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Measuring regional accessibility in urban form: A reproducible approach for urban analytics

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Abstract. Across countries, urban form is characterised by polycentric city-regions. This entails challenges in analysing urban structures with regard to their locations within these city-regions. In particular, research in regional and urban planning lacks medium-scale analytical approaches. We present a fully reproducible approach to describe regional location within urban form through accessibility. Our network-based approach relies on street-network data to derive a weighted centrality measure for each location in a region (Closeness Centrality). Considering a distance decay, we retrieve travel impediments for two modes of transportation: car-based transport and short-distance mobility (walking/cycling). To apply the approach for questions of urban analytics, we use the example of vacant lots. Given their key role for infill development, we analyse their distribution across four regions with distinct urban form characteristics. The results indicate that the approach allows for an analysis within a region to show the distribution of an urban structure of interest across different levels of centrality. The standardised description of a regional score of centrality also allows for comparing the distributions across regions. Our research contributes to align urban analytics closer to relevant conceptions of functional city-regions with urban cores, suburbs and peripheries.

Submission Type: Algorithm, Dataset, Analysis

BoK Concepts: [AM] Analytical Methods

Keywords. regional location, closeness centrality, infill development, street network

1 Introduction

In urban analytics (Boeing et al., 2022), measuring accessibility in urban form is of increasing importance, as urban form has evolved towards polycentric structures. To describe location in these structures, means to consider functional interactions of a location with others. Here, transport networks rather than geographical distance become crucial as analytical basis. Through relative location in networks, functional contexts of cities and regions can be included in conceptual and empirical research. Approaches that rely on graph theory and apply road or transport networks have proofed highly suitable to describe accessibility (Jehling et al., 2018; Xiao et al., 2016) but also explain emerging urban phenomena (Louf and Barthélemy, 2013). Through measures, such as Closeness Centrality (CC_i), polycentricity of urban form can be represented through the medium distance of a certain location i to all other locations (see Sevtsuk (2010) for an overview of centrality measures). However, while transportation research offers a broad range of approaches, tools and models for accessibility with high level of detail in modes and demand and supply (e.g.Yang et al. (2025); Gonçalves et al. (2025)), a regional scale approach appears missing for urban analytics that allows for basic differentiations of functional contexts of a location using an efficient set of input data.

For a broad application for specific questions of urban analytics, global data sets are available. OpenStreetMap (OSM) offers an opportunity to describe road or transport networks and therewith location within urban form across the globe (Weiss et al., 2018). The Global Human Settlement Layer allows for identifying urban land and also attribute estimated population information to it. It also enables the analysis of areas across nation boundaries and thus beyond heterogeneous national data models. However, the application of network analysis to describe the accessibility of locations for various thematic interests appears time consuming as new data needs to be included in workflows.

Against this backdrop, it is the aim of this contribution to present a reproducible workflow for measuring accessibility that operates based on openly available data and allows for a flexible adaptation to one or multiple study areas, and the integration of further thematic objects that can thus be described by their location. This brings the opportunity to analyze built urban form not as a topographical but functional location in cities or regions.

In the following, we describe this approach and provide a reproducible workflow. We test the application for the analysis of regional distributions of vacant lots, i.e. underused urban land (Ehrhardt et al., 2023). The repository provides data for the workflow that prepares the spatial context and integrates the road network and population data. The network analysis is conducted and every location is described through the population-weighted travel time and distance to other locations on the road network using OpenRouteService (ORS) (Heidelberg Institute for Geoinformation Technology, 2025).

2 Method and data

2.1 Describing location through Closeness Centrality

In polycentric, functional urban regions a specific location is defined through its accessibility in transport networks rather than its geographic location. Centrality measures describe this accessibility through the relation of a location to other locations based on distance or travel impediment such as costs or time within such networks. For question of functional connection of a location, the measure CC_i appears appropriate, as it shows how far a location is away from others (Sevtsuk, 2010). It uses the mean travel impediment to all other locations in a defined network to describes the relative location of a given place (Jehling et al., 2021; Xiao et al., 2016).

We adapt this measure to the suburban characteristics of polycentric urban regions, where accessibility is given through different modes of transport such as urban-rural mobility behaviour for car-based commuting, but also urban short-distance travels by foot or bicycle. A combined centrality measure is calculated through applying impedance functions by mode of transport as well as respective impedance functions to reflect daily mobility patterns.

As shown in Equation 1, Closeness Centrality CC_i is described through the average travel impediment d_{ij} on the fastest route from an origin i to all other destinations j in a defined region. This impediment is then adapted to the suburban mobility patterns through an exponential impedance function that prioritizes destinations closer to the origin. Following a detailed analysis performed by Verma and Ukkusuri (2025), we apply a power exponential function with empirically derived parameter values reflecting the specific mode of transport ($\beta 1$ and $\beta 2$). Then, each travel impediment for each route is weighted by the population at a destination W_j, producing the impedance weighted reachable population sum from location i. To avoid outlier-distortion, values are z-score standardised within each region and then scaled to a range between

Table 1. Impedance function parameters $\beta 1$ and $\beta 2$ used per travel mode taken from Verma and Ukkusuri (2025)

		Mode	β_1	β_2
Travel time	(h)	Driving	0.019	1.340
Travel distance	(km)	Walking	1.174	0.749
		Cycling	0.333	0.871

0 and 1. The resulting range describes lowest to highest centrality in each region and enables comparative analysis across regions. The meaning of a given value is defined by the relative position within the regional context, regardless of structural differences between locations with the same CC_i in different regions.

$$CC_i = \text{scale}\Big(\sum_{j=1, j\neq i} \Big(e^{-\beta_1 \cdot d_{ij}^{\beta_2}} \times W_j \Big) \Big) \quad (1)$$

with $\text{scale}(x_i) = \frac{x_i - \bar{x}}{s_x}$ (z-score) and rescaled to $[0,1]$ where $\bar{x}$ and s_x are computed within each region

2.2 Implementation and adaptation for urban analytics

In our implementation of the approach (Figure 2), the network analysis is based on a regional road network of the selected study regions and a 10 km buffer around it to avoid border effects. A 1×1 km grid of points is created and each point moved to the closest location in the road network. We then draw a 50% sample of the points and assign them a population sum value based on voronoi polygons (Casali and Heinimann, 2019). The resulting point layer serves as origin and destination points to extract a matrix of travel times (h) and distances (km) using OpenRouteService. Based on this matrix and the population sums to be used as weights, we calculate CC_i as described in section 2.1 for driving and walking/cycling separately using the β-parameter values given in Table 1. For the CC_i calculation of walking/cycling, we calculate the travel impediments for both walking and cycling and combine them. The distance/time decay function $f(d_{ij}) = e^{-\beta_1 \cdot d_{ij}^{\beta_2}}$ within Equation 1 is applied for each mode and mean values are used for weighting and scaling. CC_i values for driving and walking/cycling are then in the same scale [0-1] and for each point a mean composite index is calculated between them. Finally, the values for all locations in the region are again rescaled from 0 to 1 to allow for comparability between regions. To apply this in urban analytics, the approach maps the points with information on centrality to a set of urban structures allowing us to describe their relative centrality within the regional network on a scale from lowest to highest.

Thematically, we apply the approach to the case of vacant lots to test its practical value in urban analysis. Vacant lots

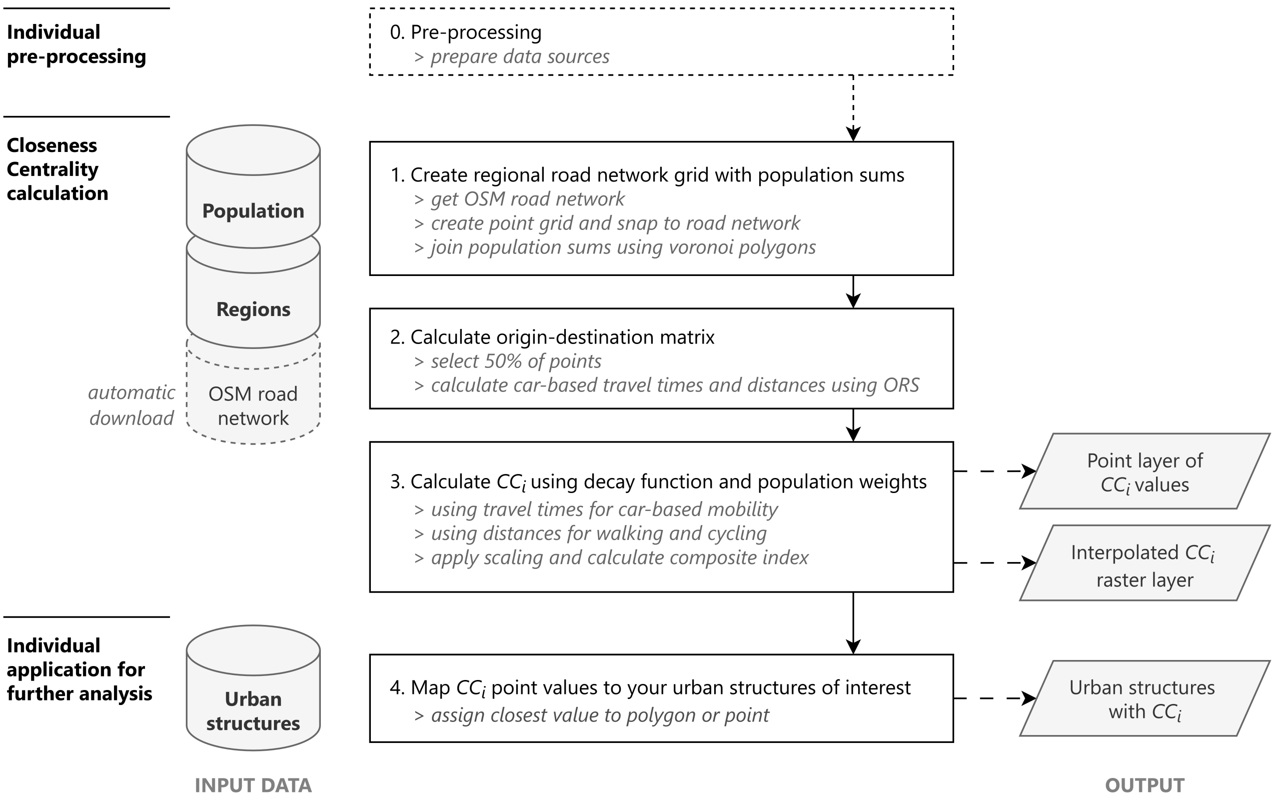

Figure 1. Schematic workflow with data, individual processing steps and output (author's own); https://github.com/urban-structure-and-policy/regional-accessibility.

are underused lots of land within urban contexts that play a vital role in planning policies for compact urban development and urban densification as they represent the potential of infill development. Vacant lots are a particularity especially in the German planning system, as urban development involves previous landowners and private individuals which have multiple interests in developing or keeping the land for future uses (Ehrhardt et al., 2025; Götze et al., 2024).

We test and apply the approach for four German regions following the delimitation of the respective formal regional planning authorities of Aachen, Northern Hesse (Nordhessen), Munich (München) and Upper Lusatia–Lower Silesia (Oberlausitz–Niederschlesien).

2.3 Data and Software Availability

We provide all code, information on data access and a test data set at: https://github.com/urban-structure-and-policy/regional-accessibility (Jehling and Kluwe, 2026). The repository contains detailed information on the workflow, input data requirements and the data sources used for the application presented here. All relevant data to reproduce the approach are available under open licenses. The test data set contains all necessary input data to run the code for the planning region of Aachen.

The input data required includes a) a polygon layer of the regions to analyse, b) gridded population data (polygon, point or raster layer) and c) a polygon layer of urban structures. In our exemplary application, the regions we use for a) are administrative boundaries of selected municipalities (Bundesamt für Kartographie und Geodäsie, 2023). To these we join the information on which planning region they belong to. The population data b) used in this case is German census data (Ämter des Bundes und der Länder, 2024). Using the Global Human Settlement Layer population grid (GHS-POP) (Schiavina et al., 2023) has also shown to be successful in other implementations of the approach. Input c) represents any type of urban structure that the centrality values should be applied to. As the approach calculates CC_i values for a grid of points and the closest point value gets assigned to the urban structures in the last step, this data can easily be replaced and is not strictly necessary to reproduce the approach. The urban structures dataset presented here represents vacant lots and is not openly available. It was generated for this analysis using an approach by Ehrhardt et al. (2023) and is spatially limited to the regions of study. The approach uses cadastral data, land-use information and building data which we acquired from the sources proposed in Ehrhardt et al. (2023). Some German federal states (e.g. Bavaria) do not openly provide cadastral data, so signing a license agreement may be necessary to gain access (Happ et al., 2022). For easy reproducibility, vacant lots for the Aachen

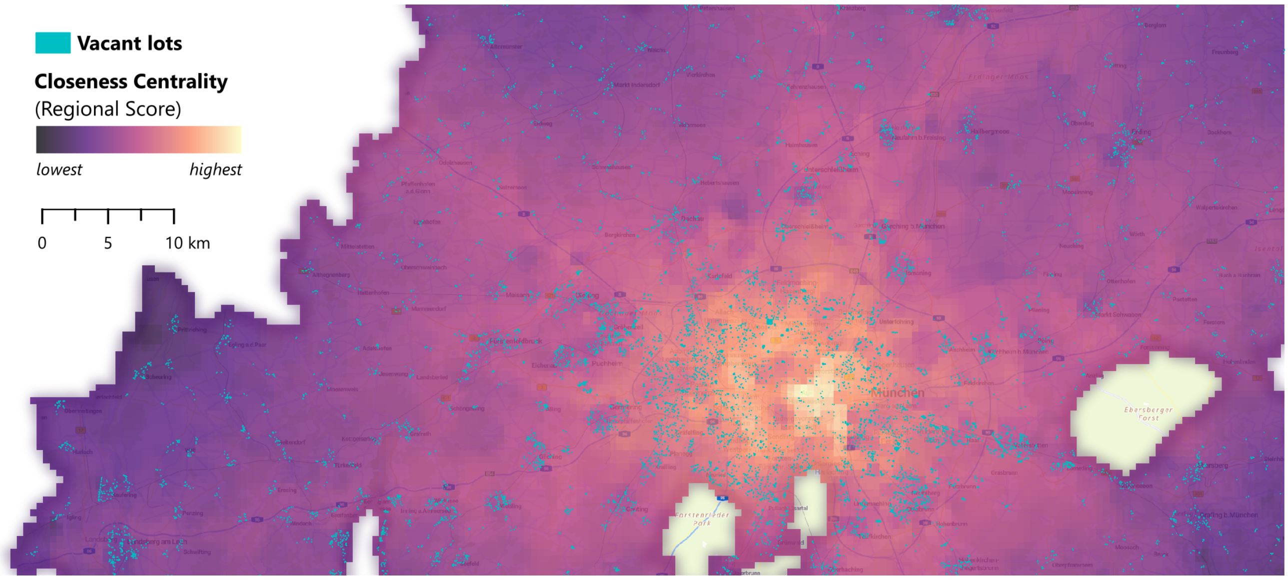

Figure 2. Spatial distribution of regional centrality score for the region of Munich (München) (author's own).

region are included in the repository as part of the test data set.

The sourcing of all further data necessary for the analysis is included in the code provided and open access. This includes the download of the road network from OpenStreetMap through the QuickOSM plugin (QuickOSM contributors, 2025). Further, OpenRouteService (ORS) (Heidelberg Institute for Geoinformation Technology, 2025) is used to calculate the duration and distance matrix between points in the region. ORS is openly available, however an own instance is necessary and can be set up as described by Heidelberg Institute for Geoinformation Technology (2024). As both QuickOSM and ORS access the most current OSM data, exact reproducibility of results can be limited. The workflow is performed using the open-source software R, Python and QGIS. Information on the versions used is provided in the repository.

3 Results

3.1 Mapping location through regional centrality

Applying the approach to the selected cases, the results allow us to show the distribution of vacant lots in a region based on the geographical location as well as the relative location through their accessibility in a network. Figure 2 shows this result for a part of the region of Munich with highest centrality in the urban core of the city of Munich. Based on the visualisation, a relatively homogeneous distribution of vacant lots across the region can be assumed.

3.2 Comparing centrality across regions

We then use the centrality measure to compare the urban form of the regions. Figure 3 gives the whole extent of the analysed regions in the same scale. Through the normalization step we can compare the regions based on their individual score, showing peripheral to central locations (lowest to highest centralities). For the Aachen region, high centralities in the north around Aachen and Düren (east of Aachen with highest centrality) are contrasted by low centralities in the south. For the Nordhessen region, the two urban centers of Kassel (north) and Fulda (south) can be identifed as most central locations, with medium centralities along mobility axes. Similarly, for the Munich region, a high centrality of the city can be seen with decreasing centralities along the mobility axes. For Oberlausitz-Niederschlesien, the figure highlights that with the buffer set for calculation, the measure reacts to population outside the area of interest. This is shown in higher centralities towards the neighbouring agglomeration of Dresden in the south-west alongside the regional poles of Bautzen (center) and Görlitz (east). Given that the population data is limited to Germany, centrality value from the Polish side is not included in the analysis, reducing the centrality of the location of Görlitz in the model.

3.3 Describing regional distributions through centrality of location

Finally, applying the approach to an exemplary case, the distribution of vacant lots can be analysed across the four regions. Figure 4 shows the regional distribution of vacant lots using the CC_i scores for all individual regions. The total area of vacant lots at specific levels of centrality are summed up. The figure indicates that in the Aachen and Munich region, vacant lots are relatively homogeneously distributed with feeble tendencies to locations of medium centralities in Aachen and lowest in Munich. In the other regions, the results describe a clear dominance of vacant lots in peripheral locations of low centrality in Nordhessen

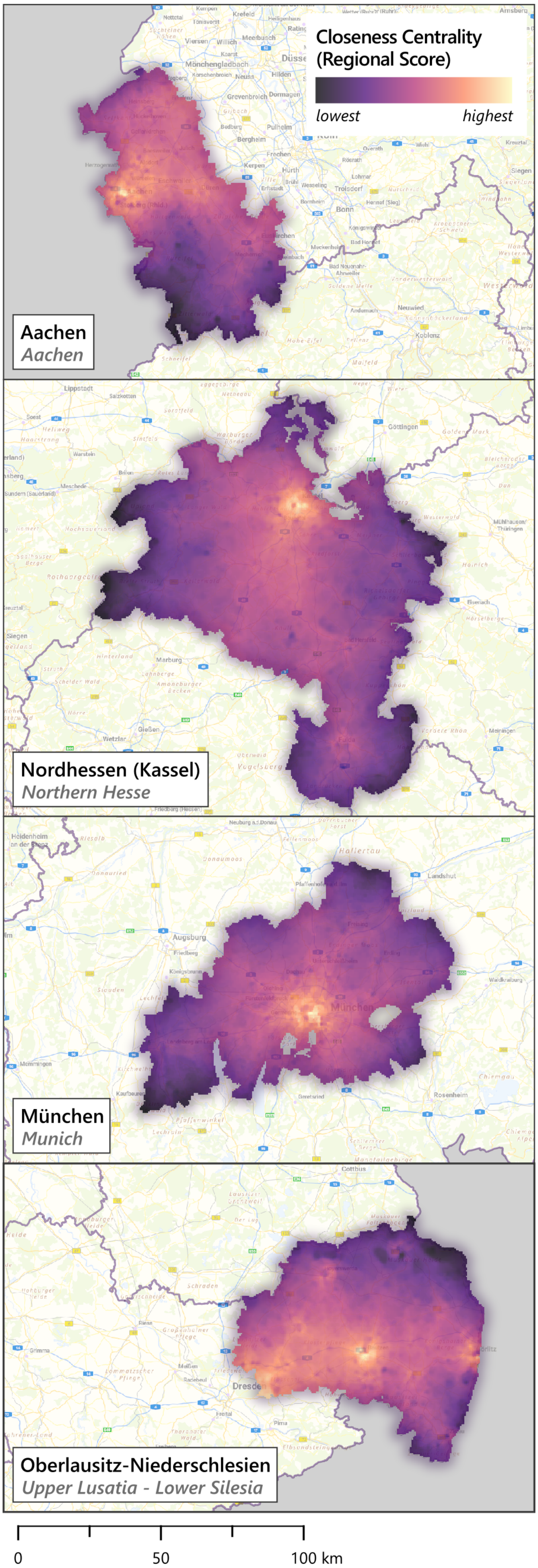

Figure 3. Location characteristics across regions (author's own).

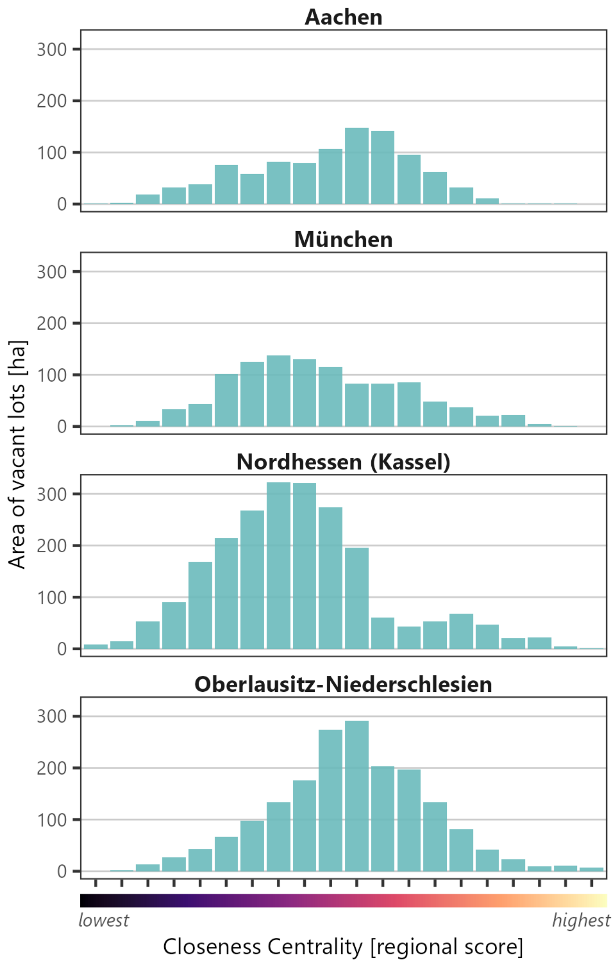

Figure 4. Regional distributions of area of vacant lots across locations from low to high level of centrality (author's own).

and medium centrality in Oberlausitz-Niederschlesien. It also shows that the sum of vacant lot areas in central locations are comparable between Nordhessen and Munich.

4 Discussion

The approach for a measurement of accessibility through CC_i allows for a reproducible workflow of regional centrality based on open data. The approach has then been tested in an exemplary assessment of vacant lots. Here, four regions in Germany with different settlement structures were used to compare the distribution of vacant lots across different levels of centrality. In the following paragraphs, the results of vacant lots will first be discussed and then our approach will be reflected upon.

4.1 Distributions of vacant lots across regions

The incorporation of CC_i into our exemplary assessment of vacant lots allows for a nuanced description and comparison among the four regions. It shows heterogeneous regional distributions of the areas identified as vacant lots. Across the regions, the lower availability of vacant lots in more central locations indicates for a higher housing demand and land values. The constant distribution throughout the Munich region could be interpreted as speculation strategies through landowners. In the Aachen region, especially in the highly central locations, extremely few vacant lots can be seen, which can be attributed to the homogeneously built-up character of the area. As central urban areas are smaller compared to peripheral locations in a region, a relative measure could allow for further interpretation of this matter (Ehrhardt et al., 2025).

The direct comparison between Munich and Nordhessen indicates the identification of contrasting patterns. While the availability of vacant lots in more central locations is comparably low, we see a much higher availability in less central locations in Nordhessen. This well reflects the much stronger housing demand in Munich that spreads into less-central locations. For Nordhessen, the reasons may be found in the relaxed rural housing market, with an abundance of lots that are kept un-built by owners for future uses. Similarly, the dominance of vacant lots in medium central locations in the Oberlausitz-Niederschlesien region can be linked to a low demand in building land in more peripheral locations in a region undergoing demographic change. In general, our approach to describe relative location has provided more depth to an analysis of urban form, as it allowed for comparing monocentral and polycentral settlement structures through accessibility in transport networks (Jehling et al., 2021; Louf and Barthélemy, 2013).

4.2 Reflections on the approach

The approach allows to add a functional dimension to urban analysis. The example shows four formal planning regions, which follow administrative boundaries. Through the approach we are able to circumvent border effects and to describe the locations in those regions in their functional context. We do recommend, that for urban contexts close to national borders, using global population data such as GHS-POP (Schiavina et al., 2023) as opposed to national data could be beneficial to ensure that regional CC_i is fully captured. Overall, the approach addresses an often raised concern in urban analytics that seeks to balance the scope of analysis in a spatial setting of interest with a contextual integration.

The approach further could be used to compare urban form across regions through a standardized measure. We used the road network to describe accessibility through car-based and active mobility with walking and cycling. The composite indicator between car-based and active accessibility is able to well represent the understanding of urban cores, suburban and peripheral areas as used in the urban planning discourse. Based on the results, we argue that this contribution helps to align urban analytics closer with the planning discourse and research on urban development through connecting land use and infrastructure (Boeing et al., 2022). A limitation of the current approach, however, is that public transportation is not included. The integration of line based networks such as public transport requires different measures of centrality and should be part of further research (Jehling et al., 2018). While the applied empirically derived impedance functions yielded plausible results, further empirical work more closely linked to city-regional functionality in Europe might be tested in future (Verma and Ukkusuri, 2025). Here, the provided reproducible code and data sample could be used and further extended.

5 Conclusion

In this contribution, we present a reproducible approach to measure accessibility and have tested its application to describe the distribution of vacant lots in four German regions. The network-based approach allows to describe and compare the location of vacant lots across regions with different settlement structures and rural and urban characteristics. Future developments should address the robustness of the applied functions to describe the modes of transport as well as extending these towards public transportation. The accessibilty approch also would allow to take the spatial opportunities, i.e. employment and services into consideration. While the interpretation has shown reliable results, empirical and statistical validation checks could enhance future applicability.

Declaration of Generative AI in writing

The authors declare that they have not used Generative AI. All intellectual and creative work, including the analysis and interpretation of data, is original and has been conducted by the authors without AI assistance.

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