

TRANSPORTATION NETWORKS AND THE OPTIMAL LOCATION OF HUMAN ACTIVITIES :

A NUMERICAL GEOGRAPHY APPROACH*

Isabelle THOMAS *Maître de recherches au F.N.R.S., Département de Géographie, Place Louis Pasteur, 3 B-1348-Louvain-la-Neuve Belgique.*

Email : isabelle@geog.ucl.ac.be

RÉSUMÉ. *Cet article vise à montrer l'importance de la forme du réseau de transport dans la localisation optimale des activités humaines. Plusieurs séries de simulations sont générées sur des réseaux théoriques de formes carrées et hexagonales. Des modèles courants de localisation-affectation sont appliqués (UFLP, k-médiane) sous différentes conditions. Les résultats obtenus sont testés sur des réseaux réels et des problèmes concrets d'aménagement du territoire (localisation de centres de santé dans une région où les pluies affectent l'accessibilité routière ; implantation de déchetteries à l'échelle communale). Plusieurs enseignements sont à tirer de ces simulations et exemples, particulièrement en termes de gestion de l'espace et aménagement du territoire.*

ABSTRACT. *This paper aims at testing the relationship between the shape of the transportation network and the optimal location of human activities. Several sets of simulations are performed on toy-networks designed on squared and hexagonal lattices of points. Often used location-allocation models are applied (UFLP, k-median) under several assumptions. The results are tested on real-world networks for land-use planning problems (optimal location of health care facilities in a region where road accessibility is affected by heavy rains ; optimal location of recycling centers at a local scale). They all lead to useful results of land-use planner.*

MOTS-CLÉS : *réseau de transport, modèles de localisation-affectation, aménagement du territoire.*

KEY WORDS: *transportation network ; location-allocation ; land-use planning.*

1. Background

The location of human activities is a fundamental problem in economic geography and one of the main concerns for the emerging new economic geography (see e.g. Krugman, 1991; Fujita, 1989). More particularly, optimal location theory generally deals with the problem of determining where to locate one or more facilities in order to serve a spatially distributed demand such that one (some) objective function(s) is (are) optimised under a set of constraints. This is obviously a very important family of problems with countless applications: location problems arise in many land-use design problems, be it location of facilities, plants, vehicles, people, services or any other systems. A comprehensive review of network facility location models can be found in e.g. Brandeau and Chiu, 1989, Mirchandani and Francis (1990), Chhajed, Francis and Lowe (1993), Daskin (1995), Drezner (1995), Jones e.a., 1995 or Labbé, Peeters and Thisse 1995. A review of examples of applications can be found in Hodgson, Rosing and Shmulevitz (1993), Eiselt (1992) or Laurent and Thomas (1999).

Transportation infrastructure is considered as one of the main instruments of the toolbox of spatial planners (see e.g. Haggett and Chorley, 1972; Taaffe, Gauthier and O'Kelly, 1996). Many decision-makers interested in the role of transportation infrastructure take it for granted that more infrastructure is always better than less because it would lead to less congestion and/or to a higher accessibility to existing facilities. Optimal location problems often take place within a given transportation system which is often represented by a network/graph with nodes (e.g. population centres) and edges connecting pairs of nodes (e.g. roads). In this context, transportation depends upon the characteristics of the nodes (demand for travel) and occurs along the edges; it is taken to connote the generalised costs of travel encountered by individuals in carrying out their activities or by firms in moving freight. By generalised costs, we mean some combination of monetary outlays, time length and/or quality of travel between specific locations. This way of considering transportation explicitly regards travel as generating negative effects for the trip-maker. These prices are primarily a function of the supply of transportation infrastructure and of the demand for travel; this latter is, in turn, derived from the demand of individuals and firms for spatially distributed activities (e.g. employment, commercial outlets or residential locations) which generate and attract trips. Generically, these activities are referred to as land use activities.

In fact, the relationships between the provision of transport infrastructure and the level and distribution of human activities is complex and can be addressed from different perspectives. First, one may wonder what is the link between the provision of infrastructure and the rate of economic growth? Second, one may also ask what is the influence of a transport infrastructure on the attractiveness of a given area in which the infrastructure is built up? We'll focus on a third question: what is the impact (if any) of the shape of the transport infrastructure on the geographical distribution of activities? This facet of the problem has not been much studied. The overwhelming majority of contributions disregard the impact of (re)shaping the transport system on the locational pattern of human activities. Either space is modeled as being one-dimensional, or the shape of the network is given. Both approaches do not permit to assess the impact of the network shape. In order to gain more insights about the impact of transportation policy on the spatial pattern of facilities, we here consider different types of toy-networks and study how the number and the locations of facilities are affected by the difference in the transport system.

The particular distribution and level of intensity of land use activities are the key factors that delineate the spatial organisation of regional and urban areas. The study of the interrelationships between land use and transportation has often been studied in urban and regional economics (see Berechman e.a., 1996). The literature often asserts that changes in the transportation system caused by – for instance – expansion of the road network will reduce travel costs. These effects, in turn, will encourage the dispersion of land use activities, and, hence, alter existing patterns of travel demand and thus costs. When transportation costs decline, what does this imply for urban patterns of spatial organisation, i.e. the compact city versus the suburbanisation and edge city developments? What does this new transport and communication systems imply in terms of systems of cities? Of regional development?

This research is devoted to one aspect of this problem: it analyses the link between the shape and size of the transportation network and the operational results of some optimal location models. More particularly we'll conduct sensitivity analyses of the facility location-allocation problem to the underlying network structure and answer the question: how far does the transportation system (existence of roads, cost associated to the edges) determine the optimal locations of human activities?

2. Simulations performed

The set of simulations performed in this research program can be divided into four parts:

First we'll first show that the description as well as the classification of networks is not an easy task. Our final objective being to evaluate the impact of network morphology on the location of human activities, it would be extremely useful if we could synthesise the morphology of a given graph by one or several indices; these indices should be conceptually descriptive, easily measurable and suitable at a variety of scales. Hence, we'll first try to associate to each graph/network one or several indices in order to describe the spatial organisation of the nodes and links (the shape of the network) and to cluster the networks in exclusive categories. What networks look alike and under which criteria? What networks are topologically identical? Hence, we first review and evaluate the existing literature about the description of the shape of the networks, and then suggest an original way of classifying networks.

Second we'll strictly concentrate on the link between the shape of the transportation network and the location-allocation results. Our objective is here to evaluate how far the morphology of the network influences the solutions of location-allocation problems. We limit ourselves to two optimal location models: the k -median and the U.F.L.P. We test the sensitivity of the solutions of the k -median model to the shape of the underlying communication network in the case of autarky. More precisely, the k -median problem is applied to different squared and hexagonal toy-networks representing various transportation networks. We then extend the preceding simulations to other toy-networks and to another location model: the Simple Plant Location Problem which optimizes the economies of scales and the transportation costs. Two types of economies are considered: the case of autarky and the case of two regions characterized by a different transportation network that forms a common market. In a last trial, we consider a common market made of two squared lattices of points; the design of the transportation networks is given and fixed in both regional economies. Here, we consider the permeability of the border between the two entities (number of links, location of the links) and also analyse the effect of a high-speed link between the centres of both economies.

Thirdly, many facility location models assume that customers select the facility they will patronise on the basis of the distance. Hence, measuring the length of the edges of a transportation network is a time consuming task that is of prime importance in most spatial analyses. Hence, when objects in space are represented by points, distance predicting functions may be used to transform the point co-ordinate differences into an estimate of the travel distance between them. In this part of the research, the transportation network is given; it is the weights associated to the edges that varies. We first use l_p -metrics and shows how far the k -median results are sensitive to changes in the l_p -distance parameters. In another set of simulations, we use economic measures of distance: we are here concerned with the financing of the transportation cost and also on how the firms exert a monopoly power over space. The results of the U.F.L.P. model are compared for different price policies. Using a price policy enables to take into account time, capital, work and the real cost of distance. Who supports these costs: the consumer or the firm? What are the consequences of such choices in optimal spatial organisation? Several price policies are used, showing the complex relations between geographical and economic distances. These two latter sets of simulations were concerned with the effects of the measure of distance on location results; it is quite clear from our everyday experience, however, that there are other costs associated with distance that are not directly borne by those generating them. Hence, in a last set of simulations performed on toy-networks the distance introduced in the optimal location model is not just a transportation distance but it is also a measure bound to the spread of a negative externality (pollution). Once again, it is shown how far the location-allocation results are sensitive to the addition of such measures.

The last part of this paper is devoted to two real-world applications illustrating and confirming the results of the simulations performed on toy-networks. We first consider the case of locating primary health care facilities in a district of Niger where travel is more difficult during the rainy season than during the dry season. We consider three types of transportation networks: the existing dry season network, the existing rainy season network and an enhanced rainy-season transportation network. We show that the location results and hence the planning decisions are sensitive to the measures of the transportation conditions. A second real-world illustration considers the location of a community recycling center within a Belgian residential commune (La Bruyère); it shows the sensitivity of the optimal location pattern to increasing levels of pollution.

3. Results

The results of the simulations can be summarised as follows :

Independently of the connectivity of the network, there is a strong relationship between the shape of the network and the optimal spatial organisation of activities, whatever the studied output of the model (locations, service areas, etc.), whatever the type of underlying lattice of points (square, hexagon), or whatever the location technique (k -median, U.F.L.P). More precisely, it has been shown that radial networks lead to more concentrated patterns of production, the centre exerting strong attractive forces. In contrast, a grid network leads to a more dispersed pattern with several locales accommodating facilities. Though such results belong to the folk wisdom of human geography, the many experiments give them more robustness. These results about the radial network were particularly strong, because the model did not include any capacity constraint and did not consider congestion. Land-use planners should be aware of this when planning facilities, as well as transportation networks.

Interesting enough, the first conclusion still holds in integrated economies. Hence, to the extent that the construction of transportation infrastructures can be regarded as irrevocable, networks are hostages of the past, and keep influence the decisions made in the new economic and/or political environment. This legacy is heavy: within the limits of the regional economy, a given spatial morphology of a network has about the same impact on the spatial organisation of activities in the case of autarky as in an integrated economy. Hence, even though the level of activity is likely to be affected by the integration of two economies, it is less obvious that the spatial organisation of human activities within each regional economy is to be drastically modified: the geographical organisation of economic and political activities might well remain approximately the same within each original territory. Accordingly, one must be careful before drawing clear-cut implications about the impact of economic integration on the spatial distribution of human activities.

Another interesting result relates to the role of the adjunction of a peripheral ring road on a given transportation network. Adding a peripheral link to a radial network modifies the shape of the transport network, but also generates important changes in the location results. The addition of a peripheral link reveals how the attractiveness of the centre may be weakened or reinforced, depending on the location of the ring road. The construction of a peripheral road around the centre of a radial network can boost a major deconcentration of human activities towards the nodes situated at the crossings between the radial roads and the ring road. If such a policy is to be implemented, the choice of the ring radius turns out to be a critical policy parameter: a too small radius leads to a circumradial network that does not depart enough from the original radial configuration to generate dispersion, while a very large radius yields nodes with too small hinterlands to become attractive. Clearly, even when the radius of the peripheral road is well chosen, it would be illusive to expect the outward pull discussed above to generate its effects in the short or medium run. The possible impact of such a policy on locations will become visible only in the (very) long run. These are only hypotheses, as no time component has been introduced in the models.

Merging two economies in a common market implies considering the way they are merged: the number of gates between the two economies, the location of those gates and/or the 'length' associated to them define the efficiency of the border. We showed that the characteristics of the border in an integrated economy is less interesting than expected: location results are little sensitive to changes in the permeability of the border expressed in number and location of the gates. The 'length' of the gate has the most important consequences on the location-allocation results; this puts forward the role played by tariffs and/or congestion at some border points in the previous and the present European regional contexts.

The building of a high-speed connection between two regional centres gives rise to some distinctive geographical features. Those can be summarised as follows: first, the high speed connection does affect the urban hierarchy, but not necessarily in a dramatic way. Second, the high speed connection wanes the lure of the gateway city between the constituent economies. Third, the high speed connection fosters some regional imbalance since one centre serves a growing market segment in the other region. Ultimately, one regional centre can become the only production centre for values of the fixed production costs which are not that high (compared to values of fixed costs obtained in the absence of high speed connection). The simulations have however revealed some structural instability of the locational pattern as the value of the fixed production costs rises relative to that of the transport costs. This seems to confirm the scepticism of some transportation analysts in that it appears to be hard to predict what the final impact of a real-world infrastructure will be.

Within the limits of the experiments, the performed simulations also show that all locations changes are generated by changes in the balance between transportation costs and polluting costs: small pollution does not modify the solutions of the location-allocation model; *high* extension/intensity of the pollution generates «competition» between facilities and modifies the reference locations. Facilities are located further apart from each other, and hence further from the consumers. *Very high* values of the intensity and/or the extension tend to push the optimal locations at the border of the studied environment. In other words, when the pollution is slight, accessibility of the supply sites remains the most important location criterion. When pollution gets more important, facilities tend to be located as far as possible from each other, tending to another spatial optimum.

Applied work should be aware of this when finding the best spatial solution: polluting is not always a source of optimality changes! We see that very large externalities annihilate transportation costs and lead to locations on the borders of the studied area.

Given the limits of this research program (some toy-networks, some location models, many simplifying assumptions, some values of the parameters), the conclusions derived from the models are suggestive rather than conclusive, and they need to be interpreted with caution in a policy context. However, the main results of this research suggest that major transport facilities are often considered as a favouring item in town and country planning. Yet, the decisions concerning large projects are most of the time taken on the basis of financial and sometimes political criteria (Klein, 1998). Arguments in terms of town and country planning are very rarely sufficiently reasonable to convince those scientists who usually work on the transport-space theme. At the same time, the reappraisal of the structuring effect concept (Offner, 1993) does not seem to give rise to any reaction or even any debate among the same scientists. The results suggested here should help the decision-makers to reappraise the spatial structuring role of the transportation infrastructure, especially in developing regions/countries.

Given the large number of questions and references already published on the relationship between the general provision in transportation infrastructure and land use or urban-regional development, we are far from asserting that every aspect in the domain has been covered and solved. We just hope that the outcome of this research (*i*) functions as a little stepping stone in the elaboration of a more general theory in economic geography and (*ii*) helps to better understand the sensitivity of the results of the location-allocation models to the measure of their inputs, and more particularly to the transportation costs and structure.

Note : (*) this set of simulations presented here are the results of a six years research program; it was presented in the form of a thesis (Thomas, 2000) and is accepted for publication (Thomas, 2001).

1.1.1. *References*

- BERECHMAN, J., KOHNO, H., BUTTON, K., & NIJKAMP, P. (1996) (Eds.). *Transport and Land Use*. Modern Classics in Regional Science: 2, Edward Elgar Publishing Company, Cheltenham.
- BRANDEAU, M. & CHIU, S. (1989). An Overview of Representative Problems in Location Research. *Management Science*, 35, 645-673.
- CHHAJED, D., FRANCIS, R. & LOWE, T. (1993). Contributions of Operations Research to Location Analysis. *Location Science*, 1, 263-287.
- DASKIN, M., (1995). *Network and Discrete Location, Models, Algorithms and Applications*. New York, Wiley Interscience.
- DREZNER, Z., ed., (1995) *Facility Location: A Survey of Applications and Methods*, Heidelberg, Springer Verlag, 571p.
- EISELT, H. (1992). Location Modelling in Practice. *American Journal of Mathematical and Management Sciences*, 12, 3-18.
- FUJITA, M. (1989). *Urban Economic Theory. Land Use and City Size*. Cambridge University Press.
- HAGGETT, P. & CHORLEY, R. (1972). *Network Analysis in Geography*. London, Edward Arnold, 348 p.
- HODGSON, J., ROSING, K. & SHMULEVITZ, F. (1993). A Review of Location-allocation Applications Literature. *Studies in Locational Analysis*, 5, 3-29.
- JONES, P., LOWE, T., MULLER, G., XU, N., YE, Y. & ZYDIK, J. (1995). Specially Structured Uncapacitated Facility Location Problems. *Operations Research*, 43, 661-679.
- KRUGMAN, P. (1991). Increasing Returns and Economic Geography. *Journal of Political Economy*, 99, 483-499.

LABBÉ, M., PEETERS, D. & THISSE, J.-F. (1995). 'Location on Networks', in: M. Ball, T. Magnanti, C. Monma and G. Nemhauser, eds. *Handbooks of Operations Research and Management Science: Networks*, Amsterdam, North-Holland, Vol. 8, 551-624.

LAURENT M.-L. & THOMAS I. (1999) Des places centrales à la localisation optimale. Revue d'Economie Régionale et Urbaine (accepté).

MIRCHANDANI, P. & FRANCIS, R. (eds) (1990). *Discrete Location Theory*. New York , Wiley.

TAAFFE, E. J., GAUTHIER, H. L. & O'KELLY, M.E. (1996). *Geography of Transportation*, Prentice Hall, Upper Saddle River.

THOMAS, I. (2000) *The shape of the transportation network and the optimal location of human activities. A numerical geography approach*. Louvain-la-Neuve, Thèse d'agrégation de l'Enseignement Supérieur, 320p.

THOMAS, I. (2001) *The shape of the transportation network and the optimal location of human activities. A numerical geography approach*. Edward Elgar Publishing Ltd. (accepted for publication).