[DM-02-015] Spatial Network Modeling

Abstract

Spatial network modeling has started with quantitative geography and its integration into GIS for analyzing transport and material flows. Concepts from graph theory were combined with spatio-temporal concepts to model spatial relationships. As GIS evolved, it established close links to transportation science and graph-based complexity models. Spatial networks thus provide a way to measure relationships between geo-located entities. Yet, though spatial networks are often modeled as spatially embedded graphs, the concepts involved are more specific: nodes can be locations or spatial objects with possibly changing locations, potentials or attractiveness scores, and edges can measure diverse quantified (extensive or intensive) relationships, such as distances, interactions, or flows. A primary example are transport networks. Here, key tasks include constructing distance networks based on road infrastructure, modeling potential interactions within defined distances, measuring accessibility by identifying proximity to services like schools, and measuring network centrality. Spatial networks also can be used to estimate flows between objects using gravity models, based on spatial interactions between the potential of origins and the attractiveness of destinations and their distance. Distances can thereby be modeled in various manners, including metric, topological or angular distances.

Keywords: network analysis, networks

Author & citation

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Explanation

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1. Introduction

In this article, we focus on spatial network models, which represent network phenomena embedded into geographic space in terms of locations, geo-located objects, and their quantified relations (Barthelemy, 2022). We shortly summarize the history of such models and explain some core analytical tasks for spatial network models. More general views on networks can be found in the complementary topics FC-04-19 (Networks) and CP-03-21 (social networks).

2. Spatial Network Modeling in the Course of Time

Geographers have recognized the importance of spatial networks for analysis since the introduction of quantitative methods in the latter half of the 20th century. Since then, spatial networks have been used as models for representing various geographic phenomena, including material flows, transport flows, as well as different kinds of measured relations between geographic objects and locations.

2.1 Networks in Quantitative and Physical Geography

One of the foundational works in this field is Peter Haggett's and Richard Chorley's book from 1969 (Haggett and Chorley, 1969), which provides a comprehensive overview of both passive networks, like drainage systems, and active transportation networks, such as roads. The key concepts for spatial networks introduced back then are:

- graphs: Their discussion included trees, circular graphs, as well as shortest path algorithms.
- flow and barrier networks: They differentiated between networks that facilitate movement (flow networks) and those that act as boundaries (barrier networks), such as the edges defining regions.
- channel order numbers: This involves analyzing the hierarchical arrangement, flow, and lengths within drainage networks.
- geometric network properties: They discussed the shapes, densities, and orientations of networks.
- distance and costs: They explored how distance affects flow and the efficiency or costs associated with networks.
- network optimization: Besides shortest path algorithms, they included methods for districting and regionalization—how to divide space into regions using networks.
- network evolution: They looked into how networks change over time.

2.2 Network Analysis and Accebility in Human Geography

Analysis based on distance between locations in space has been fundamental in human geography, planning and transport science, but was originally largely based on airline distance. Yet, it was quickly realized that valid transport distances need to be measured over spatial networks. In the 1970s and 1980s, with the advent of Geographic Information Systems (GIS), human geographers began to explore the concept of potential in geographic space (Rich, 1980). This idea ties into the concept of accessibility (Ingram, 1971), which combines distance with the potential of users at origins and and the utility of activities available at various destinations. Accessibility helps in assessing the potential interaction of people or goods between places (Masser and Brown, 1977; Curry, 1972).

Using transport network models for such kinds of accessibility analysis provided a clear improvement over airline distance, as human movement in space is largely confined to such networks avoiding obstacles. Graph theory provides methods like the shortest (or quickest or cheapest) path between two or more locations, and hence can be used to create distance tables between sets of origin and destination locations (OD matrices). According to Geertman and Ritsema van Eck (1995), key tasks for spatial network analysis in GIS include:

- Zoning: Measuring areas of maximal distance from an origin. This is the network equivalent to a spatial buffer.
- Districting: Dividing (allocating) space into tessellated areas based on the network proximity to a number of central places. This the network equivalent to spatial Thiessen polygons.
- Origin-Destination Matrices: measuring distance or flow from various starting places to

destinations.

In transport geography, Kansky (1963) developed graph-based spatial network indices as early as 1963, which can measure the efficiency, redundancy and connectivity of spatial network geometry, including the α, β, γ, η, θ index and the cyclomatic number, see also Ritsema van Eck (1993).

2.3 Transport GIS

During the 1990s, research shifted towards developing network data models that integrate transportation science into GIS databases. This field, known as GIS-T, focused on the best ways to incorporate data structures and algorithms for transportation research into GIS (Miller et al., 2001). During the 1990s, road network models were made available whose level of detail increased considerably with the world wide acceptance of GPS-based navigation systems. However, modeling transport networks also comes at a cost; information that goes beyond geometry, such as modes of transport, directionality, maximum speed, effective speed and turntables are required. The emphasis has since moved to creating formal models for efficient database design across different software environments, as well as efficient querying of network data, including graph databases and moving objects on networks (Guting et al., 2006).

2.4 Network Complexity, Statistics, Cognition, and Conceptualization

Some researchers have turned their attention to network complexity (Arlinghaus et al., 2002; Jiang and Claramunt, 2004) measures for spatial graphs, picking up method developments in graph theory and general network science (Barab´asi, 2016). While this approach abstracts away from the traditional concepts of network analysis in geography, it provides valuable insights into the structural properties of spatial graphs, including graph centrality and inter-connectivity measures, like betweenness and page rank centrality. Atsuyuki Okabe pioneered methods to extend spatial statistical techniques to networks (Okabe and Sugihara, 2012). As an application of such an approach to explain spatial processes, city network theory (Batty, 2013) posits that cities function as interconnected systems of nodes and links, where spatial and social interactions drive urban dynamics. When the concept of centrality is combined with urban geometric complexity, we arrive at valuable models of perceived urban distance, as proposed by space syntax research (Hillier et al., 1976). Researchers have also examined transport network models from the perspective of environmental cognition, focusing on how people navigate and perceive their surroundings. This includes studies on wayfinding activities and the concept of affordances, which refers to the opportunities for action that the environment provides (Winter, 2002). A broader, interdisciplinary approach to understanding networks was presented in the context of core concepts of spatial information. In this view, networks figure as one essential concept required to interpret the environment (Kuhn, 2012). Spatial and geographic network models are regarded as more specific than implied by the general models for graphs or matrices, see also Neal et al. (2023).

3. A Conceptual View on Spatial Networks

What kind of concept is represented by a spatial network model? One way of understanding spatial networks is in terms of spatial measurements (Sinton, 1978), i.e., in terms of controls and measures, an approach that goes back to Chrisman (2002). In this view (Scheider and de Jong, 2022), a spatial network can be regarded as a measured relation between different kinds of entities that are controlled and localized in space (Figure 1). A matrix is considered a network that has a control pair for every combination of entities; in this case we focus on the context of origin-destination (OD) matrices. For example, a distance matrix between cities uses all possible pairs of objects as controls and measures distances between them. This is the reason why networks can be represented as graphs, where controls become nodes and relationships become edges and their labels.

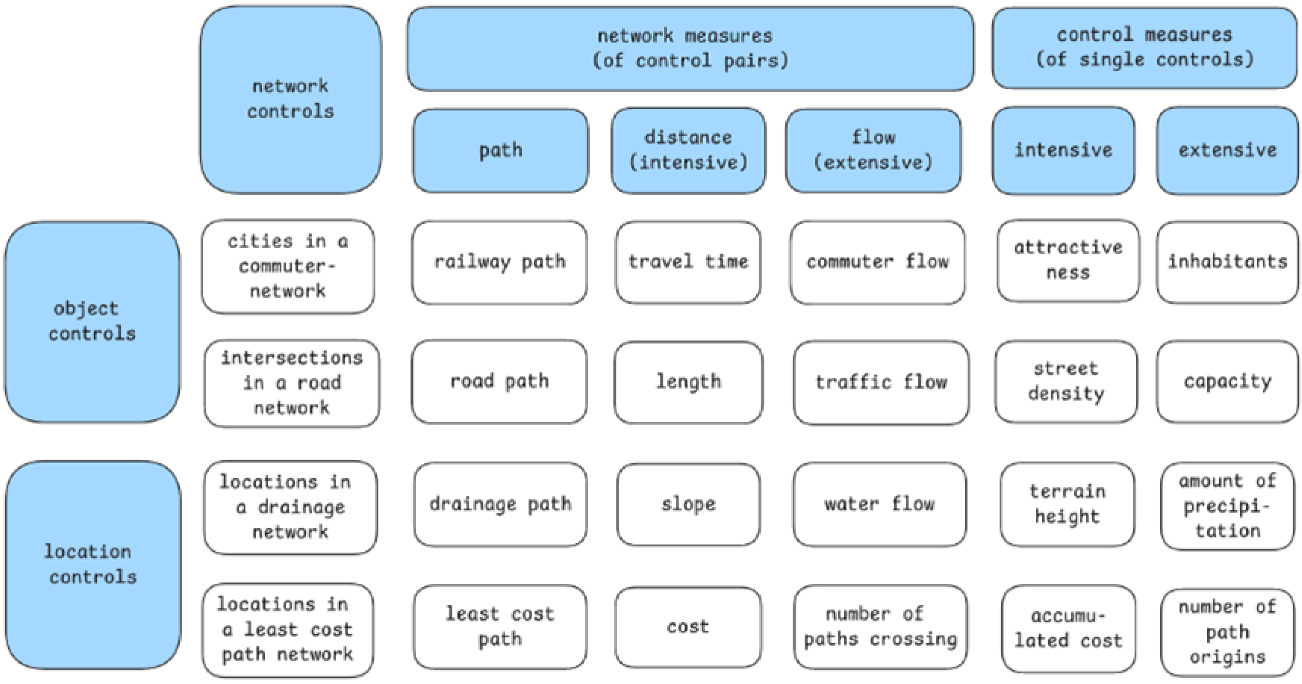

Figure 1. Overview of spatial network types according to the conceptual view. Source: authors.

In spatial network models, various types of networks can be distinguished based on the type of control. For example, prominent GIS methods like visibility analysis, drainage networks or least cost path networks can be understood as Boolean or ratio-scaled relations between locations in space. Most transport network models, instead, are controlled by discrete spatial objects that play the role of origins and destinations and which have time-dependent properties. Note that such objects can evolve or change their location, leading to network evolution (e.g. a city’s spatial region can increase).

Further types of spatial network models can be distinguished based on the kind of relation that is measured. For instance, an important kind of network measure is a geometric path between origin and destination, e.g., the shortest or quickest one (path networks). Measuring the geometric properties of this path is the basis for constructing various network distance assessments (see below). When studying movement over a network, it is often necessary to summarize it in terms of a flow: For example, analyzing a drainage network in a catchment area requires summing up a hydrological field (such as rainfall or water content) within the river catchment to determine network flow (Haggett and Chorley, 1969). In contrast, transport flows can either be measured by moving objects and their trips over this network, or be derived from extensive quantities measured for origins and destinations, such as amounts of inhabitants or facilities of connected cities.

Depending on whether such measured quantities of networks sum up with the product of spatial areas covered by both origin and destination objects, we can speak about spatially extensive and intensive measures for spatial networks (Scheider and de Jong, 2022). Flows are an example of an extensive network measure controlled by the spatial extents of the object controls. For instance, with commuter flows, if a destination region like a city merges with a new destination such as a satellite town, the commuter flow between the origin and the merged destination will increase by the sum of flows from the origin to both destinations, thus increasing with the cross product of both places. An intensive spatial network quantity would be the distance measured between two object regions. In spatial network modeling, extensive measures of origins or destinations play a distinctive role: they are used to model potentials for interactions over the network, whereas intensive measures are used to measure attractiveness. Together with network distances, potentials and attractiveness are used to model potential flows.

4. Core Analytical Tasks for Spatial Network Models

One of the most prominent examples of spatial network models are models of transport networks. Based on our conceptual view, we highlight the different analytical tasks that can be performed with such models. We shortly explain the purpose of each task in terms of a corresponding question, where concepts are provided in square brackets. Note that basic models for determining optimal paths are a prerequisite for all these models.

- **Distance network construction**. The purpose is to construct a network that represents the spatial distance between objects based on the spatial embedding of object controls and path measures. What is the [distance] from each [object] to each [object] by [path] in [extent]? For example, what is the distance from each municipality to each football club by road in the Netherlands? To answer this question, we need a representation of network infrastructure given as geometric line objects:
  - **Metric distances**. In the simplest case, we can measure metric distances by constructing spatial intersection objects between lines, and measure a distance between intersections by taking intersected line lengths as measures. When constructing a distance matrix between discrete spatial objects such as buildings, this additionally needs to include the “last mile” between infrastructure and origins or destinations.
  - **Topological and angular distances**. As suggested by space syntax theory (Hillier and Iida, 2005), we can also measure topological distance (counting steps between nodes) and angular distance (sum of direction changes along a path) in spatial networks. This is used e.g. in axial and angular maps, which better reflect perceived distances in urban network environments (Turner, 2007).
- **Distance-potential analysis**. Distance potential analysis makes use of a distance matrix between controls as well as of the measurement of a potentials at both origin and destinations. The purpose is to derive quantities for individual objects in the network.
  - **Threshold analysis**. What is the [potential] reachable within a [distance] from each [object]? For example, what is the amount of children reachable within 4 kilometers from each school? What is the [distance] to reach a [potential] from each [object]? For example, what is the travel time needed to reach at least 1000 fans from each football club in the Netherlands? The first variant is called a threshold amount analysis, the second one a threshold distance analysis, depending on whether we either control or measure distances or object-bound potentials. Note that a zoning (network buffer) is a special case of threshold

distance analysis.

- **District/Accessibility/Catchment Analysis**. What is the [distance] to the closest [object] from each [object]? For example, what is the distance to the closest school from each building in Amsterdam? In this type of analysis, which is often called accessibility analysis, we minimize a distance matrix between objects to determine the closest goal object (here: school) for each origin object (here: building). This determines a district (or catchment area) for each goal object (here: school districts), and in turn attributes a distance as a measure to each origin (or destination) object.

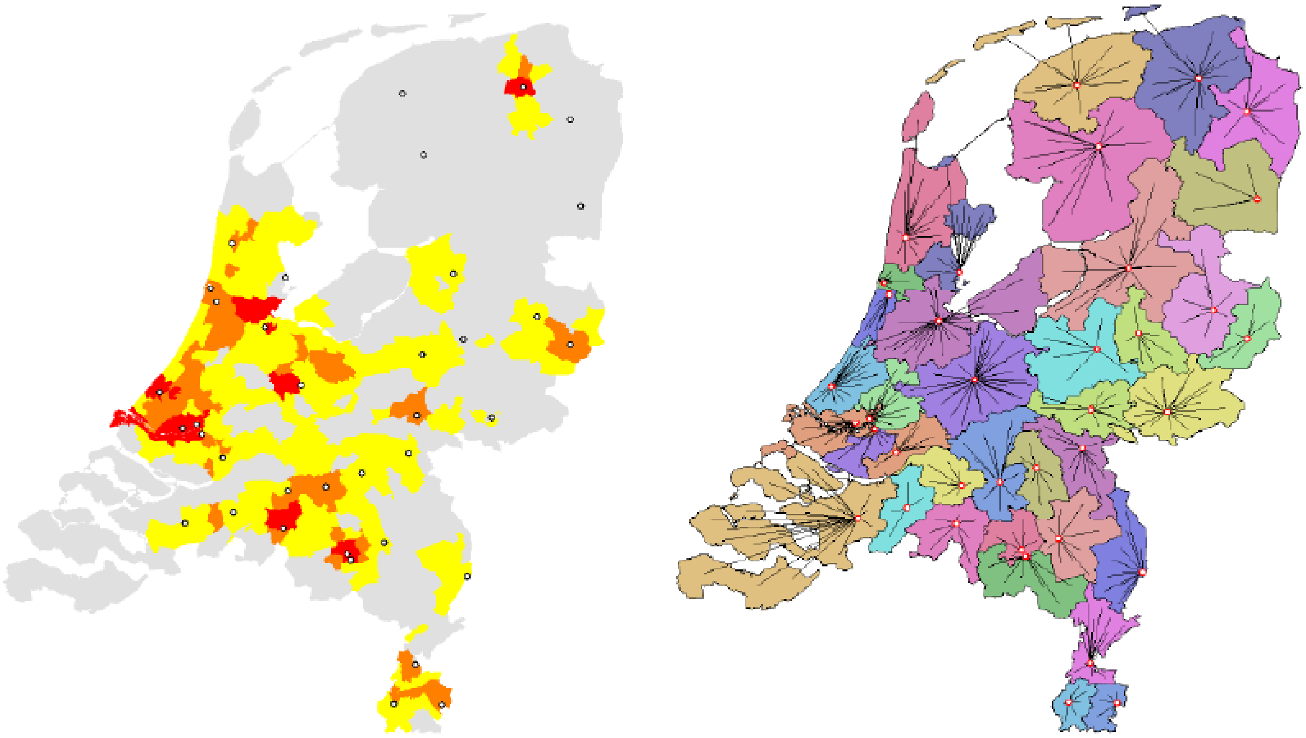

Figure 2a (left). Example of threshold analysis with football fan potential (amount of fans reachable within 10 minutes as graduated color). Figure 2b (right). Example of catchment area analyiss with football club districts (lines indicate allocations of Dutch municipalities to nearest football club). Source: Scheider and de Jong (2022); used with permission.

- **Interaction (Flow) Generation**. Here, the purpose is to generate flows and interactions corresponding to extensive network measures between objects. We can generate such network measures using less fine grained flows between objects, potentials and attractiveness scores at origin and destination objects, as well as distance networks.
  - **Traffic Load Assignment**. What is the [flow] on each [object], given flow and distances between each pair of [objects]? For example, what is the commuter flow on each street segment, given commuter flows for each pair of municipalities in Amsterdam? To answer this question, we need a model of route choice for each origin destination pair (e.g., using the shortest or quickest path) that makes use of network distances. We assign a flow to a path for each origin destination pair, and finally sum up these flows over each object that is located on such a path.
  - **Gravity Modeling**. What is the [flow] between each pair of [objects], given the [potential] for each [object] and the [distance] between each pair of [objects]?

For example, what is the commuter flow between each pair of cities, given the number of their inhabitants and the distance between cities? In a doubly constrained gravity model, we use extensive measures for potentials on both origin and destination objects, and generate an (intensive) attractiveness score for destinations, while for a singly constrained gravity model, we make use of some extensive origin potentials and some (intensive) attractiveness scores for destinations to generate extensive destination potentials.

- **Interaction (Flow) Analysis**. In spatial interaction analysis, we combine distance matrices with flow matrices for the purpose of deriving measures that quantify how flow is distributed over the entire network. We illustrate two examples of such a kind of analysis.
  - **Trip Length Distribution**. What is the distribution of [distance] for a [flow] measured for every destination (or origin) [object]? For example, what is the average distance of a migration flow, measured for every destination country of a journey (starting from any other country)? In this type of analysis, we average distances of trips weighted by quantifications of flows sharing the same origin and destination, and controlling for some destination or origin object.
  - **Trade Area Analysis**. What is the smallest region enclosing a sum of [flow] greater than a [threshold], such that the sum of distances to some [object] in this region is minimal? For example, what is the smallest region enclosing 50% of the fans of a football club? In this analysis, we estimate the smallest region (based on minimizing distance sums) that contains a minimal sum of interactions between its constituting objects.
- **Centrality Analysis**. In this type of analysis, we control for objects and measure their centrality in a given network (Freeman (1977), cf. Arlinghaus et al. (2002)). The type of network needed is indicated below.
  - **Degree Centrality (local connectivity)**. This uses a boolean network. What is the number of neighboring [objects] for each [object] in a [network]? For example, what is the number of neighboring football clubs for each municipality?
  - **Closeness Centrality (global integration).** This uses a distance network. What is the inverse of the average [distance] to all [objects] for each [object] in a [network]? For example, what is the inverse of the average distance to all cities for each city?
  - **Betweenness Centrality (through-movement potential)**. Measures how often a node lies on the shortest paths between all other pairs of nodes within a distance network. What is the number of crossing [paths] between [objects] for each [object] in a [network]? For example, what is the number of crossing paths between buildings for each intersection in a road network? The latter includes the construction of a path matrix.

References

Arlinghaus, S. L.; Arlinghaus, W. C.; Harary, F. (2002). Graph Theory and Geography: An Interactive View (eBook). New York: John Wiley and Sons.

Barabási, A. L. and Pósfai, M. (2016). Network Science (Vol. 3). Cambridge, UK: Cambridge University Press.

Barthelemy, M. (2022). Spatial Networks A Complete Introduction: From Graph Theory and Statistical Physics to Real-World Applications. Springer Cham.

Batty, M. (2013). The new science of cities. MIT Press.

Chrisman, N. R. (2002). Exploring Geographic Information Systems, 2nd edition. New York, NY: Wiley.

Curry, L. (1972). A spatial analysis of gravity flows. Regional Studies, 6(2), 131–147.

Freeman, L. C. (1977). A Set of Measures of Centrality Based on Betweenness. Sociometry, 40(1), 35–41.

Geertman, S. C. M., & Ritsema Van Eck, J. R. (1995). GIS and models of accessibility potential: an application in planning. International Journal of Geographical Information Systems, 9(1), 67–80.

Güting, R.H., de Almeida, V.T. & Ding, Z. (2006). Modeling and querying moving objects in networks. The VLDB Journal 15, 165–190.

Haggett, P. and Chorley, R. J. (1969). Network Analysis in Geography. London: Edward Arnold Publishers.

Hillier, B., and Iida, S. (2005). Network and Psychological Effects in Urban Movement. In: Cohn, A.G., Mark, D.M. (eds) Spatial Information Theory. COSIT 2005. Lecture Notes in Computer Science, vol 3693. Springer, Berlin, Heidelberg.

Hillier, B., Leaman, A., Stansall, P., & Bedford, M. (1976). Space Syntax. Environment and Planning B: Planning and Design, 3(2), 147-185.

Ingram, D. R. (1971). The concept of accessibility: A search for an operational form. Regional Studies, 5(2), 101–107.

Jiang, B., & Claramunt, C. (2004). Topological Analysis of Urban Street Networks. Environment and Planning B: Planning and Design, 31(1), 151-162.

Kansky, K. J. (1963). Structure of transportation networks: relationships between network geometry and regional characteristics. University of Chicago Press.

Kuhn, W. (2012). Core concepts of spatial information for transdisciplinary research. International Journal of Geographical Information Science, 26(12), 2267-2276.

Masser, I., and Brown, P.J.B. (1977). Spatial representation and spatial interaction. Papers of the Regional Science Association 38, 71–92.

Miller, H. J., and Shaw, S. L. (2001). Geographic Information Systems for Transportation: Principles and Applications. Oxford University Press.

Neal, Z. P., Derudder, B., & van Meeteren, M. (2023). When Is a Matrix a Geographical Network? Annals of the American Association of Geographers, 114(8), 1631–1638.

Okabe, A., & Sugihara, K. (2012). Spatial Analysis Along Networks: Statistical and Computational Methods. John Wiley and Sons.

Rich, D. C. (1980). Potential Models in Human Geography. United Kingdom: Geo Abstracts.

Ritsema van Eck, J. R. (1993). Analyse van transportnetwerken in gis voor sociaal-geografisch onderzoek. Amsterdam/Utrecht, Koninklijk Nederlands Aardrijkskundig Genoots.

Scheider, S., & de Jong, T. (2022). A conceptual model for automating spatial network analysis. Transactions in GIS, 26, 421–458.

Sinton, D. F. (1978). The inherent structure of information as a constraint to analysis: mapped thematic data as a case study. In Harvard Papers on Geographic Information Systems, Edited by: Dutton, G. Reading, M. A.: Addison-Wesley. Volume 6

Turner, A. (2007). From Axial to Road-Centre Lines: A New Representation for Space Syntax and a New Model of Route Choice for Transport Network Analysis. Environment and Planning B: Planning and Design, 34(3), 539-555.

Winter, S. (2002). Modeling Costs of Turns in Route Planning. GeoInformatica 6, 345–361.