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Andrakakou, Maria; Keßler, Carsten

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Investigating configurational and active centralities: the example of metropolitan Copenhagen

Maria Andrakakou, Carsten Keßler

Abstract. Identifying centralities in cities helps determine how public space is perceived and utilized in everyday life. Sustainable mobility, social sustainability, and spatial justice can be examined by investigating centralities in the urban form. In this study, we investigate configurational centralities in metropolitan Copenhagen created by the road network based on space syntax analysis and active centralities of land-use patterns with a geographical approach. The purpose of the research is to present a reproducible methodology for determining the active and configurational centralities. Using this methodology, we explore the meaning of the centralities in terms of pedestrian and cyclist accessibility, as well as the role of the configurational centralities in shaping land-use patterns. The results serve as input to an analysis of their relation through Kernel Density Correlation and spatial correlation. The results of correlations indicate that areas close to the city centre and around the Finger Plan – Copenhagen's strategic development plan – tend to be more central and favourable for pedestrians and cyclists. On the contrary, central areas far from the city centre, especially in Northern Copenhagen, and areas between the axes of the Finger Plan are more car-oriented since centralities are dispersed and located around highways or road segments designed for cars. The workflow presented in this paper is provided as a set of open-source R scripts that draw largely on data from OpenStreetMap, thus enabling replications of the study for other cities.

1. Introduction

Contemporary urban studies have raised awareness of the efficiency of cities when it comes to both pedestrian and vehicular mobility within the urban system. This concern touches upon factors such as sustainability and spatial justice of the urban structure towards serving people's needs in every-day life (Zhong et al., 2015; Legeby, 2013). Regardless of those needs, metropolitan cities have turned into spaces with low population density and car-oriented suburbs (Buliung, 2011).

Cities are often 'spontaneous' and 'organic' spaces where centralities are created based on human activity and vice versa. As Hillier suggests in *Space is the machine*, "Places do not make cities. It is cities that make places" in what he calls a "city creating process" (Hillier 2007, p. 125; Hillier 2003, p. 6). This process is composed by the configurational pattern and land-use distribution, and it acknowledges the human factor as co-presence in the public space. This creates hierarchies such as centralities within the urban form which sometimes succeed while others fail (Hillier, 2007). More specifically, successful centralities take into consideration all three factors – configurational patterns, land-use distribution, and human factors –, while failed centralities do not, hence affecting human presence in the public space.

This perspective views the built environment as an organized system where social patterning can be determined by analysing its spatial extent. The street network in this system is created by two elements: relations of similar spaces in the cities and relations with social life and activities (Batty, 2012). Centrality plays an important role in land-use patterns, economic, and social activities (Iranmanesh and Atun, 2018; Jacobs, 1962). In this context, network centrality is the key towards understanding the urban form and its relations to place structure entities. In this sense, built-up entities are physical and functional but cannot represent the place character which refers to the society's cultural background (Lee et al., 2014).

Active centrality reflects the land-use patterning and density (Batty, 1997), whereas configurational centrality deals with the urban structure, particularly with the road network (Hillier, 1999). In other words, the former is a geographical approach, whereas the latter is configurational. Implementation and combination of both approaches can help investigate their complementary nature as well as their variation.

Space syntax and Kernel Density Estimation are the main tools which help explore centralities in the study area as well as to identify 'active' centres. We focus on evaluating neighbourhood-level pedestrian and cyclist accessibility. We compare configurational and active centralities of each municipality to evaluate the network infrastructure for its users. Finally, there is a comparison with the global scale to highlight centralities which are primarily designed for cars. Furthermore, the study investigates the character of land-use patterning at a municipality level which contributes to understanding how well residents satisfy their every-day needs in a sustainable manner by moving at a local scale.

To achieve these goals, we propose a reproducible workflow based on open data for a multi-scale analysis of active centres. The analytical workflow has been implemented as a series of open-source R scripts that enable other researchers to easily conduct the presented analyses for other cities. The workflow is implemented and tested within an investigation of metropolitan Copenhagen's urban structure and social patterning for municipalities included in the *Finger Plan*, an urban plan that guides the metropolitan area's development since 1947 (Fingerplanen, 2020). The specific contributions of this research are:

1. A thorough investigation of the potentials and limitations of space syntax analyses based on open data when it comes to analyses of centralities for pedestrian, cyclist, and vehicular traffic.
2. A reproducible process that facilitates automated multi-scale analysis of active centres beyond hard to document and replicate "point-and-

click" desktop GIS workflows that focuses on pedestrian and cyclist accessibility.
3. An evaluation on the efficacy of the workflow on the well-researched *Finger Plan* for metropolitan Copenhagen that puts the findings from this study in the context of existing literature on polycentricity.

The remainder of this article is organized as follows. The next section provides the theoretical background for the study, reviewing core analytical concepts and introducing the study area. Section 3 describes the analysis approach, followed by the results in Section 4. Section 5 discusses the outcome of our analysis, followed by a discussion (Section 6) and concluding remarks (Section 7).

2. Theoretical background

This section introduces the main concepts of space syntax theory and centrality, along with the corresponding mathematical and geographical tools and their utilization in this research.

Centralities

According to Hillier (1999), centres of cities can be distinguished by a clustering of mixed land use and activities at a certain location. Both geographical and configurational factors can reveal centres. More specifically, centres can be identified by their linear or convex shape (Hillier, 2007). Linearity of centres includes single line segments or two lines intersecting at an angle of up to 45 degrees. Convexity is the gridded expansion of the activity centres within a radius (Hillier, 2009). Research has also shown that centres contain small and compact road segments while non-centres expand due to longer road segments (Hillier, 2007; Lee et al., 2014).

Space and social activities are closely related and influence each other; shops attract movement and movement attracts shops (Hillier and Vaughan 2007; van Nes and Yamu 2018). However, to understand the urban morphology, it is important to consider that cities define the places and not vice versa (Hillier, 2007). Configurational research examines the movement generated and directed by the street network at local scale which contributes to the global scale patterns, from places to the entirety of a city (Vaughan et al., 2010; Shen and Karimi, 2017; Hillier, 1999; Hillier, 2007). The global scale integrates the entire system with large-scale, usually vehicular movement, while the local scale does the opposite and attracts pedestrian movement. For example, the most integrated streets tend to be located in centres showing a hierarchy in the system's accessibility (Hillier, 1999; Hillier, 2007; Nes and Yamu , 2018). Accordingly, investigation of the street network's configuration should go beyond the metric centrality and focus on geometrical and topological centrality (Lee et al., 2014). Space syntax is the key to understanding people's flow within a city's configurations (Hillier, 2007; van Nes and Yamu, 2018).

Our discussion of configurational centralities is grounded in an analysis of Angular Choice for the road network. Angular choice $CHO_{(i,r)}$ within a certain radius r measures the frequency of a segment n_{jk} to be used in angular shortest routes from the starting segment j to the end segment k (Shen and Karimi, 2017; see Eq. 1). We focus on Angular Choice since pedestrian movement is our primary focus. Probability of reaching a street segment at various scales is prioritized in order to examine centralities in individual municipalities of metropolitan Copenhagen.

$$CHO_{(i,r)} = \sum_{k=1}^{K} \quad n_{jk}, \{dis_{(i,j)} \leq r;\ dis_{(i,k)} \leq r\} \quad \text{(Eq. 1)}$$

Configurational centrality deals with the urban structure and especially with the road network (Hillier, 1999) while active centrality reflects the land-use patterning and density (Batty, 1997). Throughout our study, we use active centrality to identify non-residential activity functioning as service and administration attractors, including, among other things, working spaces within the centres (Hillier, 1999; Batty, 2008). Active centralities function as attractors to movement and promote co-presence.

Kernel Density Estimation as a measure of centrality

Kernel Density Estimation (KDE) helps identify centralities in urban areas by utilizing non-residential spaces in the urban environment. In this study, KDE takes into account both the angular choice calculated by space syntax analysis depicting configurational centres and the land-use pattern depicting active centres. We implement KDE for angular choice both globally and for various local scales (Porta et al., 2012). KDE is applied for configurational and geographical patterns formed by the road network and the land-use, respectively. This step is required in order to proceed to Kernel Density Correlation and spatial correlation at a municipality level.

KDE is an interpolation method which weighs nearby entities more than further ones within a specified window which is represented by one value and therefore creates a continuous field while smoothening discontinuities (Bailey and Gatrell, 1995; Porta et al., 2009). Bandwidth approximates the size of a neighbourhood (h=300) as defined by Perry (1929) and used in multiple studies for 10x10 metre grid cells (Porta et al., 2012; Porta et al., 2009). We interpret cell and grid size as well as bandwidth in a way to make the raster outputs comparable using a gaussian kernel. Cell size is adjusted to the scale of the input data which represents the mean length of a building block in Copenhagen, which is approximately 100 meters.

Study area

Urban planning in metropolitan Copenhagen is based on the Finger Plan shown in Figure 1 which has been guiding the urban development for more than half a century[1] (Knowles, 2012). The study area covers the municipalities surrounding Central Copenhagen which are included in the Finger Plan. The reason is that it has been developed to plan and design residential and non-residential land-use as well as to preserve green spaces in the metropolitan area. Areas describing non-residential land-use extents are also the central areas (centralities) planned by the authorities.

The Finger Plan covers 34 municipalities with over 2 million inhabitants and was last revised in 2019 (see Figure 2). Planning extends from the city centre towards suburban areas and shows municipalities which are located “on the fingers”, but their centralities are not well developed yet. The aim for the areas “between the fingers” is to keep them as green spaces and protect them from urban development. As metropolitan areas turn into polycentric systems (Van Criekingen, Bachmann, Guisset and Lennert, 2007), polycentricity in Greater Copenhagen is introduced by the Finger Plan in which smaller centres gather around the main axes of the network and their aim is to be used mainly by the locals. Moreover, the plan is transit-based and extends five axes within metropolitan Copenhagen, so that local centres have been developed around train stations (Fertner et al., 2012).

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[1] https://www.retsinformation.dk/eli/lta/2019/312

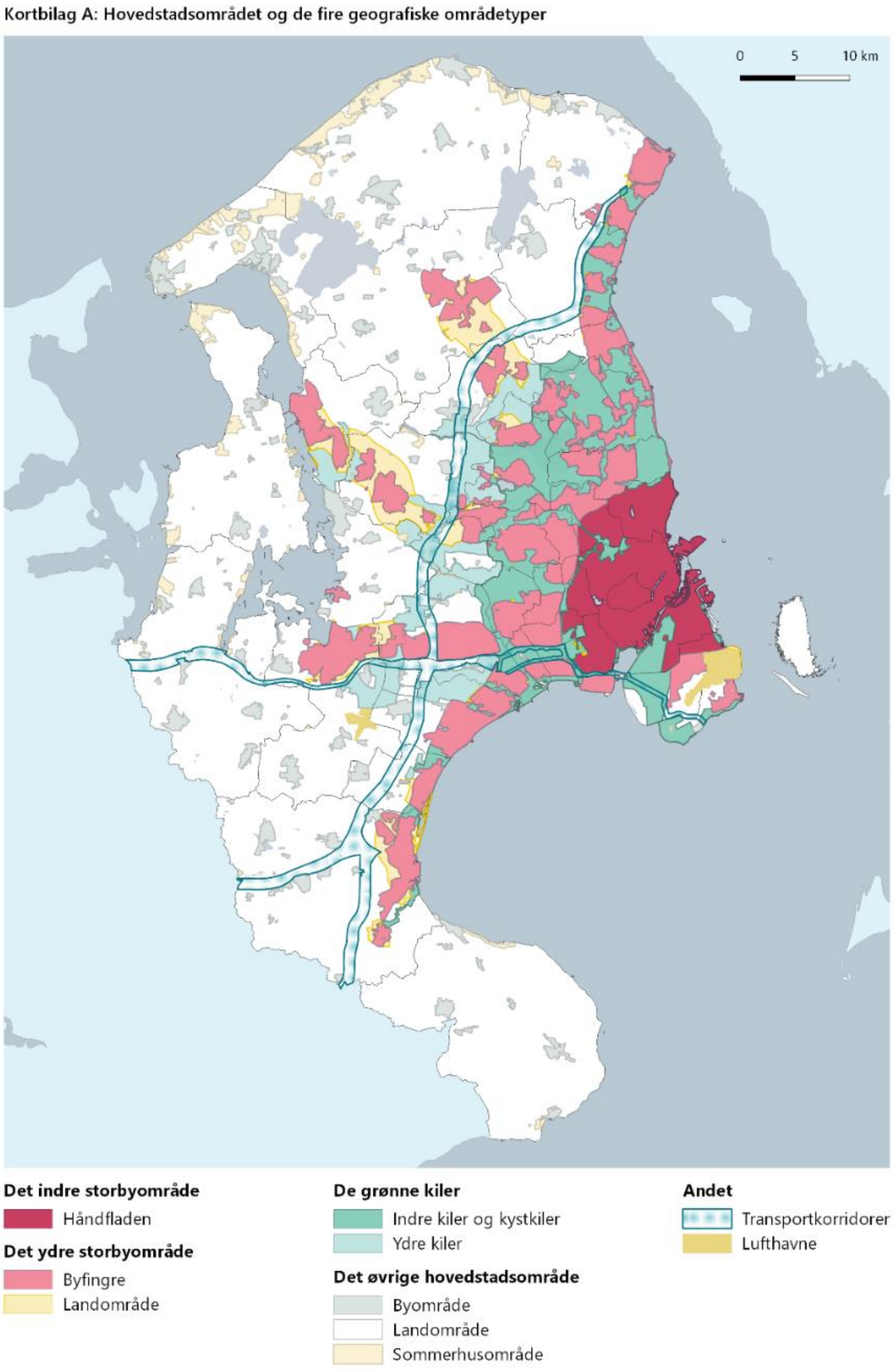

Figure 1: Copenhagen's Finger plan as of 2019 (source: https://planinfo.erhvervsstyrelsen.dk/)

Figure 2: Municipalities in the Copenhagen metropolitan area.

3. Analysis approach

The analysis outlined in the following paragraphs follows a two-step approach. Firstly, the configurational pattern is analysed based on the road network and the angular choice calculations. Secondly, the geographical pattern of active centralities is identified based on the land-use pattern, derived from point data. The road network, obtained from the Danish government's kortforsyningen.dk ("*map supply*") platform, has been topologically corrected by creating a segment map and then angular choice (AC) calculations were executed. Lines were turned into points with AC values assigned to them to create a point pattern and then proceed to weighted KDE for this layer.

Land-use as point data, obtained from OpenStreetMap (OSM; Keßler, 2015), was used for KDE production without any classification, which elaborated in identifying active centralities created by land-use distribution. Land-use point data refer to non-residential activities within the study area which also attract human activities. For this purpose, points of interest that fall into one of the following 8 categories have been extracted from OSM: *Service* (including data about public institutions such as municipalities, embassies, etc.), *entertainment* (pubs, restaurants etc.), *office spaces* used by companies, lawyers etc., *healthcare* (hospitals, clinics, etc.), *education* (universities, schools etc.), *green spaces* (parks, forests etc.), *culture* (theaters, libraries etc.) and *retail* (shops of any kind, e.g. clothing or furniture stores).

According to Jacobs (1961) urban vitality is settled where dense and diverse human activity takes place. In other words, a high land-use mix of activities is a precondition when it comes to characterize the vibrancy and vitality of a city's public space. We therefore calculated the diversity index (Shen and Karimi 2016) across all land use classes to represent the entropy of land-use mix for each municipality in the study region. As shown in Figure 3, the results only vary slightly between the municipalities. The remainder of the analysis therefore focuses on the total number of land use points of interest across all 8 categories to produce Kernel Density Estimates, in the following referred to as land use patterns.

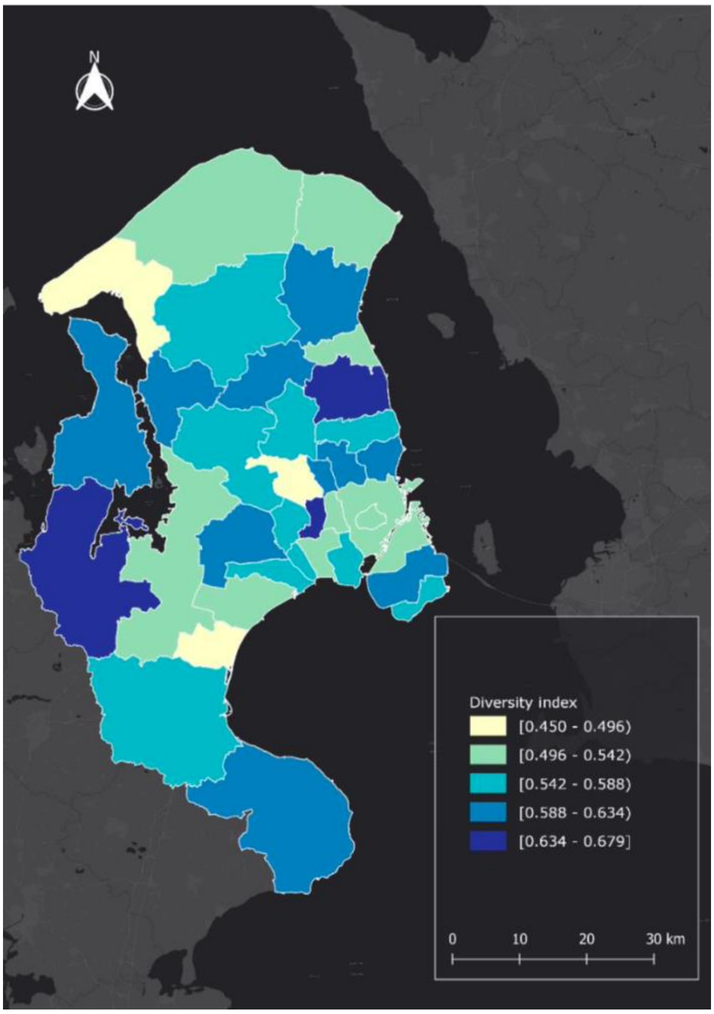

Figure 3: Diversity index of land-use within municipalities

The produced raster layers from the configurational and geographical patterns containing the values of KDE calculations were used for kernel density correlation (KDC) and spatial correlation. These two different correlations focus on the metropolitan extent and the extents of centres acknowledged by the Finger Plan.

Kernel Density Correlation

Kernel Density Correlation (KDC) is a methodology to combine and correlate KDE values cell-by-cell (Thurstain-Goodwin and Unwin, 2000; Strano et al., 2007). Values of two correlated raster outputs are used to create a correlation table and compare them . In this work, we calculate the KDC between the KDE of the land-use pattern and the KDEs of angular choice at 400m, 800m, 1600m, and 2400m, respectively. Spearman's rank correlation method is used since the values of raster outputs are not normalized and thus are not following a normal distribution. The range of KDC values is ρ=[-1,1], covering the whole range from strong negative correlation to strong positive correlation. Values of raster layers are interpreted by creating a vector matrix of the values of each layer and correlate them.

The land-use pattern layer concerns all land uses regardless of their type since the aim is to examine configurational and active centralities provoking co-presence in the public space. Positive layer values are chosen during the creation of the matrix because correlation must take place where centralities are created either by the road network or by the land-use pattern. Results produce one KDC value for each combination which indicates to what degree centralities are related.

Spatial correlation

Although cell-by-cell correlation indicates whether road network and land-use centralities correlate, there is need for a further investigation. For this purpose, Rochette's (2018) method is applied to find the spatial correlation of the raster layers. This method suggests using the focal function of the raster package in R on two raster layers simultaneously (Hijmans et al., 2020). This function calculates values inside a square moving window using all neighbouring cells inside it by weighting them. By using it on two raster layers it allows calculating a local correlation matrix of space. Firstly, positions of cells and their values in two raster layers are recorded, then a 5x5 square window of cells is created where all values are ranked using Spearman's method and a correlation measure is then put inside an empty matrix. Results indicate where spatial correlation is strong or weak.

During the implementation phase, a window 5x5 was chosen for all combinations of raster layers mentioned above (see Section 4.3). All raster layers consist of 10x10 meter pixels. The extent of the square moving window reaches up to 25 of these cells for a total of 0.25km^2. This extent has been considered as representative for walking distance; however, this means that the calculated values have no major effects in neighbouring centres. In order to calculate correlations inside centres addressed by the Finger Plan at larger scales, zonal statistics were applied in which the mean value of correlation cells is measured divided by the number of cells within their boundaries.

Overall, the road network data was prepared and utilized for Angular Choice calculations and was used as an input for the KDE raster production. Land-use data was prepared for the KDE raster production, respectively. Kernel Density Correlation was applied for combinations of raster layers between KDE raster outputs of the road network and the land-use pattern for the entirety of the study area. We have also conducted a further investigation for centres described by the Finger Plan by applying spatial correlation to the same combinations of the KDE raster layers. Figure 4 shows an overview of the methodology; for a detailed description, please refer to the methods section in the supplement.

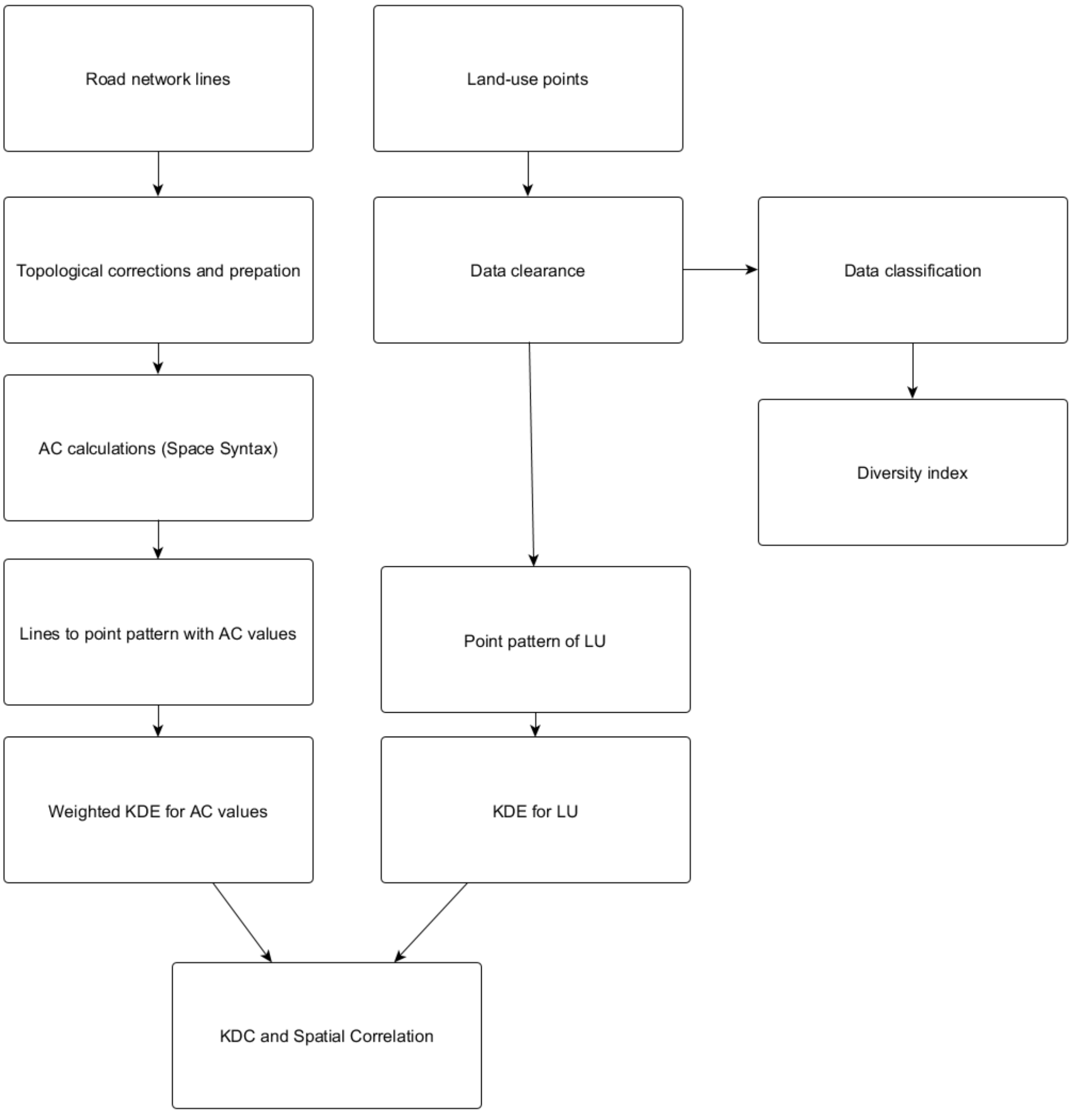

Figure 4: Methodology workflow

4. Results

This chapter presents the results of the analysis, focusing on the following main issues:

1. Configurational and active centralities (KDE)
2. Kernel Density Correlation between configurational and active centralities
3. Spatial correlation between configurational and active centralities within Finger Plan centres in the study area

The results are interpreted for the entirety of the study area as stated in Copenhagen's Finger Plan and in centres designed or acknowledged by the Plan.

We have acquired angular choice calculations for various radii representing local and global scales from 400 meters to 10 kilometres. The study focuses on pedestrian flows, using 400m and 800m radius to represent 5- and 10-minute walks respectively and are compared to larger radii.

Figure 5 depicts the frequency after KDE implementation and form the configurational centralities. The results indicate that configurational centralities for pedestrian use are better for 800m radius corresponding to a 10-minute walk. Moreover, in this radius centralities are close to the main axes of the Finger Plan and inside the city centre. A 400m radius highlights centralities at the western part of Copenhagen's city centre and in Albertslund, Greve and Ishøj municipalities.

Radii of 1600m and 2400m, which correspond to 10 and 20-minute cycling, are more pronounced for areas around the main axes of Copenhagen's Finger Plan. This configurational type shows the polycentricity of metropolitan Copenhagen which focuses on the main axes, but not on the areas between them. Configurational centralities which are created and are not located on the main axes are dispersed and are not designed for these local scales.

The global radius of 10km flows focuses on long-distance travel by car, substantially exceeding the typical trip taken by bike. It suggests that while moving towards the city centre, intermunicipal flows are encouraged towards Copenhagen's central area. Another area which receives intermunicipal flows from central Copenhagen and its surrounding municipalities is Roskilde municipality. This indicates that all other configurational centralities in local scales are designed for local users and are more car-oriented, meaning that active centralities are expected to concentrate around highways or roads prioritizing cars. Additionally, intermunicipal usage is discouraged for areas outside Copenhagen's city center and its surrounding areas except for Roskilde, Egedal, Hillerød and Helsingør municipalities. Supp Fig 3 – 7 show angular choice calculations and the corresponding KDEs for additional radii.

Analyses based on Copenhagen's public transit network consisting of the local S-train, the largely underground Metro system, and buses, have not been included here separately. The S-train network follows the "fingers" of the finger plan, and the Metro system is only available in central Copenhagen. As such, these two means of transport are not available across the study area and would need to be investigated with other accessibility measures that are out of scope for this paper. While buses do run throughout the study area and access is provided by a dense network of stops, they follow the street network and are, in the context of this study, considered part of the vehicular traffic.

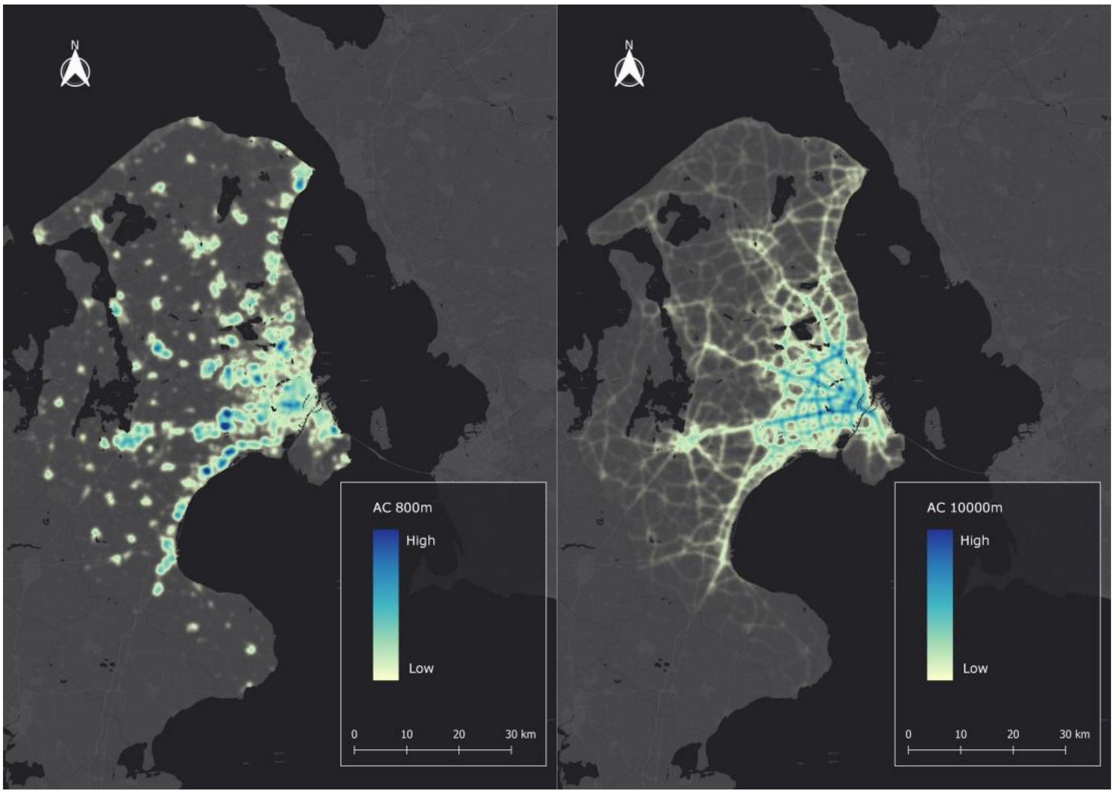

Figure 5 : Angular choice calculations KDE for local and global scales

Figure 6 highlights active centralities after KDE implementation for non-residential land-uses across all categories. Active centralities are illustrated more intensely in areas of the city center, Roskilde, Glostrup, Ballerup, Herlev, Lyngby-Taarbæk, Furesø, and Tårnby. It is worth noting that Roskilde municipality and Copenhagen's central area, which includes the city centre and its surrounding areas, are characterised by polycentricity, but all other active centralities are dispersed. Dispersed centralities are closer to the edges of the study area and within areas further away from the main axes of Copenhagen's Finger Plan. This type of dispersed active centralities is more likely to be car-oriented than the clustered and more smoothened centralities near the city centre and Roskilde municipality.

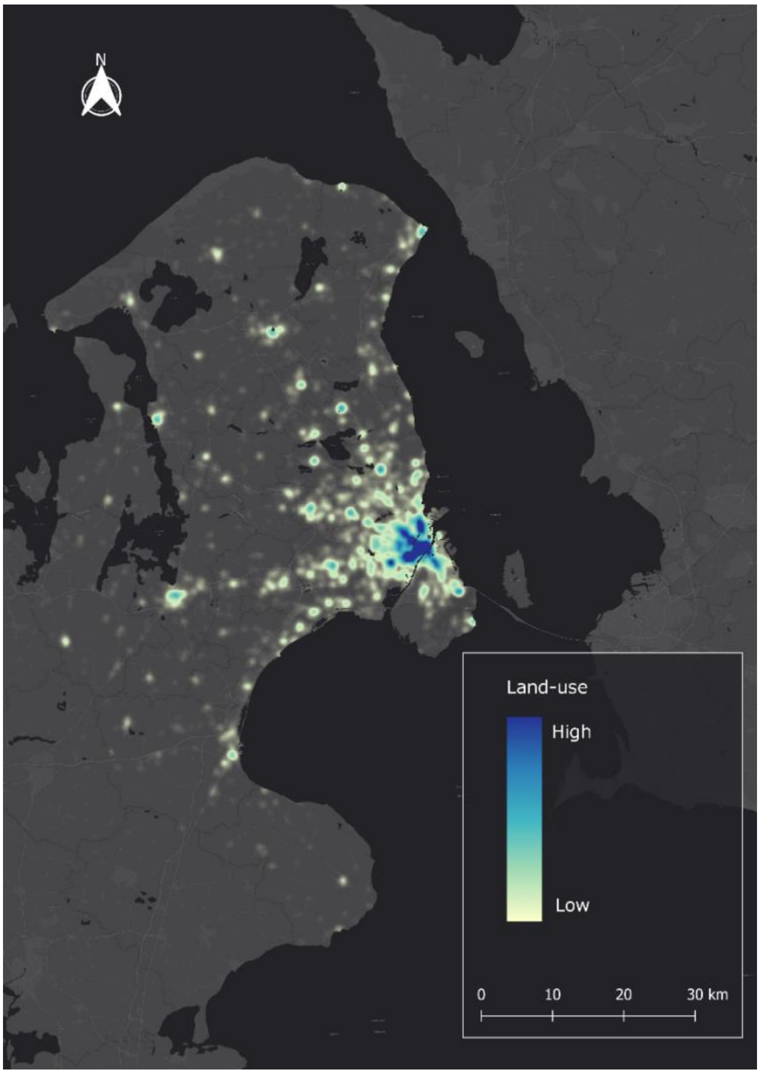

Figure 6 : Land-use KDE

The kernel density estimation (KDE) for values of angular choice of each radius and the land-use pattern are a step towards proceeding to KDC. Spearman's rank correlation ρ was calculated for combinations of raster layers as shown in Table 1. Local scales of angular choice (AC) have strong positive correlation with the land-use (LU) pattern, i.e., the density of land use points of interest is higher in areas with higher values for the angular choice, making them accessible to pedestrians and cyclists. We have only taken values above zero into consideration in all raster layers which means only configurational and active centralities are correlated. Thus, centralities in both configurational and geographical patterns are associated. Copenhagen's image as a cycling city is also reflected when looking at the global scale, where there is still a positive correlation, but lower than at the local level. Active centralities are not necessarily concentrated around highways, but also between them, forming a convex shape and reflecting a less car-oriented urban form.

		Correlation
AC 400m	LU	0.7465
AC 800m	LU	0.7495
AC 1600m	LU	0.7442
AC 2400m	LU	0.7465
AC 10000m	LU	0.6677

Table 1: Correlation values among KDE of choice values and KDE of land-use

As Table 2 suggests, there is similarity among different local scales for radii from 400m up to 2400, representing the extent that can easily be reached by foot or on bike. The car-focused global radius of 10km shows more dispersion than at local scales (second to last row and column, respectively). Again, this indicates high land use densities easily reachable by car, but also outside of these areas. When it comes to comparison between AC and LU there is a repeated trend for local scale radii while in the global radius, values are not following the same trend. The explanation behind the comparison between local and global scale with LU is that there are several centres designed for pedestrians and cyclists but not as many as for cars.

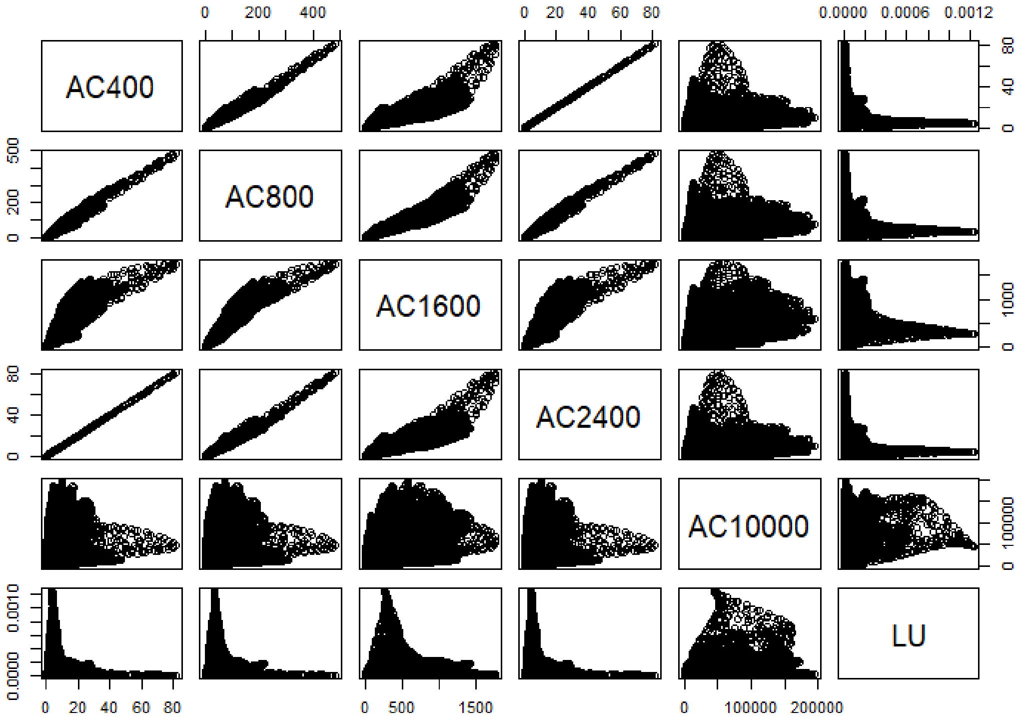

Table 2: Pair plot of KDE values produced from AC and LU patterns

Correlation values of local scales show that urban planning in Copenhagen promotes walking and cycling towards activities, and it encourages co-presence in the public space. However, a mildly positive correlation indicates that in some districts within the study area there is no easy access to centres by walking and cycling (areas with lower values in the left half of Figure 7). The correlations for all combinations are statistically significant ($p<0.01$).

Further correlations are applied for the combinations of the same layers as stated before to highlight differences between configurational and active centralities patterns. The centres described by the Finger Plan within municipalities of the study area are examined. The maps shown in Figure 7 are the product of spatial correlation between configurational and active centres. Values of correlation fluctuate from –1 to 1 since they are results of Spearman's rank correlation.

The maps in Figure 7 show that centres in Copenhagen's suburban area starting from the edges of the city centre to the edges of the study area have very strong and strong spatial correlation between configurational and geographical patterns for the walking distance of 400m (Supp Fig 8) and 800m. Patterns for 1600m (Supp Fig 9) and 2400m (Supp Fig 10) are correlated similarly, but centres created by the Finger Plan and urban centres in the North-East part tend to be less related. However, small urban areas in the suburban areas tend to be designed for walking and cycling. Copenhagen's city centre has either very weak or weak positive correlation for all scales. A closer look shows that there is weak positive correlation for pedestrian usage and even weaker positive correlation for vehicular movement, meaning that there is potential for improvement of the road network for pedestrians and vehicles or the land-use distribution.

Some centres on the edges of the study area such as those in municipalities of Gribskov, Halsnæs, Helsingør, Køge and Lejre appear to have a strong or weak negative correlation between the configurational and geographical patterns. One possible explanation can be that they are "spontaneously" and "organically" developed centres and there is not a planning process involved yet. Centres located on the main axes of the Finger Plan outside the city centre appear to have a strong positive correlation for radii from 400m to 2400m, but there is lower positive correlation in the North-Eastern centres in municipalities such as Hørsholm, Fredensborg and Helsingør.

Centres all over metropolitan Copenhagen with very strong or strong positive correlation are planned for pedestrians and cyclists while the comparison with the 10km radius highlights those which are also car-oriented. These car-oriented areas have developed their centres around highways or roads designed for cars.

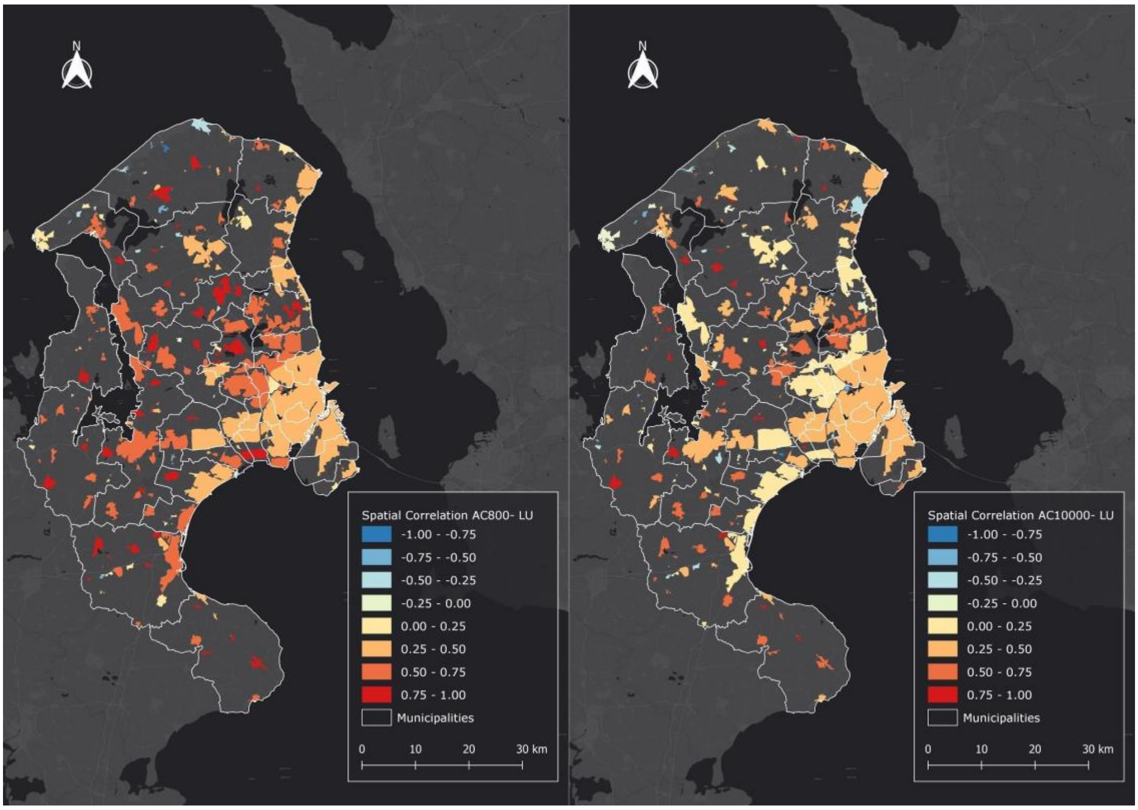

Figure 7: Spatial correlation of KDE for angular choice values and land-use KDE at municipality level

6. Discussion

This research is a contribution towards understanding configurational and active centralities. A methodological framework focusing on publicly available data is provided for visualizing and analysing those areas to better explore urban mobility. The outcome can be a starting point towards exploring smaller areas, such as specific municipalities, more thoroughly. Applying the framework to the case study of metropolitan Copenhagen shows that districts close to the edges of the study area and far from the city center are more car-oriented and there is potential for improvement in land-use distribution and the road network as KDE, KDC and spatial correlation showed. Similar adjustments need to take place in Northern urban areas for walking and cycling, as indicated by our spatial correlation analysis. Weak, very weak and negative correlations in Northern districts of the study area and in districts between the Finger Plan's main axes might exist due to either lack of urban planning in particular areas which are far from the city center, or due to missing data provided by OpenStreetMap.

The configurational centrality is classified based on the relativity of the entire network so it represents data as a whole and cannot be compared to other cities without adjustments. Furthermore, centralities concentrated around the Finger Plan's axes are decentralized, more clustered and more continuous, reflecting its transit-oriented focus. In-between areas which are decentralized and dispersed need further research in terms of population density to locate those which must be included in the plan. In other words, these areas have potential for better centrality distribution.

One limitation of this study is in the complementarity of the different datasets used. OpenStreetMap (OSM) does not provide information about residential use, and the Danish authorities do not provide detailed information about non-residential land-use. Moreover, potentially missing data from OSM may affect the analysis, which is most likely to be located in areas far from the city center, where population density is low and thus there are fewer potential contributors to the volunteer-driven platform. This weakness will also affect the results of analyses in other metropolitan areas, as completeness and timeliness of OSM data is known to correlate with population density, in combination with several other socio-demographic factors such as level of education and age distribution (Arsanjani & Bakillah 2015). These two OSM factors add uncertainty to the results based on KDE, KDC and spatial correlation.

Besides this specific weakness of an approach entirely based on open data, it is worth noting that a high-level analysis of centralities based on concepts from space syntax cannot capture the entire socio-spatial complexity of residents' movement in their urban environment, especially when incorporating several scales and travel modes. As Netto (2016) points out, social practice – how residents live in a city and go about their everyday lives – goes far beyond movement and can therefore only partially be described by the movement opportunities that the street network affords. Even focusing on mobility within a city, such an approach can only shed an initial view on how individuals actually travel, their intentions, and the – intended and unintended – consequences (Freudendal-Pedersen 2009). Likewise, more comprehensive notions of access and the large range of indicators to describe it (Levinson & Wu 2020) cannot fully capture this very individual behaviour and the intentions, preferences, and choices that drive it. As such, any analysis based on space syntax concepts, such as the one proposed here, can only begin to shed light at a city at a macroscopic level. Notwithstanding its limitations, the utility in this method is its role as a starting point for more comprehensive and interdisciplinary analyses. As such, having a quick, reproducible method that relies on easily accessible data facilitates the identification of neuralgic points in a city and frees up resources for more detailed, in-depth research on the socio-spatial behaviour that creates them.

7. Conclusion

This study explores the relation between configurational and active centralities in metropolitan Copenhagen, investigating the meaning of the configurational (syntactic) and active (geographical) centralities. The small-scale configurational centrality shows that Albertslund, Greve and Ishøj Southwest of Copenhagen promote 5-minute walks and less highlighted centralities in the same radius are on the Finger Plan's axes. Moreover, all centralities concentrated on the main axes of the finger plan are designed for a 10-minute walking distance. The best centralities for cycling are also identified on the Finger Plan's axes. This indicates that areas on the axes of the Finger Plan for walking and cycling are prioritized for all local scales. Similar is the case of active centralities with most of them concentrating in the city center and its nearby municipalities, as well as in Roskilde. Results also indicate that areas further from the city center, especially those between the main axes and municipalities in the Northern part of the study area, lack more equally distributed centralities. The large-scale analysis also shows that Copenhagen's and Roskilde's municipalities are used for intermunicipal mobility.

Kernel density correlation shows that configurational and geographical patterns correlate strongly for local scales and less strongly for the global scale. This indicates that configurational centralities are an important factor for shaping land-use (active) centralities. Angular choice captures possible places to pass-through to a great extent.

Additionally, spatial correlation indicates that certain centres have to be improved for pedestrian and cycling usage. When comparing local scales to the global, there are particular suburban centres that seem to be more car-oriented, since centralities are located around highways or main roads, so there is also need for a better planning process as configurational centralities are highlighted. Central areas showing less spatial correlation between the configurational and geographical pattern are also close to the Northern edges, so there are two possible explanations for these results: these areas may lack urban planning and are going to be developed later from the Finger Plan, or the dataset of land-use points from OpenStreetMap may miss many features. The issues will also need attention in the future considering the ongoing increase of population in metropolitan Copenhagen.

Finally, the Finger Plan is well established as configurational and active centralities show. The KDE of active centralities with dispersed and decentralized urban areas indicates a polycentric city; however, this can only be partially confirmed looking at the individual characteristics of polycentric cities (Halbert 2008). A polycentric morphology can clearly be observed, and our investigation of land-use types also shows a functional dispersion among the centres. However, given the low diversity index (Figure 3), functional complementarity appears to be low. From a transport perspective, there are clear relations between the different centres. Looking at the spatial distribution of jobs and commuter statistics, Grundfelder et al. (2015) actually conclude that Copenhagen is clearly a monocentric city, yet developing towards more polycentric characteristics. This aspect, policy aspect of polycentric cities, shows that an approach based on space syntax like the one proposed here only provides initial results and needs to be augmented with temporal, sociological, and policy-oriented analysis for a more complete picture.

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Supplementary Materials:

Code

The implementation of the methods described below is available from https://doi.org/10.5281/zenodo.5786969.

Methods

This supplement details the data sources, manipulation, and preparation process, including the main tools used throughout the research.

Software and tools

Various tools were used in order to prepare, process and visualize the data. Preparation of the network and land-use datasets took place in QGIS. The results of the preparation were handled in R to run the analysis and the outputs were in then visualized as maps in QGIS.

The main preparations in QGIS cocern road network adjustments and space syntax calculations. Place syntax tool is a QGIS plugin developed in C++ by a group of researchers from KTH School of Architecture, Chalmers School of Architecture and Spacescape AB. It was created as an extra input in Space syntax theory called Place syntax and calculates space syntax parameters as well as attraction reach parameters towards points of interest (Stavroulaki et al., 2019).[2]

This research utilizes the road center lines and thus it is easy to calculate angular and not metric choice values. The segment map is created, and calculations are performed. The distance mode is chosen as walking distance for the various radii since metric distance from each point needs to be taken into consideration. There is no need for normalization after angular choice calculations. Raw values are then firstly utilized to visualize space syntax analysis and secondly, after densifying and turning lines to points, as input to statistical calculations in R.

The land-use point dataset is validated and adjusted to the project needs in QGIS. Then the land-use points are used as an input in R. Both point patterns support the Kernel Density Estimation and subsequent Kernel Density Correlation and spatial correlation. The raster adjustments (including masking the study area), raster calculations and zonal statistics are also computed in R. All resulting layers produced are imported in QGIS in order to map them.

Data sources and description

Our study required two main datasets and two supplementary datasets. The main datasets are those used during the process itself, such as segments of the road network and the points of land-use within the study area. The supplementary

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[2] Documentation about the tool and examples can be found on their website https://www.smog.chalmers.se/pst.

datasets are datasets not utilized during the process but for pre-processing and post-processing tasks. Examples include the municipality boundaries within the study area and the lakes as raster masks. All datasets, apart from land-use points, are downloaded from Kortforsyningen.[3] Land-use point data are collected from Open Street Map (OSM) through the Overpass API (see Supp Fig 1).

```
overpass_query = """[out:json];area["ISO31661"="DK"][admin_level=2]-
>.searchArea;(node["shop"](area.searchArea););out center;"""

response = requests.get(overpass_url,params={'data': overpass_query})

data_shops = response.json()

print('data_shops',data_shops)
```

Supplement Figure 1: Code snippet example in python for downloading shops in Denmark with Overpass API

The road network layer is described as the Road Center Lines (RCL) within the study area and contains road segments and paths. Paths can be those passing through train stations and connecting two public spaces. They were excluded since space syntax analysis must include segments with potential pedestrian and vehicular movement in the public space and paths only support pedestrian movement, potentially in private spaces.

Land-use points were used to detect active centers in the private or public sphere which are also spaces of co-presence and economic activities. Four main tags were included in the queries to the Overpass API after research conducted in OSM Wiki about their terms: *amenities*, *shops*, *offices* and *leisure*. The corresponding land use points were carefully examined afterwards and modified based on the project needs. An example of modification is the removal of features such as benches, traffic lights, barbeque sites etc. which do not represent spaces provoking co-presence or economic activity and are mainly covered by spaces in which they are placed in, such as parks.

Previous research points at the varying quality and completeness of the OSM data, often with more complete and more accurate data in areas with higher population densities and, therefore, more potential mappers (Cipeluch et al, 2010; Haklay,2010; Basiri et al., 2016). Bearing in mind these issues, OSM was still the best available data source for our study, particularly considering that it focuses on the largest urban area of Denmark.

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[3] See https://www.kortforsyningen.dk/.

Data preparation and process

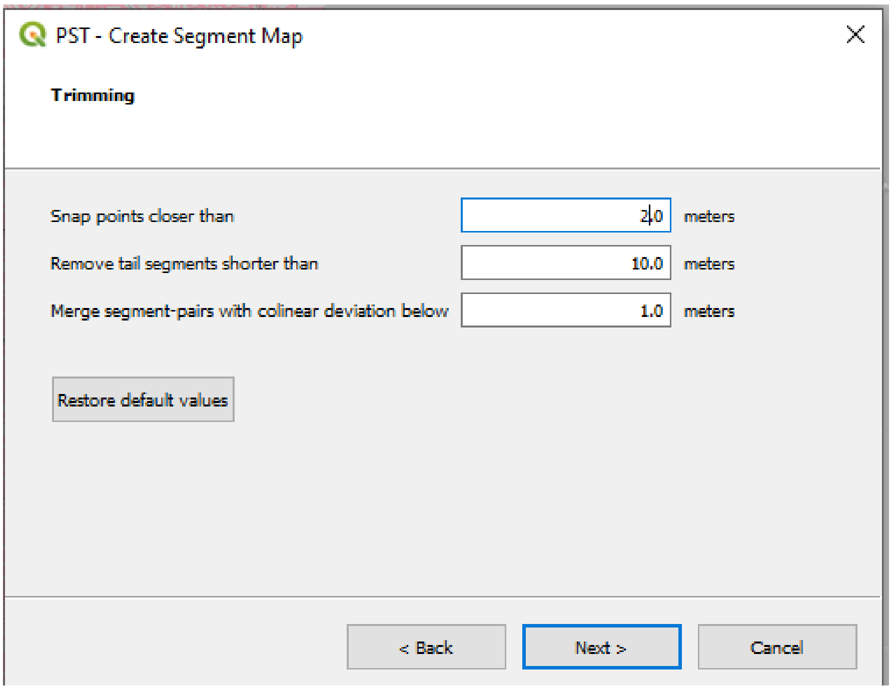
The data was explored and prepared for road network and land-use, individually. After the preparation, both datasets are processed either individually or are combined and their results are analyzed.

Road network

The study area was defined by Copenhagen's finger plan where municipalities that include centers and other urban areas specified by the plan were selected. The road network intersecting a 3KM buffer around these areas was selected, and another buffer was applied to minimize the edge effect of space syntax analysis. The results are clipped to the initial extent again.

The place syntax tool[4] for QGIS is used to create a segment map of the road network (see Supp Fig 2). The segment map tool then proceeds to topological corrections such as:

1. Splitting polylines to lines
2. Splitting lines at intersections
3. Snapping end-nodes which are falling within a specific threshold
4. Removing duplicate feature lines
5. Removing zero-length features
6. Removing tails of lines by a given threshold
7. Merging two segments which are connected into one if the collinear deviation of the three nodes creating those lines is falling within a specific threshold.


PST - Create Segment Map

Trimming

Snap points closer than 2.0 meters

Remove tail segments shorter than 10.0 meters

Merge segment-pairs with colinear deviation below 1.0 meters

Figure 2: Place Syntax Tool and creation of segment map

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[4] See https://www.smog.chalmers.se/pst

The procedure described above created a topologically correct road network. Disconnected parts were fixed by using the Disconnected islands plugin.[5] It distinguished the islands and helped review them. Those parts turned out to be either segments crossing parking lots or auxiliary lanes, so they were removed.

Before running the analysis, line simplification was applied since natural movement supports neglecting small changes of angles both during vehicular and pedestrian movement. The QGIS simplification tool was utilized and a tolerance of 5 meters was applied.

The space syntax tool was then used to calculate the angular choice within different radii. The study focuses on pedestrian movement but in order to make a comparison on how centralities are approached, the analysis has to be repeated for various scales. Selected radii are 400 meters depicting a 5-minute walk, 800 meters for a 10-minute walk, 1600 meters for 5-minutes cycling distance, 2400 meters for 10-minutes cycling distance and 10 kilometres for the global scale which represents movement by car (Hillier, 2007; Porta et al., 2012; Porta et al., 2009, Paraskevopoulos and Photis, 2019).

The results of the analysis were used as input to a collection of R scripts where a further manipulation was implemented in order to correlate centers created by the road network with active centers created by land-use points. Kernel Density Estimation (KDE) is applied for both datasets with the same pixel sizes so that the comparison of centers will be pixel based. Since there seems to be no R package that supports Kernel Density Estimation from lines, this function has been implemented based on ESRI's ArcGIS product documentation.[6] Documentation suggests that the algorithm calculates Density as shown in Supp Eq 1, in which L1 and L2 are standing for the two line lengths, V1 and V2 represent the population values and the area of the circle is taken into account.

$$Density = \frac{(L1*V1)+(L2+V2)}{area\_of\_circle} \quad \text{(Supp Eq 1)}$$

Our implementation densified the nodes of the road network by 20-meter interval, turned lines to points from their nodes and assigned the values calculated from space syntax analysis as attributes. A point pattern was created, and weighted KDE analysis was implemented for each population field, which in this case are the Angular Choice calculations for various radii.

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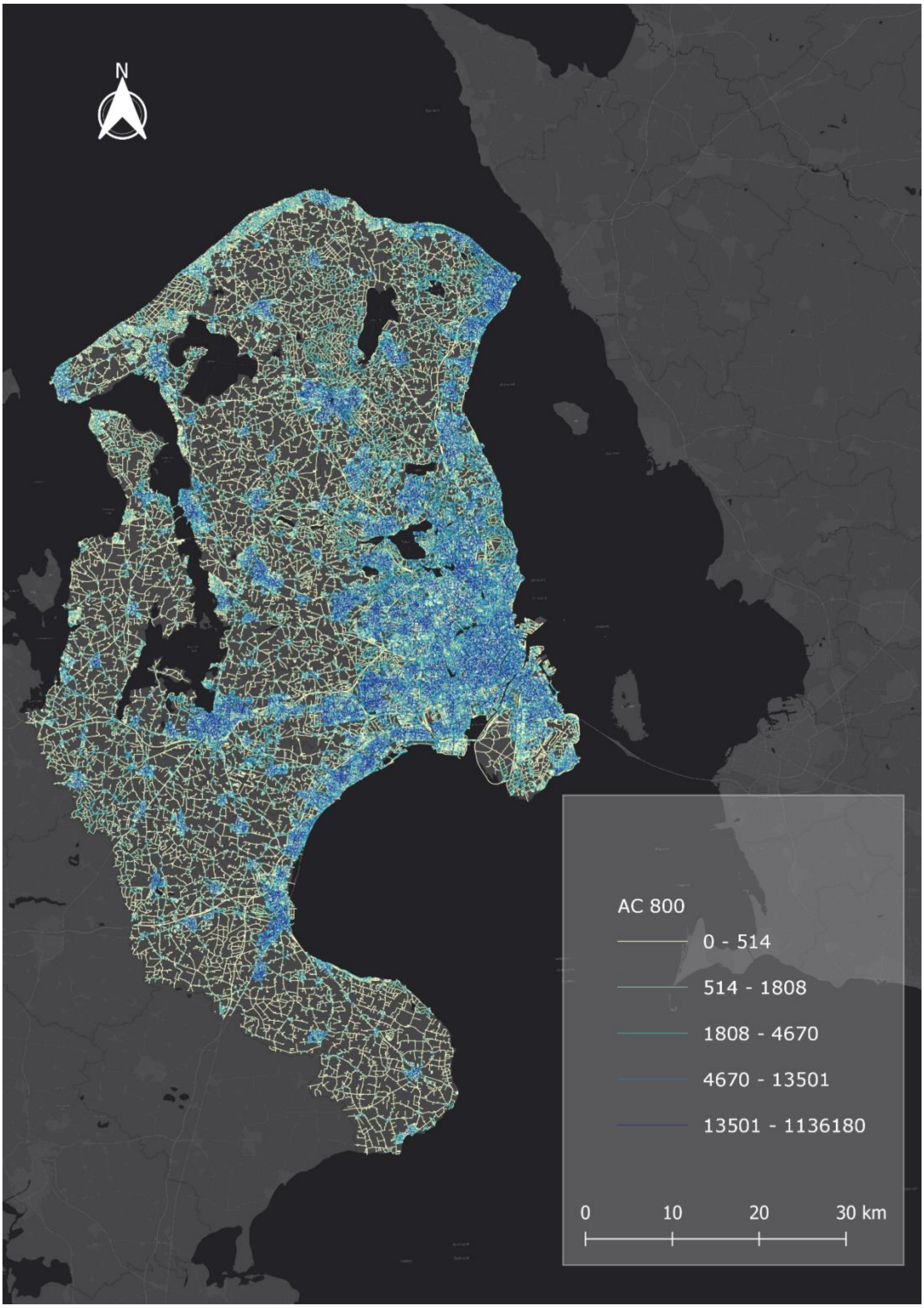
[5] See https://plugins.qgis.org/plugins/disconnected-islands/

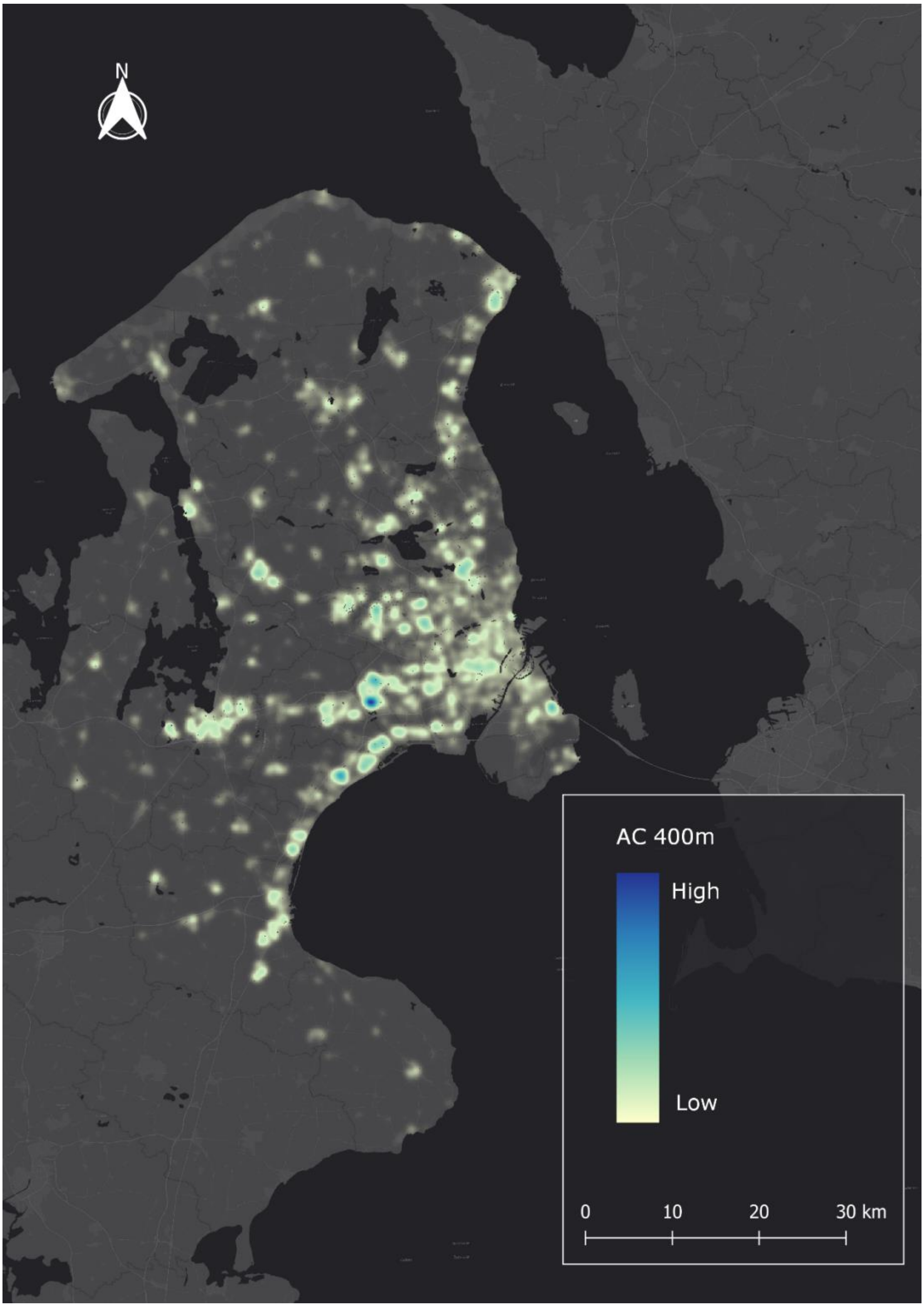
[6] See https://pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/how-line-density-works.htm

Supplemental Figures

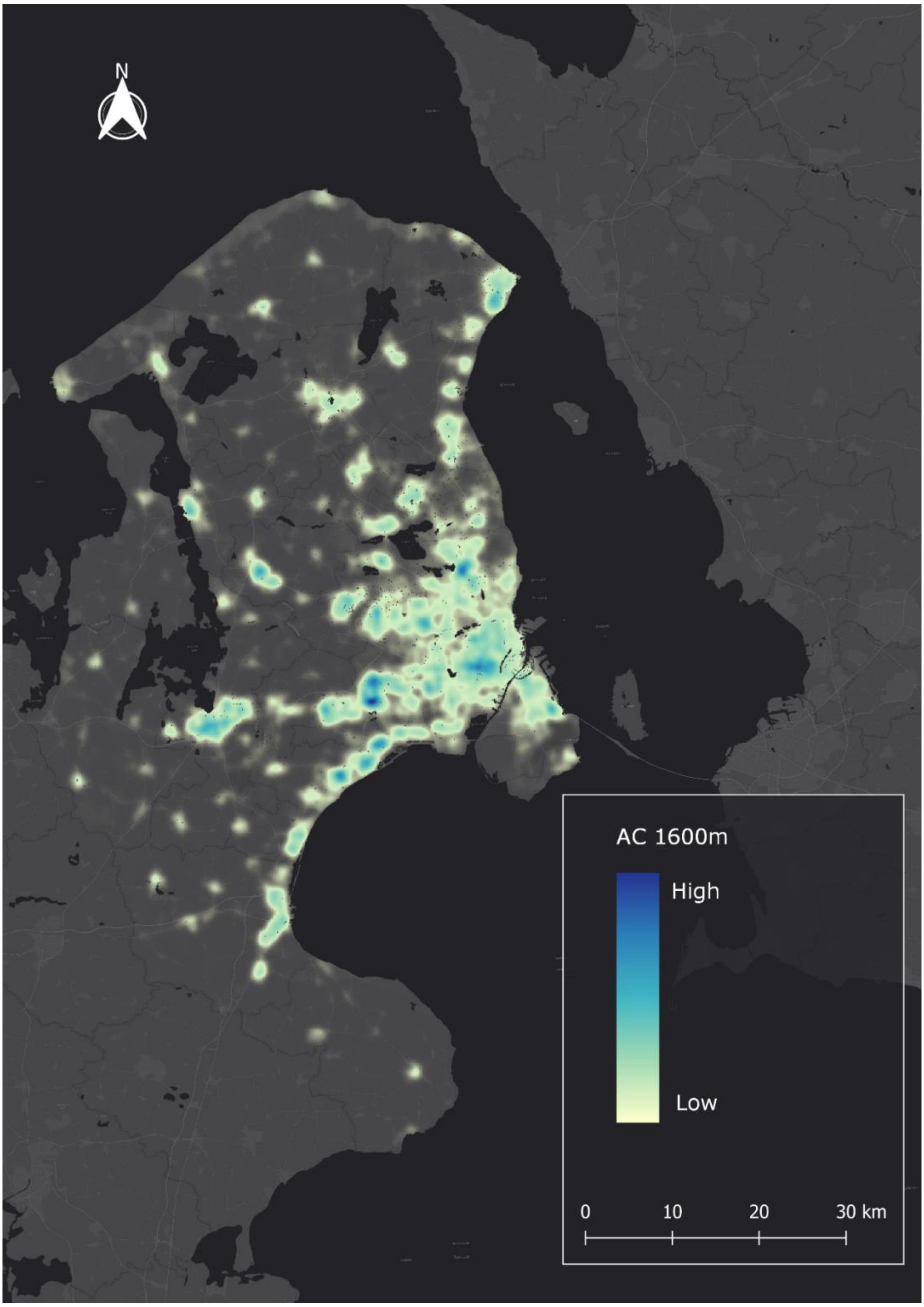


Supplement Figure 3: Angular choice calculations for 800m.

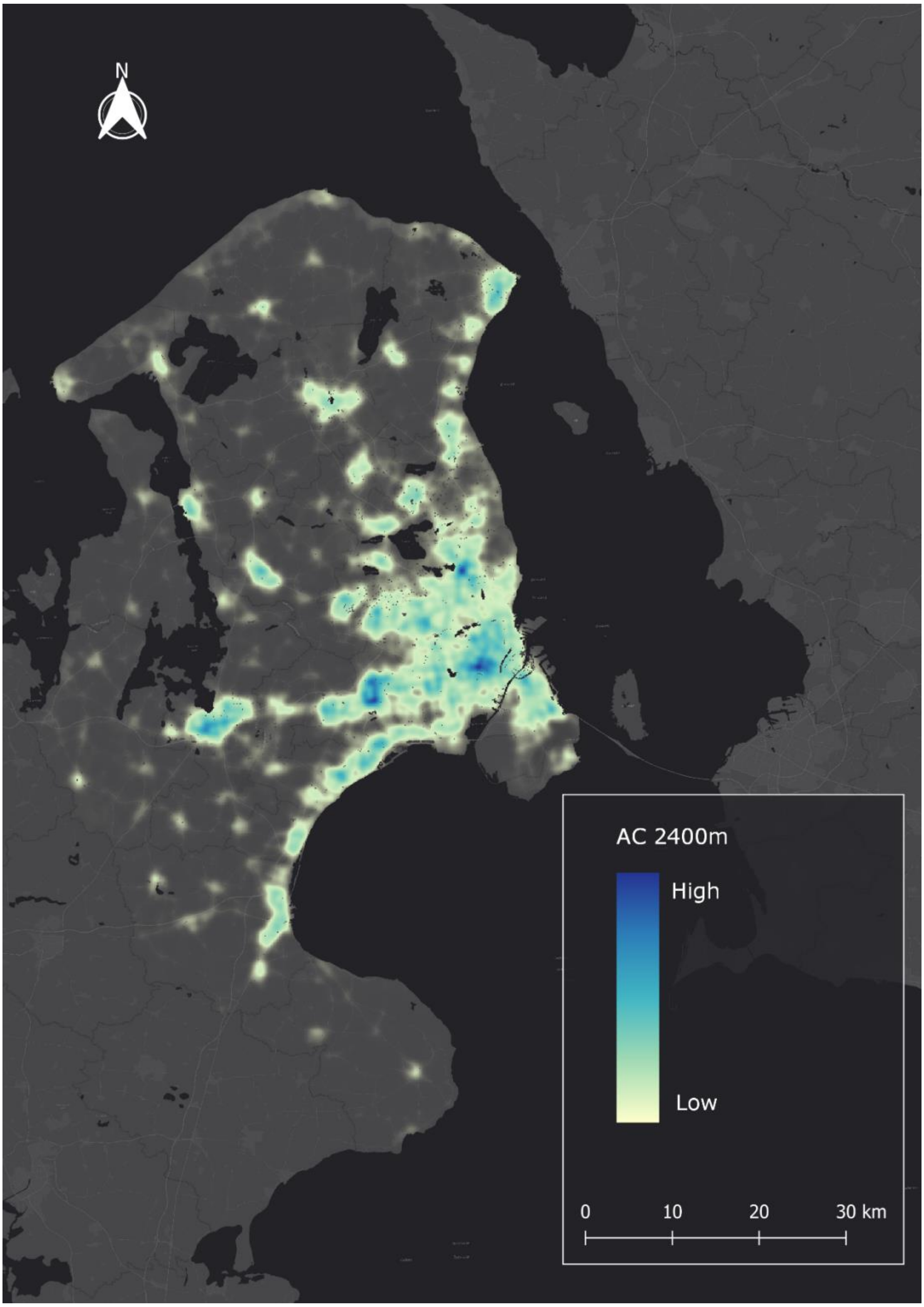
Supplement Figure 4: Angular choice calculations for 10000m.



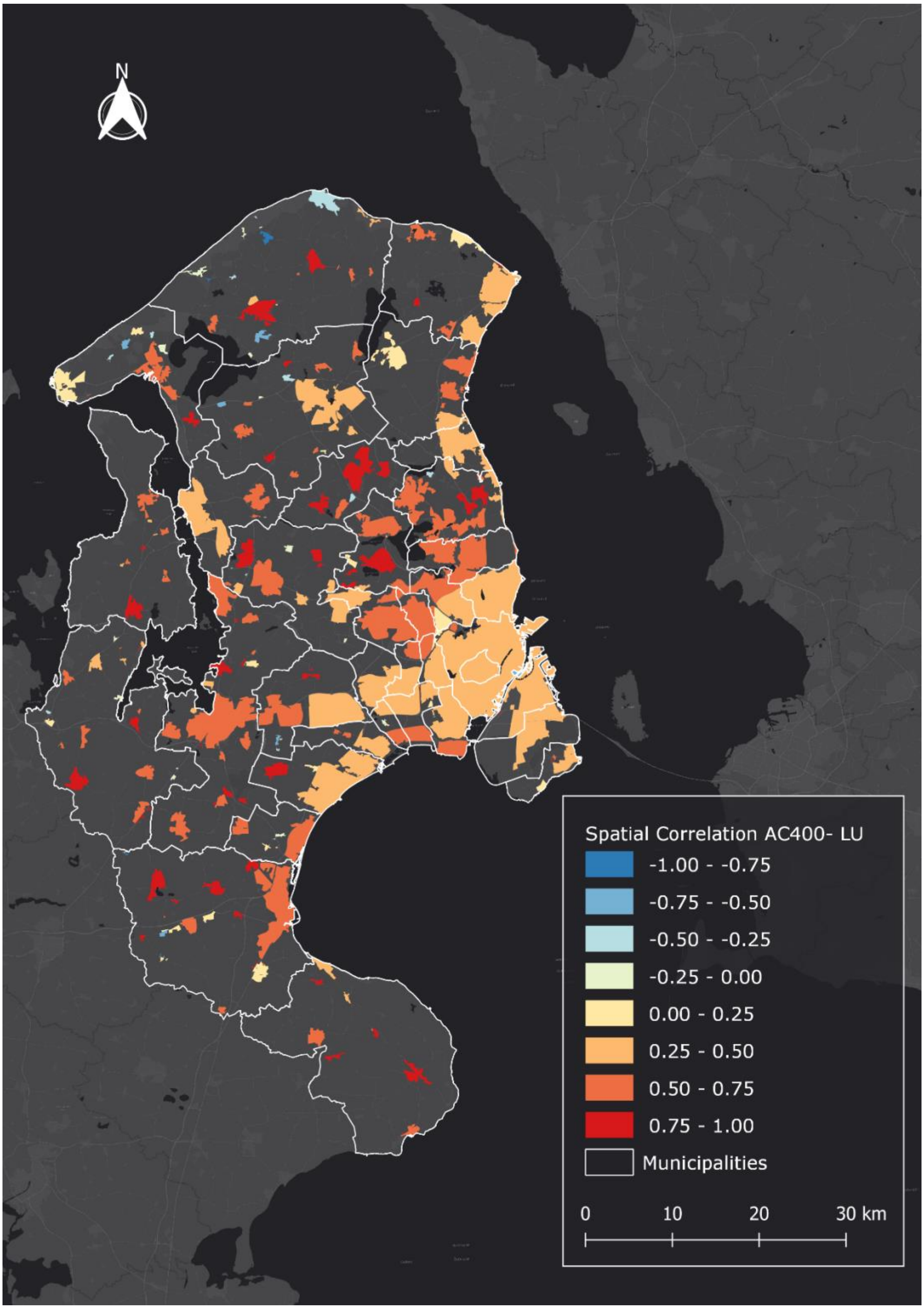
Supplement Figure 5: Angular choice KDE calculations for 400m.



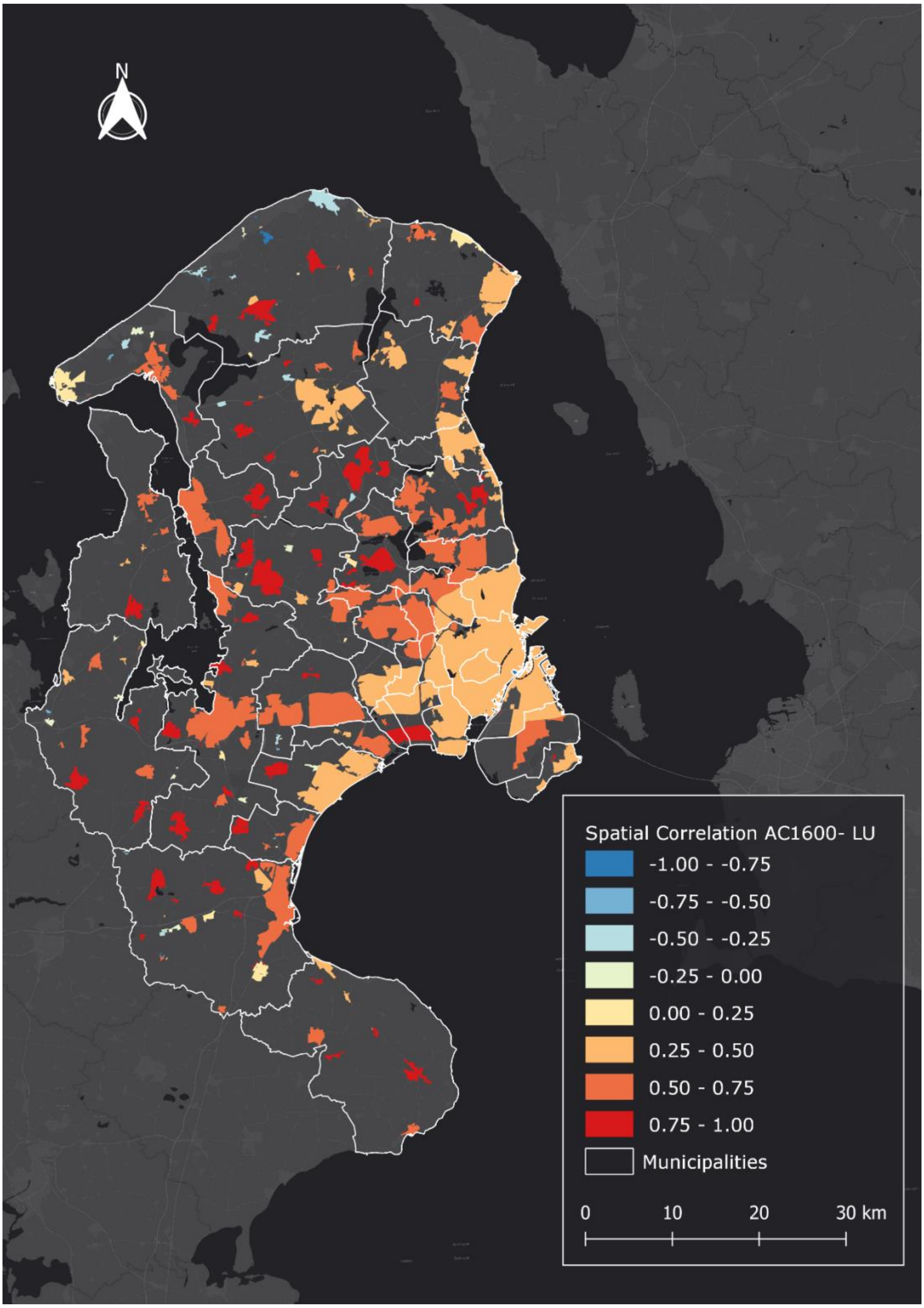
Supplement Figure 6: Angular choice KDE calculations for 1600m.



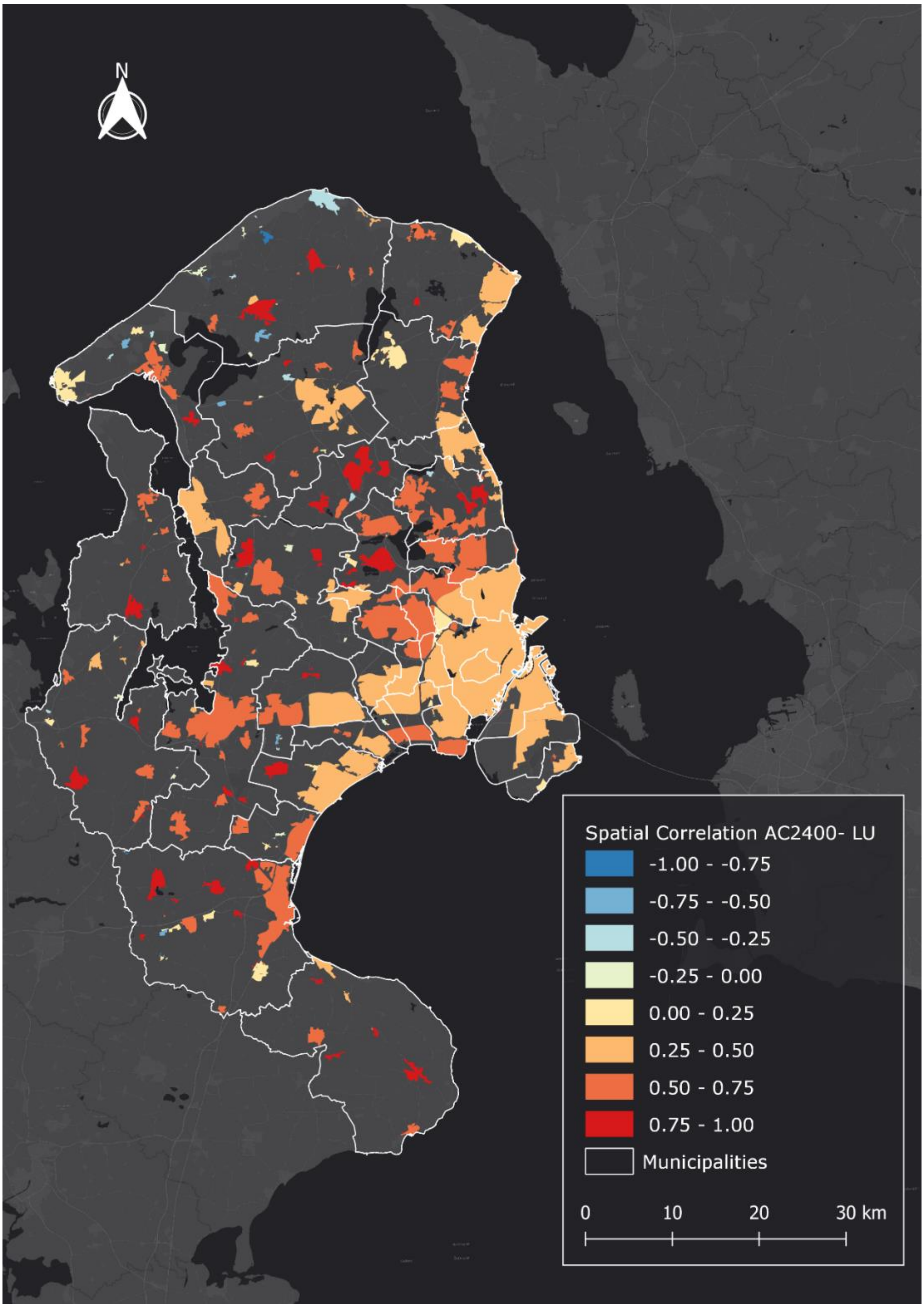
Supplement Figure 7: Angular choice KDE calculations for 2400m.



Supplement Figure 8: Spatial correlation of KDE for angular choice values and land-use KDE at municipality level for AC400.



Supplement Figure 9: Spatial correlation of KDE for angular choice values and land-use KDE at municipality level for AC1600.



Supplement Figure 10: Spatial correlation of KDE for angular choice values and land-use KDE at municipality level for AC2400.