ADDING AN UNDERGROUND LAYER TO URBAN MORPHOLOGY -- CASE STUDY OF BEIJING SUBWAY’S IMPLICATION ON URBAN FORM

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ABSTRACT

Since the advent of the underground metro system in London in 1863, it has played a significant role in connecting within urban areas, especially for those mega-cities with expanding boundaries. In urban morphology studies, the hierarchy of urban form elements is crucial in understanding urban form. Prior research has established comprehensive hierarchies that depict the composition of urban form elements (Conzen, 1960; Kropf, 1996, 2014; Osmond, 2010; Scheer, 2001), but some elements are still missing from the theoretical frameworks. This preliminary research contributes a novel perspective on urban morphology by adding a new underground layer to urban form elements. Based on the case study of Beijing, we argue that the underground system is impactful on the overall network structure of cities, especially on global levels. This research also suggests that the angular metric is the ideal option in investigating hybrid urban form. Further research is needed to refine the new model that integrates urban form on and under the ground.

Keywords: underground morphology, metro system, accessibility, betweenness, sDNA.

INTRODUCTION

The subject of urban morphology deals with "main physical elements that structure and shape the city – urban tissues, streets (and squares), urban plots, buildings, to name the most important" (Oliveira, 2016: 2). The traditional epistemology of urban morphology is grounded in the recognition and reflection on the substantial physical space that is either organic or planned. Prior research has established comprehensive hierarchies that depict the composition of urban form elements (Conzen, 1960; Kropf, 1996, 2014; Osmond, 2010; Scheer, 2001), but elements are still missing from the theoretical frameworks. In the context of contemporary cities, underground spaces become prevalent in mega-cities thanks to the development of underground transportation networks as well as underground pedestrian systems (Cui et al., 2012a). Therefore, while urban morphology seeks to capture the intricate relationship among urban forms, agents and dynamic processes in shaping urban spaces, it is essential to cast an underground system in the existing frame of urban morphology. The inclusion of the underground system furnishes researchers with another variable in modelling and interpreting space as well as human behaviours and facilitates them to draw further implications on how and to what extent can the built environment impact socio-economic development of cities. To this end, we investigated the impact of underground networks (metro) on urban street networks in Beijing in terms of network centrality, considering the circular causality between land use, transportation and network accessibility. The research questions anchored with this proposition are: 1) Why do we need a new lens of the underground layer for urban morphology studies? And 2) How the addition of a new underground layer reshaped the urban networks of Beijing?

BACKGROUND

Cities are complex objects, and so are the abstractions/models that attempt to conceptualize them. Urban morphologists have widely acknowledged the idea of decomposing urban built environments into "urban tissues" (Kropf, 1996), and the street system has garnered extensive
attention from scholars with space syntax theory (Hillier et al., 1976) been the most cited work in this vein. The street network is often viewed from the spatial-temporal perspective (Scheer, 2001) and classified into the relatively durable and static structure of urban form, and it is common to see the heritage of street network layout in cities such as Mexico City, Barcelona, Pingyao (China), and even New York. As such, streets are perceived as "space" in many studies (Ashihara, 1983; Jacobs, 1993, 1961) instead of as connections that facilitate the internal flows and human mobility of the urban system. Based on the notion of "natural movement" and "movement economy" (Hillier et al., 1993), the configuration of street networks has been placed at the center of interpreting urban form and predicting socio-economic activities that take place along the physical links. The general assumption is that regardless of functional magnets, the configuration of street networks has generated spaces with high and low accessibility, respectively, thereby directing human flows pooling to central spaces with high accessibility. In view of this, the urban form can be explained and predicted through the quantitative indicators of "accessibility," which has been proved in a body of empirical studies (Papa et al., 2016; Srinurak et al., 2016; Zhou and Gao, 2020). Parallel to the morphological approaches of space syntax, the research of transportation and spatial analysis also embark on the idea of reading urban space via "accessibility" (Davidson, 1977; Hansen, 1959a; Ingram, 1971).

The concept of the accessibility itself has spawned a strand of literature that focuses on the measurement (Hansen, 1959b) and interpretation (Batty, 2009) of this particular description of relations and connectivity of the urban space. The theoretical foundation of spatial network analysis is the graph theory, which has widespread ramifications in physics, sociology, transportation, and geography (Crispin H. V. Cooper, 2015). As thoroughly examined by Batty (Batty, 2009, 2004), there are two representations of relations between street and junctions (primal problem vs dual problem) and three types of definition of the term accessibility. The space syntax approach, though focusing on the topological links among different "axial lines," has long been criticized for being biased on relation instead of physical geometry (Euclidean distance) and too theoretical (Batty, 2010; Jiang and Claramunt, 2002; Ratti, 2004; Turner, 2007). However, with years of updates and improvements, the normalized angular choice analysis (Hillier, Yang, & Turner, 2012) has become the most advanced method to evaluate urban form. The space syntax approach and spatial network analysis domain have made consensus on that the metric of angular change can best reflect human movement pattern given that people tend to follow the "line of sight" in navigating their trips (Crispin H. V. Cooper, 2015; Hillier, 2003; Hillier et al., 1993). It is worth noting that while accessibility advantage can favour the increase of density and diversity of local human activities, the accessibility gap can be filled by the provision of transportation services/connections, which conversely redistribute the accessibility. The complexity and dynamics of this cycle have complicated the process of understanding urban form and challenged the traditional static view of urban morphology.

There is a dearth of literature on investigating underground urban form in mainstream urban morphology research, at least to the best of our knowledge, except for limited attempts (Chiaradia et al., 2005; Law et al., 2012). In the discourse pivoting the two juxtaposed concepts, place vs space, much attention has been paid on the space side where underground space is treated primarily as traffic space (metro transportation, tunnels, and underpasses), with a small amount of research highlights the significance of underground space's role in placemaking (Cui et al., 2012). From the morphological perspective, the physical dimension of underground space, especially that of metro space is best conceptualized as connections between origins and destinations, the function of which is equivalent to streets on the ground. In this regard, the broad concept of "accessibility"
of street networks can be defined as defining a morphological feature inherent in urban form. To wit, if people flow through routes both on the ground and underground in cities, it is by no means to ignore the portion that hides under the horizon when interpreting urban spaces/places. It is the diversity and density of human activities that determine local land use and built form. Following this lead, it is concluded that the redistribution of accessibility is vital to the reconfiguration/restructuring of urban form.

**METHODOLOGY**

The emerging geographic information systems (GIS) is a potent tool for urban morphologists to create a more granular model to simulate urban spaces (Moudon, 1997). The advancement of spatial technology has also added to the toolbox of urban scholars with a wide variety of analytical methods, including Depthmap (Turner, 2004), Urban Network Analysis (Sevtsuk and Mekonnen, 2012), sDNA (Cooper and Chiaradia, 2015), and Form Syntax (Ye et al., 2017). In this research, we used sDNA to conduct spatial network analysis, given that it has been widely acknowledged and applied in network analysis related to transportation (Cooper, 2018; Papa and Bertolini, 2015; Sun et al., 2019; L. Zhang et al., 2015). The crowdsourced OpenStreetMap (OSM) is a popular source to extract urban road network data, and the data quality has been improving in recent years in the Chinese context (Zeng et al., 2017; Y. Zhang et al., 2015). On this account, we prepared our street network and metro network of Beijing based on the data retrieved from OSM using plugins in QGIS. In addition, secondary data such as street walking score (see details in Zhou and Long, 2017) and Point of Interests (POIs) counts from Beijing City Lab (https://www.beijingcitylab.com/) are incorporated in this research to validate the analysis results.
The research procedures are displayed in the diagram as follows (Figure 1). It is worth noting that we borrowed methods from Law et al. (2012) to merge the street network with the metro network by linking two networks with a short segment at metro stations. This small segment could represent the mild distance but sharp angular change. Besides, we performed calculations based on three metrics and investigated results at four radius level. The selection of radius aims to model the urban spaces from local to the global scale. The weight is given to the metro lines in the multimodal network to show its impact on the variation of urban structure. Conventionally, there are two common indicators in spatial analysis, being closeness denoting "to-movement" and betweenness denoting "through-movement" (Cooper, 2015). We select betweenness in this research, and the betweenness centrality (Freeman, 1977) of the results is validated by referring to walking scores and POI counts.

Figure 2 shows the research boundary and two different networks of the study area. This boundary line geospatially coincides with Beijing's second ring road, and the area within it is considered as the ancient Beijing City (62.5 km²). In order to avoid edge effects, we prepared Both networks with

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**Figure 1** Research procedures

**Figure 2** Research area and boundary
extensions outside the boundary. After topological check and data clean, there are 5014 street objects left in total with 66 metro link objects and 55 metro stations.

**FINDINGS**

We created three sets of analysis results arranged by the three metrics: Euclidean (distance), angular (change), and topological (depth), and we will present our findings from these three aspects. All the maps show the relative values of betweenness (also known as "through-movement") of each link, which represents the polyline(s) between two junctions, and the darker is the link, the higher the value. Prior research has reported high correlations between betweenness centrality and human movement pattern, including pedestrian and vehicular traffic (Cooper, 2015; Sarkar et al., 2018; L Zhang et al., 2015) and land use pattern (Xiao et al., 2017). In this light, our findings suggest that the multimodal network model can be impactful on the network structure, and the impact becomes more pronounced as the scale (radius) increases.

This is partially due to the length of each metro link since, in reality, the average distance between two metro stations is around 1.5 km. As can be seen from Figure 3, Figure 4 and Figure 5, this feature is best captured when comparing a-3, a-4 with b-3, b-4. Conversely, we argue that the underground network is much less effective at the local level as row (a) and row (b) remaining very consistent in all results except that d-2 in angular analysis showcases a slight variation. While these findings are very descriptive, they resonate with people's perception of metro lines being a commute approach for long-distance trips. Hence, in the local area, like area with radius of 400m where pedestrian is the optimal/dominant way of being mobile, underground morphology is not necessarily a factor to consider.

Moreover, it is important to distinguish between the three metrics used in this research. While the topological connection is at the crux of space syntax theory and methods, the topological metrics used here is different from that of space syntax. While ignoring length and angularity, the mere counting of junctions conveys information only related to network structure itself, meaning that the results should not be used to predict the real world. As for the Euclidean model, the Euclidean metric measures along the network in distance units, which is the everyday notion of distance. While this metric relies on the shortest path, it does not necessarily identify the "simplest route" (Cooper, 2015). The discrepancy mainly lies in human's intrinsic navigation strategy that seeks to make fewest-turn routes, which has led to the emerging widely accepted approach of using angular metrics in modelling human movement patterns. As for the results of the Euclidean metric, it is concluded that with the increase of the metro network's weight, the metro network becomes more
noticeable (see columns 3 and 4 in Figure 4). Besides, the addition of metro networks does not undermine the structure representing the global scale of the original street network (a4); instead, the two networks are mutually reinforced to a certain extent. In Figure 4, the structure of a4 is inherited by structures below it (b4, c4, d4), and d4 has the most complicated and inclusive structure pattern.

The most compelling findings are derived from angular analysis (Figure 5). The widely acknowledged idea is that with the increase of the searching radius, the analysis results tend to demonstrate a grid system where long horizontal and vertical structural lines become clear (in a gridiron planning system). This situation is consistent with the "law of fewest turns" mentioned above. Surprisingly, when taking a closer look at the two sets of diagrams, namely c3/d3 and a4/b4, the orthogonal pattern is obscured and substituted by one where right angular junctions become less prevalent. More importantly, the structure of d4 even resembles that of b4 in Euclidean analysis (Figure 4). How is it possible that the contradiction between the Euclidean metric and the angular metric (Cooper, 2015) is eliminated? The key to this question lies in that the metro network in our study is constructed based on direct connections (as the shortest route per se). The construction approach is not by improvising but based on our daily perception of metro lines: it is never to our knowledge how the real underground rails traverse in our city, but we always plan our trips according to the topological metro diagram that posted everywhere. Therefore, when dealing with underground morphology, the dialogue indeed pivots around abstract linkage rather than the distance. On this basis, we argue that the angular metric is ideal regarding investigating underground morphology or hybrid morphology.
Finally, we performed the quantitative analysis by looking into the descriptive statistics of the betweenness values of each simulation and conducting the correlation analysis among betweenness values and street walking scores and POI counts at all metro stations. The findings suggest that the mean value of the betweenness of the multimodal network increases with the increase of weights assigned to the metro network, but the results are not all higher than that of the original street network. In terms of the correlation analysis, regrettably, no significant correlations are reported. We attribute this to that both walking scores and POI counts are not direct and effective indicators of human movement. Due to the limitation of data in this research, we suggest that further research delves into the predictive power of the multimodal model regarding the human movement pattern and land use.

CONCLUSIONS

This research is a preliminary exploration of the underground urban form. While the underground system (metro system in this study) has emerged for long, it is somewhat neglected in the mainstream discourse of urban morphology. Based on the case of Beijing, we argue that the underground system should be encapsulated in either "superstructure" (Scheer, 2001) or "the hierarchy of elements" (Kropf, 2014, 1996) of urban morphology. Furthermore, the underground system is more impactful on the global scale than the local scale, and the angular metric is ideal in evaluating the urban structure involving underground networks. Further research is needed to refine the multimodal approach and identify the best radius and metric composition of the model so as to effectively interpreting physical urban fabrics.

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