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Accessibility patterns based on steps, direction changes, and angular deviation:

Are they consistent?

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ABSTRACT

Modeling spaces and their relationships is at the core of syntactic analysis, including reach analysis. In a syntactic model, two spaces can be described as close together or far apart based on the directional distance between them. In this study, we compare three different ways of measuring directional distance—namely, by number of steps, by number of direction changes, and by angular deviation—in the context of accessibility and reach analysis. By graphically showing how choosing a different way of measuring directional distance can result in a different reach or accessibility pattern, we provide an intuitive understanding of the different natures of the syntactic measures. By demonstrating how the modeling conventions and the geometric composition of lines at a local scale can have a huge impact on the results of syntactic analysis at a larger scale, we call for more attention to the conventions and principles used for modeling street networks.

KEYWORDS

Space syntax, street network, directional distance, reach, accessibility

1 INTRODUCTION

Analyzing directional distances[1] between locations in a street network is key to understanding urban spatial syntax. The syntactic structure revealed by the average directional distance (rather than Euclidean distance) from each location to any other location in an urban street network has

[1] Peponis, Bafna and Zhang (2008) have provided a formal definition of directional distance and a procedure for computing it. Here, however, we use the term "directional distance" in a more general sense.

been shown to have an effect on movement, distribution of commercial activities, and spatial cognition (Hillier *et al.*, 1993; Hillier, 1996; Ozbil, Peponis and Stone, 2011; Penn *et al.*, 1998; Peponis *et al.*, 1989; Scoppa and Peponis, 2015; Feng, Wang and Rao, 2012; Sakellaridi *et al.*, 2015; Kim and Penn, 2004; Christova *et al.*, 2012).

Directional distance, however, can be measured differently (Figure 1). In an axial map, the directional distance (often called "topological distance" in the space syntax literature) between two locations along different lines is measured by counting the number of steps taken (i.e., the number of lines traversed) in moving from one location to the other (Hillier and Hanson, 1984). In a segment map[2] or a street centerline map, the directional distance between locations along different line segments can be measured by computing the cumulative angular deviation or counting the total number of direction changes involved in moving from one location to another (Turner, 2007; Peponis, Bafna and Zhang, 2008). The different ways of measuring directional distance have propelled the development of different—albeit closely related—syntactic measures which are often compared against each other based on their correlation with pedestrian or vehicular movement (Turner, 2007; Peponis, Bafna and Zhang, 2008; Hillier and Iida, 2005; Hillier *et al.*, 1993).

While empirical studies based on the different syntactic measures abound, research on the effect of street modeling conventions on the different measures of directional distance is surprisingly lacking (Koch, 2019). The few studies that explicitly discuss the effect of modeling conventions on directional distance focus only on a single representation of street networks or a single definition of directional distance (Ratti, 2004; Feng and Zhang, 2019; Krenz, 2017; Dhanani *et al.*, 2012; Eisenberg, 2007). To fill this gap, we compare three different ways of analyzing directional distance—namely, by number of steps, by number of direction changes, and by angular deviation—in the context of accessibility and reach analysis (Peponis, Bafna and Zhang, 2008; Feng and Zhang, 2019; Ståhle, Marcus and Karlström, 2005). By graphically comparing the accessibility patterns generated based on the various measures of directional distance, we discuss the reasons behind the observed inconsistencies from the perspective of street network modeling conventions.

[2] Throughout this paper, the term "segment map" refers to a map that is created by breaking the axial lines at intersections in an axial map (Turner, 2004).

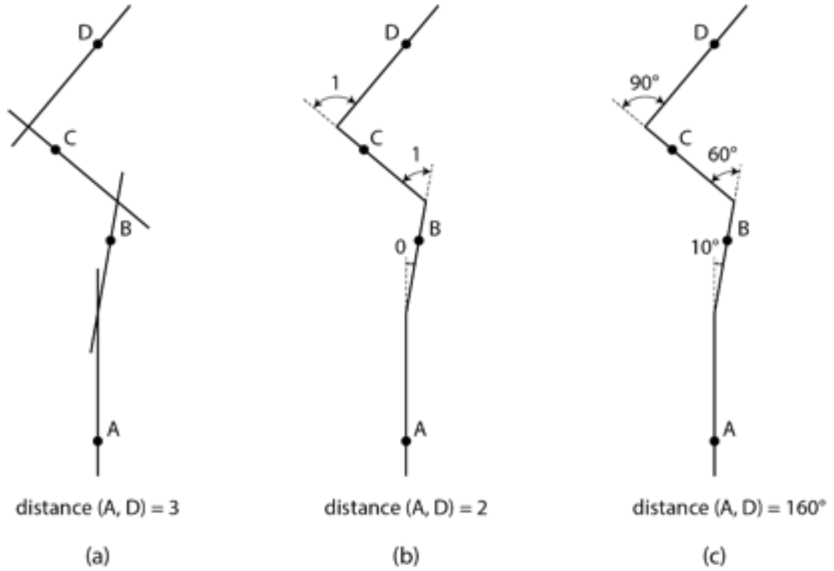

Figure 1. Three different ways of measuring directional distance. (a) Distance measured by counting the number of steps; (b) distance measured by counting the number of direction changes (with the threshold angle used for defining a direction change set to 20°); (c) distance measured by computing the cumulative angular deviation. In each subfigure, the black dots indicate four random locations along the four lines/segments.

2 DATA AND METHODS

2.1 Preparation of street network models

To study the different ways of measuring directional distance, we created three models—an axial map, a segment map, and a street centerline map—to represent the walkable street network of the city of Uppsala, Sweden.

As a device originally developed by Hillier and Hanson (1984) to describe a spatial system, an axial map is formally defined as "the minimal set of axial lines such that the set taken together fully surveils the system, and that every axial line that may connect two otherwise-unconnected lines is included" (Turner, Penn and Hillier, 2005, p. 428). The axial map of Uppsala was developed in an iterative process. The first version was completed in 2018, partly based on the axial map from the consulting firm Spacescape (Legeby, Koch and Miranda Carranza, 2019). The second version—also the latest version—was completed in 2021 for the research project Uppsala Segregation (Legeby and Feng, 2021). When drawing the latest version of the axial map, we referred to a high-resolution satellite image (dated 2020) shared by the Uppsala municipality. Additional sources, including Google Earth, Google Street View, and several GIS files shared by the municipality that show the location of bicycle lanes and hiking trails, were also consulted as needed. The Uppsala municipality reviewed the axial map and gave feedback (mostly related to the new developments in the city) which we have incorporated in the axial map used in this study.

A segment map can be produced by breaking the axial lines at intersections (Turner, 2004). We converted the axial map of Uppsala to a segment map using Place Syntax Tool (PST)—an open source tool that can be installed in a GIS environment for performing spatial network analysis (Ståhle, Marcus and Karlström, 2005; Stavroulaki *et al.*, 2019).

We used road network data from OpenStreetMap (OSM) as the basis to create the centerline map. Compared to the official data sources such as Swedish national road database (NVDB), the OSM data included more detailed information regarding the pedestrian paths in the city of Uppsala. OSM is a digital map database that contains road network data for many cities around the globe. As a form of crowdsourced, volunteered geographic information (VGI), it is freely available and has gained recognition within the space syntax community (Dhanani *et al.*, 2012; Krenz, 2017; Gil, 2015). Swedish municipalities and governmental organizations regularly add data to OSM. The OSM road data, in its raw form, however, is often unsuitable for syntactic analysis due to the presence of inconsistent, inaccurate, and redundant information. We followed the protocol used by Stavroulaki and Berghauser Pont (2019) to tidy the OSM road network data.

The axial map and the centerline map were prepared independently of each other. In other words, no explicit effort was made to match the axial lines and the centerlines in the maps. Consequently, there are some noticeable differences between the two maps. For instance, compared to the centerline map, the axial map generally shows more details in the densely built-up areas but fewer details in the underdeveloped and natural areas (Figure 2). The axial map also includes informal paths that are not recognized in the OSM data—detailed examples will come later in the text. It partly explains why the total length of axial lines in the axial map is greater than the total length of centerlines in the centerline map (Table 1). Despite the maps' differences, the analysis of 1 km metric reach—which measures the total length of lines or segments that can be reached as one walks in all possible directions from the midpoint of a line or segment without exceeding 1 km—resulted in similar patterns (Figure 2).

Table 1

Basic information about models

Model name	Total length of lines/segments (m)	Total no. of lines/segments
Axial map	1659045	16576
Segment map	1658996	74363
Centerline map	1423209	47268

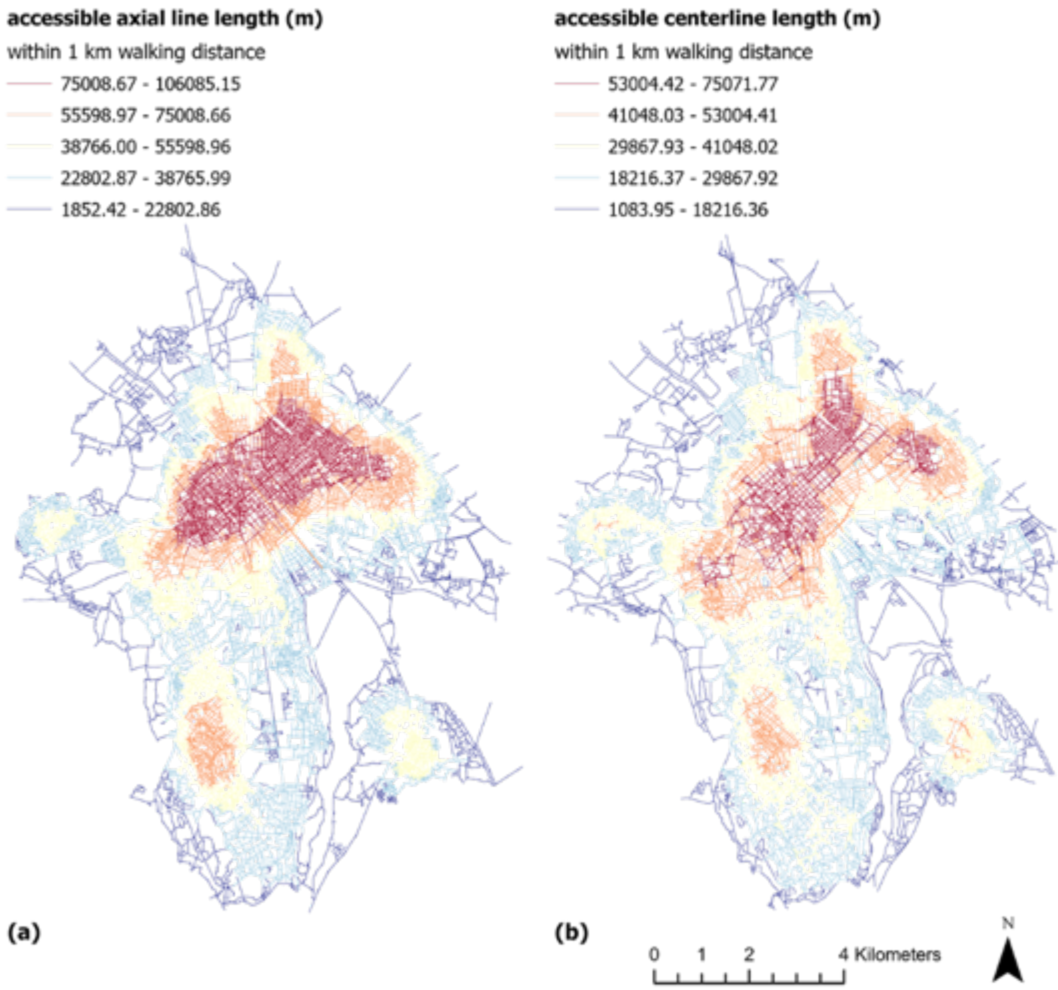

Figure 2. Patterns of metric reach. (a) 1 km metric reach analysis conducted based on the axial map; (b) 1 km metric reach analysis conducted based on the centerline map. Red indicates high values; blue low values.

2.2 Measures of reach and accessibility

According to the three different ways of measuring directional distance, we define three different measures of reach. Although reach analysis was originally developed with the street centerline map in mind, we treat it as a broad type of analysis which revolves around the general question: How much street length—measured by the length of axial lines, segments, or centerlines, depending on the model used—can be reached from a given origin within a certain distance limit? Specific measures of reach can be further defined based on the specific distance metric used in the analysis.

(1) Directional reach

We define directional reach as the total length of streets that one can reach by walking in all possible directions from a given origin without taking more than a specified number of direction changes. The above definition is consistent with how directional reach is defined in earlier research (Peponis, Bafna and Zhang, 2008; Feng and Zhang, 2019). Throughout this study, we used 20° as the threshold angle to determine whether there is a direction change as one moves from one street to another. In the following text, directional reach calculated based on *x* number of direction changes will be simply called "*x*-direction-change reach".

(2) Step reach

We define step reach as the total length of streets that one can reach by walking in all possible directions from a given origin without taking more than a specified number of steps (i.e., traversing more than a specified number of axial lines). While the step reach analysis is conducted based on an axial map, the step reach values can be transferred to a segment map that is derived from the axial map. In that case, each segment in the segment map would simply be assigned the step reach value of the corresponding axial line. In the following text, step reach calculated based on *x* number of steps will be simply called "*x*-step reach".

(3) Angular reach

We define angular reach as the total length of streets that one can reach by walking in all possible directions from a given origin without making more than a specified cumulative angular deviation. The angular reach analysis is conducted in the context of street centerline maps or segment maps. In the following text, angular reach calculated based on *x*-degree cumulative angular deviation will be simply called "*x*-degree angular reach".

The street network reach for a given location is analogous to the accessibility to cumulative opportunities, which is frequently studied in the fields of urban and transportation planning (Hansen, 1959; Koenig, 1980; Bhat *et al.*, 2000). However, reach analysis does not require any information about land use, and the purpose is to characterize the urban potential associated with a given location based on the street network structure alone. In this paper, the measures of step reach and angular reach were computed by using PST, and the measures of directional reach were computed by using the software "UrConnect" developed by Dr. Haofeng Wang and his team from Shenzhen University, China.

2.3 Comparative analysis

Visual and statistical comparisons were made between patterns of reach and accessibility, including:

1. A comparison between 6-step reach and 6-direction-change reach.
   The axial map was used to conduct the step reach analysis, while the centerline map was used to conduct the directional reach analysis. Although one could conduct the directional reach analysis based on the segment map that is automatically derived from the same axial map, it would be of less interest because the pattern of step reach would look identical to that of directional reach if the threshold angle for the directional reach analysis is set to zero degrees (Figueiredo, 2015). Furthermore, since a threshold angle in directional reach analysis is often used with the intent to capture similar information as embedded in axial lines—colloquially referred to as "number of turns" in both cases—we compare 6-step reach in the axial map with 6-direction-change reach in the centerline map. We chose 6 steps as the distance limit as, on average, it corresponds to a scale comparable to 1 km walking distance—considering that the mean step reach within

6 steps for the whole city roughly equals the mean metric reach within 1 km walking distance for the whole city. Since there lacked a one-to-one correspondence between the set of axial lines in the axial map and the set of centerlines in the centerline map, a correlation analysis could not be immediately applied. To enable both a visual and a statistical comparison, we also analyzed the total number of preschools accessible from each residential address point within 6 steps and 6 direction changes, respectively.

2. A comparison between 6-step reach and 450° angular reach.
   For this comparison, the angular reach analysis was conducted based on the segment map, while the step reach analysis was conducted based on the axial map. The results from the step reach analysis were transferred to the segment map for ease of comparison. Here, we used 450° as the distance limit for the angular reach analysis because among the eight multiples of 90° we tested (from 180° to 810°), 6-step reach correlated best with 450° angular reach (Figure 3). The intent was to compare the measures of reach that were most closely related to one another so that our analysis, if it is skewed in any direction, is skewed towards where the measures match one another most.
3. A comparison between 6-direction-change reach and 540° angular reach.
   For this comparison, both the directional and the angular reach analysis were conducted based on the centerline map. Here, we used 540° as the distance limit for the angular reach analysis because among the eight multiples of 90° we tested (from 180° to 810°), 6-direction-change reach correlated best with 540° angular reach (Figure 3). The intent of this choice is the same as just mentioned above.

These comparisons can help us better understand to what extent *measures* can be used to reduce differences in *modelling*—such as how a change in direction in a centerline map may approximate a transition between axial lines in an axial map. The analyses will show how directional change in a centerline map compares to step depth in an axial map, and how angular measures compare to both.

When coloring the maps to make the pairwise visual comparisons, we classified the values in each map based on the Jenks Natural Breaks algorithm implemented in ArcGIS Pro (version 2.8.2). We did not color each pair of maps based on the same class breaks because each map had a different range of values and we were more interested in comparing the spatial *distribution* of values than the values themselves.

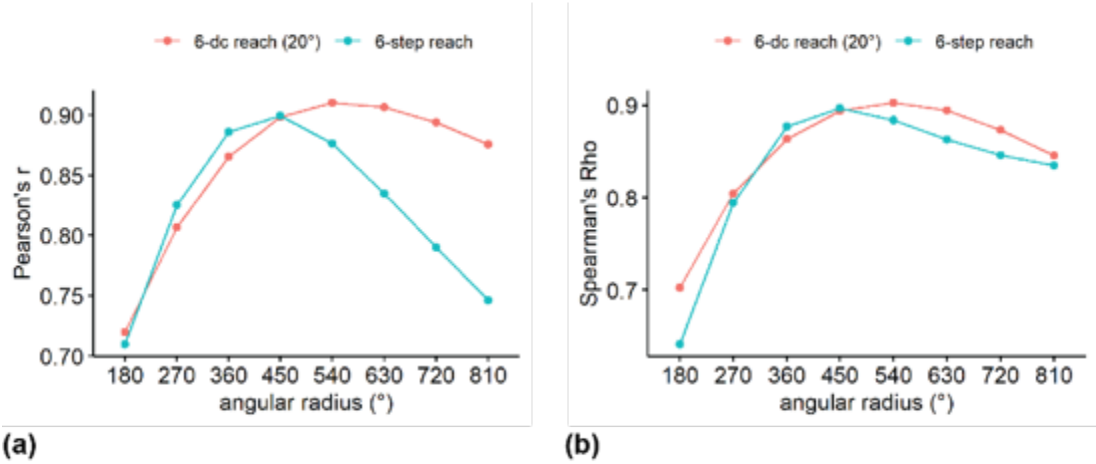

Figure 3. Correlation coefficients between angular reach (computed based on different angular distance limits) and both 6-step reach and 6-direction-change reach, respectively. (a) Pearson's correlation coefficients; (b) Spearman's rank correlation coefficients.

3 RESULTS

3.1 Comparison between 6-step reach and 6-direction-change reach

Both the 6-step reach analysis and the 6-direction-change reach analysis showed that the central area was the most accessible area in the city (Figure 4). The other parts of the city—including those that had a good metric reach within 1 km walking distance (Figure 2)—appeared to be rather segregated. Despite this general similarity, there were also some differences. For example, the most accessible lines picked out by the 6-step reach analysis all lay within the center. By contrast, the most accessible lines picked out by the 6-direction-change reach analysis covered a wider area, reaching neighborhoods outside the city center. One reason for the difference is that by using a threshold angle for determining whether there is a direction change, the directional reach analysis smoothed out the differences among the segments that comprise a quasilinear street. Thus, the high reach values could be propagated from the center to remote areas along the curvilinear streets (two examples are pointed out with arrows in Figure 4b).

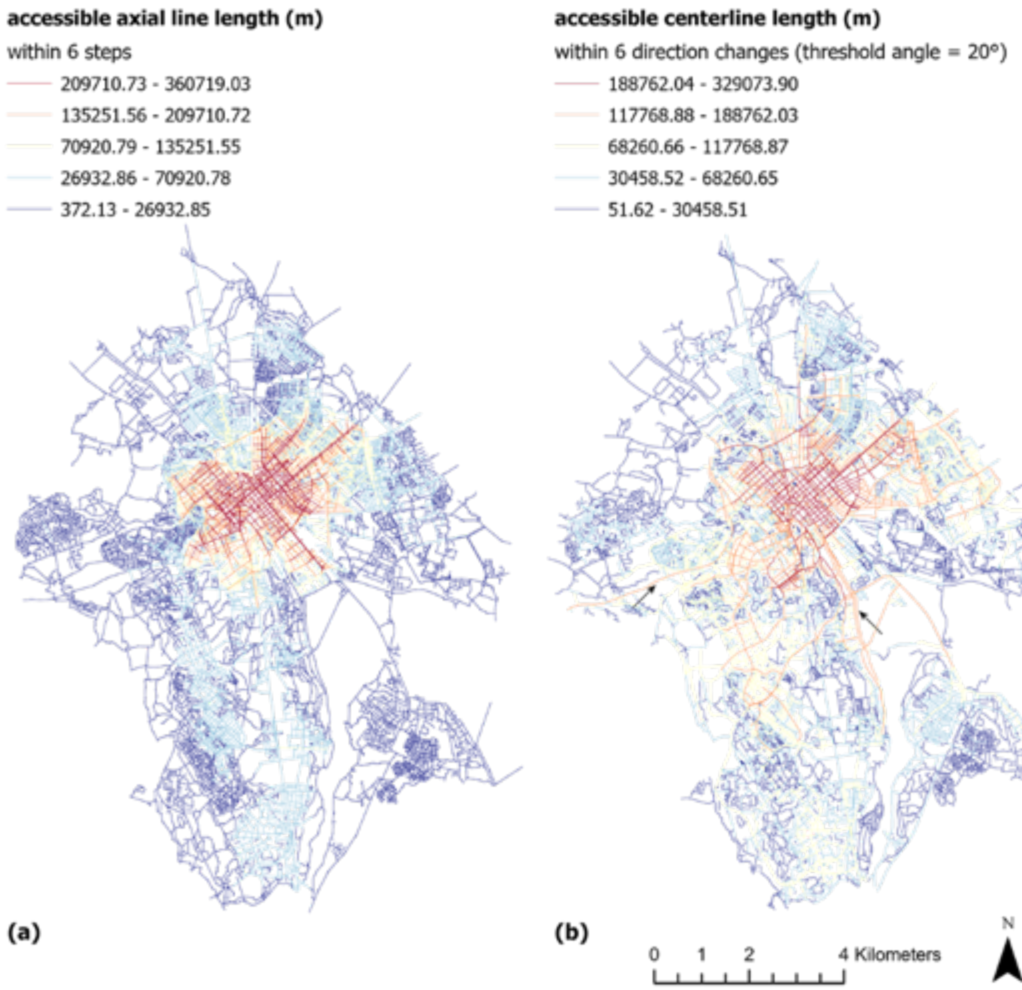

Figure 4. Patterns of step reach and directional reach. (a) 6-step reach analysis conducted based on the axial map; (b) 6-direction-change reach analysis conducted based on the centerline map. Red indicates high values; blue low values.

We could not immediately run a correlation analysis between the two measures of reach because the units of analysis were different due to the different maps used. To address this problem, we instead analyzed the total number of preschools that can be accessed from each residential address point within 6 steps and 6 direction changes, respectively. Preschool is an example of basic public service that many people use on a daily basis, therefore it has practical relevance. Using preschools for this analysis has also additional advantages: first, they are rather equally distributed and thus less spatially biased; second, there are not too few, but also not too many, of them, so that each residential address is generally close to one or two of them but there is also some differentiation. A statistical correlation analysis was possible since the units of analysis (i.e., the set of residential address points) stayed the same regardless of which map was used to carry out the analysis. The points indicating the locations of the preschools and residential addresses were paired with the closest axial lines or centerlines to enable the network analysis. A Pearson correlation coefficient was computed to assess the relationship between the total number of preschools accessible within 6 steps and the total number of preschools accessible within 6 direction changes. There was a strong, positive correlation between the two variables, *r*(23715) = .81, *p* < .001. It was not surprising, given the similarity between the 6-step reach and the 6-direction-change reach patterns (Figure 4). Next, a visual comparison was made to see where the discrepancies occurred.

As shown in Figure 5, the overall accessibility patterns looked similar: people live in the city center can reach more preschools within 6 steps or within 6 direction changes. The main inconsistencies between the two patterns seemed to be located in places immediately surrounding the central area, as highlighted in the maps (Figure 5). Some residential addresses that scored high in the 6-step accessibility analysis scored poorly in the 6-direction-change analysis. And vice versa.

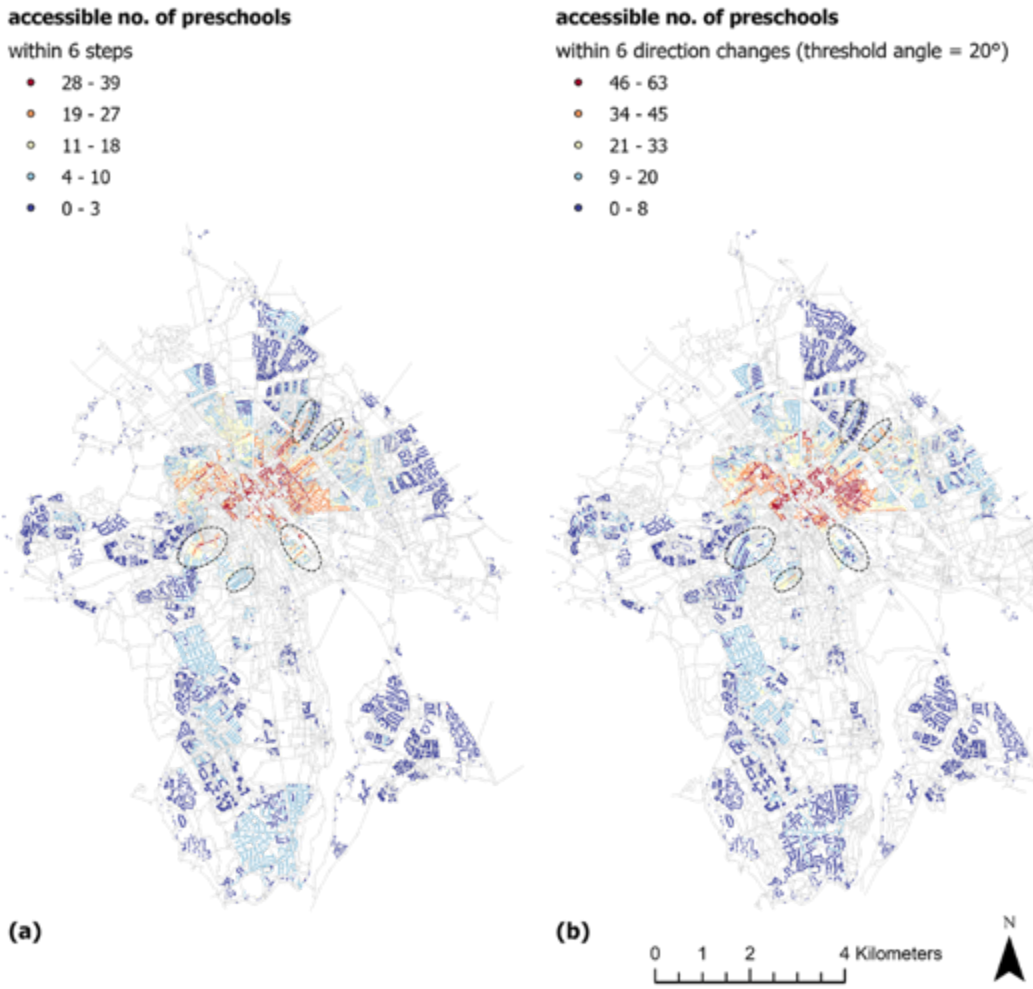

Figure 5. Accessibility of preschools. (a) Total number of preschools accessible within 6 steps from each residential address point. (b) Total number of preschools accessible within 6 direction changes from each residential address point. Red indicates high values; blue low values.

To better understand the reasons behind such inconsistencies, we highlighted the 6-step reach and the 6-direction-change reach for two specific residential address points (Figure 6 and Figure 7). As shown in Figure 6, the 6-step reach for the address point along Råbyvägen—a major street connecting the center to the northeastern part of the city—was much greater than its 6-direction-change reach. While the 6-step reach covered almost the whole central area, the 6-direction-change reach barely touched anything lying to the southwest of the address point. What prevented the growth of its 6-direction-change reach in that direction?

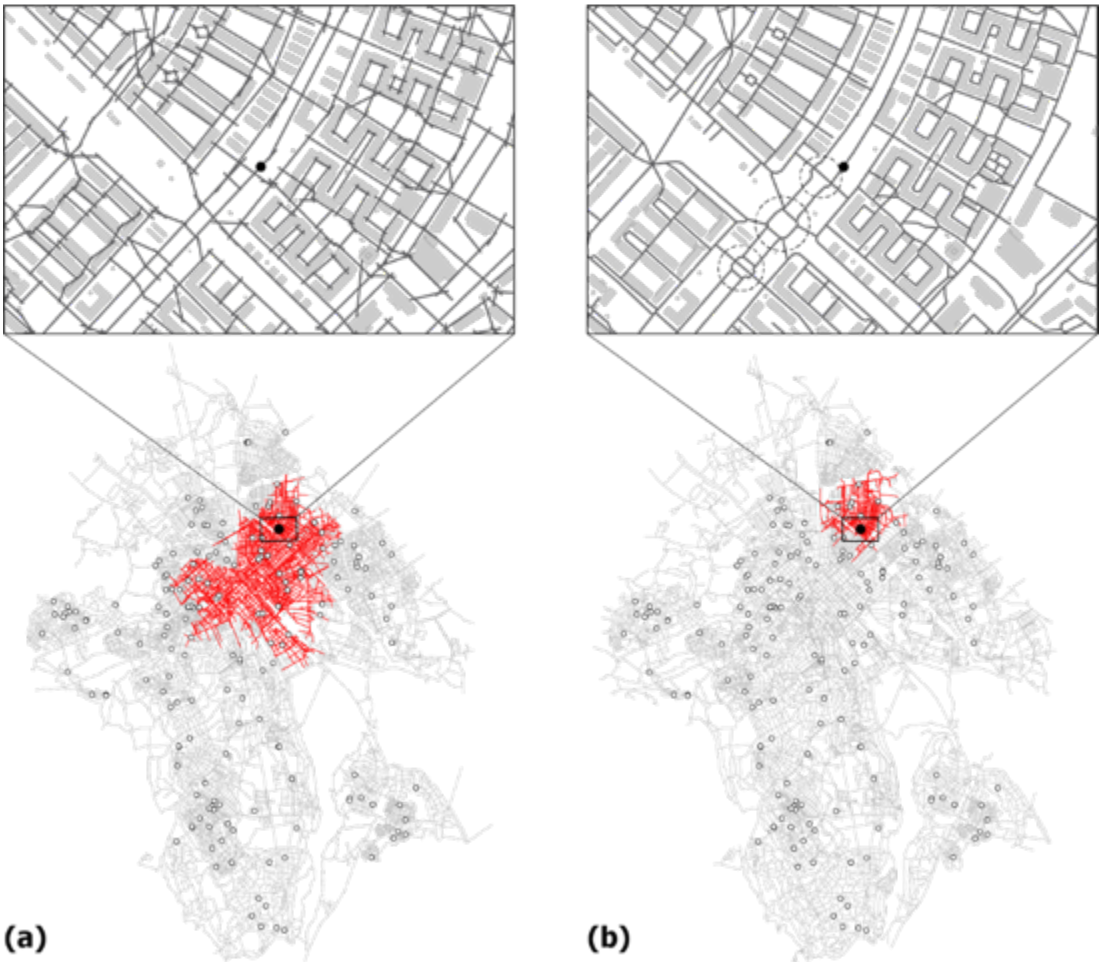

Figure 6. A residential address where the 6-step reach is much larger than the 6-direction-change reach. (a) 6-step reach; (b) 6-direction-change reach. The lines within reach are highlighted in red. The black dots indicate the address point chosen for analysis, and the white circles indicate the locations of preschools.

A closer look at the centerline map revealed that because of the many bends modeled near the pedestrian crossings along Råbyvägen (marked with circles in Figure 6b), it would involve as many as ten direction changes to move from the address point towards the city center. This is in sharp contrast to what we observed in the axial map. As shown in the close-up view in Figure 6a, no step was involved in moving from the address point along Råbyvägen towards the southwest because the excessive details about road geometry were omitted in axial models. That is why one could reach far into the city center within 6 steps based on the axial map but could only touch the edge of the center within 6 direction changes based on the centerline map.

Figure 7 shows a residential address where the 6-step reach was much smaller than the 6-direction-change reach. The discrepancy is again caused by the different modeling conventions. When drawing the axial map, we added lines to represent the paths inside the courtyards of the perimeter blocks (as long as they were not deliberately closed to the public). As a result, if one starts from a residential address point that is paired with one of the internal paths of the courtyards, it may take three or more steps to first get out of the courtyard to reach a street. By contrast, the paths inside the blocks were generally not included in the centerline map. Thus, the address point shown in Figure 7b was paired with a street outside the block, which saved a few direction changes that would have been needed if the paths inside the courtyard had been included in the map. While the overall patterns of the 6-step reach and 6-direction-change reach look quite similar and one might be used to emulate the other, different decisions on (a) what space to include in the model, (b) what is represented as different spaces, and (c) how to measure distance can lead to significant discrepancies in the results of reach analysis on a segment-by-segment basis.

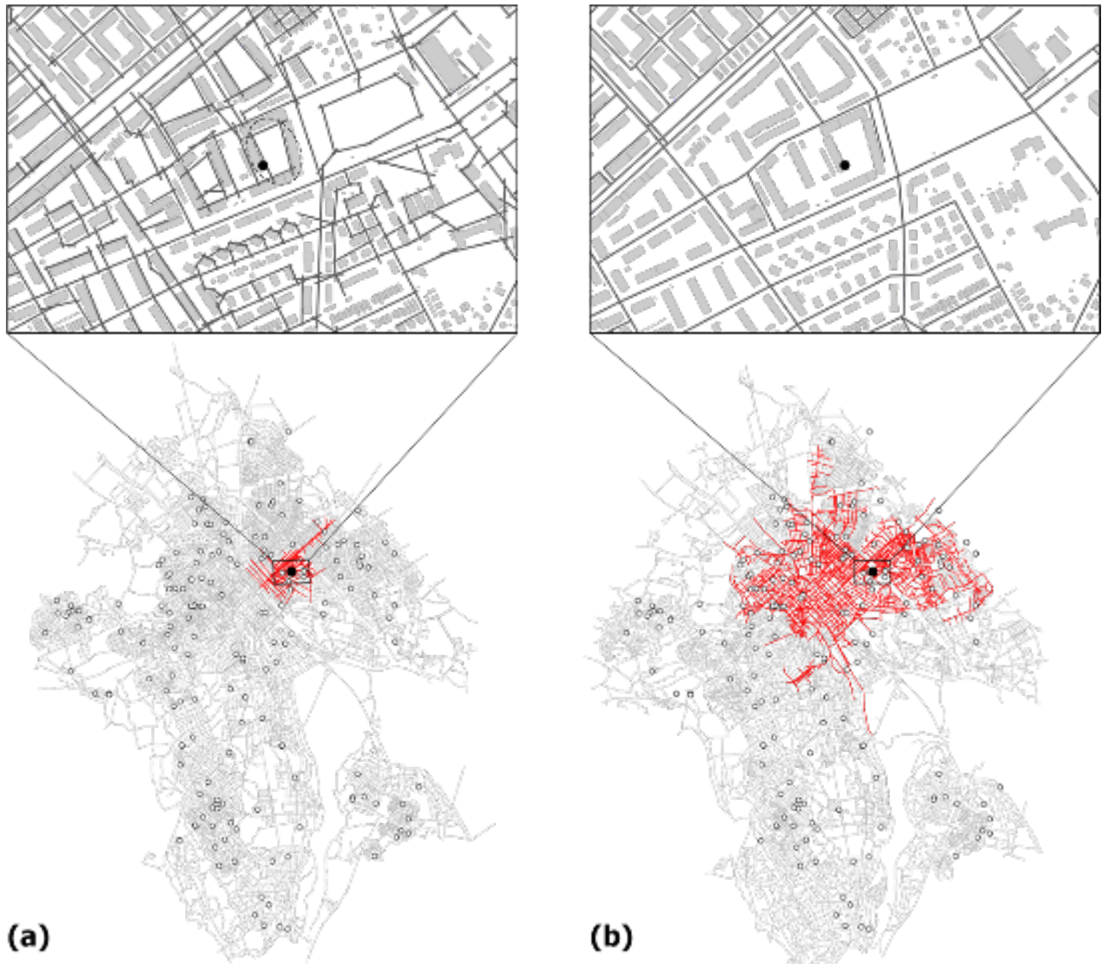

Figure 7. A residential address where the 6-step reach is much smaller than the 6-direction-change reach. (a) 6-step reach; (b) 6-direction-change reach. The lines within reach are highlighted in red. The black dots indicate the address point chosen for analysis, and the white circles indicate the locations of preschools.

3.2 Comparison between 6-step reach and 450° angular reach

Both a Pearson correlation coefficient and a Spearman's rank correlation were computed to assess the relationship between the 6-step reach and the 450° angular reach. The results indicate that there was a strong, positive correlation between the two variables (Figure 3).

As shown in Figure 8, the overall pattern of 6-step reach was also consistent with that of 450° angular reach: the central area stood out in both patterns as it generally had a much higher reach than any other part of the city. Despite the overall similarity, one noticeable difference was that compared to the 6-step reach pattern, the "red lines" (i.e., the ones that assume a relatively high reach value) in the 450° angular reach pattern tended to form longer sequences, extending further into the southern and northern part of the city (Figure 8b).

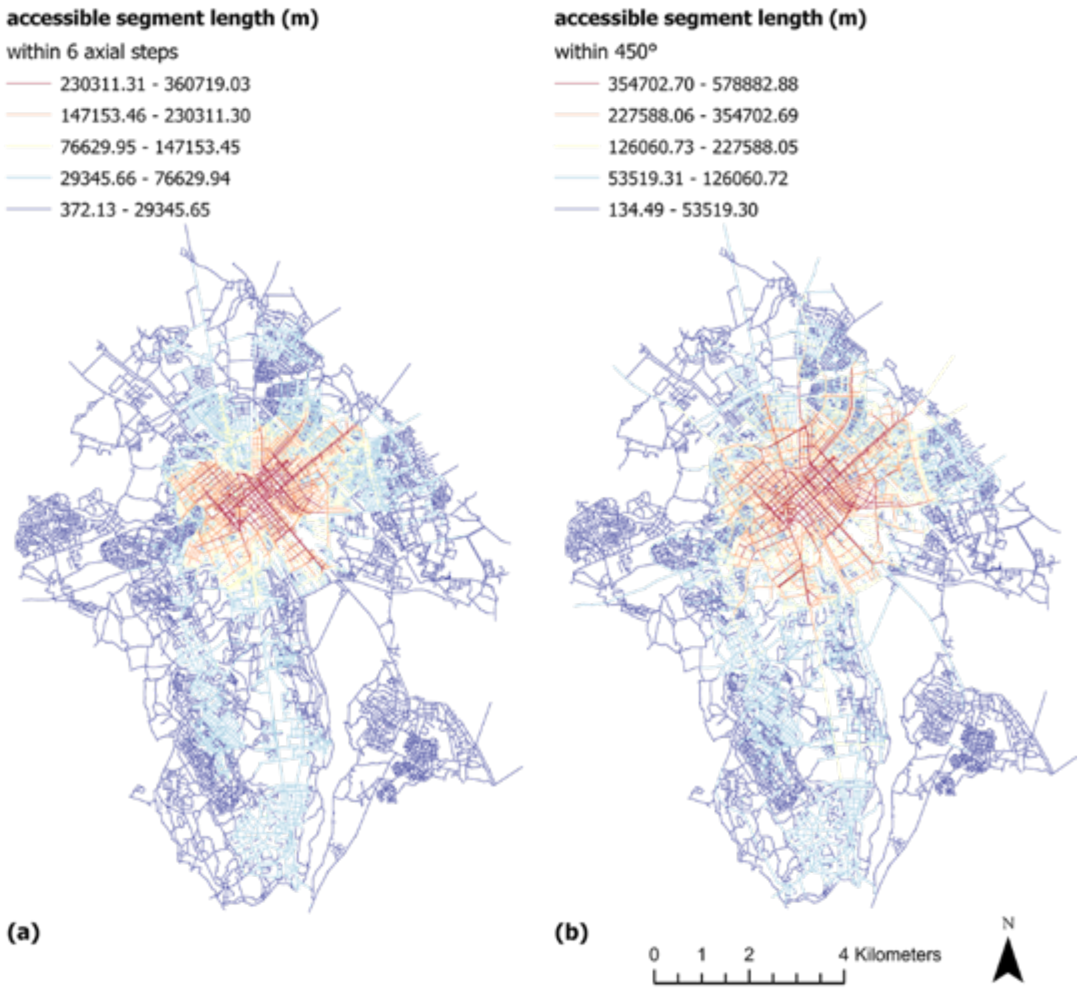

Figure 8. Patterns of step reach and angular reach. (a) 6-step reach analysis conducted based on the axial map; (b) 450° angular reach analysis conducted based on the segment map. Red indicates high values; blue low values.

To better understand the difference, we selected a location where the 6-step reach was much smaller than the 450° angular reach and made a visual comparison (Figure 9). The detail views in Figure 9 show that starting from the black dot and moving along the gently curved south-north running road would involve quite a few steps but only a small angular deviation. That is the main reason why one could reach deep into the center and the northern part without exceeding the angular distance limit but would quickly exhaust the maximally allowed number of axial steps. If we interpret this result from the perspective of choosing a measure of directional distance to maximize reach, then it suggests that using cumulative angular deviation rather than number of axial steps to define the distance limit would most likely benefit a location along a gently curved street (which consists of many lines in an axial representation) in a reach analysis. In this case, even though the overall patterns of reach look similar and the distance measures were analyzed based on the same model and were closely related, the results can still be drastically different at the individual-segment level.

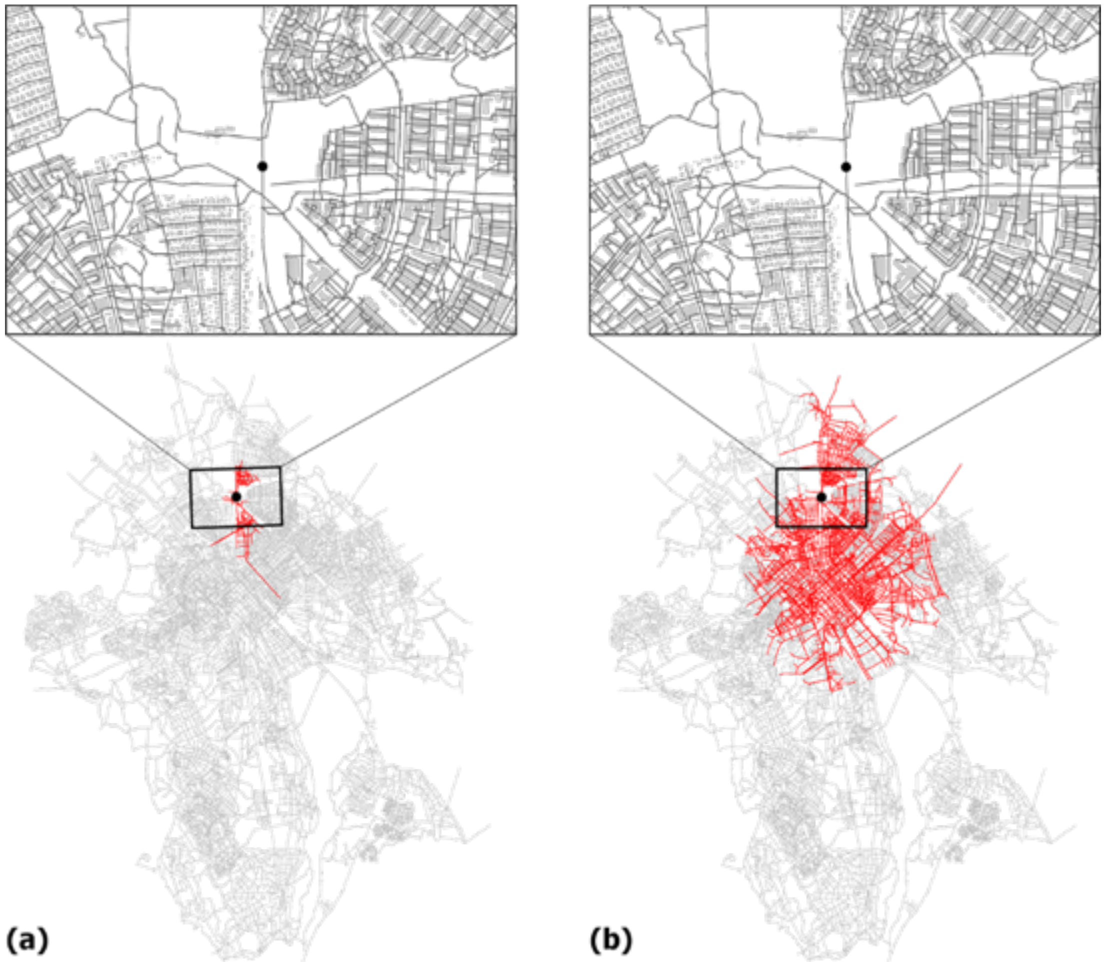

Figure 9. A location where the 6-step reach is much smaller than the 450° angular reach. (a) 6-step reach; (b) 450° angular reach. The black dots indicate the location chosen for analysis. The lines within reach are highlighted in red.

3.3 Comparison between 6-direction-change reach and 540° angular reach

Both a Pearson correlation coefficient and a Spearman's rank correlation were computed to assess the relationship between the 6-direction-change reach and the 540° angular reach. The results indicate that there was a strong, positive correlation between the two variables (Figure 3). As shown in Figure 10, the pattern of 6-direction-change reach and the pattern of 540° angular reach were very similar: both showed that the central area had a higher reach than the other parts of the city. The main difference was that compared to the 540° angular reach pattern, in the 6-direction-change reach pattern, the "orange lines" (i.e., the ones that assume not the highest but the next highest reach values) tended to form longer sequences and extend far beyond the city center (Figure 10a).

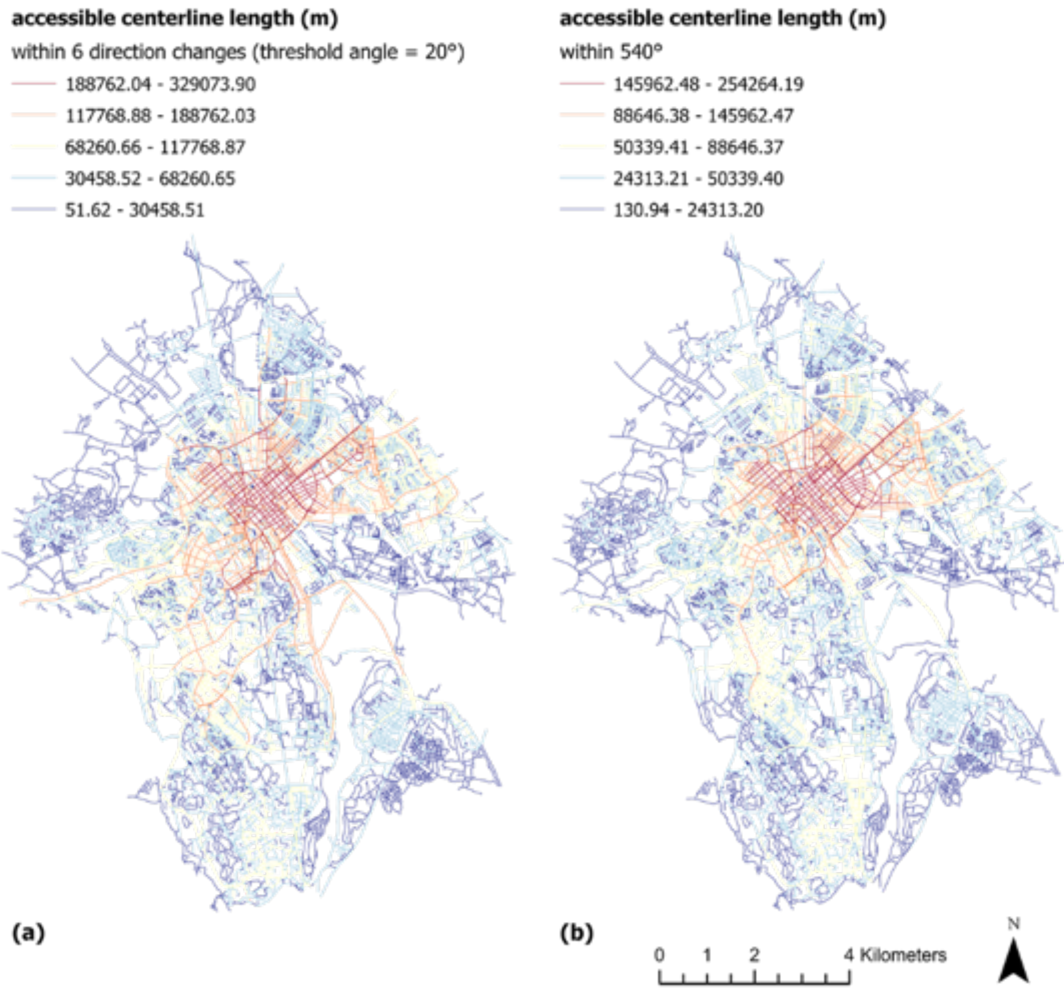

Figure 10. Patterns of directional reach and angular reach. (a) 6-direction-change reach analysis conducted based on the centerline map; (b) 540° angular reach analysis conducted based on the centerline map. Red indicates high values; blue low values.

We further selected a location where the 6-direction-change reach was much larger than the 540° angular reach and made a visual comparison (Figure 11). The detail views in Figure 11 show that starting from the black dot and moving along the south-north running road would involve very few—if not zero—direction changes, because most deviations along the path were smaller than the threshold angle we used to define a direction change. (As long as the angular deviations are small along a curvilinear path, no direction changes will be identified. And in that sense, the curvilinear path would be treated the same as a straight path.) By contrast, in angular reach analysis, any angular deviation, no matter how small it is, would be added to the cumulative sum. That is the main reason why the directional reach for the given location covered a greater area than the angular reach. If we interpret the result from the perspective of choosing a measure of directional distance to maximize reach, then it suggests that using number of direction changes rather than cumulative angular deviation to define the distance limit would most likely benefit a location along a gently curved street (represented by a sequence of line segments with only slight angular deviations from one to the next) in a reach analysis. Again we found that both ways of measuring distance generated similar overall patterns, but could result in noticeable differences on a segment-by-segment basis.

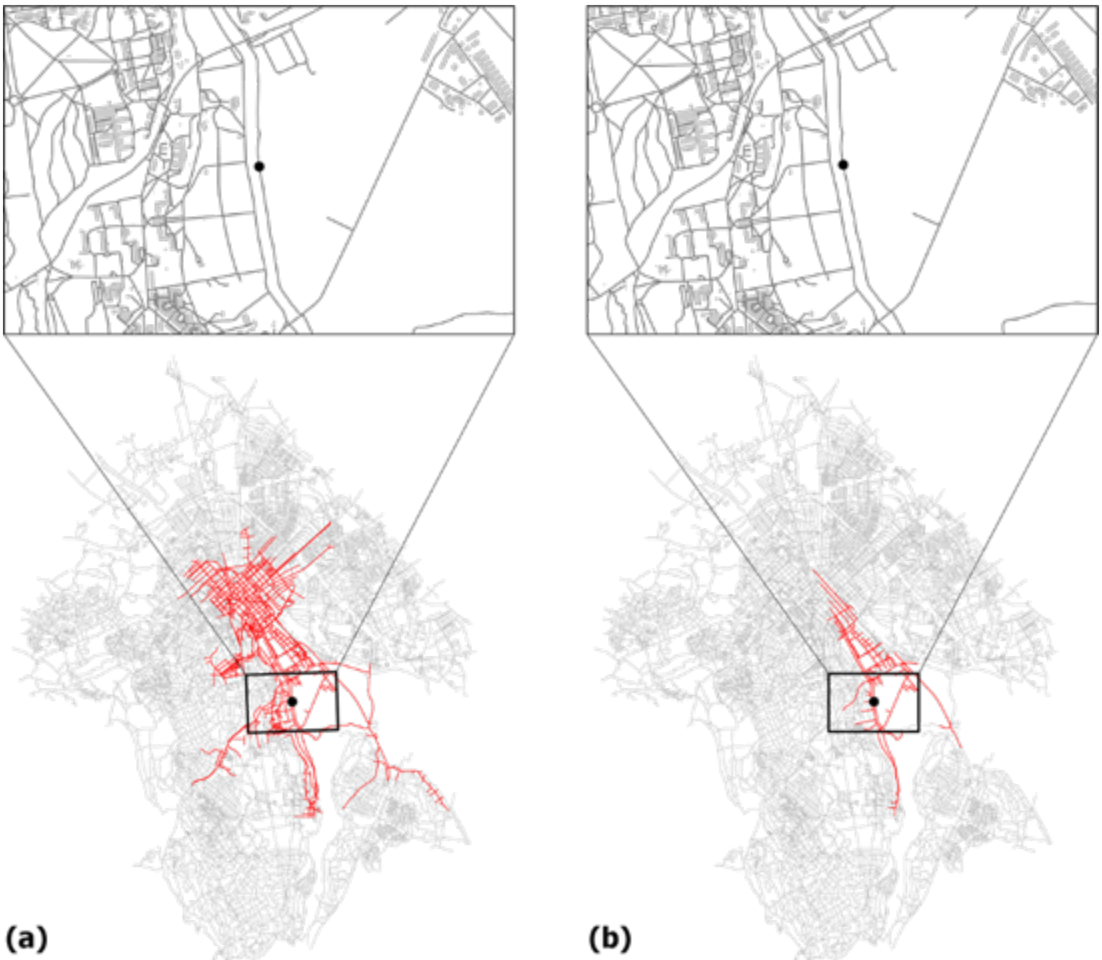

Figure 11. A location where the 6-direction-change reach is much larger than the 540° angular reach. (a) 6-direction-change reach; (b) 540° angular reach. The black dots indicate the location chosen for analysis. The lines within reach are highlighted in red.

4 DISCUSSIONS AND CONCLUSIONS

By measuring the directional distance differently—namely, by counting the number of steps, by counting the number of direction changes, or by computing the cumulative angular deviation—we specified the distance limits differently, which gave rise to different reach and accessibility measures. We compared the different reach and accessibility measures both visually and statistically. We showed that the observed inconsistencies among the patterns were largely attributed to the geometric composition of lines or segments used to represent the streets. Specifically, by comparing the step reach and the directional reach patterns produced based on two different models, we showed that inconsistencies could result from both "overrepresentation" (e.g., excessive details about how the sidewalks and the crosswalks meet along a street) and "underrepresentation" (e.g., missing paths in the courtyard of a perimeter block) in one of the models. By comparing the step reach and the angular reach patterns based on the same model, we showed that for a location along a quasilinear street represented by a sequence of lines, using the cumulative angular deviation to define the distance limit for a reach analysis would most likely generate a larger reach than using the number of steps; by comparing the directional reach and the angular reach patterns based on the same model, we showed that for a location along a curvilinear street represented by a sequence of line segments (with small angular deviations between each pair of adjacent segments), using the number of direction changes (with a generous threshold angle to determine a direction change) to define the distance limit for a reach analysis would most likely generate a larger reach than using the cumulative angular deviation. All the visual comparisons suggested that the geometric composition of lines at a rather local scale can have a considerable effect on the measurement of reach at a larger scale.

While our focus was on the inconsistencies among the patterns, we should point out that despite the inconsistencies found on an individual street basis, the overall patterns were largely consistent—both visually and statistically. The Spearman's rank correlation analysis between the 6-step reach and the angular reach defined by various angular deviations suggested that the patterns of angular reach tended to converge at larger scales—in other words, after a certain point, the rankings of the lines would largely stay the same even if we continue increasing the distance limit for the angular reach analysis. The finding makes intuitive sense and highlights the question of to which extent the inconsistencies observed in the current study can be increased or reduced by changing the scale of reach analysis (i.e., the distance limits used for reach analysis). Numerous syntactic measures have been proposed based on the different ways of measuring directional distance. With the advanced computational tools, one can easily produce the different measures in a few clicks. Oftentimes, it is not the shortage of measures, but rather the indiscriminate use of them, that undermines the credibility of syntactic research. By graphically showing how choosing a different way of measuring directional distance could result in a different reach or accessibility pattern, we provide an intuitive understanding of the different natures of the syntactic measures.

Last but not least, we call for more attention to the models themselves. Once a research question is formed, the choice of models—for example, whether to use an axial map or a street centerline map—and the decisions related to modeling—for example, whether or not to simplify the lines representing a roundabout—should depend on the question at hand and be informed by theory. Even when data availability becomes a key issue and makes one biased towards certain models, one should be aware that the difference between models is not always a matter of technicality but sometimes rather due to the models' theoretical roots (or lack thereof)—despite the fact that all the models may deliver similar visual and statistical patterns. Without a clear understanding of the theoretical basis of each model, one could easily fall into the trap of treating the different models as interchangeable not just in statistical terms but also in theoretical terms (Koch, 2019). In that regard, modeling is a theory-laden process which operates independently of the measures, and the differences between the models cannot and should not be resolved by measures alone.

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