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Examining the amenability of urban street networks for locating facilities

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HIGHLIGHTS

- Facility locations are strongly affected by street network structures.
- A set of novel efficiency and centrality measures to evaluate siting facility.
- Most urban street networks are efficient in service provision.
- Planned cities tend to be more efficient and robust to access distributed service.

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ABSTRACT

This paper aims to characterize urban street networks from the perspective of facility location that is widely used for siting public or private services. Both topological and geometrical features of urban street networks are investigated to examine their impacts on the performance of facility location. We propose a set of efficiency and centrality measures to evaluate the amenability of street networks for locating facilities. The evaluation of 15 large cities in the U.S. reveals that facility locations are strongly affected by road network structures. For realistic street networks, grid planned road network are more amenable to locating facilities than irregular networks. The analyses on idealized network offer further evidence of the correlations between network properties and service provision efficiencies.

1. Introduction

In the last decade, the underlying structural properties and geometric features of urban street networks have gained substantial research interest [1–3]. Street networks, as they take the form of near-planar graphs, are strongly constrained in space due to planar embedding. Because most road links do not cross each other and most of them intersect at end nodes, urban street networks are featured with limited average node degree and sparse long-range connections [1]. A large proportion of the literature has been dedicated to the quantitative characterization of geometric and topological properties on real-world network data, including node degree, clustering coefficient, number of cycles, network diameter, and path length, revealing interesting statistical regularities such as exponential behavior and power-law scaling [4–6]. Another

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stream of research focuses on the measurement of advanced centrality indices: degree centrality, closeness centrality, betweenness centrality (BC), straightness centrality, and information centrality [7,8]. Centrality-based assessment offers a convenient way to capture the uneven distribution of location advantages for complex street networks.

Studies have been extended to investigate the correlation between complex road network characteristics and socio-economic phenomena in cities. Most analyses focus on human mobility and traffic flow because they are directly interrelated with street networks [9,10]. Spatial patterns of other socio-economic activities such as land use and business services also receive considerable attention [11,12]. Most previous research efforts, however, do not apply network science analytic methods to quantitatively evaluate particular locations that are selected by location optimization models, which can identify central locations in a rigorous manner.

Facility location aims to site facilities to deliver the coverage of specific services for demands across space and time, such as the deployment of ambulance vehicles, police or fire stations in highly populated urban areas. In the realms of Operations Research and Geographic Information Science (GIScience), facility location has a long and substantive research history. The *p-median* problem (PMP) was firstly formulated by Hakimi [13] and has been extensively used to solve location problems. By solving the PMP, we can identify and locate p necessary facilities such that the total weighted distance between demands and the closest sited facility is minimized. In this study, we adopt the p-median model since it is a representative facility location model and can explicitly account for the distances between facilities and distributed demands.

Intuitively, the spatial distribution of facility services would be affected by geometric and topological characteristics of urban street networks. Some street networks may be easier to be covered than others, due to their intrinsic structural properties. Then research questions arise: *what are the correlations between specific network properties and the spatial distribution of the solutions of facility location models? Do the statistical regularities of structural measures entail similar patterns of optimal locations?*

For the rest of this paper, after a brief introduction of the p-median model, we present an empirical study on a set of street networks in the US, which manifest diverse social, economic, and geographic contexts. Except New York, Los Angeles, and Chicago, the 15 largest US cities by population were analyzed. We chose not to study the top three cities because they present much more heterogeneous street networks and demographics characteristics than other cities. The investigation of the correlations between location performance and graph properties leads to some interesting findings, which are corroborated by an analysis of idealized street networks.

2. *p*-median problem

A classic p-median model can be formulated as follows:
Minimize

$$\sum_{i\in I}\sum_{j\in J} w_{ij}x_{ij}. \tag{1}$$

Subject to

$$\sum_{j\in J} x_{ij} = 1 \quad \forall i \in I \tag{2}$$

$$x_{ij} \le y_j \quad \forall i \in I; \forall j \in J \tag{3}$$

$$\sum_{j\in J} y_j = p \tag{4}$$

$$x_{ij} \in \{0, 1\} \quad \forall i \in I; \forall j \in J \tag{5}$$

$$y_j \in \{0, 1\} \quad \forall j \in J \tag{6}$$

where i is the index of demand areas and I is the set of demand areas, j denotes the index of potential facility sites and the entire set of j is represented as J. w_{ij} is a non-negative weight that encodes the travel costs between i and j. For any decision variable x_{ij}, $x_{ij} = 1$ if demand area i is served by facility j and otherwise $x_{ij} = 0$. y_j is a decision variable that is set to 1 if a possible site j is selected to site a facility, otherwise y_j equals 0. p is the number of facilities to site. The objective (1) is to minimize the sum of the weighted costs for serving all demands areas. Constraints (2) guarantee that each demand area i is served by only one facility. Constraints (3) specify that only sited facilities are allowed to serve demand areas. Due to limited resources, only p facilities are located, which is described in constraint (4). Constraints (5) and (6) enforce integer restrictions on x_{ij} and y_j.

Every location in the study region can be possibly selected as the site of a service facility. Nevertheless, solving p-median problems in continuous space incurs expensive computation, especially in network-constrained space. Instead, a finite set of potential locations are pre-identified as the cell centroids of regular grids before we apply the p-median model to finally determine the optimal sites of service facilities. On the other hand, area-based representation is used to describe continuously distributed demands. In this study, we used census block groups to represent basic demand areas, each of which is associated with a nearest accessible road. The traditional p-median model does not consider the