framework of a dynamic approach. A further challenge is posed by the already mentioned presence of multiple feedback chains besides

the claimed environmental one leading to partly opposing effects of policy measures with respect to the goal variables (such as population, jobs, unemployment, etc.). It is particularly in this case that the magnitude and intensity of opposing effects must be assessed. Summarizing, it can be said that it is the main task of the present contribution to assess the mutual influences between pollution as a consequence of land use activities on the one hand and the distribution of household and jobs over an urban region on the other.

A natural corollary to this problem is the question to what extent environmental policy can exert an influence on urban change. The studies undertaken so far in this field, due to theoretical shortfalls and even more so the present data situation do not permit as yet to calibrate an empirically valid model based on econometric parameter estimation. (As a sideline it should also be mentioned that econometric work in this field is particularly costly). Not being endowed with the necessary resources it was hence only possible to do a pilot study (supported by the Austrian "fund for scientific research") aiming at the formulation of an adequate model structure. On this basis a simulation model was developed which is capable of representing numerically complex dynamic processes (see e.g. Whithed, Sarly, 1974; Bossel, 1986). The parameter values were taken partly from partial empirical work done on some model components (Maier, 1987; Brunner, Schubert, 1985) which permitted to pin down the order of magnitude of these parameters, and to vary them in different simulation runs. For some of these variables, however, no relevant information for quantitative assumptions was available and systematic variations of the corresponding parameters had to help out.

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As regards the target of assessing the effects of various environmental policy measures, special emphasis is placed upon the relation between these policies and the intensity of emissions due to land use activities which lead to a change in the spatial distribution of residuals' concentration. Additionally an attempt is made to investigate to what extent a bias in the diffusion process of pollutants in a certain direction (by predominant winds coming from the opposite direction) has any impact on the settlement structure. A further question of analytical as well as practical interest is to what extent changes in the preferences of households in the sense of a negative marginal utility of pollution lead to modifications in the pattern of urban change. The simulation results of a reference variant, in which this marginal disutility is set equal to zero can be compared to a variant in which this environmental feedback is included.

The role of enterprises with respect to the environmental side of the model is only the production of goods and services as well as pollutants as by-products and their adjustment strategies to environmental policy measures. Strategies regarding a change of location as a reaction to policy measures are to be included in further steps in the development of the model.

In the second section of this contribution the basic model (i.e. without environmental feedback) is briefly sketched. (A more detailed description of the model structure can be found in

emissions (predominantly as a consequence of energy transformation processes). The diffusion component deals with the spreading of the residuals over the spatial system, the accumulation of which leads to the levels of residuals' concentration at the different locations of the urban region. The way residuals' concentrations can affect locational choice are modeled in this section as well. Additionally the possibilities of environmental policy as being treated in this paper are briefly discussed.

The fourth section presents and discusses some selected simulation results. At the end of this contribution a short summary and outlook is presented.

2. Model Description

In the following section the most important components of the simulation model will be described. As the main concern of this contribution are the feedbacks between the environment and urban change, the emphasis is placed upon the formulation of the environmental submodel. The equations representing the other model components are fully given in the appendix. An additional remark has to be made here: At this stage of our research we consider the main task of this modeling exercise to be the clarification of the interactions between different components of a model describing urban change. We are hence dealing with a hypothetical urban region. Precise parameter estimates for most of the model components for specific cities are not available, yet (although it is the intention of the authors to continue this research in the direction of adding empirical content to the theoretical skeleton).

Basic assumptions:

- The functional urban region consists of 4 zones which are of equally large area. One of these zones is the "center", the other 3 zones are considered "suburos", which are all at equal distance from the core (figure 1 represents the spatial layout of this urban region).
- The geographical location is important in the environmental submodel; in one simulation run it is assumed that winds blow from west to east hence biasing the spatial distribution of pollutants.

Urban change within this framework is defined as spatial redistribution of population, jobs, infrastructure, etc. over time. These different variables are connected via various feedback chains. The following submodels constitute the framework in which simulations can be undertaken:

- Population
- Production and labor market
- Infrastructure
- Land market
- Income formation and
- Pollution. (which is treated in more detail in the following section).

Figure 2 represents a graphical description of the main elements of the model structure. The model is spatially closed, i.e., there are no effects on model variables which emanate from without the urban region. There are exogenous variables, such as technological progress which raises productivity, however. The accessibility structure of the model, the distances between the different zones, is also exogenously given. We do hence, not consider any technical progress in the transportation system or possible congestion leading to changes in the accessibility

structure. The spatial closure is particularly cumbersome in the population submodel. In this contribution we keep total population of the urban region constant, thus permitting only zero-sum spatial redistributions, i.e. neither immigration nor emigration from the region as a whole are considered.

A further essential simplification of the model is implied by the assumption of "representative" decision-makers. Social stratification in the population, differences in production technology, the age of infrastructure or productive capital stock, or differential quality of land, are not taken into account. The model is hence incapable of making any predictions about spatial segregation processes.

The basic decision structure is such that, at the beginning of each period, the actors make plans, which are based on their last experience including the prices for various economic goods. These plans are then coordinated in the various markets and lead to a new set of prices. As the theoretical considerations are essentially based on a disequilibrium approach, markets also provide indicators for surplus supply/demand (e.g. unemployment, vacancies).

2.1. The Population Submodel

The population component consists of equations A.1. to A.6. reproduced in appendix 1. It constitutes basically a spatial redistribution mechanism, driven by migration, the central element of which is the migration rate μ . This rate is sensitive to the varying attractiveness of the urban zones leading to migration as a reaction thereupon. The migration rate μ is the result of a "nested-logit" model which is based on a location decision of

the Alonso-von Thünen-type (Alonso, 1964; Von Thünen, 1826). The hypothesized representative individual decides simultaneously how much out of his income is going to be spent on consumption, land and transportation. These variables are elements of a direct utility function of the decision-maker and are subject to an income constraint. Additionally the utility function also contains certain "attributes" of the zones, such as infrastructure and environmental quality. Given the income constraint this direct utility function can be used to deduce an indirect utility function (Varian, 1978) and can then be used to formulate a nested-logit-model. Using a log-linear direct utility function leads to the indirect utility function given in equation A.5. The functional form of the migration rate, as indicated in equation A.4., is a direct result of the assumptions of the logit model. The income which co-determines the spatial choice of the individual results from the other levels of the nested-logit-model, i.e. the participation and commuting decision, as well as the land market submodel (see equation A.29.) (A brief discussion of the participation and commuting decision will be given in the next section on the labor-market components). The land use and spatial choice decision is made simultaneously. Equation A.6. describes the area demand for residential purposes, which is the result of the above sketched decisions.

2.2. The Labor-market Submodel

The bridge between the spatial distribution of population and the supply of labor is constituted by the participation and commuting submodel (equation A.7). The decision behind this macro-model is the location decision, which is modeled sequentially with the

participation and commuting decision in a nested-logit approach. This implies that the participation decision on the one hand is conditional upon the location decision and on the other hand, the result of the participation decision is considered in the location decision. The coupling between participation and commuting is solved analogously. (The feedback is modeled via the variables EW and EY , where the latter influences the location decision via equation A.29). Equations A.8 and A.10 describe the participation and commuting rate, A.11 and A.12 the respective expected incomes.

The (exogenously given) share Ω indicates the percentage of the total residential population in the working age bracket. Together with the participation and commuting rate these variables permit the calculation of labor-supply given the distribution of the residential population (equation A.7). Labor demand is determined on the basis of a general production and production-factor demand decision made by a "representative" entrepreneur. The basis is a production function (A.13.), consisting of two parts, one determining the long run production potential (in form of a Cob-Douglas-function) the other, the short run component, represents the short run frictional losses in production as a consequence of "production detours" (Böhm-Barwerk, 1989). Assuming that in a dynamic context, the goal of the enterprise is the maximisation of long run profits (discounted stream of earnings) a problem of "optimal control" arises (see Brunner and Schubert, 1985) the Pontryagin optimality conditions can be utilized to solve for the various dynamic factor demands, such as labor, land and capital. In the present contribution only the long-run term is considered, and the accumulation of capital is neglected.

The demand for labor and land contains two elements, i.e. a stock given from the previous period and adjustment components (equations A.14 and A.15). The latter contains the control variables of the entrepreneurs. Their optimal value is determined by the respective deviation of the price from the value of the marginal product. The price level, constituting demand for goods and services is determined on the basis of a spatial demand function, the most important determinant being the income potential (equations A.16 and A.17).

In the labor market employment and wages are determined given labor supply (A.7) and demand (A.14). Employment results from a symmetric reaction of the market to surplus demand (equation A.18.) which ascertains that actual employment cannot exceed labor supply or demand. Unemployment and vacancies are residuals, the unemployment rate the ratio between the absolute number of unemployed persons, to labor supply (equation A.19 - A.21). Equation A.22 describes the wage determination. The parameter τ indicates the degree of rigidity of the wage rate over time. The exponential function used in this formulation ensures higher flexibility of wages upwards than downwards.

2.3. The Land-market Submodel

The demand for land by households and enterprises was already briefly dealt with in the section above (A.6 and A.15). Total demand is the sum of both of these components (equation A.23). The land market model is simpler in structure than the labor market's, as no explicit disequilibrium mechanism is assumed to exist. The demand for land can always be met. The supply of land (AS) is assumed to be equal in all urban zones. Actual

land use can exceed the exogenously given land area, thus permitting multi-storey use of land. Land prices are determined in a Walras-type of price determination formulation (A.24).

2.4. The Infrastructure Submodel

The capacity of local infrastructure is seen to be given by an infrastructural capital stock, which accumulates via investment (equation A.25.). A constant rate of obsolescence is assumed to be operative on the stock from the previous period. Infrastructure investment (equation A.26.) depends on the demand given in the urban zone, which is simply hypothesized to depend on population change expected, which in turn is seen to be proportional to actual previous population change. Expectations are hence modeled as a simple extrapolation of experiences in the past. A restriction is imposed, ensuring that in zones with heavy population losses infrastructure investment cannot become negative, and the stock is only diminished by obsolescence.

2.5. Income Determination

Income formation occurs in the labor-market and land-market in this model. The wages are determined in the labor-market and land prices in the land-market. As we do not assume any social stratification to exist and the property structures are not explicitly modeled, we assume that all income made in the land market is used in the zone where it was gained, there are hence no spatial spillovers of land rents. Earnings from work do originate in the location of the job, but "diffuse" back to the residential zone of the workers via commuting where they become

effective (equation A.27). The effective demand for goods and services in an urban zone is represented by the income potential (equation A.28) constituting a spatially discounted sum of zonal incomes.

The expected maximal per capita income (YC) still remains to be defined. It is given by the prices and quantities of the previous period, as well as the optimal participation and commuting decisions (see equation A.29.).

These briefly sketched components yield an operational, consistent simulation model of urban change which is capable of reproducing numerous urban dynamic processes. Depending on the parameter constellations, the resulting time-paths can be stable or unstable, can demonstrate oscillations with long or short amplitudes and processes in which there is a superimposition of short run, business cycle like waves and long run waves over much longer time horizons.

3. The Pollution Submodel

The economic and social activities in a city lead to a set of environmentally relevant effects, such as the emission of residuals into the receiving media air, water, and soil. These emissions are seen as byproducts of various land use activities such as production and consumption. For some of these emissions abatement facilities are available, others are at least partially emitted directly into the receiving media. It is particularly the latter we are interested in, as they constitute negative externalities, if they are sufficiently perceivable as nuisances, which influence the various land use decisions of the actors driving the urban system. They hence provide feedbacks between land use

activities and environmental conditions in an urban region which, it is hypothesized, exert a strong influence upon urban dynamics.

Within a spatial system as considered in this contribution, particularly such emissions diffusing over sufficiently long distances, such as air-pollutants, deserve attention. Land use activities lead to a whole host of waste materials and residuals, some of which interact strongly leading to synergistic effects (such as photochemical smog, etc). These complexities will not be analysed in this paper, only a simple approach equivalent to the simple modeling strategies applied in the various components of the model is chosen. Our starting point is hence a simple indicator which can be considered an aggregate of various emitted residuals. The volume of pollutants and thus the level of the indicator, is hypothesized to depend on the level of the respective activity.

Figure 3 illustrates the basic structure of the environmental submodel. A given land use pattern in a specific period in an urban zone leads to emissions which are related to the activity-level by constant emission-coefficients. The residuals diffuse over the spatial system (see e.g. Nijkamp, 1976, 1977), thus creating negative externalities, not only at the location of emission but also in others the pollutants are distributed over. Total emissions in a zone are thus the sum of the stock of residuals from the previous period and all the residuals arriving at the given location via the diffusion process.

Three sources of emission are distinguished: production, residential land use and transportation (commuting). While the first two land use-activities represent point-emissions which can be uniquely ascribed to certain locations, the transportation caused emissions originate on the connections between the diffe-

rent spatial units. The total volume must hence be attributed to the various zones. The simple spatial structure underlying this model permits a proportional distribution between the zone of origin and destination of a commuting stream. (Note that transportation in our model is only necessary for commuting). Total emissions in a zone i in period t are thus given by:

$$EMISS_i^t = e_1^t * PROD_i^t + e_2^t * Y_i^t + \sum_j e_3^t (Pend_{ij}^t + Pend_{ji}^t) / 2 \quad (1)$$

where

$$Pend_{ij}^t = r_{j|i}^t * \pi_i^t * \Omega_i^t * Pop_i^t \quad (2)$$

The volume of residuals produced as a byproduct of residential land use activities is hypothesized to depend on total disposable income in a given urban zone, i.e. on factor income (labor and land) and the income-earning part of the residential population. Especially air pollution is a typical byproduct of energy-use, which is positively related to income.

The diffusion process leads to a spatial redistribution of residuals. As already mentioned pollution (residuals' concentration) is a stock resulting from an accumulation process.

$$IMMISS_i^t = IMMISS_i^{t-1} * \beta + \sum_j Z_{ij} * EMISS_j^t \quad (3)$$

Where β is the rate of absorption of residuals by natural processes and the Z represent diffusion coefficients. The latter are influenced by a whole host of factors, such as windspeed, humidity, temperature, atmospheric pressure, natural topology, vegetation, height of chimneys, etc. Most of these factors of influ-

ence tend to change rapidly, leading to diffusion models as used in meteorology which are of the very short run.

The concern in this contribution, however, are much longer periods of time, for which constant meteorological conditions can not be assumed to exist. We thus make use of a very simple diffusion model, in which the diffusion of residuals is considered a random process (see e.g. Benarie, 1980). Residuals concentration at a specific location is thus the sum of the motion of all residuals, following a bivariate normal distribution. This model possesses the advantageous property that the average residuals' concentration resulting from different meteorological conditions again follows a normal distribution (the sum of normally distributed variables follows itself a normal distribution).

We do, however, consider that an urban area may be characterized by a predominant wind direction leading to a spatial bias in the diffusion process. As the spatial structure of the model for this exercise is considered symmetrical, we can, without loss of generality assume a priori that westerly winds dominate. This leads to the claimed bias in the diffusion of residuals in a west-east direction, hence only the mean value and the variance must be adjusted in this direction. The diffusion coefficients are thus given by the following formula:

$$Z = 1/(2\pi\sigma_x\sigma_y) * \exp(-1/2*\{[(d_x-\mu_x)/\sigma_x]^2+(d_y/\sigma_y)^2\}) \quad (4)$$

where d_x represents the distance from the source of emission in the west-east-direction, d_y distance in the north-south-direction, σ_x and σ_y are the corresponding standard deviations and μ_x is the distance of the mean of the normal distribution from the source of emission. The parameter σ_y is kept constant at a value of 5. The influence of the wind leads to corresponding changes of

P_{ij} and σ_{ij} . For illustration, residuals' concentration without wind and three different windspeeds are shown in figure 4.

Equations 1 to 4 together yield the levels of pollution in the urban zones given the spatial structure of the activities. Environmental quality (or its inverse - pollution) is itself considered an important attribute of an urban zone, which is relevant for the land use decisions made by the various actors. In the framework of this contribution, we assume, however, that only the residential location decisions are affected directly, but not those made by enterprises. Different levels of pollution, hence, are not considered to make any difference in the location of businesses.

The feedback between residuals' concentration and the location-decision is modeled by introducing the level of pollution as an additional decision-variable in the utility-function. Equation A.5 in the appendix is thus replaced by

$$U_{j|i}^t = (u_1 + u_2) * \ln(YC_j^t) - u_2 * \ln(P_j^{t-1}) + u_3 * \ln(INFRA_j^{t-1}) - u_4 * DIST_{ij} - u_5 * \ln(IMMISS_j^t) \quad (5)$$

This implies, ceteris paribus, that locations with lower pollution-levels are preferred. Due to the log-linear form of the indirect utility-function the marginal rate of substitution between income and pollution is equal to:

$$dYC/dIMMISS = u_5 * YC / [(u_1 + u_2) * IMMISS] \quad (6)$$

This implies that given the other attributes, a raise in per-

capita-income leads to a rising significance of environmental quality for location decisions.

Environmental policy attempts to influence the various components leading to pollution to improve the situation. The various available instruments as well as the economic considerations in the evaluation of these, cannot be discussed in this framework (see e.g. Baumol & Gates 1975, Schelling 1983, etc). The main concern in this contribution are the effects upon urban change of different bundles of measures of environmental policy, given the complexity of urban systems. It is argued here, however, that it is essential to consider this complexity as direct effects may often be (over-)compensated by indirect ones.

In accordance with the utmost simplicity of the model formulation an attempt is made to adhere to these principles also with respect to the environmental submodel. Two types of environmental policy measures are considered in the framework of this contribution. Both aim at a decrease of emissions originating from the land use activity "production of goods and services" and become effective when total emissions in an urban zone exceed an exogenously given emission standard. This can be achieved in two different ways:

1. The first policy measure "freezes" the production at that level which is still compatible with the given emission standard. It can be considered hostile to production as it does not permit an adjustment of production-technology to the environmental standards. The emission-coefficients remain at their given level, the restrictions of emissions are exclusively coped with by decreases in the volume of production.

2. The second policy measure attempts to affect the emission-coefficients. They are reduced until the given standards are met. These measures can be considered production-oriented, as the adjustment of production-technology, leading to the decrease of the emission coefficient, does not imply any reduction of the volume of production. This can be achieved, e.g. by subsidizing the necessary investments from sources exogenous to the model.

4. Simulation Results

The basis of the simulations is the model briefly sketched in the previous sections and the values of the respective parameters. An overview of the model can be found in appendix 1, the parameter values utilized in the simulations are given in appendix 2. As already mentioned many of these values do not come from econometric parameter estimations for specific urban places.

The results of the following five simulation variants will be discussed:

1. Basic variant. It is assumed that environmental quality does not influence location decisions. Emissions and residuals' concentrations are computed in this run, but there is no reaction to these by population as the relevant parameter in the indirect utility function is set equal to zero. The mathematical structure of this variant is the one given in appendix 1 and will be used as a reference for all other simulation runs.
2. Environmental feedback. Pollution does now enter the indirect utility function of population, but the diffusion of

residuals follows a symmetric pattern. i.e. no predominant wind direction in the urban region is assumed to exist.

3. Predominant winds. The difference between variant 2 and 3 is only that the hypothesised westerly winds bias the diffusion of residuals leading to an a priori uneven residuals' concentration in the various urban zones.
4. "Production control" - environmental policy. The starting point is the same as in variant 2 but it is assumed that environmental policy imposes emission standards, which can only be met by freezing production levels (see section 3).
5. "Restructuring of production" - environmental policy. Emission standards are met by reductions of the emission intensities, achieved by various abatement policies, the financing of which is exogenous.

4.1. Basic variant

As there is no negative pollution feedback and given the spatial pattern of the four urban zones, one of them develops into the economic and residential focus. It is the most accessible zone (zone 1 in figure 1) which becomes the core of the urban region. There are more inhabitants, more production and employment than in any other spatial unit (see figure 5); this comes at the cost of higher land prices, however, (figure 6) and higher emissions. As there are no predominant winds the diffusion of residuals is symmetric, the core suffers from the highest residuals' concentration. All zones are most affected by their own emissions, but the core, due to its central position receives more residuals via diffusion from the other spatial units than

any of the other zones. This fact, does, however, not lead to any reactions by population.

4. 2. Environmental feedback

Pollution now enters the indirect utility function on the basis of which locations are evaluated by households ($u_3 = 2.0$) as a negative attribute. The center although still the most accessible zone of the region, now loses population and eventually becomes the zone with the lowest number of inhabitants (figure 7). Despite the fact that we do not assume firms to evaluate locations also by the criterion of environmental quality among other factors, production does follow population to the ring-zones (figure 8). There are two reasons for this phenomenon: The income potential representing effective demand in the center has decreased. This even more so than in the basic variant (although it is still the highest of all zones); secondly, enterprises must pay higher wages in the core (figure 9) in order to provide an incentive for labor to commute. In the center there are now higher wages, lower land prices, less production and employment and emissions have decreased. Because of its central position, however, the core receives comparatively high loads of residuals, implying that despite the lower emissions in this zone, the residuals' concentration is still the highest (figure 10).

4.3. Predominant wind direction

Taking into account a predominant wind direction ($\mu_x = 6.46$, $\sigma_x = 7.5$, $u_3 = 2.0$), i.e. an asymmetric diffusion process, it is

the ring-zone situated east of the core (zone 2) which receives the most pollutants (figure 12). This zone drastically loses population (figure 12), eventually production and employment. Its lower environmental quality is not compensated by high accessibility. Land prices are lower (figure 13), wages higher than in all other urban zones.

4.4. "Production control" - environmental policy

As was to be expected a stringent policy of this nature leads to stagnation. Production (figure 14), employment, wages (figure 15), population and land prices are all eventually frozen at certain levels. The differences between the zones however, remain. There is no spatial equilibrating mechanism that could become effective after this environmental policy has been implemented. Note however, that the absolute level of production at which the constraint becomes effective is very important for the overall stability of the dynamic system. If environmental policy measures of this kind are executed relatively late in the process (at high income levels), the attributes infrastructure capacity and environmental quality become relatively important in the location decision and explosive oscillations are the consequence.

4.5. "Restructuring of production" - environmental policy

This kind of policy, leading to a lowering of emission coefficients, produces somewhat surprising results. One could expect some kind of transition from the development path with environmental feedback towards the one without such a feedback. In fact this policy leads to a transient stagnation of production

in the core (figure 16) and a significant loss of population (figure 17) and employment. This happens, because environmental policy becomes effective in the ring-zones first, as the activity levels at this point in time are higher there. The emissions' reduction policy reduces the negative side-effects of production, without constraining production itself. This leads to increases in attractiveness of these ring-zones in comparison with the core, which eventually leads to the effects just mentioned.

5. Summary and Critical Outlook

In the present contribution an attempt was made, by means of a simulation approach, to explore the interdependencies between urban development and environmental quality. Despite its simplicity the dynamic simulation model permits the derivation of some interesting results concerning this field of inquiry. Some indirect feedback effects make this venture not entirely surprise free.

As already mentioned in the introduction, this contribution represents an other step in an ongoing research effort which should make it possible in the future to remove some still very limiting constraints of the present model formulation. Among these, the assumption of more or less homogeneous preferences of the various actors (only random variations from the representative decision maker are permitted), leads to overreactions in the spatial mobility patterns. Thus the distinction of several different social groups in the population submodel, as well as different sectors in the labor demand submodel (especially the introduction of a basic sector) could imply considerable improvements in the results of the simulation

experiments. The outcome, e.g., that production tends to follow population, stems directly from the assumption that all demand for goods and services comes from within the urban region. The same holds in the environmental quality and policy submodel. Besides the obvious need of distinguishing different land use activity caused social costs (such as pollution, noise, etc.), further extensions of the set of instruments available in environmental policy could make this model more relevant for possible practical applications.

Summarizing, one has to reemphazise, however, that the basic model structure as used for the presented simulations here is capable of yielding interesting insights. Further work in terms of model improvement and particularly in putting empirical flesh on the theoretical skeleton could make such a model interesting for policy applications in the future.

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figure 1: The spatial lay-out

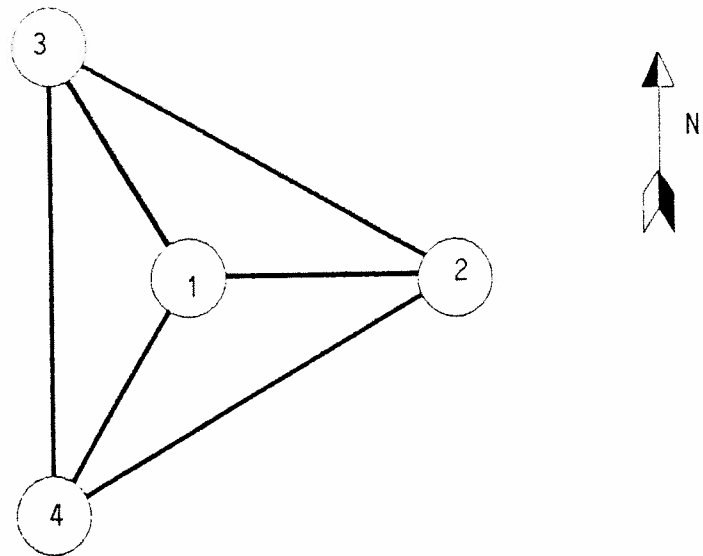


figure 2: Basic structure of the model

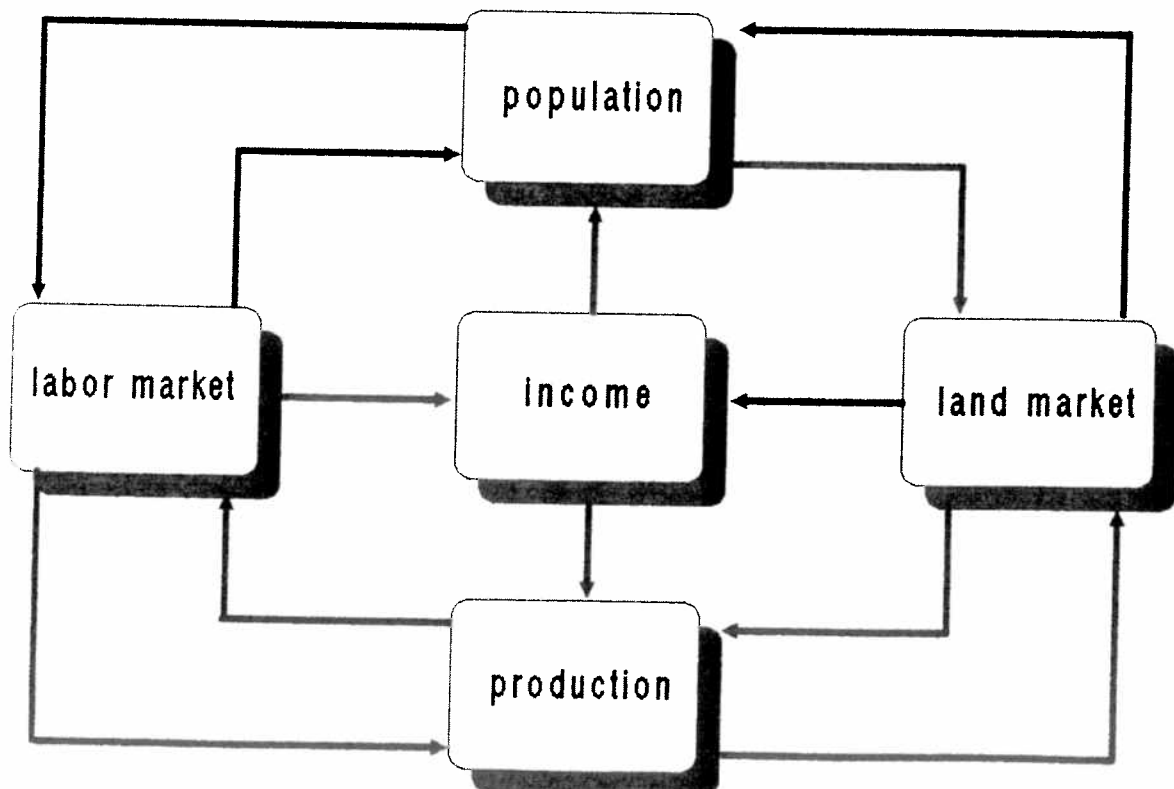
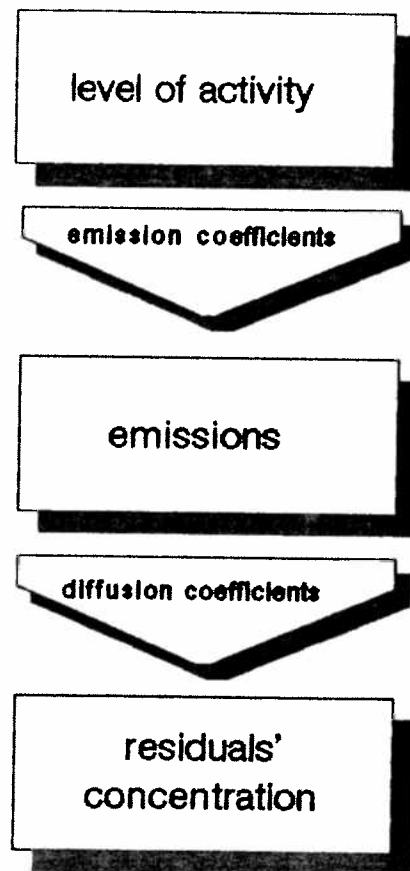


figure 3: Basic structure of pollution submodel



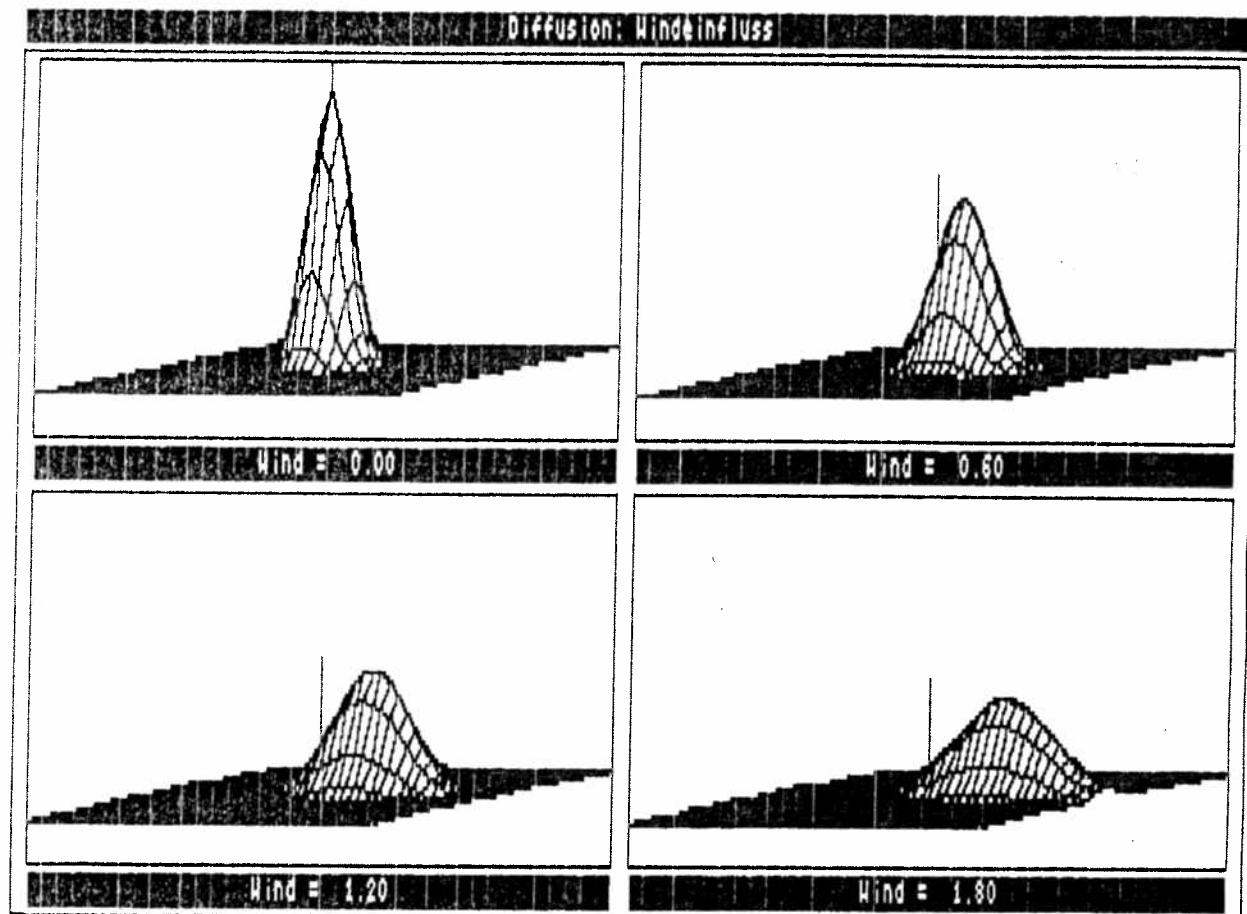


fig. 4: residuals' concentration with different wind speeds

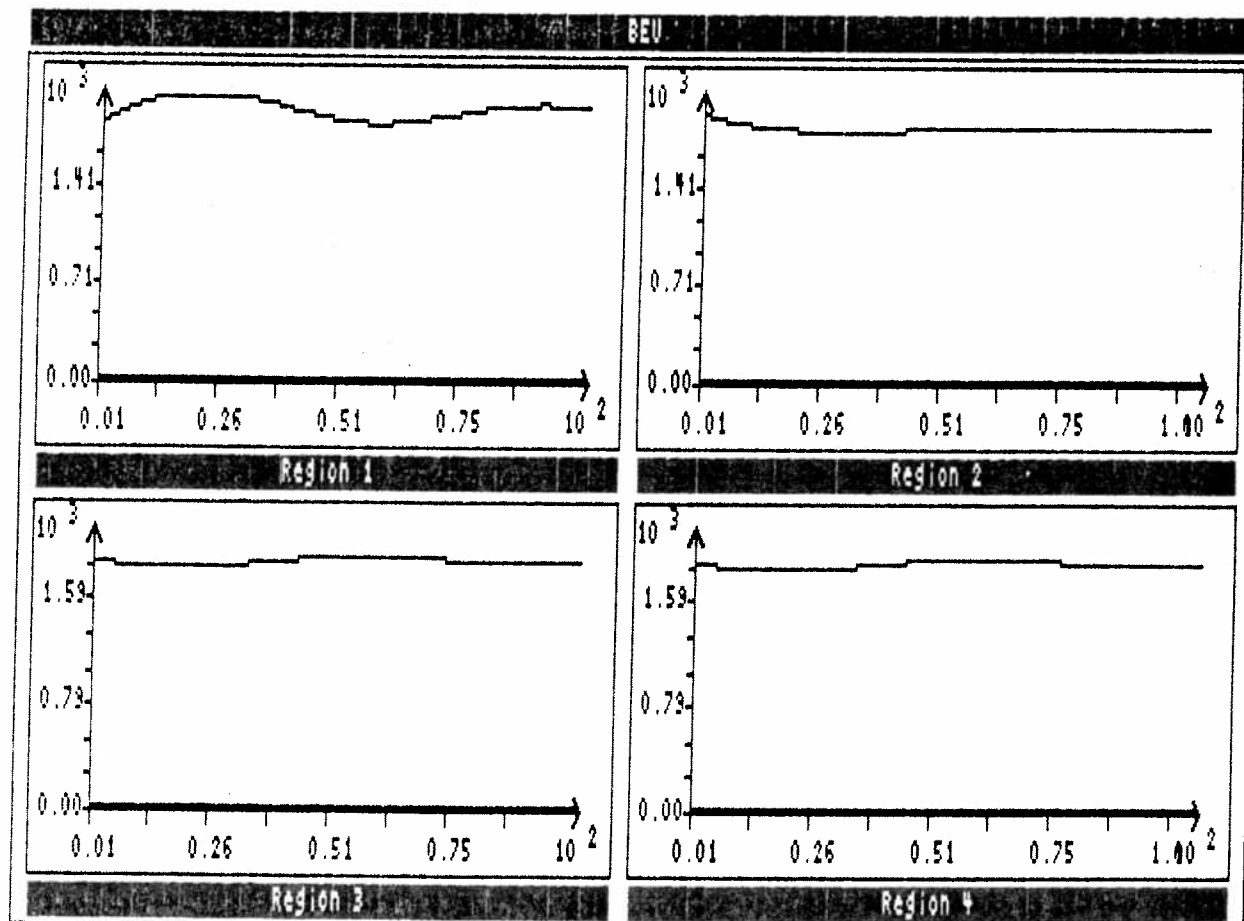


fig. 5: Basic Variant - Population

fig.6: Basic Variant - Land Prices

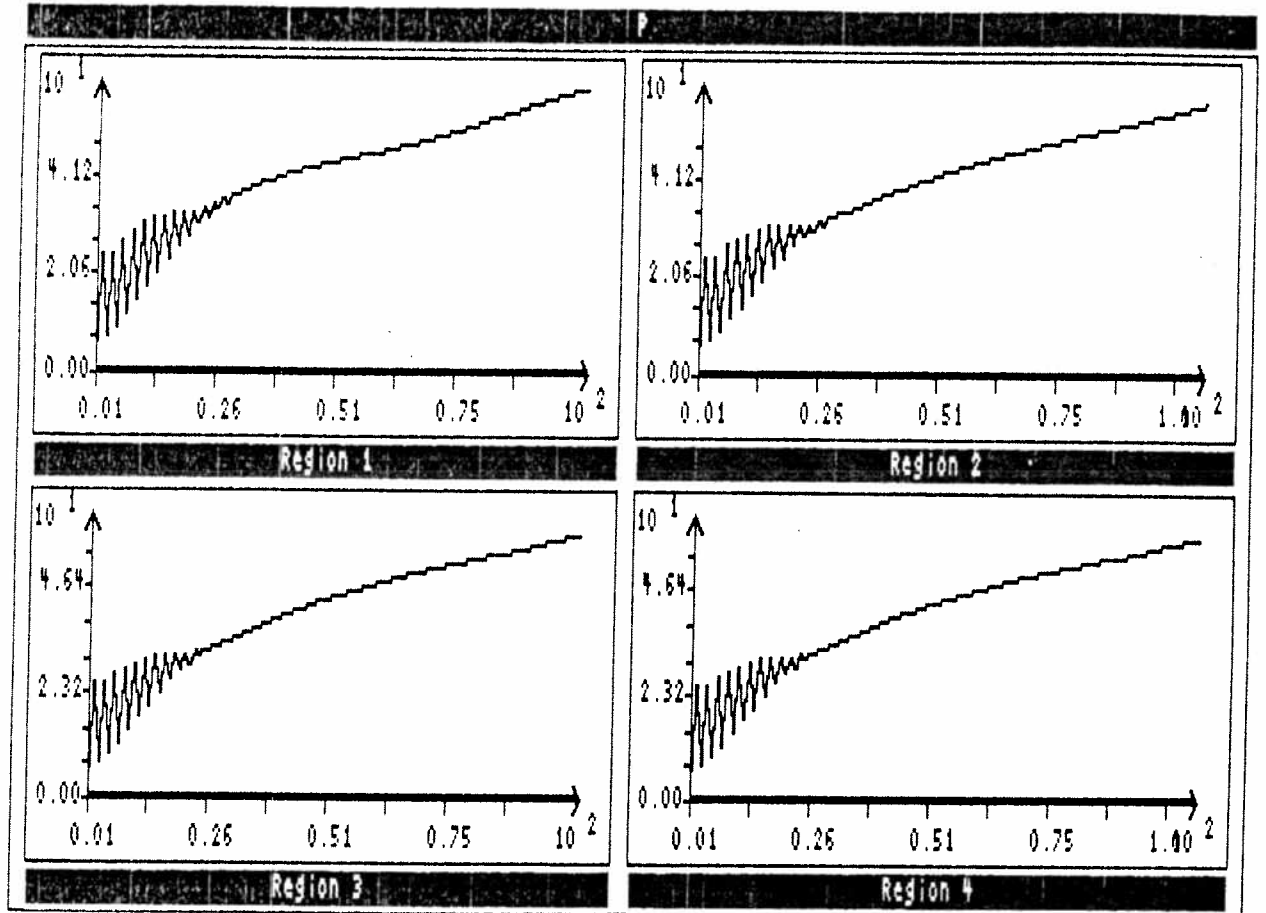


fig.7: Environmental Feedback - Population

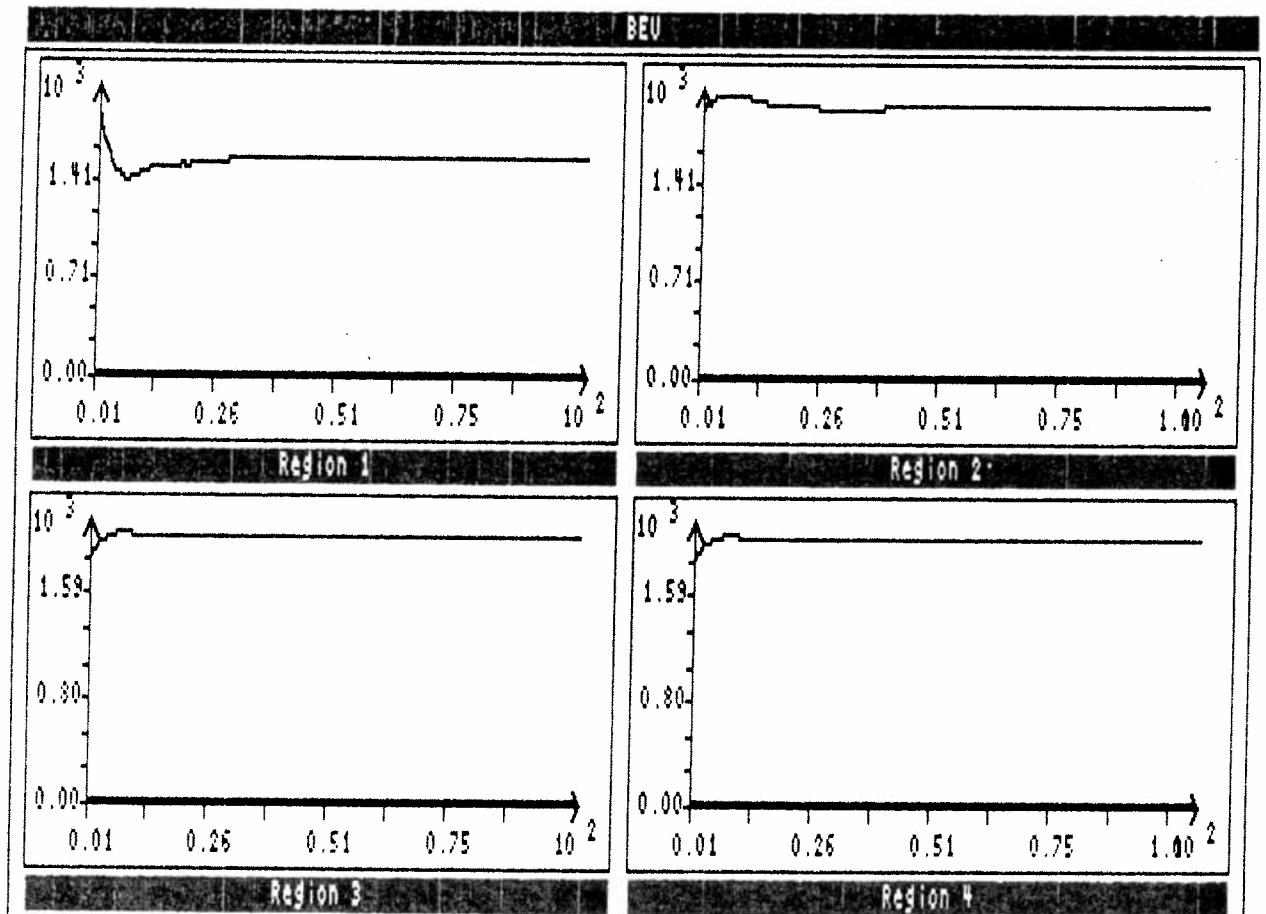


fig.8: Environmental Feedback - Production

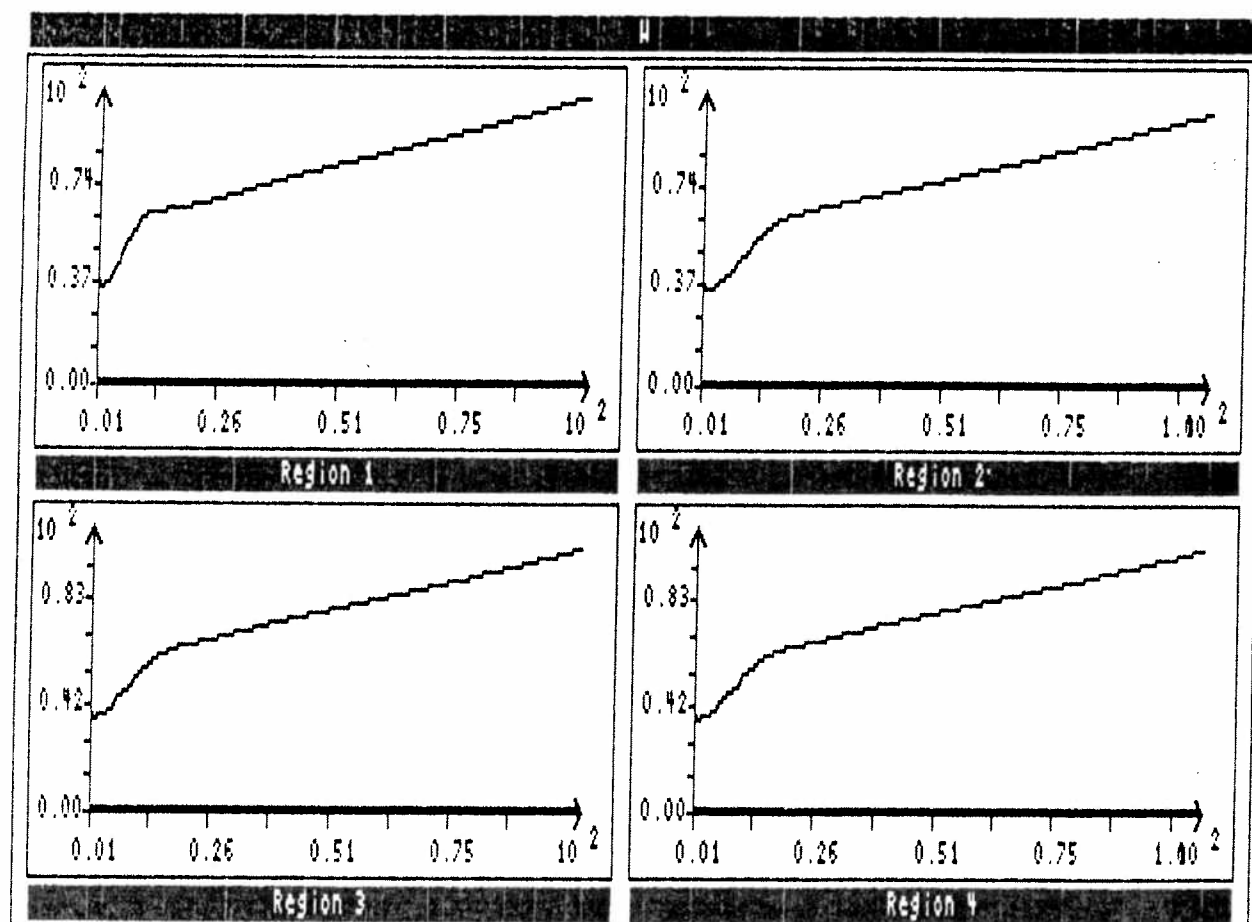
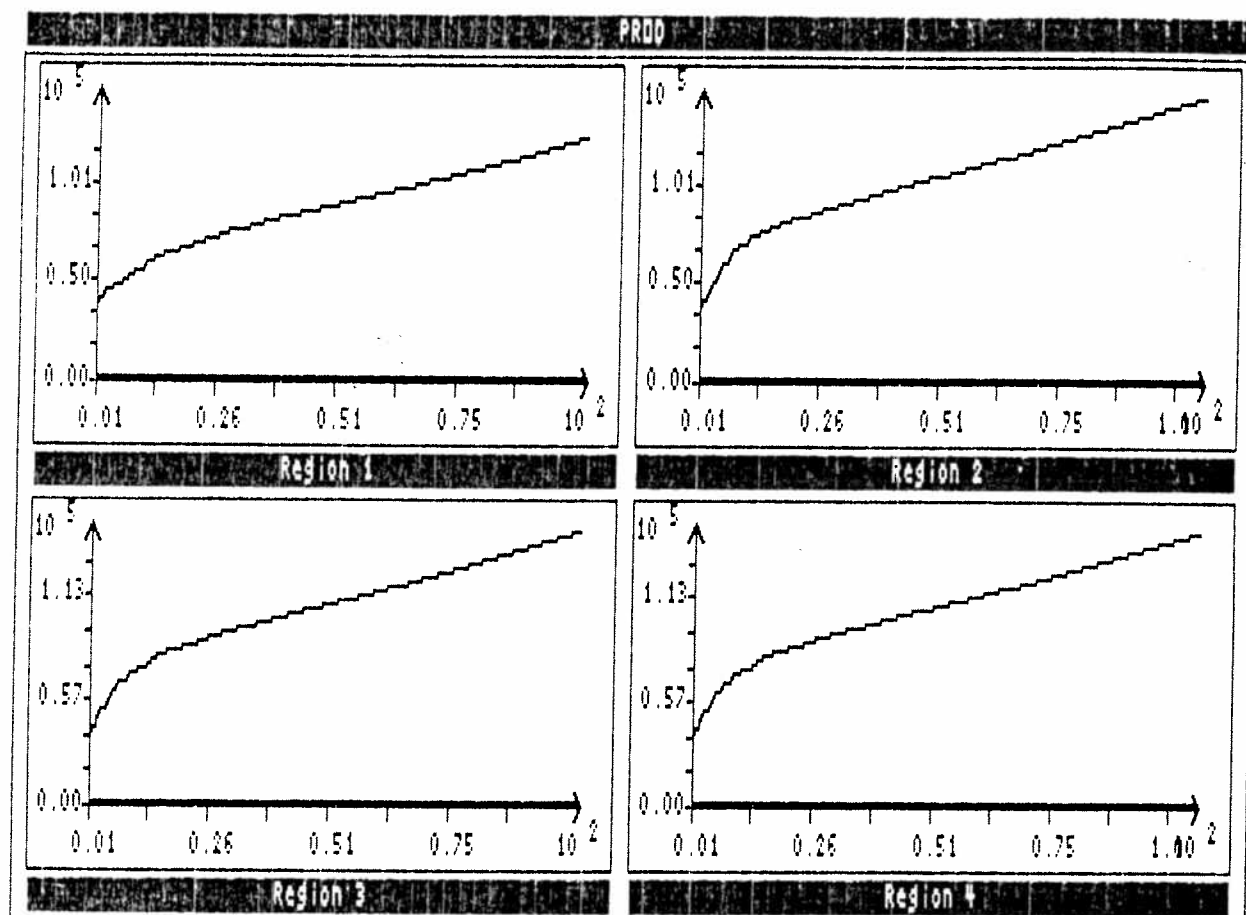


fig.10: Environmental Feedback - Residuals' Concentration

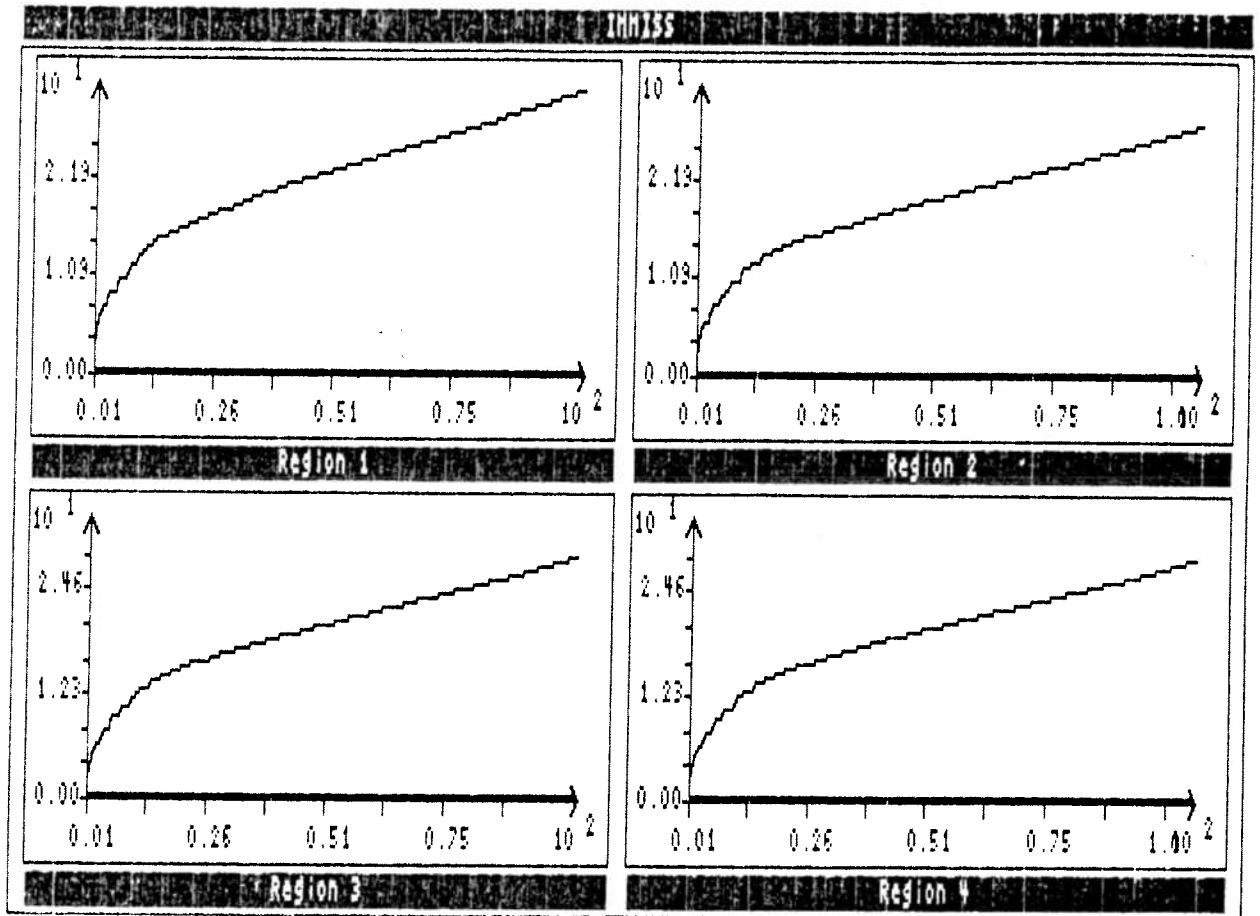


fig.11: Predominant Wind Direction - Residuals' Concentration

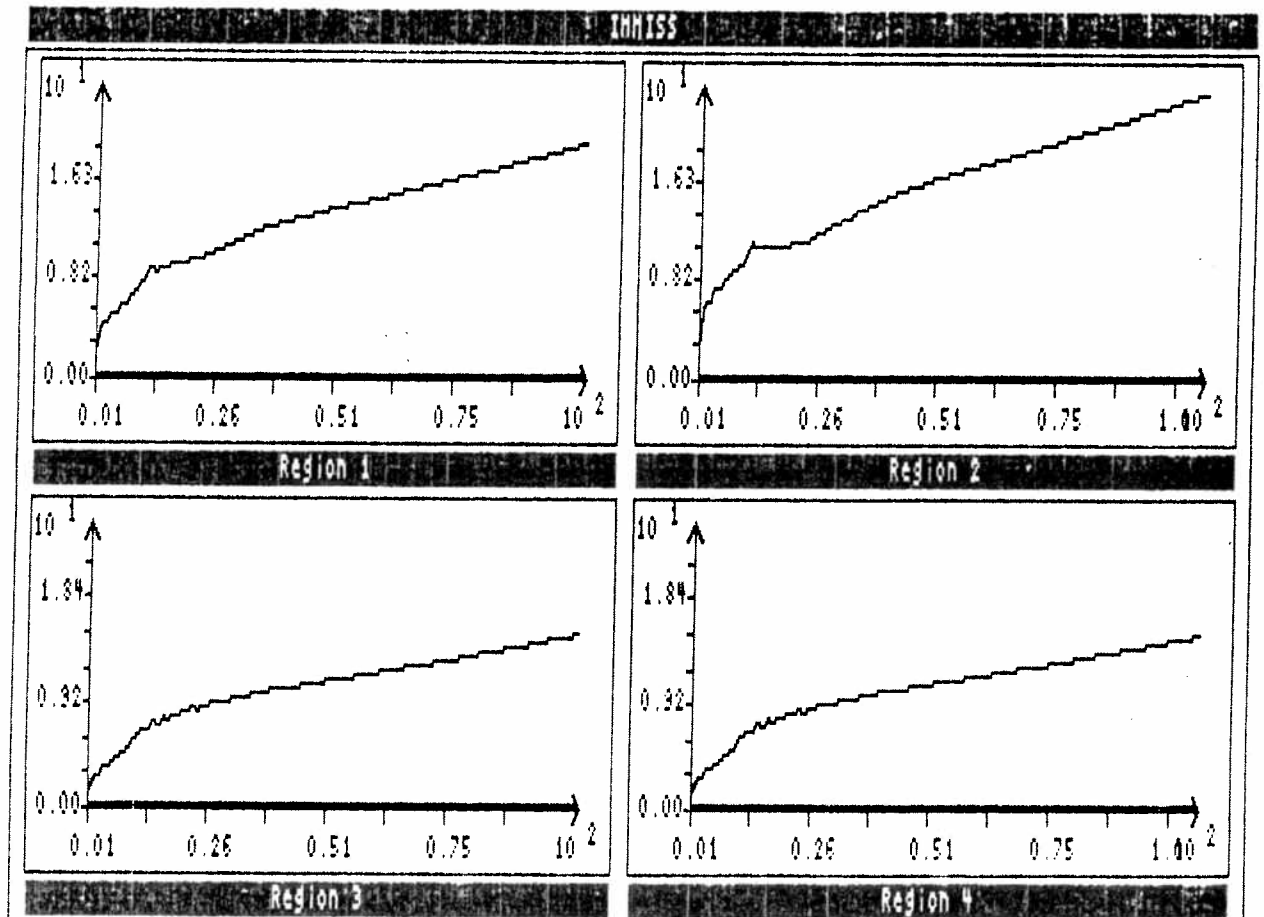


fig.12: Predominant Wind Direction - Population

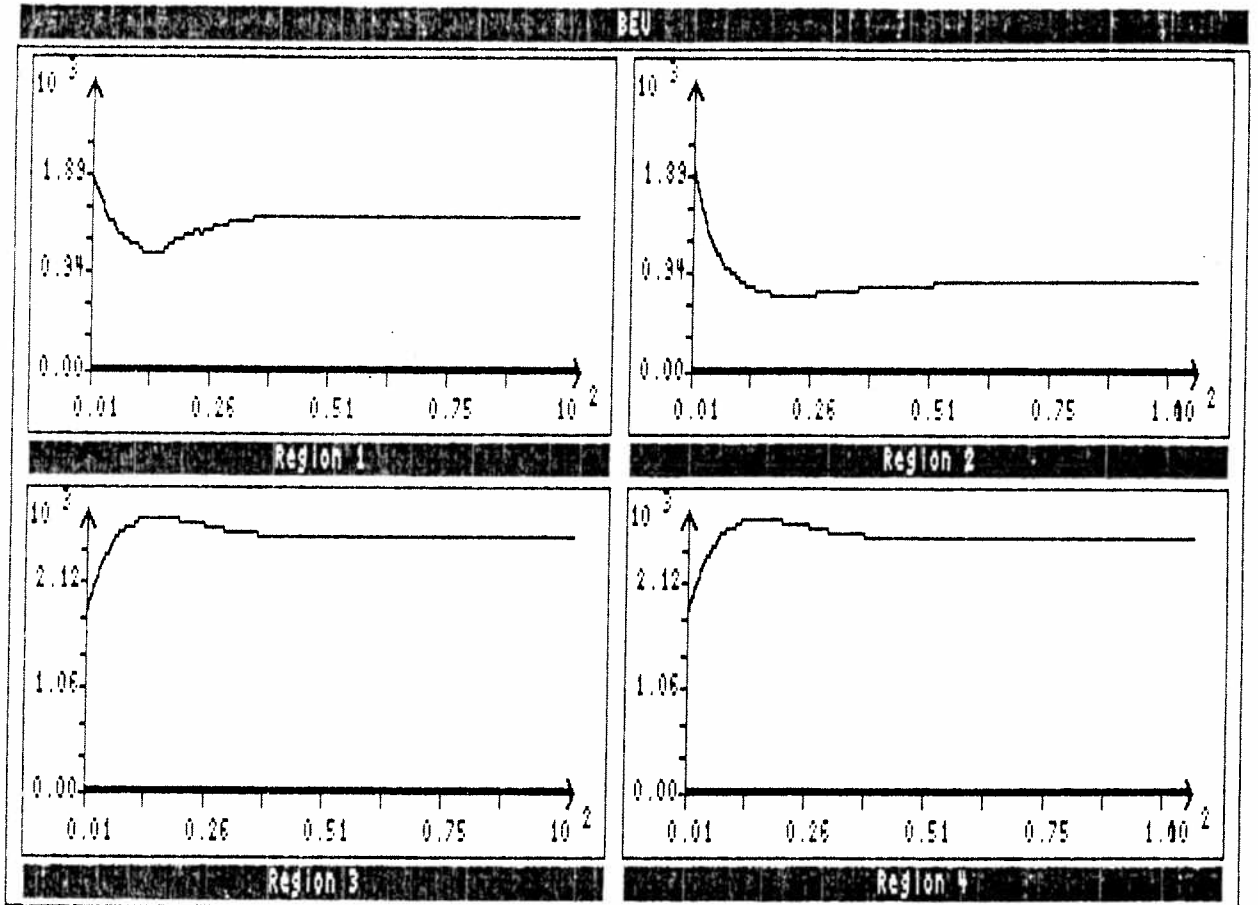


fig.13: Predominant Wind Direction - Land Prices

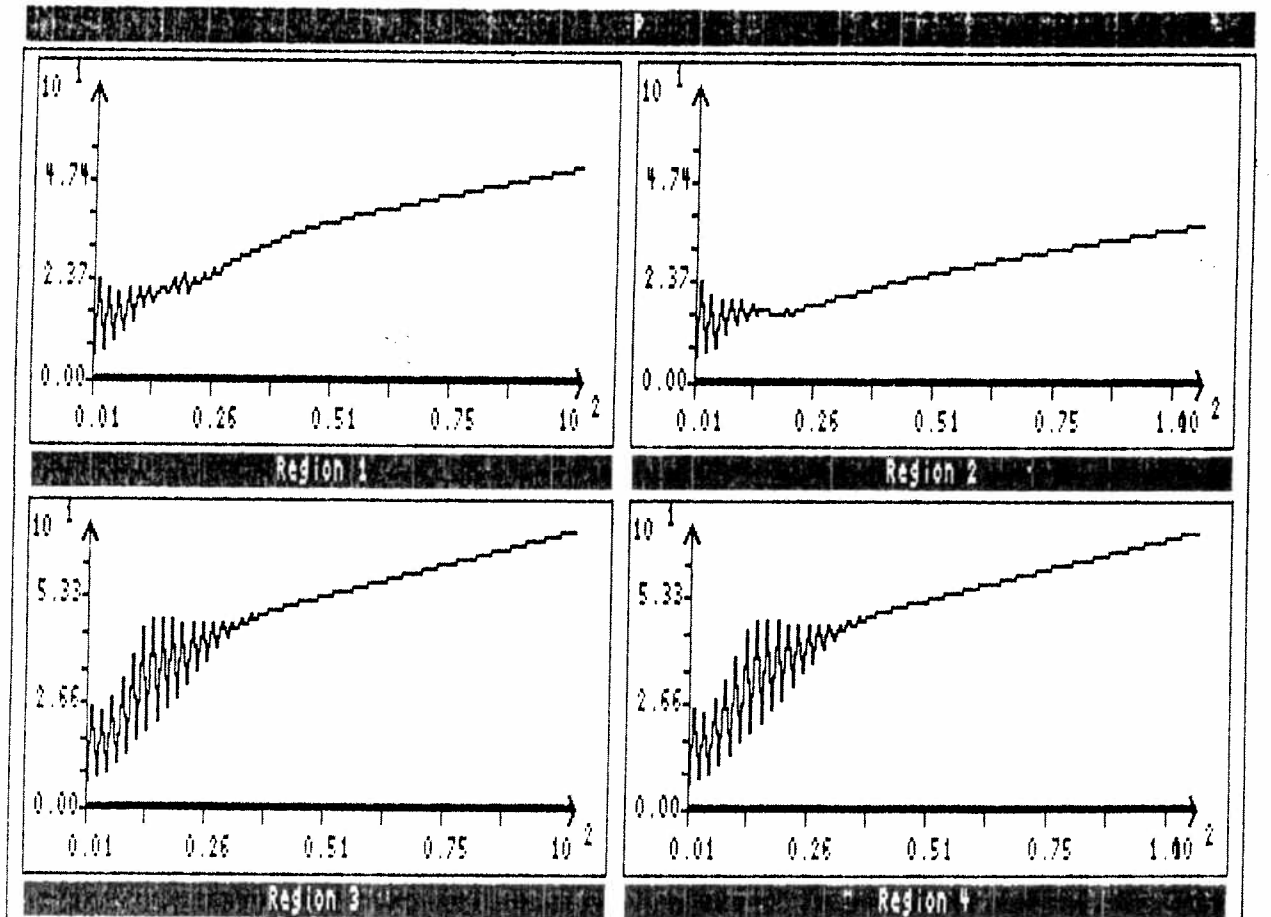


fig.14: "Production Control" - Production

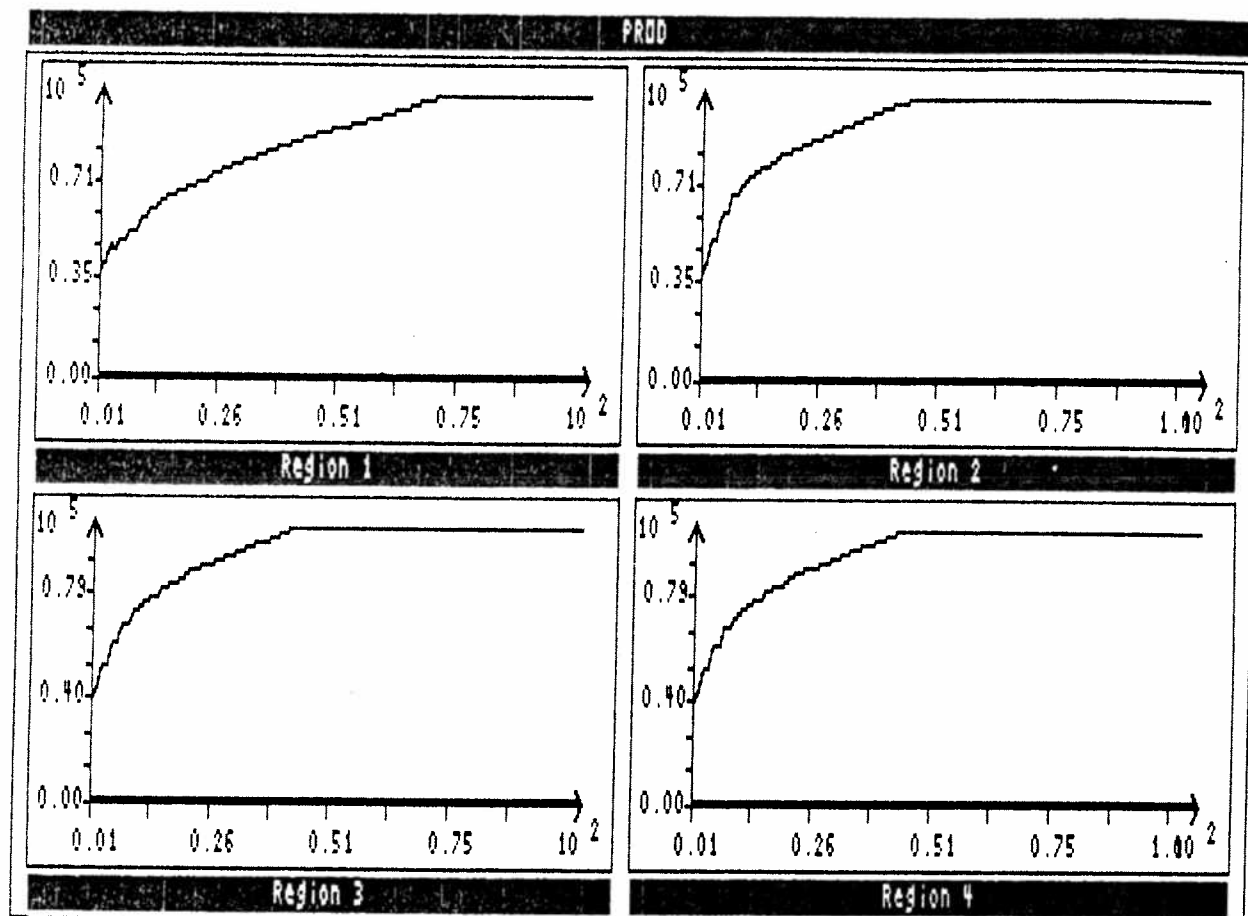
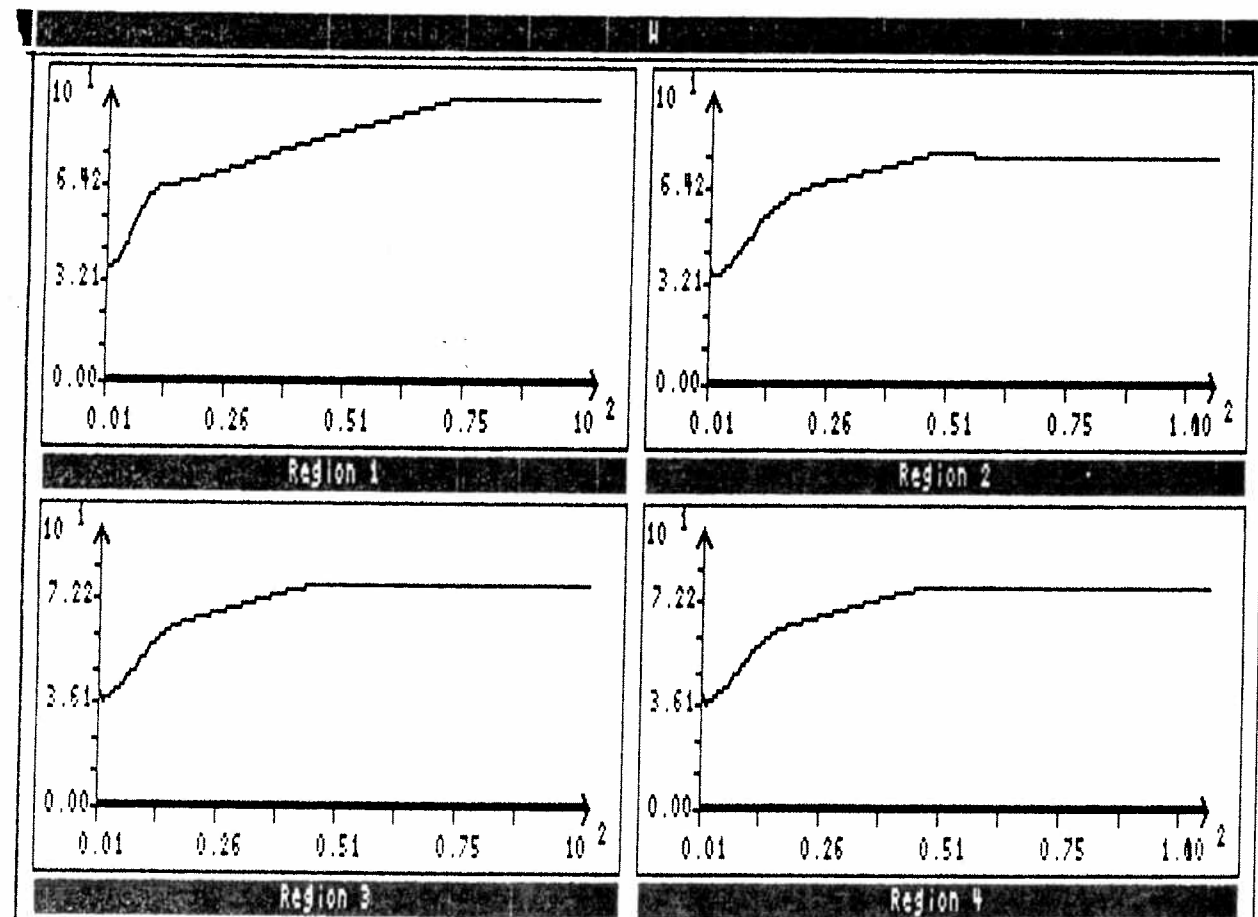


fig.15: "Production Control" - Wages



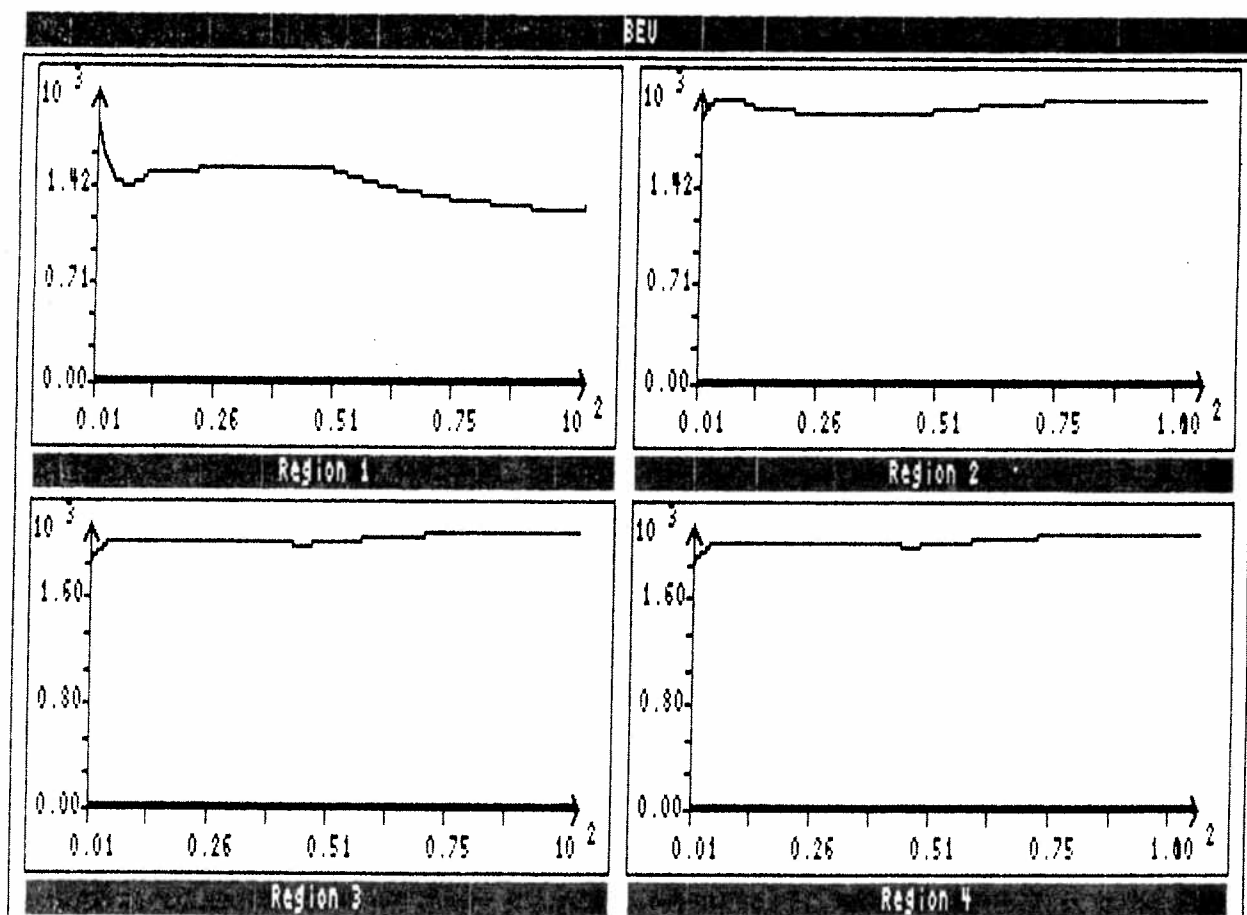
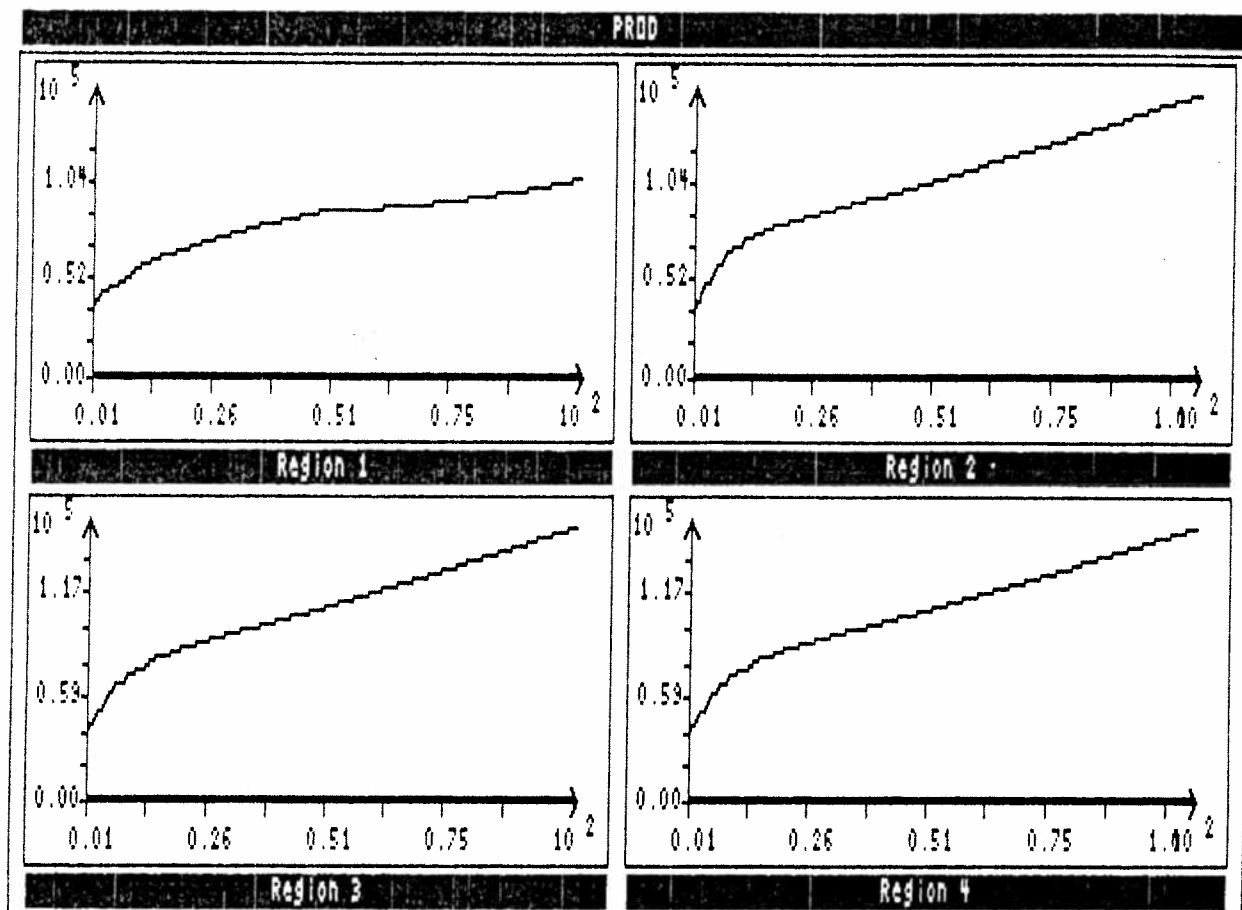


fig.17: "Restructuring of Production" - Population

Appendix 1: The Basic Model

$$Pop_i^t = Pop_i^{t-1} + Im_i^t - Em_i^t \quad (A.1)$$

$$M_{ij}^t = U_{j|i}^t Pop_i^{t-1} \quad (A.2)$$

$$\sum_j M_{ij}^t = Em_i^t \quad \text{und} \quad \sum_j M_{ij}^t = Im_j^t \quad (A.3)$$

$$p_{j|i}^t = \exp(U_{j|i}^t) / \sum_{j'} \exp(U_{j'|i}^t) \quad (A.4)$$

$$U_{j|i}^t = (u_1 + u_2) * \ln(YC_j^{t-1}) - u_2 * \ln(P_j^{t-1}) + u_3 * \ln(INFRA_j^{t-1}) - u_4 * DIST_{ij} \quad (A.5)$$

$$AHH_i^t = (Pop_i^t * YC_i^{t-1} / P_i^{t-1}) * u_2 / (u_2 + u_1) \quad (A.6)$$

$$LS_j^t = \sum_i r_{j|i}^t * \pi_i^t * \Omega_i^t * Pop_i^t \quad (A.7)$$

$$\pi_i^t = 1 / (1 + \exp(-a_1 * EW_i^t)) \quad (A.8)$$

$$EY_i^t = (1/a_1) * \ln(1 + \exp(a_1 * EW_i^t)) \quad (A.9)$$

$$r_{j|i}^t = \exp(a_2 * V_{j|i}^t) / \sum_{j'} \exp(a_2 * V_{j'|i}^t) \quad (A.10)$$

$$EW_i^t = (1/a) * \ln \left(\sum_{j=1}^J \exp(a * V_{j|i}^t) \right) \quad (A.11)$$

$$V_{j|i}^t = (W_j^{t-1} - d * DIST_{ij}^{t-1}) * (1 - ALR_j^{t-1}) + (ALR_j^{t-1} * UB) + \ln(LS_j^{t-1}) \quad (A.12)$$

$$PROD_i^t = S * (E_i^t)^\alpha * (AUN_i^t)^\beta * \exp(gt) - (p_1 * HF_i^t + p_2 * AC_i^t) \quad (A.13)$$

$$LD_i^t = (1-m) * LD_i^{t-1} + HF_i^t \quad (A.14)$$

$$AUN_i^t = AUN_i^{t-1} + AC_i^t \quad (A.15)$$

$$HF_i^t = -b_1 * (W_i^{t-1} - MPL_i^{t-1}) + b_2 * (YPOT_i^{t-1} - YPOT_i^{t-2}) \quad (A.16)$$

$$AC_i^t = -c_1 * (P_i^{t-1} - MPA_i^{t-1}) + c_2 * (YPOT_i^{t-1} - YPOT_i^{t-2}) \quad (A.17)$$

$$E_i^t = - \left\{ LS_i^{t-1} + LD_i^t - \sqrt{[(LS_i^{t-1} - LD_i^t)^2 + c * (LS_i^{t-1} + LD_i^t)^2]} \right\} \quad (A.18)$$

$$AL_i^t = LS_i^t - E_i^t \quad (A.19)$$

$$OS_i^t = LD_i^t - E_i^t \quad (A.20)$$

$$ALR_i^t = AL_i^t / LS_i^t \quad (A.21)$$

$$W_i^t = r * MPL_i^{t-1} * \exp(w_i^t * (LD_i^t - LS_i^t) / E_i^t) + (1-r) * W_i^{t-1} \quad (A.22)$$

$$AD_i^t = AHH_i^t + AUN_i^t \quad (A.23)$$

$$P_i^t = p_0 + p_1 * \exp(p_2 * (AD_i^t - AS_i^t)) \quad (A.24)$$

$$INFRA_i^t = (1-i_1) * INFRA_i^{t-1} + INVEST_i^t \quad (A.25)$$

$$INVEST_i^t = i_2 + i_3 * (Pop_i^{t-1} - Pop_i^{t-2}) \quad INVEST_i^t \geq 0 \quad (A.26)$$

$$Y_i^t = AD_i^t * P_i^t + \sum_j (r_{j|i}^t * \Omega_i^t * \pi_i^t * Pop_i^t) *$$

$$(ALR_j^t * UB_j^t + (1-ALR_j^t) * (W_{j-1}^t - d * DIST_{ij}^t)) \quad (A.27)$$

$$YPOT_i^t = \sum_j Y_j^t * f(DIST_{ij}^t) \quad (A.28)$$

$$YC_i^t = AD_i^{t-1} * P_i^{t-1} / Pop_i^{t-1} + FV_i^t \quad (A.29)$$

Pop population
 Im, Ew .. immigrants and outmigrants
 μ probability for migration from i to j
 YC expected maximum per capita income
 P land price
 INFRA ... stock of infrastructure
 INVEST .. infrastructure investment
 DIST distance
 AHH amount of land used for residential purpose
 LS labor supply at place of work
 π participation rate
 EY expected maximum income from work
 τ commuting rate from i to j
 AL number of unemployed
 OS number of vacancies
 ALR unemployment rate
 W wage rate
 EW expected maximum income from participation
 UB unemployment benefits
 PROD gross production (NUP) (20)
 E employment
 AUN amount of land used for productive purpose
 LD labor demand
 MPL marginal product of labor ($\alpha \cdot \text{PROD}/E$)
 MPL marginal product of land ($\beta \cdot \text{PROD}/AUN$)
 Y regional gross income
 YPOT income potential
 HF "hiring and firing" of firms
 AC change in area used for productive purpose

 t time index
 i,j,j' .. region indexes

 m replacement rate for labor demand
 i -i , u -u , p -p , a -a , b -b , d , w , c -c ,
 1 3 1 4 0 2 1 2 1 2 1 1 1 2
 S, g, α , β , τ , Ω , c positive parameters

Appendix 2: The Parameters of the basic model

COMMUTING
 $d_1 = 3.0$

POPULATION
 $u_1 = 0.8$
 $u_2 = 0.2$
 $u_3 = 0.42$
 $u_4 = 0.3$

LABOR SUPPLY
 $\Omega = 0.8$
 $a_1 = 0.005$
 $a_2 = 1.0$

LABOR DEMAND
 $m = 0.0$
 $b_1 = 5.0$
 $b_2 = 0.001$

LABOR MARKET
 $c = 0.000112$
 $w_1 = 0.55$
 $\tau = 0.3$

INFRASTRUCTURE
 $i_1 = 0.05$
 $i_2 = 5.0$
 $i_3 = 0.14$

PRODUCTION FUNCTION
 $S = 100$
 $g = 0.005$
 $\alpha = 0.7$
 $\beta = 0.3$

AREA DEMAND
 $c_1 = 0.47$
 $c_2 = 0.0005$

LAND MARKET
 $p_0 = 2.0$
 $p_1 = 20.0$
 $p_2 = 0.003$