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Recent advances in accessibility research: Representation, methodology and applications

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Abstract. In this article we examine recent advances in accessibility research and their implications for future studies. We base our discussion on three intersecting dimensions that are useful for evaluating the contribution of recent studies: representation, methodology and applications. Various examples are selected to show that research concerned with representation and methodological problem solving is often applied to issues of broad concern in policy and planning. It is, however, not clear that the simultaneous treatment of representation, methodological and application issues has ever been fully worked out. The questions raised in this article may serve as a foundation for addressing issues pertinent to accurate representation, improved model building, and more rigorous applications in accessibility research.

Key words: accessibility, applications, methodology, representation, spatial analysis

JEL classification: C60, R40

1 Introduction

In this article we reflect on recent advances in accessibility research and their implications for future studies on this topic. We base our discussion on three intersecting dimensions that are useful for evaluating the contribution of recent studies: representation, methodology and applications. These themes have particular resonance for aggregate and disaggregate spatial modeling.

2 Representation

Representation refers to the ways in which geographic space and entities are structured in the analytical framework of a particular study. It is closely related to a set of spatial concepts, including location, spatial interaction and scale. Spatial representation not only influences what questions can be asked and the ways they are framed, but it also affects the tools that can be used to process and analyze spatial data.

Perhaps the most important feature distinguishing different approaches to the study of accessibility is the representational framework on which specific methods are developed. Different representational frameworks can be identified in recent accessibility studies. For instance, geographical access can be conceived as an attribute of either locations (place accessibility) or individuals (personal accessibility). It can be analyzed through a zone-based, aggregate spatial framework (e.g. census tracts or block groups) or through a point-based framework (Guy 1983; Hanson and Schwab 1987; Kwan 1998) that uses individual-level data (e.g. activity-travel diary data). Analytical methods may represent accessibility at a global scale, or they may seek to capture variations in accessibility at a local scale. Finally, the manner in which diverse social groups and individuals, differentiated through multiple axes of dissimilarity (e.g. gender, race, ethnicity, class and income), are represented in an analytical framework is also an important element in any study of accessibility.

With the capabilities offered by geographic information systems (GIS) and available spatial data, we increasingly face the question of how objects/features should best be represented when assessing accessibility. Spatial simplification in evaluating, measuring and modeling accessibility is often relied upon (Miller 1996; Murray and O'Kelly 2002). For example, most techniques represent areas and objects as point locations and use them as origins and destinations when evaluating accessibility. Research is only now beginning to examine the degree to which abstracting spatial features is appropriate and acceptable in the broader context of representation. As recent studies observed (e.g. Horner and Murray 2002), spatial scale can have a significant effect on analytical results, and identifying a proper representational framework remains a challenge for future accessibility research. In addition, as some formulations of accessibility measures tend to be less susceptible to the effect of scale (as showed by Weber and Kwan 2003), developing scale-independent measures is another fruitful direction.

A key to all accessibility studies is a firm understanding of the behavioral responses to the spatial separation of locations of supply to the locations of demand. Simple spatial distances measures, such as spherical distances or interaction costs on a network are only first approximations to a more complex evaluation of spatial separation under constraints in relative space. The geographical concepts of *isolation versus accessibility* and *periphery versus centrality* need to be distinguished carefully. Periphery and centrality measure the location of spatial objects in absolute space whereas isolation and accessibility take additional spatially distributed attributes into account to express the relational structure of the spatial objects in relative space. Logically both concepts are independent; however, in empirical settings they are often highly correlated.

3 Methodology

As space and time play an important role in shaping people's access to activity locations, an active area of accessibility research in recent years focuses on the influence of individual space-time constraints on accessibility. Based on the time-geographic perspective (Hägerstrand 1970), the central notions in this framework are space-time constraint and the space-time prism (Lenntorp 1976). Space-time constraint refers to the restrictive effect on activity choices that arises from the spatial and temporal attributes of a person's activities (Kwan 2000). A space-time prism identifies the feasible activity space for an individual with a particular set of space-time constraints. The mapping of this space-time prism onto geographical space delimits the potential action space, which is the area containing all reachable activity places given an individual's space-time constraints (Burns 1979; Villoria 1989; Dijst and Vidakovic 2000).

This time-geographic framework has been applied in accessibility research along two distinct but related directions: (a) formulation of space-time accessibility measures using GIS-based geocomputational methods and exploration of the effect of geographical context and scale on individual accessibility (Kim and Kwan 2003; Kwan 1998, 1999; Miller 1999; Weber 2003; Weber and Kwan 2002, 2003); and (b) development of the action space model and examination of the impact of spatial configuration of opportunities on people's activity choices (Dijst et al. 2002). Both approaches conceive accessibility in terms of the geographical scope or the number of opportunities individuals can reach (individual accessibility) given the space-time attributes of their daily activities and fixed locations (home, work, etc). The accessibility measures derived based on this conceptualization therefore reflect individual accessibility (and hence are good indicators of qualify of life) instead of how easily locations or places can be reached by the population (place accessibility).

These and related recent studies suggest that time-geographic research can yield important insights about individual accessibility and its relationship to the urban environment. Time geography is a helpful perspective and a useful point of departure for analytical work in this area. Future research, however, needs to pay attention to several issues. First, since people do not have information on all opportunities, their cognitive environment and constraints may play an important role in determining which opportunities are accessible to them (Kwan and Hong 1998). Second, the use of information and communications technologies (ICT) will likely lead to changes in people's activity patterns in space-time and in the opportunities that are available (or accessible) to them (Kwan 2001, 2002). Much work is needed to collect and incorporate cognitive data into a GIS environment, and to develop methods that can answer questions about how people's use of ICT will affect their individual accessibility and quality of life.

Although location models have long been used for assessing accessibility to goods and services, advances continue to be made in the use of these basic approaches for evaluation and planning of accessibility. While there are many fundamental traditions in location modeling (see Mirchandani and Francis 1990), two are prominent in recent accessibility studies. One tradition in location analysis is centered on maintaining a stipulated maximum accessibility criterion – coverage (Toregas et al. 1971; Church and ReVelle 1974). Another tradition in location modeling focuses on the intention to minimize average access (time and/or distance) – location-allocation (Hakimi 1965; ReVelle and Swain 1970).

There are many open research problems associated with the use of location models in the context of accessibility. Perhaps the most significant is using these approaches for both strategic and operational purposes. The evaluation of accessibility may necessarily mean that certain realities are ignored, such as route integration in the case of transit, in order to better understand system-wide inefficiencies. Alternatively, a challenge remains in adding more operational and behavioral reality to these measurement/modeling approaches as they may be extremely important components of accessibility in certain contexts. For example, a classic assumption in most location-allocation models is that users will travel to their closest facility or center, yet this may not be the case for a particular study. Another commonly ignored application feature is temporal variation in demand or service. Finally, an important issue continues to be improving capabilities for evaluating small scale problems in a GIS environment. Most location models have not historically been applied to problems with thousands or hundreds of thousands of analysis areas. Thus, carrying out accessibility analysis using location models tends to approach or exceed computational limitations.

Spatial interaction expresses the underlying structure of objects in a spatial system. Recent advances in GIS make it possible to enhance our understanding of these spatial relationships. Behavioral models are among the most useful approaches to achieve linkage between represented units and aggregate resultant flows. Such models present a host of challenging issues arising from coupling of local and global processes. Spatial interaction models represent the flows that occur between spatially separated origins and destinations. In a way then spatial interaction is a necessity required to overcome the spread between services and demand for those services. In that there are varying degrees of proximity (or accessibility) to services, it is not surprising that the notion of accessibility measurement and deductions about its levels have been a fundamental component of interaction studies. Among the classics is the work of Hansen (1959), who made a convincing case that accessibility shapes land use, but now of course we realize that land use distribution in our cities act to shape the accessibility of residents to activities. Recent examples of these close couplings are studies by Horner (2002) and Horner and Murray (2003) on the required levels of interaction intrinsic to the organization of cities and the spatial separation between places of residence and work.

The methodological progress, in combination with specific theoretical arguments about the underlying behavioral dimensions of the migration process, has led to substantial refinements in the analysis of spatial interaction patterns. Some of these advances are just becoming publicly accessible with the dissemination of GIS and advances in statistical computing techniques. The statistical method of neural spatial networks to predict interaction flows (Fisher and Reismann 2002) and Bayesian estimation of interaction flows under prior information (Congdon 2000) are two prominent examples. Statistical data analysis also advances our knowledge by thoroughly scrutinizing the residual component of the interaction model for any hidden patterns. Interaction modeling advances have been made in testing for network autocorrelation (Berglund and Karlström 1999; Bolduc et al. 1995; Black 1992; Boots and Kanaroglou 1988) and by mapping residuals. Embedded in the geographical tradition are the investigation of spatial aggregation effects (Ferguson and Kanaroglou

1995), the exploration of local variations around global migratory processes (Nakaya 2003), and the relaxation of the isotropic assumption (Fotheringham and Pitts 1995). We can expect to see more research on the spatial structure effects underlying interaction processes in the future.

There is a lot of experience in transportation and network analysis on the use of matrices to measure connectivity and deduce properties of accessibility from those matrices. Among the many well-known ideas is producing counts of the numbers of ways to reach specific destinations from a specific origin by paths of length 1, 2, … These in turn may be weighted (to downplay less likely or more intricate paths) and also may be used to get an idea of the number of network hops needed to navigate between nodes. If values or costs can be attached to the network links, we can also derive the least weight (or shortest path) between many origins and many destinations (the so called multi-terminal shortest path). Interesting adaptations of this idea to realistic network analysis can be made to consider, for example, the ease of movement within a city on a subway system or on a street car network and may be easily adapted to consider the extra steps needed to make transfers between modes (see Lee and Lee 1998).

Open research opportunities exist when we realize that geographers and spatial analysts regularly encounter some of the most intractable and difficult problems in mathematics and operations research (determine numbers of unique paths; find first, second, … kth shortest paths; solve embedded traveling salesman problems; etc.). An important source for future work on this is the excellent monograph of Carre (1979). This book carefully shows that the creation of chains and paths in a network can be accommodated through string processes.

4 Applications

Substantive applications demonstrate that research concerned with representation and methodological problem solving is often applied to issues of broad concern in policy and planning. The following examples are chosen to illustrate some of the close connections between applied problem solving and insights derived from accessibility research. We avoid a stark dichotomy between methods and substance, realizing that many methodological questions are in fact directed to substantively important issues.

Nowhere is the application of accessibility more pressing than in the area of linking disadvantaged households to jobs (e.g. Scott 2000; Shen 1998). There have been many examples provided of the unsatisfactory ways in which some residential zones are isolated from work place opportunities with concomitant disadvantages (e.g. McLafferty and Preston 1996), and perpetuation of dependence on welfare. Although the methods used in these studies vary considerably, they have informed the design and implementation of social programs that seek to match workers to jobs and to provide them with the means to overcome spatial inaccessibility. Research on job access has recently been expanded to include other topics of concern to social scientists. For example, a study by Wang and Minor (2002) found, after controlling for spatial autocorrelation, consistent inverse relationships between gravity-based job accessibility and crime rates, especially that of economic crimes.

Another important area in applied accessibility research is the provision of social services such as hospitals, clinics, senior centers, parks and schools. Studies in this research area evaluate whether access to a particular social service is socially equitable or discriminatory, and seek to identify areas of service deprivation that need special attention. They examine the relationships between the spatial pattern of access and the spatial distribution of specific population subgroups (e.g. ethnic minorities). For instance, Talen (1997) observed some spatial association between differences in park access and differences in the racial composition in the study area. A fruitful direction in this area of research is the examination of the relationships between access to social services and other social phenomena. For example, the study of Gimpel and Schuknecht (2003) showed that access to ballot boxes affects people's political participation (voting). Talen (2001) found that access to elementary schools had a significant and inversely related effect on student achievement for certain groups of students. Church and Marston (2003) formulated a series of measures for evaluating accessibility for people with physical disabilities. This research focus is particularly relevant to concerns with social equity in service distribution (distributive justice).

The evaluation of public transit, using location-allocation models and coverage models, has also been an important application area for accessibility measures. Gleason (1975) was one of the first to apply a location model for siting bus stops in order to ensure coverage of ridership as well as promote travel time efficiency. A similar area of work by Wirasinghe and Ghoneim (1981) focused on optimal bus spacing. More recently, Murray et al. (1998) examined regional transit access as a common planning goal to provide residents suitable access, where access is stipulated as coverage maximum (typically that a residence will be within 400 meters of a stop or station). Looking beyond access, O'Sullivan et al. (2000) evaluated accessibility offered by transit, taking into account access and travel speeds. Both of these works highlighted how GIS could be utilized for evaluating transit accessibility concerns.

On the modeling side, public transit accessibility was evaluated in Murray (2001, 2003) by examining service coverage redundancy. Given a service coverage maximum, stop placement was examined using coverage models to assess whether redundant services are being provided. In support of planning, the existence of service redundancy suggests an opportunity for system improvement, and potentially greater utilization of transit in the long term. Murray and Wu (2003) developed extensions of the classic p-median problem to analyze bus transit route accessibility. The intent was to minimize average access to a stop while simultaneously seeking to improve travel speeds along the route by eliminating redundant stops.

Recent accessibility research has also examined the geographical distribution and movement of people, especially in context of modeling spatial interaction and population potential. New migration datasets are becoming available that allow modeling of interaction patterns in fully-fledged as well as partially specified spatial systems. These new datasets will help us gain a better understanding of the shifting population distributions across space. After all, understanding the spatial distribution of the population at risk is of relevance for any accessibility study. The spatial and temporal scales of these migration datasets are changing. They become more spatially disaggregated and relate to shorter accounting intervals recording interaction flows.

In addition, migration patterns are also becoming more disaggregated by key characteristics of the migrants. For instance, migration between the U.S. counties of the 1990 census (Bureau of Census 1995) can be retrieved for specific demographic and socio-economic population segments. In particular, migration time series are becoming sufficiently long nowadays. This allows us to move from comparative longitudinal studies toward a full-fledged dynamic analysis in migration analysis. This dynamic perspective has been demonstrated in the information sciences when monitoring communication flows in a network over time (Cao et al. 2000). Some of these recently available migration time series are the annual migration patterns among the U.S. states for 10 consecutive years (Plane 1999; Davis et al. 2001) or the annual migration patterns (Tiefelsdorf and Braun 1997) among the 23 district of the city of Berlin, Germany, which is now available for 10 years. This dataset allows studying how the effects of the former physical and mental barrier, which separated both parts of the city, are slowly eroding over time.

There are several innovative applications in recent accessibility research, especially in using notions of network accessibility to enhance our understanding of social networks and the vulnerability of information infrastructure. For example, friendship patterns and transmission nets have both come under study using common frameworks and tools (see Barabasi 2002). These turn out to be important in disentangling the influences of peers, clusters, and ultimately the importance of locality in social actions. Many networks have been shown to display an interesting "small-world" characteristic in that there are relatively few links needed to make connections between seemingly disparate cases. This small world property has been shown to apply to diverse social phenomena as well as many physically based networks. Further, Barabasi and Albert (1999) found that many of these small-world networks are scale-free. By this they mean many social and physical networks have a few highly connected nodes (which we might be thought of as hubs) and many more sparsely connected nodes. Clearly the metaphor here helps us to relate to the centrality of certain opinion leaders and role models.

Methods for analyzing network accessibility have been applied to examine infrastructure vulnerability. If we measure the degree of a node as the number of connections it has, then some nodes have many connections, but most nodes have few. Plots of these "shares" show a straight-line plot on log-log paper and are referred to as having a power law distribution. What is the relevance here? Many phenomena have this "accessibility" and usage pattern such that some highly centralized locations are highly connected and so dominate interactions. (See for example the role of Atlanta as an air traffic hub, O'Kelly 1998). The explanation for this is that networks grow and the preferential attachment of new nodes to exiting highly connected nodes produces the aggregate scale-free property (Barabasi et al. 1999).

The spatial implications for the reliability of infrastructure built around such centralized networks have been explored recently by Grubesic et al. (2003). They have noted that while Internet hub-based nets confer high degrees of centrality (and hence accessibility) on hub locations, there are threats to the network's viability because of their exposure to destruction of hubs. Of course this potential "down-side" of high accessibility has not gone unnoticed and the studies of network vulnerability have drawn attention to the exposure of such nets to destructive forces.

5 Conclusions

It is not clear that the simultaneous treatment of representation, methodological and application issues has ever been fully worked out. The open research questions that arise from this special issue and those highlighted in this concluding article should serve as a foundation for addressing accurate representation, improved model building, and more rigorous applications. It does appear that the research frontier keeps expanding to include many new and exciting areas of research.

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