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INTERREGIONAL COMMODITY FLOW MODELLING: COMPARATIVE ANALYSIS AND APPLICATION OF THE STRUCTURAL COEFFICIENTS METHOD AND GRAVITY MODEL

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Abstract

Spatial delivery of commodity flows, considered as materialization of spatial interactions is explained and modelled according to two spatial distribution methods: gravity modelling and the structural coefficients method. The concept of interaction, defined in many ways (economical, geographical, physical...) is presented in order to understand spatial interactions in transport economics. A description and an empirical application of the two methods are proposed and compared with advantages and inconvenients. The main and original contribution of the structural coefficients method is highlighted. It corresponds to the assessment of a sub-model of structural coefficients, explaining the "structural dimension" of spatialized flows. The comparison deals with the same subject, that is to say interregional commodity tons. A concrete use of this original method is carried out within a sequential model of spatialized freight simulation, yet in production.

INTRODUCTION

We search for the determining factors of interregional freight evolution. The particularity of our approach is to divide exchanges in two parts. The first one concerns goods production and the second one the spatial organisation of productive system.

Interregional flows are considered as materialization of spatial interactions. With the help of the structural coefficients method, we will more particularly analyse the evolution and the spatial structure of interactions. This is an original method in the modelling of spatial distribution.

We will develop a methodological and an empirical confrontation between two methods of spatial distribution : gravity modelling and the structural coefficients method.

This paper is also a mean to describe a new and quite unknown methodological tool opposed to a more traditional one whose several applications have already been presented.

SUBJECT AND RESEARCH FRAMEWORK

Freight spatial distribution analysis leads to concepts of spatial interaction and systemic dynamics.

Systemic definition of the spatial framework

The subject dealt with is spatial distribution of aggregate commodity flows between 21 French regions (Corsica is with Provence Alpes Côte d'Azur) within several years (from 1975 to 1994). We consider only inside (or national) flows. The hypothesis is that external (or foreign) flows do not take part in the development of structure, sectorial composition and intensity of spatial interactions.

Within this framework, the national economic space is considered as a system in which spatial interactions are executed. These interactions correspond to the dynamics of the system as B. Vermot Desroches (1994) said : *"l'interaction spatiale s'identifie le plus souvent à une notion de dynamique économique qui spécifie et caractérise l'interdépendance entre les régions"*.

Definitions of spatial interactions

Interaction is a complex notion (Park and Burgess, 1907), as it does not only concern exchange or collision, but also inside change of people or areas taking part in the interactions. Interaction is therefore a notion close to interdependence. As spatial economics is concerned, we have seen such changes in the socio-economic structures of towns or regions during their economic growth and their spatial interactions. In geography, goods exchanges are considered as interactions. Even interregional flows are the privileged indicator of interactions according to W. Isard (1972).

Spatial interactions are generally considered as human relationships, materialized by people, goods or information exchanges and as the dynamics of the geographic and economic system. The definition of interaction economically speaking is inspired by geographical and physical concepts (universal gravitation and thermodynamics). Economic space is identified as a gaseous system, regions being masses or densities and relations between them being spatial interactions. According to B. Vermot-Desroches (1994), interaction is an economic concept , which expresses link, exchange, even causality.

Thus, exchange arises from interaction, in different forms, be it freight or people travel, called « modality ». To know the modalities is important for choosing the analytical and modelling methods. Besides that, interaction is more precisely defined by phenomena (modalities) directly generated. An empirical approach leads to research explaining factors or « constraints » of the spatial distribution of modalities.

Two methods will be compared in this paper. The well-known « gravity model » and the less-known « structural coefficients method ». The problem is then to understand why one of the methods is more adapted than the other to solve a given problem.

GRAVITY MODEL AND THE SPATIAL INTERACTIONS LOGIC

Spatial interaction models have two major aims : explanation and prediction. Explanation deals with attributes of locations or regions that promote flows of people, goods or ideas among themselves. Explanation also deals with global spatial configuration of productive system.

There are two major families of spatial interaction models : maximising entropy and simple gravity models. The logic of maximising entropy models is more used to explain spatial configuration of a system and less to simulate spatial flows with explaining factors. So, we will limit our analysis on interaction models relating to simple gravity logic.

Definition of gravity model

Gravity model is an economic application of Newton's universal gravitation law and of spatial interactions in geography. The formalisation is an analogy of Newton's law, related to gravitational force.

$$Tij = k * \frac{M_i * M_j}{d_{ij}^a} \quad (1)$$

Some differences exist therefore between gravitational law and gravity model in economy and geography. In spatial economy, there isn't, or seldom, mutual attraction between two masses. The specification of the distance function may also be different : exponential or power form. And the parameter also varies : it may be transport time or generalised cost.

Advantages and drawbacks

The traditional gravity model is included in statistical approach. Thus it has its advantages and drawbacks. The main advantage is the flexibility of introducing new explaining variables and the availability of goodness-of-fit measures (Flowerdew, 1991). In contrast, it has some drawbacks. It's a descriptive and not an explaining method. It suffers from the lack of theoretical basis, which the pragmatic way of spatial interaction models tries to give by integrating entropy concept or tools from the utility theory. Maximising entropy models have brought mathematical basis, which reduced the analogy with gravitational model.

Application on interregional freight

Gravity model expresses the role of the economic and geographic space, thanks to indicators of geographic distance and areas size, according to the following general formulation:

$$T_{ij} = \frac{T_i * T_j}{f(d_{ij})} \qquad (2)$$

The resolution of this model is produced in accordance with Stewart's method, thanks to a multiple regression. The regression coefficients are the exponents of masses and distance. We test the two usual specifications of the distance function:

Power: $$T_{ij} = k * \frac{T_{i.}^{\alpha} * T_{.j}^{\gamma}}{d_{ij}^{\beta}} \qquad (3)$$ Exponential: $$T_{ij} = k * \frac{T_{i.}^{\alpha} * T_{.j}^{\gamma}}{\exp^{\beta * d_{ij}}} \qquad (4)$$

Modalities used are emitted and received tons and « real » interregional distances. The indicator of distance is calculated according to the ratio between tons-kilometers and tons. We have carried out fittings for several years and results were roughly the same whatever the year.

- with a power specification of the function of distance, we obtain for 1994:

$$T_{ij} = 12.10^{-5} * \frac{T_{i.}^{1,0621} * T_{.j}^{0,899}}{d_{ij}^{1,379}} \qquad (5)$$

In this case, 78% of the variance of interregional flows are determined by tons emitted and received annually by regions and by the friction of space. Geographic distance is the most explaining factor according to its exponent superior to 1. The Student's test is also the best for this variable.

- with an exponential specification, we obtain :

$$T_{ij} = 1{,}13.10^{-8} * \frac{T_{i.}^{1,072} * T_{.j}^{0,907}}{\exp^{0,0033 * d_{ij}}} \qquad (6)$$

With this specification, the variance is explained by 71%. It is difficult to choose between the two specifications. The power specification favours small distances. This methodological point could explain why results are better with power specification since small distances are numerous. We notice therefore that it is difficult to highlight the own impact of each factor. In return, this point is characteristic of the method of structural coefficients, that we are going to present.

A NEW APPROACH OF SPATIAL DISTRIBUTION : THE STRUCTURAL COEFFICIENTS METHOD

In the structural coefficients method, a structural dimension of flows assesses spatial interactions. This dimension is expressed by structural coefficients. The method comprises an under-model of structural coefficients assessment. This one gives an assessment of the difference between flows in the observed situation and flows in a theoretical situation of independence between areas of exchanges.

Definition

Structural coefficient is a ratio between tons exchanged in the « real »situation and those whi could be potentially carried out in a theoretical situation of independence between areas and withc space friction.

$$CS_{ij} = \frac{T_{ij}}{\dfrac{T_{i.} \times T_{.j}}{T_{..}}} \quad (7)$$

Csij : structural coef. bet. the origin region *i* and the destination region *j*
Tij : exchanges « really » carried out between regions *i* and *j*.
Ti. : tons emitted by region *i* towards all others French regions
T.j : tons received by region *j* from all others
T.. : total interregional tons

The denominator is theoretical tonnage. It is equal to the product of flows generated by the t regions of exchanges divided by total interregional tonnage. So, only transportation data are used determine structural coefficient and the spatial structure of freight.

The meaning of structural coefficient is very simple. If it is superior to 1, real exchanged tons a higher than tons in theoretical situation. The exchange link is then named « privileged ». In contra if it is inferior to 1, the link is said to be « disadvantaged ». Privileged links are considered dynamic in the sense that tons are more important than they would be if any exogenous spatial economic factor had brought one's influence.

Methodological contributions and drawbacks

(1) This method divides freight spatial distribution in two parts. The first one concerns goc production or economic growth and the other the spatial organisation of the productive system.

(2) The mode of calculation has the particularity of using only transport data or explained variables a not exogenous or explaining variables. This point differs from gravity model which uses exogenc variables in its formalisation. The resort to a unique family of variables (transport data) makes tl method easily usable.

(3) The under-model of structural coefficients expresses a spatial structure of interregional freig Structural coefficients are confronted with socio-economic and spatial factors. Econometric relatic are used to explain the level of these coefficients and their evolution and, like this, the spat structure of goods exchanges.

(4) A detailed descriptive analysis is allowed with this method. Structural coefficients lead to spat structure of freight and thus strong trade relationships between regions. The expression of spatializ freight with structural coefficients highlights a structuring of the economic space.

(5) During the last twenty years (1975-1994), structural coefficients have developed in a particular w which can easily be modelled.

(6) Like gravity model, the structural coefficients method is flexible. New explaining variables c easily be added. Econometric relations used can be relatively simple like multiple regression. T contribution of the new variable is measured by the variation of residual variance. An effecti contribution corresponds to a diminution in the residual variance.

(7) Thanks to the method of calculation, it is possible to compare all structural coefficients. This meth has statistical foundations which deal with assessment of strengths in an theoretical independen situation.

Therefore, this method comprises some drawbacks :

(1) Structural coefficients depend on the quality and the availability only of transport statistics. If thc are not reliable or exhaustive in all areas, it may be difficult to use this method.

(2) This method includes the same drawbacks as other statistical methods using ordinary least squai regression.

(3) This method has the further disadvantage of a great number of causes giving high or low coefficients. In reference to the formalisation, the level of different coefficients for the same origin area may come from two points :

- The importance of freight annually generated by the other area ($T.j$),
- The importance of the crossed exchange, Tij.

Some socio-economic variables intervene in the level of generated or exchanged freight. Economic regional weights and economic structure, that is specificity or specialisation, may intervene in the coefficient level. Sectorial structure of freight may also have an impact as a result of the unit weight of agricultural or industrial goods. However, it may be sometimes difficult to separate the influence of the national economic dynamics relative to an area of operations, in which some regions are more specialised, from the influence of the only regional economic dynamics. Further to this last point, a detailed descriptive analysis of goods exchanges turns out to be essential in order to highlight some spatial or socio-economic factors which could explain spatial structure of exchanged freight and its evolution in the long term.

Descriptive analysis and spatial structure fittings

The main point of the descriptive analysis was to represent all structural coefficients on a graph in order to obtain a global vision of the structural dimension of exchanges. Structural coefficients have been represented for example with an indicator of interregional geographic distance (functional distance, or transport time, can also be used and results were approximately the same).

Static analysis

For all exchange links (between the 21 French regions), the distribution of structural coefficients gives a scatterplot drawn out with the extension of the interregional distance (Figure 1). Two trends can be identified in this distribution : a vertical direction with high coefficients on short distances and a horizontal direction with low coefficients on medium and long distances.

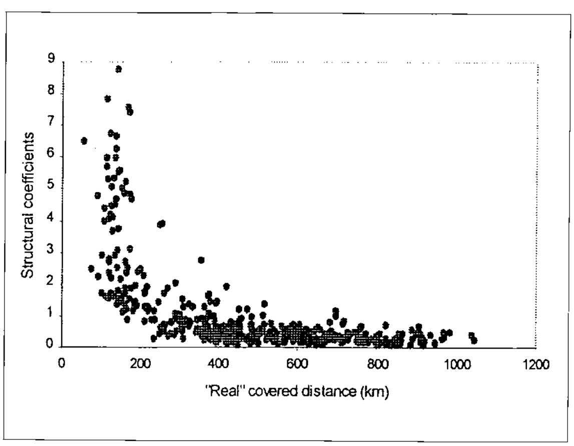


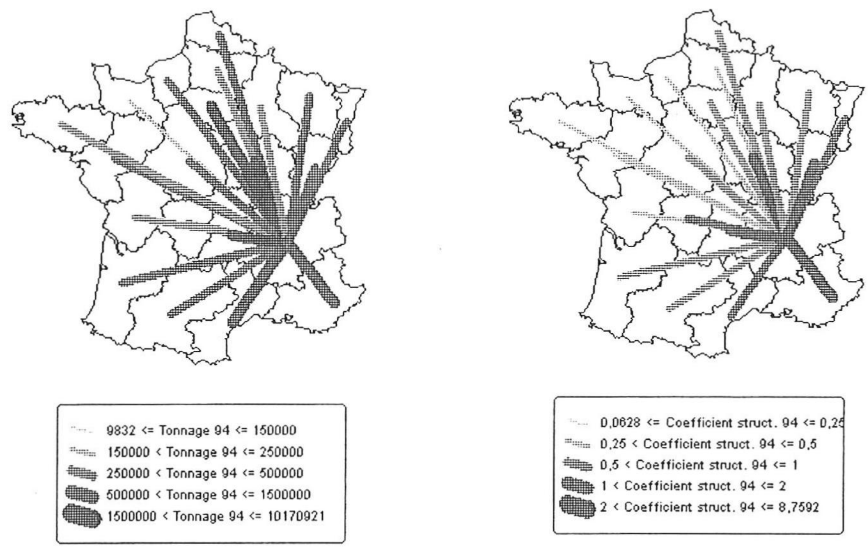
Figure 1. Structural coefficients with distance (1994)

This analysis has been deepened for each exporting (versus importing) region. Then two units of flow are used for this analysis : tons and structural coefficients. The result of the representation of structural coefficients with distance is interesting. Whatever origin (versus destination) region we may consider, we obtain a similar spatial distribution of freight towards (versus from) all other regions. Thanks to a cartographic representation, this distribution gives a hierarchy of exported (versus imported) freight, represented by concentric places around the regional « centroïde », that is the main economic and demographic town (Figure 2). We can almost draw contour lines or « iso-lines » like « isodistance » or « isochrones ».

In other terms, for each exporting (versus importing) region, privileged trading links (that is with high coefficient) are particularly stronger since the region of destination (versus origin) is nearby. On the contrary, the further destination (versus origin) regions are, the lowest coefficients are. Finally, if regions are too far, coefficients are under 1 and links become disadvantaged.

Dynamic analysis

During the last two decades, this spatial structure has been common to all regions and approximately the same whatever the year.



Lines express exported tons on the left or structural coefficients on the right. The thicker and the darker lines are, the higher tons or coefficients are.

Figure 2. Spatial structure of regional exportations from Rhône-Alpes (1994)

Heterogeneity of space emerges from the maps through the intensity of tons or structural coefficients. The expression with coefficients highlights privileged and disadvantaged links. Systematically, privileged links concern nearby or bordering regions.

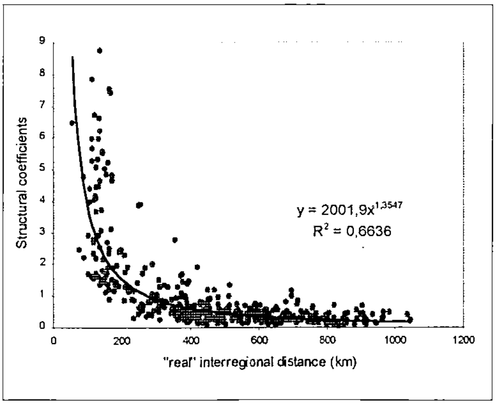
The first lesson is distance and adjacency parameters may have a significant impact on the spatial structure of interregional freight. However, some other factors may interfere as economic or demographic weight as shown in the link with the region of Ile de France (the most densely populated region and with the higher G.D.P. in France).

Fitting of the assessment model of structural coefficients

Two exogenous variables have been firstly tested, geographic distance and adjacency, as it was suggested in the descriptive analysis. We have introduced the distance factor before the adjacency factor. Fits have been tested for many years between 1975 to 1994 and results have been roughly the same whatever the year.

Explaining power of the factor distance

The two specifications for distance function, power or exponential, have been tested. For 1994, the power function gives a correct goodness-of-fit, which explains 66% of the variation around the mean.



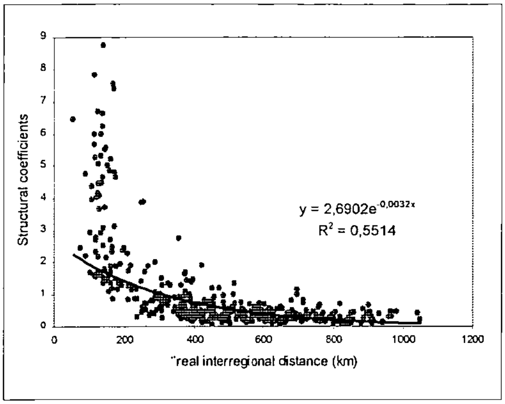


Figure 3. Fittings with power and exponential functions of distance (1994)

With a power function, the model equation has an important coefficient of spatial friction (higher than 1) which expresses the significant role of distance. This model does not fit perfectly the distribution especially higher coefficients, whereas power specification advantages short distances. So, it would be possible to improve this fit by introducing one or several new exogenous variables.

With an exponential function, goodness-of-fit is not satisfactory (R^2 = 0,55), but some lessons emerge from this fit. First, long distance is an important factor which slows down exchanges. Secondly, spatial proximity does not explain the highest levels of structural coefficients. The main consequence is that spatial proximity is not predominant to explain high levels of interregional goods exchanges. Then social or economic factors may favourably influence exchanges, particularly between neighbouring regions.

Adjacency impact

The regional adjacency is expressed by a dummy variable. This variable takes the 0 value when regions are not bordering and the 1 value when they are. Its introduction in the model improves the fit. The explained variance increases and the value of Rsquare is 0,70 with the power specification and 0,69 with the exponential one. Two important points can be noticed:

- The part of the explained variance is roughly the same with the two specifications of distance, whereas it was very different before introducing adjacency variable.
- Residuals have a particular scatterplot which shows the existence of two explaining logics of the structural coefficients level, and perhaps two different explaining models.

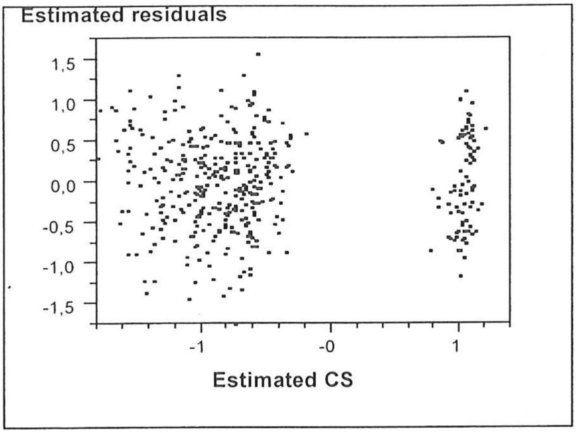


Figure 4. Residuals scatterplot with exponential function (1994)

Two opposite phenomena emerge as shown in the descriptive analysis (Figure 1). On the one hand, short distance exchanges (< 300 km) have a strong variability in the values of structural coefficients that distance factor does not explain but some economic or social variables could. On the other hand, longer distance exchanges have coefficients which are often inferior to 1. These low values explain themselves in a large part by the important spatial separation. Consequently, the structure of spatial interactions could be explained by two distinct models.

Fitting of the structural coefficients' development

Over the period 1975-1994, most structural coefficients did not undergo a significant development. We note a relative temporal invariability of the level of structural coefficients for many exchange links.

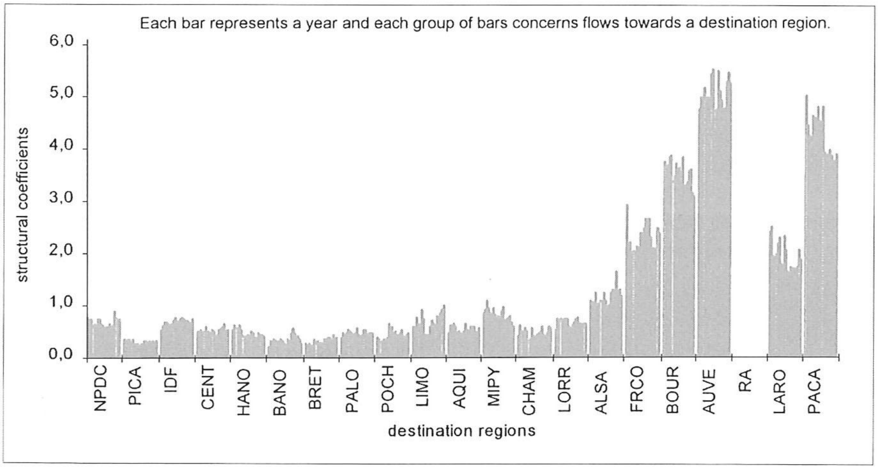


Figure 5. Spatial structure development of interregional freight from region Rhône-Alpes (1975-1994)

Therefore, some interactions have undergone changes during this period. This point expresses that some developments in interregional freight could arise from changes in spatial structure and not only from conjectural economic fluctuations. These inflexions remain in the minority but often concern privileged links (Figure 5). These changes may express a slow change in the spatial organisation of economic activities. Then, these observations confirm the importance of a detailed descriptive analysis, particularly on sectorial structure of freight and on regional economic structures.

The validation method of a temporal constancy hypothesis is to assess the structural coefficient of the year *n* by the one of the year *n-1*. For this purpose we have used an autoregressive model with the following form:

$$Y_t = b_0 Y_{t-1} + v_t . \qquad (8)$$

In order to have a positive test, the value of the regression coefficient, b_0, must be near 1. In the case of structural coefficients, the test is positive. The hypothesis of temporal constancy is accepted. This test has been carried out for several years and results are satisfactory. In particular, coefficients for 1994 were explained by those of 1993 with an Rsquare of 0,97 and a regression coefficient of 0,98. There are however some random errors and some changes for a few coefficients.

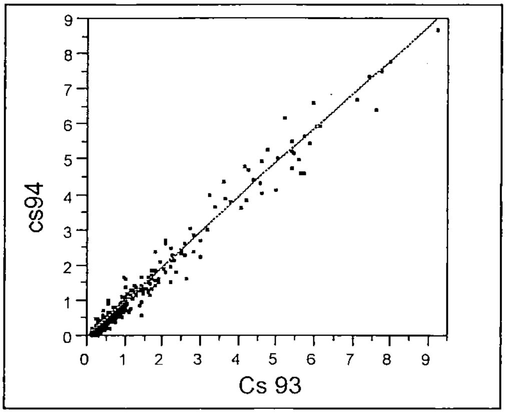


Figure 6. Temporal constancy test - 1993 and 1994 -

CHOICE OF SPATIAL DISTRIBUTION METHOD

With the two empirical experiments, we have seen that results converge. In addition, with the two methods, geographic distance is the determining factor of the spatial structure of interregional freight.

Therefore, its explaining part varies with the specification of the distance function and with the method adopted. Moreover, with the gravity method, the explaining part of each factor remains blurred because it is difficult to determine exactly these parts since they are considered simultaneously. In contrast, it is easier with the structural coefficients method to separate the part of each factor by calculating the improvement of the explaining variance as soon as a new variable is introduced.

In addition, the structural coefficients method presents a serious methodological advantage of dividing spatial interactions in two dimensions, the one which comes under the structural dimension of freight and the other one which comes under the conjectural one. We only exposed the structural dimension in this paper, owing to the problematic of spatial interaction. Finally, this method allows to highlight and classify variables and their impacts between order or sensitivity variables with respectively conjectural and structural impacts. Order variables in national development or in economic growth, which acts on goods exchanges of each region, are then more precisely determined regardless of spatial structure of exchanges.

We think consequently that choice criteria between the two methods are methodological. It is not a problem of choice in a predictive logic but more in a descriptive and explaining logic. Then, we have chosen the structural coefficients method to explain and simulate the spatial structure of freight in our freight transportation model of simulation yet in production.

CONCLUSION

The structural coefficients method may be integrated in a simulation model of transportation. It fills the function of a spatial distribution model. The sequential model then contains two phases: the generation of total regional importations and exportations and the spatial distribution between origin and destination regions. According to the adopted methodological logic, interregional tons are assessed thanks to the structural coefficients method by the following formula:

$$\hat{T}_{ij} = CS_{ij} * T_{i.} * T_{.j} / T_{..} \qquad (9)$$

Simple or multiple linear regressions are used for the generation phase and fits are carried out according to annual growth rates. The method is to take into account variable elasticities of tons with industrial growth or with other explaining variables. These elasticities express the phenomenon that tons amplify industrial or economic fluctuations (Latreille, 1997). They are taken into account with linear fits.

Spatial distribution is carried out according to the structural coefficients method. At a given date, distribution is explained partly by interregional distances and regional adjacency. The evolution on a long term depends on structural coefficients projection, thanks to the validation of temporal constancy hypothesis.

We try now to explain more precisely the levels and the evolution of structural coefficients. We intend to test the explaining contribution of the following factors: functional distance, interregional road infrastructure density, interregional accessibility, regional industrial specificities or specialisations and factors of spatial division of labour. The main problem is to build interregional indexes like absolute or relative differentials for accessibility and socio-economic factors.

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