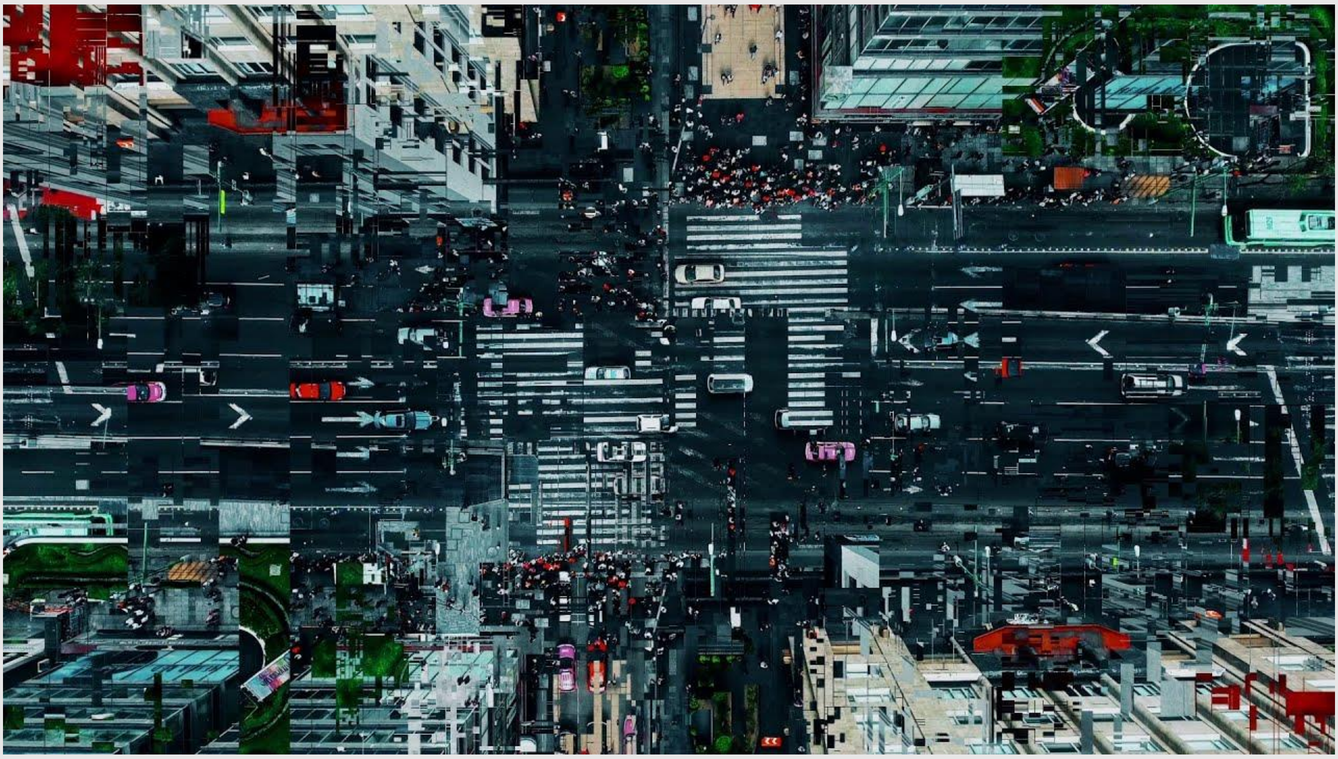
Investigating configurational and active centralities:

the example of metropolitan Copenhagen



Andrakakou Maria

Supervisor: Carsten Kessler

Copenhagen, 2020

Cover is a snapshot from: Perpetual Motion. 2019. [video] Directed by M. Cooper and N. Cobby.

Acknowledgements

This master thesis offered me the opportunity to combine coding and spatial analysis and has improved my knowledge on Copenhagen's urban structure. However, that would not have been achieved without the support of certain persons.

Initially, I would like to thank my thesis supervisor and professor, during my studies at Aalborg University Copenhagen, Carsten Kessler for providing his guidance and support when it was a necessity. His contribution was beneficial during the implementation phase of this research as well as during the development of this report.

Additionally, many thanks to Yannis Paraskevopoulos for inspiring me with this idea and for motivating me. His main suggestion was to develop an open source workflow in R for processing space syntax calculations which would assist many researchers with similar interests.

Summary

Contemporary metropolitan cities tend to be less dense and more car-oriented than in the past. Centralities existing within cities help determine how public space is perceived and utilized in everyday life. Sustainable mobility, social sustainability, and spatial justice can be examined by investigating centralities within the urban form. Following this rationale, the study focuses on pedestrian flows in Copenhagen's metropolitan area and provides a methodological framework for visualizing and analyzing them.

More precisely, the current master thesis study aims to investigate configurational centralities created by the road network based on space syntax analysis and active centralities of land-use patterns with a more geographical approach; finally, it analyzes their relation. Kernel Density Correlation is the tool applied to examine their relation. Furthermore, land-use mix is calculated for certain municipalities in metropolitan Copenhagen based on the Diversity Index. The combination of these approaches allows locating areas that have potential for improvement of their land-use distribution or their road network infrastructure.

Land-use mix calculated based on Diversity Index remains at a descent level for all municipalities. However, land-use mix has potential for improvement in particular municipalities. Areas with lower land-use mix are in proximity to areas with higher land-use mix and a good example of that is central Copenhagen's case and its neighboring municipalities.

Configurational centralities highlight two cases receiving intermunicipal thus car-oriented flows; Roskilde and Copenhagen municipalities. Centralities in Albertslund, Greve and Ishøj municipalities are designed for 5-minute walks as KDE for AC-400 highlights while centralities clustered around the axes of the Finger Plan are designed for 10-minute walks as KDE for AC-800 suggests. However, equally distributed centralities lack in northern municipalities as weel as in areas between the Finger Plan's main axes. Active centralities, resulting from non-residential land-use KDE, are more intense in areas of Copenhagen and Roskilde city centre and in several other municipalities. Dispersed active centralities are closer to the edges of the study area and within areas located far from the main axes of Copenhagen's Finger Plan.

Kernel density correlation shows that configurational and geographical patterns have stronger correlation with local scales and less strong with the global scale. This verifies the hypothesis that configurational centralities are an important factor for shaping land-use (active) centralities.

The results of correlations indicate that areas close to the city center and around the Finger Plan tend to be more central and friendlier for pedestrians and cyclists. Furthermore, centralities concentrated around Finger Plan′s axes are decentralized, more clustered and more continuous showing that its transit-oriented purpose has succeeded. On the contrary, central areas far from the city center, especially in the Northern part, 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.

Overall, the analysis indicates that there should be better organized for northern municipalities regarding their land-use distribution and road network. In addition, the Finger Plan is well established according to configurational and active centralities. A better land-use dataset and a further investigation including Angular Integration calculations as well as a combination with population census data are necessary tools for exploring the relations among municipalities and centralities. However, this study is a useful input for investigating the role of centralities within metropolitan Copenhagen and for highlighting areas in need of further research.

Contents

Glossary

KDE: Kernel Density estimation
KDC: Kernel Density Correlation
AC: Angular Choice
LU: Land-use
DIV: Diversity index

Table of figures

Table of equations

1. Introduction

Contemporary urban studies have raised an awareness on how efficient cities are when it comes to mobility, pedestrian and vehicular, within the urban system. This concern includes 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). Metropolitan cities have turned into spaces with low population density and car-oriented suburbs (Buliung, 2011).

Built environment can be perceived as organized system where social patterning can be determined by analyzing its spatial extents. Additionally, street network 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 on land-use patterns, economic and social activities (Iranmanesh and Atun, 2018; Jacobs, 1961). In this context, network centrality is the key towards understanding the urban form and its relations to place structure entities (Lee et al., 2014).

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

This research is a step towards understanding metropolitan Copenhagen's urban structure and social patterning for municipalities included in the Finger plan. Space syntax and Kernel Density Estimation are the main tools which help explore centralities in the study area as well as to distinct 'active' centers. Pedestrian movement is the key factor of this research so there is need to compare centralities created by the road network in various scales. 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.

Space syntax is a theory which helps identify centralities created by the road network while land-use pattern helps locate active centralities formed geographically. Their relation is explored during this research in order to highlight their role in metropolitan Copenhagen. More specifically, an investigation is conducted to seek their relation, if centralities are successfully planned and the type of mobility they attract. An additional, exploration is conducted on land-use pattern and its mix at a municipality level. This creates an index on how successful centralities are in each municipality in terms of sustainable mobility.

Problem statement & research questions

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" and terms this mechanism as a "city creating process" (Hillier,2007; Hillier 2003). This process is composed by the configurational pattern, land-use distribution and acknowledges 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 while failed do not and this affects human presence in the public space.

This study focuses on identifying the configurational and active centralities of municipalities within Copenhagen's metropolitan area. It also aims to explore the geographical (active) and configurational (syntactic) role and the character of the centers within the study area by applying space syntax analysis and analyzing the land-use pattern by Kernel Density Estimation. Correlations are made between configurational patterns created by the road network and geographical patterns of active centralities created by land-use for the entirety of the study area and at municipality level.

The main research questions formed by the problem statement include:

- Which is the character of active centralities based on their non-residential land-use mix within the study area?
- What kind of mobility do configurational and active centralities attract?
- Is there association of configurational and active centralities within metropolitan Copenhagen?

2. Theoretical background

In this chapter, there is a short introduction on space syntax theory and the meaning of centrality. Mathematical and geographical tools are also mentioned and there is a brief explanation on how they are utilized throughout the research.

2.1 Space syntax as a measure of configurational centrality

Space syntax is the key towards understanding urban structure by emphasizing either urban integration or segregation of areas within the entire system. The configurational approach highlights how complex cities are by investigating the connection within the local and global scales (Hillier, 2009). Local scales reflect movement within small areas in the entire system and most of the times refer to pedestrian flow while global scales reflect larger areas such as regional cities and refer to vehicular flows. In other words, a pedestrian thinks in local scale during their movement while a vehicle driver considers the global scale.

Research has shown that social and economic patterns can also be determined by the complexity of spatial patterns (Hillier, 1999). Spatial sustainability, which explores the geometries and configurations of the urban structure, is strongly linked to the spatial patterns of economic activities (Grazi, 2009). This term describes three main aspects associated to centralities within the urban form; environmental, social and economic which will be described further below.

Jacobs supports that by reorganizing the network structure of the cities, one may find more sustainable patterns than the existing ones (Jacobs,1961). Accessibility is the primary factor for describing the viability and vitality when it comes to movement from all points to all others in the cities (Hillier, 2009). Additionally, consumed energy for travelling inside the urban structure is related to the ecological footprint of cities (Rees and Wackernagel 1996). Moreover, in terms of social sustainability, space plays an important role on how it supports social interaction in a residential area or an activity center (Hillier, B. and O. Sahbaz. 2009). Urban structure affects the social character of areas either by promoting people's existence in the public space or by creating anti-social behavior. As Friedrich et al. suggest 'neighborhood cohesion' is a factor which creates a general trust among residents while more distinct roads in the urban system tend to be cores of higher crime rates (Friedrich et al.,2009).

As aforementioned, spatial sustainability is related to centralities within the urban structure in a way that economic activities can take place in a nearby small center while they also appear in a not far bigger center. This means, centers are highlighted for different but certain scales based on *natural movement* (Hillier, 2009). *Natural movement* as described in "Space is the machine: a configurational theory of architecture" is the volume of movement generated by the lines of the urban grid and not so much by attractors (Hillier, 2007). In other words, people's activities happen in a specific scale, such as pedestrian or vehicular movement, while behavior and choices organize the spatial structure (van Nes and Yamu 2018). Additionally, those different but certain scales can be described by pervasive centrality in the urban form (Hillier, 2009). A phenomenon like this, is common in metropolitan regions where polycentricity is created in an organic manner. That explains why, some centers of activities defined by the urban grid tend to be hidden from other larger centers which are in close proximity to the first ones.

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

There are two distinct types of centrality: active and live. Active stands for non-residential activity functioning as service and administration attractors and contain among other things working spaces within the centers while live centers concentrate functions of retails, entertainment etc (Hillier, 1999; Batty,2008). Both function as attractors to movement and promote co-presence. The "Space is a shape, and function is what we do in it" as Hillier suggests describes the shape of the expansion of centers as well as their purpose (Hillier, 2007).

Relation between space and social activities is a reality; shops attract movement and movement attracts shops (Hillier and Vaughan 2007; van Nes and Yamu 2018). However, in order to understand the urban morphology it is important to consider that cities define the places and not the opposite (Hillier, 2007). People are attracted by centers that are within metrical and topological central location. Lee et al. mention three types of centralities: metric centrality, topological centrality and geometrical centrality (Lee et al., 2014). Metric is described by the Euclidian distance from one point to all others, topological takes into account the direction change of the street segments from one line segment to all others and geometrical calculates the least angle-change for one line segment to all others (Lee et al., 2014; van Nes and Yamu 2018).

Configurational research examines the movement generated and directed by the street network within a 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). Global scale integrates the entire system with large-scale movement such as vehicular while local does the opposite and attracts pedestrian movement. For example, most integrated streets tend to be located in centers showing a hierarchy in the system's accessibility (Hillier, 1999; Hillier, 2007; Nes and Yamu , 2018). Accordingly, investigation of 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 city's configurations (Hillier, 2007; van Nes and Yamu, 2018).

Space syntax theory, which is developed by Bill Hillier in 1980s, can be utilized in urban design and for configurational analysis in urban structure. It analyses the road network and can detect its relation to activities and functions with spatial extents (van Nes and Yamu, 2018). Space syntax is used to describe the social patterns created inside the urban structure (Lee et al., 2014). There are two things that are calculated; the accessibility of the street segments and the possible used street segments while moving from one segment to all others. Various radii can be used in order to perform an analysis and highlight local and global scales of centrality (Hillier and Iida, 2005 ; van Nes and Yamu, 2018 ; Hillier, 2007). For instance, local accessibility indicates pedestrian movement and global accessibility vehicular (Iranmanesh and Atun, 2018).

Aforementioned calculations that can be achieved through space syntax analysis are also called syntactic integration (closeness) and syntactic choice (betweenness). Integration is utilized to measure the accessibility of each street segment towards all others as destinations. It takes into account the amount of paths needed to be crossed from the starting points to the end points. Choice shows how possible is a path to be selected while using the network. It calculates the frequency of a street segment passing through the shortest travel distance from the starting points to the end points within the network (Hillier, 2009). However, people tend to move through simple paths, and not short, defined by linearity as well as they choose routes with the least angular change during their movement (Montello, 1991; Hillier, 2009; Conroy Dalton, 2003; Lee et al., 2014).

This tendency of movement is well described by angular integration and angular choice and can measure spatial accessibility. Both include the angular distance in their calculations which measures the angular turns required to move from one point to another while using their shortest path. These indices use the equations shown below.

$$INT_{(i,r)} = \frac{(N_i - 1)}{\sum_{j=1}^{J} Dep_{(i,j)}},\ \{dis_{(i,j)} \leq r\} \qquad CHO_{(i,r)} = \sum_{k=1}^{K} n_{jk},\ \{dis_{(i,j)} \leq r;\ dis_{(i,k)} \leq r\}$$

Equation 1: Angular integration (INT(i,r)) and angular choice (CHO(i,r)) equations (source: Shen and Karimi, 2017)

Angular integration *($INT_{(i,r)}$)*, at a certain radius *r* is acquired by the mean angular depth *($Dep_{(i,j)}$)* from a starting segment *i* to an end segment *j*. Angular choice *($CHO_{(i,r)}$)*, within a certain radius *r* calculates 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). Network analysis theory calculates betweenness and closeness based on metric distance and space syntax theory takes into consideration the 'natural movement' as introduced by Hillier.

The study proceeds to Angular Choice calculation since pedestrian movement is the main focus. Probability of reaching a street segment in various scales is prioritized in order to examine centralities in individual municipalities. In that sense economic activities, co-presence and sustainability in each municipality are depicted by Angular Choice calculations. Angular integration would be of equal importance if the study were focusing on how easy one can travel to another municipality, but instead it explores the probability of not needing to travel to another municipality.

2.2 Kernel Density Estimator as a measure of functional centrality

Kernel Density Estimator (KDE) can help identify centralities in urban areas by utilizing non-residential spaces in the urban environment. KDE focuses on active centrality which in other words depicts centres created by activities of non-residential character. It is a measurement of density and diversity of various centralities created by functionality (Batty et al., 2003).

KDE method requires selection of cell-size and bandwidth which should correspond to the typical size and magnitude of a centre. KDE in this study, takes into account both the angular choice calculated by space syntax analysis depicting configurational centres and the land-use pattern depicting active centers . KDE for angular choice is implemented for various local scales and the global one. This step is important since it considers configurational centrality as well as active centrality (Porta et al., 2012).

KDE method, weights nearby entities more than further ones within a specified window which is represented by one value and therefore creates a continuous field while discontinuities are smoothened (Bailey and Gatrell, 1995; Porta et al., 2009). Bandwidth will approximate the size of a neighbourhood (h=300) as defined by Perry (Perry,1929) and used in multiple studies for 10x10 metre grid squares (Porta et al., 2012; Porta et al.,2009). Kernel density estimator is calculated by the equation shown below:

$$\hat{f}(x) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x - x_i}{h}\right)$$

Equation 2: KDE function (source: Porta et al., 2009)

KDE at *x* point implements the kernel function *K* with a bandwidth equal to *h* for *n* entities. *Xi* represents all entities within the specified bandwidth.

During the study KDE was applied for configurational and geographical patterns formed by the road network and the land-use, respectively. This step was required in order to proceed to Kernel Density Correlation and spatial correlation at a municipality level. Cell and grid size as well as bandwidth were interpreted in a way to make comparable the raster outputs. Cell size was adjusted to the scale of the input data which represented the mean length of a building block in Copenhagen which was approximately 100 meters. Choice of this cell size does not distort results and make the calculations faster (Paraskevopoulos and Photis, 2019).

2.3 Study area

Copenhagen's metropolitan area is planned based on Finger Plan which provides directives[1]. Study area is surrounding municipalities which are included in the Finger Plan. The reason is that is has been developed in order 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.

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

Figure 1: Finger plan 1947 (source: (https://planinfo.erhvervsstyrelsen.dk/)

It consists of 34 municipalities with over 2 million inhabitants, began in 1947 and the last revision was conducted in 2019. Some of the adjustments are cases where some municipalities are taken into consideration by the plan, green areas vary and changes are made in the transportation system. Regulations and restrictions organize the urban and road network development. Data which include the city centre, green areas and urban centres of the metropolitan area can be downloaded directly from http://kort.plandata.dk/spatialmap.

The map shown below highlights with light and dark pink, centralities designed during the implementation of the Finger Plan while polygons with grey colour are urban areas acknowledged by the plan. Planning extends from the city centre towards suburban areas and shows municipalities which are included in the Plan but their centralities are not developed yet. Moreover, the Plan is transit based on and extends 5-axes within metropolitan Copenhagen meaning that local centres have been developed around train stations (Fertner et al.,2012).

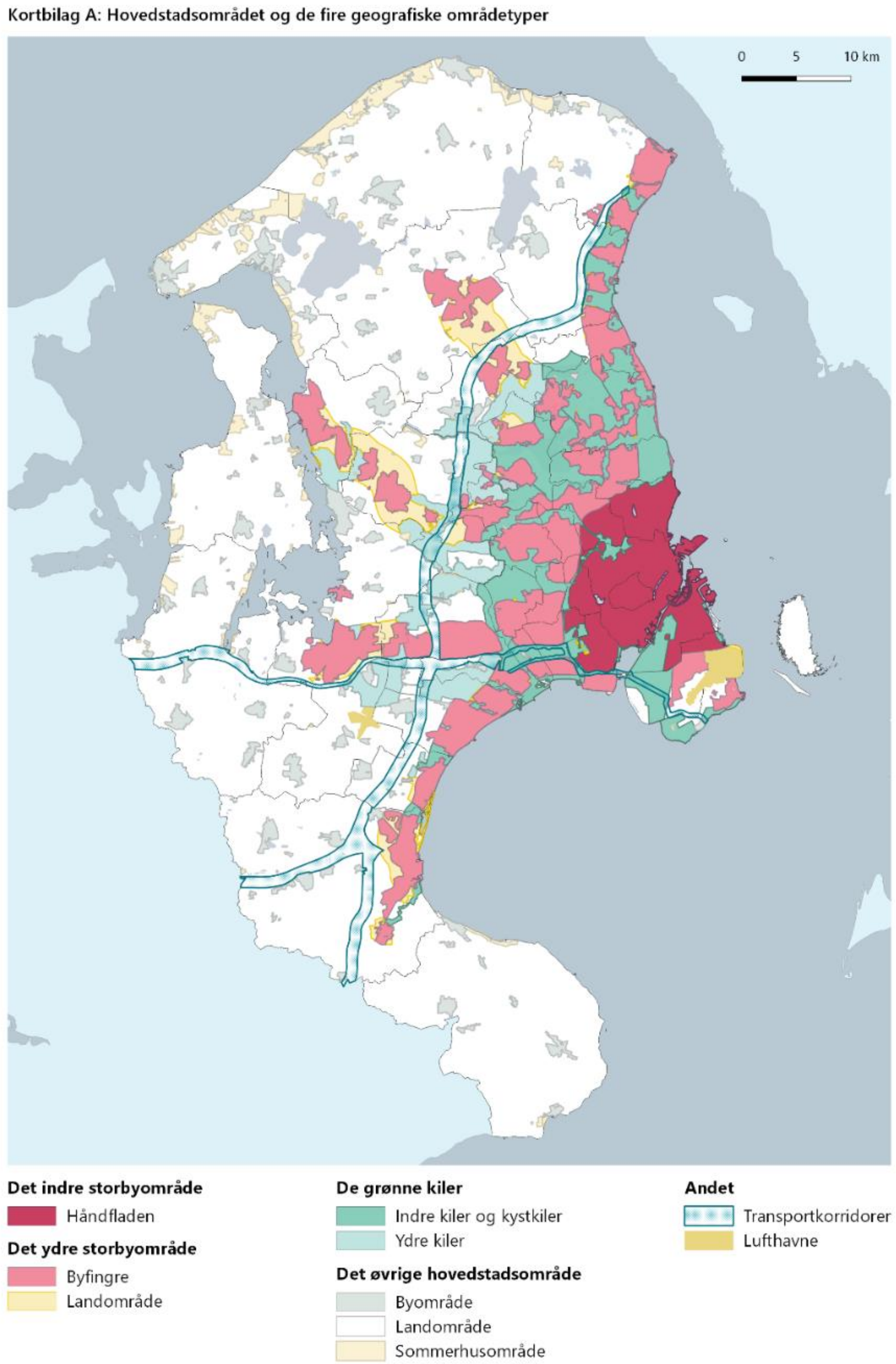


Figure 2: Copenhagen's Finger plan 2019 (source: https://planinfo.erhvervsstyrelsen.dk/)

3. Methodology

Research followed the methodology as shown in the figure below. Three elements are essential towards exploring the answers to the research questions. Firstly, configurational pattern is created by the road network and the angular choice calculations. Secondly, the geographical pattern of active centralities is formed by the land-use pattern, derived from point data. Thirdly, the character of active centralities in each municipality is explored by measuring their land-use mix. Road network lines and land-use points are the primary datasets processed for analysis.

In the beginning, road network was 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 in order to create a point pattern and then proceed to weighted KDE for this layer.

Land-use as point data were used for KDE production without any classification, which helped in identifying active centralities created by land-use distribution. 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 in the metropolitan extent and the extents of centers acknowledged by the Finger Plan. All parameters taken into consideration are mentioned in the next chapter.

Additionally, land-use points were also used for the calculation of the diversity index (DIV). DIV required classification of the land-use points as stated in the next chapter. The index helps understand the character of active centralities within municipalities by exploring the current state of their land-use mix.

All three explorations help highlight centralities planned for pedestrian or vehicular movement and evaluate land-use distribution individually, but their combination measures their quality. Quality oriented towards sustainable mobility, spatial justice and human presence in the public space.

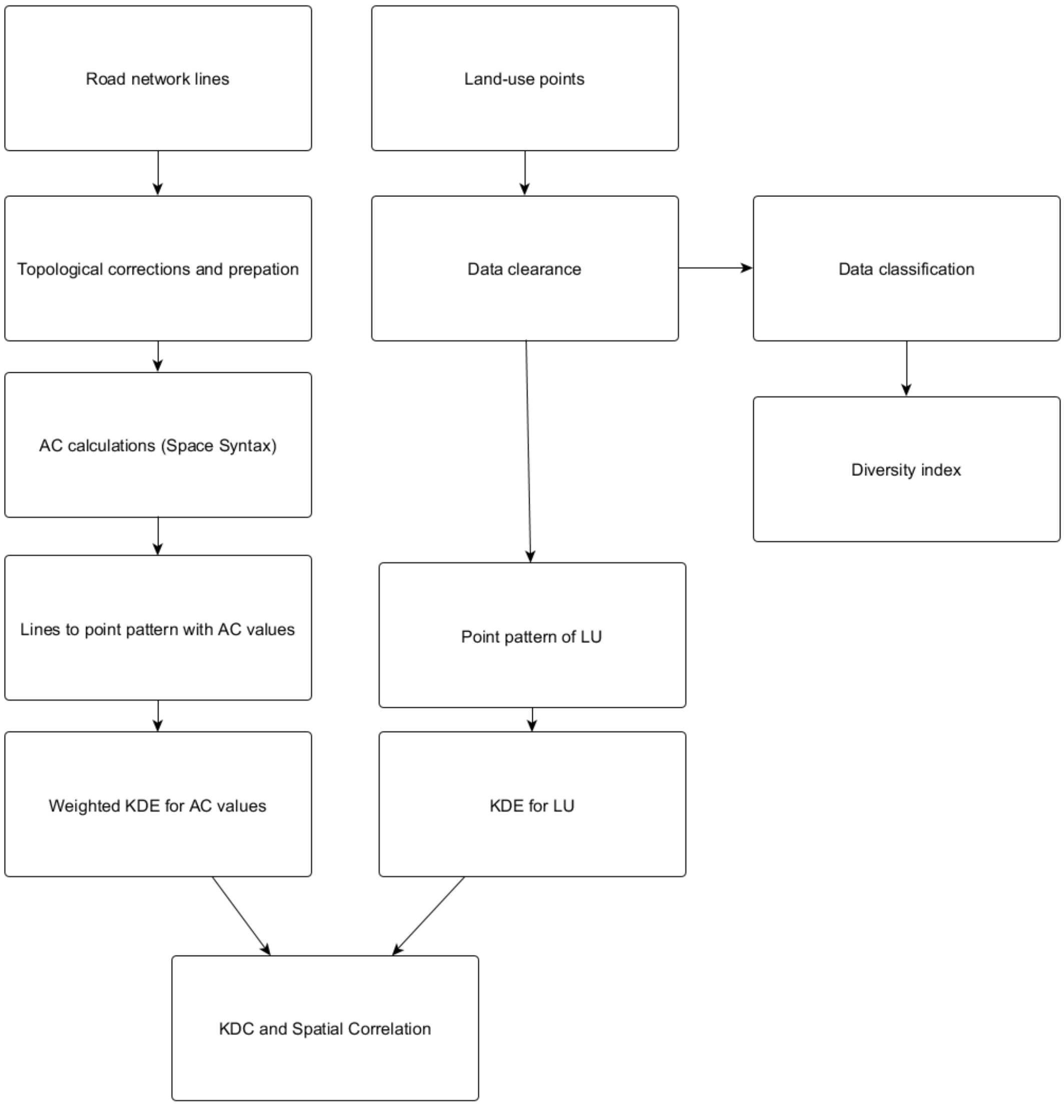


Figure 3: Methodology workflow

4. Data manipulation

In this chapter, there is information provided about data sources, manipulation, preparation and process. Main tools used throughout the research are also mentioned.

4.1 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. Results of preparation were handled in R to run the analysis and outputs were used as an input in QGIS in order to visualize them as maps.

Road network adjustments and space syntax calculations are the main preparations in QGIS. 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. Documentation (Stavroulaki et al. ,2019) about the tool and examples can be found on their website https://www.smog.chalmers.se/pst.

Research utilizes the road center lines and thus it is easy to calculate angular and not metric choice values. Segment map is created and calculations are made. 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 an input in R for statistical calculations.

Land-use point dataset is supervised and adjusted in QGIS based on research's needs. Then land-use points are an input in R. Both point patterns help in Kernel Density Estimation and afterwards Kernel Density Correlation and spatial correlation. Raster adjustments including masking the study area, raster calculations and zonal statistics also take place in R. Diversity index (DIV) calculations are executed in Microsoft Excel since it helped smoothen the workflow. All resulting layers produced are imported in QGIS in order to map them.

4.2 Data sources and description

Study required two main datasets and two supplementary datasets. Main are these used during the process such as segments of the road network and the points of land-use within the study area. Supplementary stands for datasets not utilized during the process but for pre-processing and post-processing tasks such as municipalities within the study area and the lakes. All datasets, apart from land-use points, are downloaded from https://www.kortforsyningen.dk/. Land-use point data are collected from Open Street Map (OSM) through Overpass API.

```python
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)
```

Figure 4: Code snippet example in python for downloading shops in Denmark with Overpass API

Road network layer is described as the Road Center Lines (RCL) within the study area and contain road segments and paths. Example of paths can be those passing through train stations and connect two public spaces. Paths were excluded since space syntax analysis must include segments with potential pedestrian and vehicular movement in the public space and paths refer only to pedestrian movement in private spaces.

Land-use points were used in order to detect active centers in the private or public sphere which are also spaces of co-presence and economic activities. This explains how queries are made through Overpass API. Four main tags were included in the queries after research conducted in OSM Wiki about their terms. These tags are amenities, shops, offices and leisure which were carefully examined afterwards and modified based on the research's needs. Example of modification is the removement of features such as benches, traffic lights, barbeque sites etc. which do not represent spaces provoking co-presence or economic activity and are further covered by spaces in which they are placed in, such as parks.

However, many researchers point out that OSM data lack of quality in some cases. Researchers mention that there is lack of data while comparing them to other services, there are not many updates and most of the data is within dense areas of cities. As a result, much information is missing from more distant areas (Cipeluch et al, 2010; Haklay,2010; Basiri et al., 2016).

Polygons of municipalities are collected in order to help determine the spatial extent of the analysis. Municipalities and lakes are also used to mask out water bodies from the study area.

4.3 Data preparation and process

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

In the beginning study area was defined by the Copenhagen's finger plan where municipalities that include centers and other urban areas specified by the plan were selected. A polygon of the area was shaped and a 3 kilometer buffer was applied. Road network intersecting the buffer was selected. Buffer was applied to minimize the edge effect of space syntax analysis. Results are shown for the initial extents.

Place syntax tool (https://www.smog.chalmers.se/pst) launched in QGIS is used to create a segment map of the road network. Segment map tool, 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.

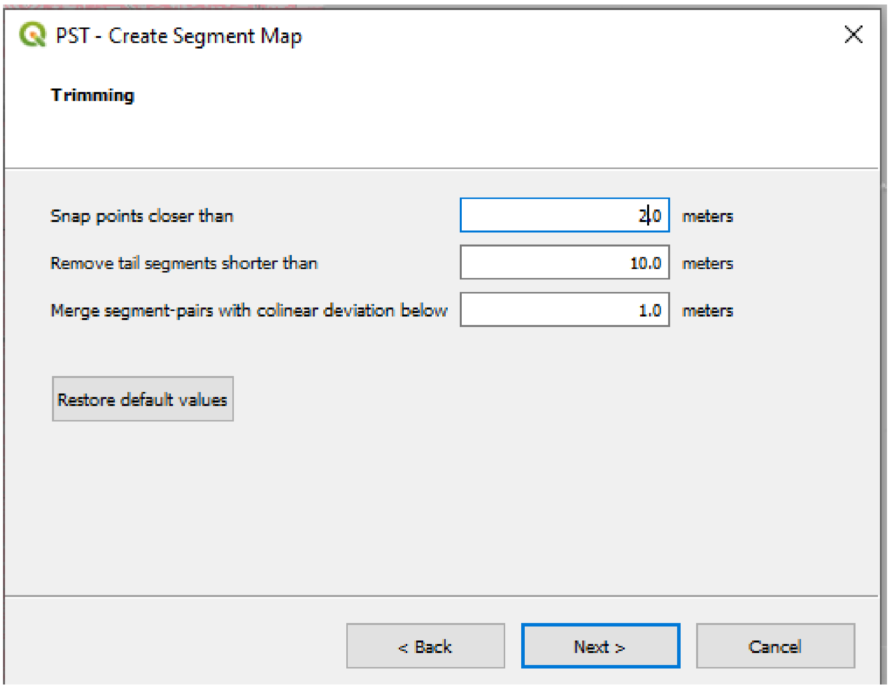


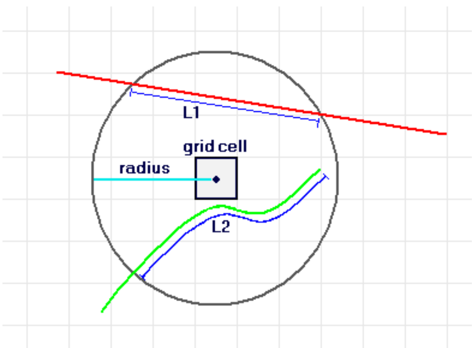
Figure 5: Place Syntax Tool and creation of segment map

The procedure described above created a topologically correct road network. Parts of it where disconnected so the problem was solved by using the Disconnected islands plugin (https://plugins.qgis.org/plugins/disconnected-islands/). 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 either the movement is vehicular or pedestrian. Simplification tool of QGIS was utilized and a tolerance of 5 meters was applied.

Space syntax tool was then used to calculate the angular choice within different radii. As aforementioned, the study focuses on pedestrian movement but in order to make a comparison on how centralities are approached there is need to run the analysis for various scales. Selected radii are 400 meters which depict a 5-minute walk, 800 meters for a 10-minute walk, 1600 meters for a 5-minute cycling, 2400 meters for a 10-minute cycling and 10 kilometres for the global scale which represents the car movement (Hillier, 2007; Porta et al., 2012 ; Porta et al., 2009, Paraskevopoulos and Photis, 2019).

Results of the analysis were used as input in R where a further manipulation was implemented in order to correlate centers created by the road network with active centers created by land-use points. As already mentioned, Kernel Density Estimation (KDE) is applied for both datasets with the same pixel sizes so that the comparison of centers will be pixel based. R does not give the ability the apply KDE on lines in contrast to the commercial software of ESRI's ArcGIS product. ArcGIS's documentation was reviewed and resulted to an open source solution. Documentation suggests that the algorithm calculates Density as shown in the formula below, 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 = ((L1 * V1) + (L2 * V2)) / (area_of_circle)
```

Figure 6: Line density methodology provided by ESRI (source: https://pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/how-line-density-works.htm)

An open source solution was to densify the nodes of the road network by 20 meter interval, turn lines to points from their nodes and assign 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.

Land-use data

Land-use point data was used in two different ways throughout the research. Firstly, its attributes were classified in order to investigate the non-residential land-use mix in municipalities which is termed by literature as *Diversity Index* (Shen and Karimi 2016). Secondly, the dataset was imported as raw data without classification and after modifications mentioned above in order to proceed to Kernel Density Estimation and locate active centralities.

According to Jacobs urban vitality is settled where dense and diverse human activity takes place (Jacobs, 1961). In other words, high land-use mix of activities is a precondition when it comes to characterize the vibrancy and vitality of a city's public space. It is where co-presence, sustainability and economic activities are prioritized (Shen and Karimi 2016). Diversity index (DIV) is measured by the entropy of land-use mix method developed by Cervero and Kockelman as shown in the equation below. Calculation is then normalized in order to make different results comparable, so ranges are between DIV= [0,1] after the normalization.

$$DIV = -\frac{\sum_k (p_k \ln p_k)}{\ln N}$$

Equation 3: Diversity index (source: Cervero and Kockelman, 1997)

Where:

k: is the class a land-use type

p: is the ratio of land-use type per municipality

N: is the total number of individual classes of land-use

Non-residential land-use needed to be classified after examining their different types. It is an essential step which allows to interpret the results better as well as understand the character of each municipality. The eight classes of point data as created during the study can be seen in Table 1. Service contains data about public institutions such as municipalities, embassies etc., entertainment refers to pubs, restaurants etc., office spaces to companies, lawyers etc., healthcare refers to hospitals and clinics, education to universities, schools etc., green spaces to parks, forests etc., culture to theaters, libraries etc. and retail to shops of each kind such as clothing and furniture stores. Data was divided into classes based on Shen's and

Karimi's (2016) and Mavoa et al. (2018) studies, was adjusted to the study area and depended on its attributes' availability.

Land-use type	Code
Service	0
Entertainment	1
Office	2
Healthcare	3
Education	4
Green spaces	5
Culture	6
Retail	7

Table 1: Land-use classes characterization

4.4 Kernel Density Correlation

Kernel Density Correlation (KDC) is a methodology to combine and correlate KDE's 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. Spearman's rank correlation method is used since the values of raster outputs are raw and are not following a normal distribution. Range of results is between ρ=[-1,1] with close to minus one values indicating strong negative correlation and close to positive one values showing strong positive correlation.

$$\rho = 1 - \frac{6\sum d_i^2}{n(n^2-1)}$$

Equation 4: Spearman's rho correlation coefficient calculation (source: https://statistics.laerd.com/)

Where:

d_i= is the difference of ranking of the values

n= number of values

An example of the correlation table as built in the study can be seen in Figure 7. R is used to interpret the values of raster layers by creating a vector matrix of the values of each layer and correlate them. The figure shows the different KDE raster layers produced on the left, where the cell values of each layer are placed inside vectors of one column and then correlation is executed for different combinations of columns.

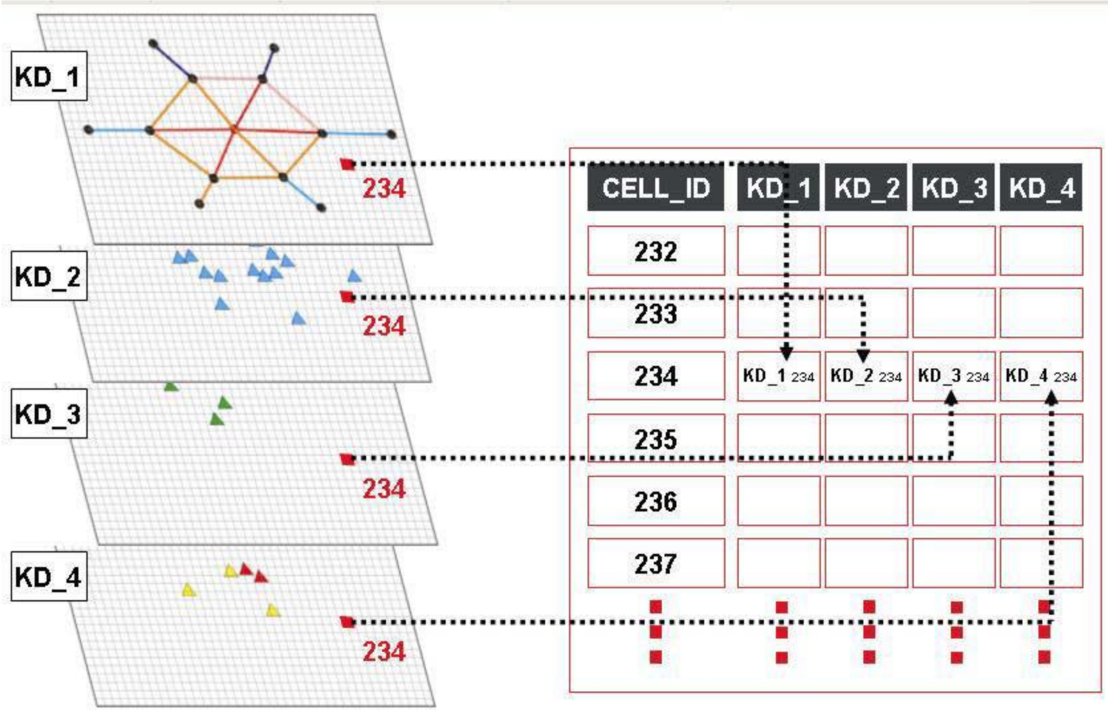


Figure 7: KDE raster layers creating the correlation table (source: Strano et al. 2007)

Raster layers correlated during this study are:

1. KDE of Angular choice (400m) – KDE of Land use pattern
2. KDE of Angular choice (800m) – KDE of Land use pattern
3. KDE of Angular choice (1600m) – KDE of Land use pattern
4. KDE of Angular choice (2400m) – KDE of Land use pattern
5. KDE of Angular choice (Global- 10000m) – KDE of Land use pattern

Land-use pattern layer concerns all land uses regardless their type since the aim is to examine configurational and active centralities provoking co-presence in the public space. Valid layer values above zero 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 correlation number for each combination which indicates if centralities are related.

4.5 Spatial correlation at a municipality level

Although cell-by-cell correlation provides results on if road network and land-use centralities correlate, there is need for a further investigation. This happens because the previous results show the overall image of their relation but a rather understandable result will be given if correlation is upscaled at a municipality level where centralities are designed or acknowledged by the Finger Plan. For this purpose, Rochette's (2018) method is applied in order to find the spatial correlation of the raster layers.

This method suggests using *focal* function of raster library in R, on two raster layers simultaneously. This function calculates values inside a square moving window using all neighboring cells inside it by weighting them (https://www.rdocumentation.org/packages/raster/versions/3.0-12/topics/focal). By using it on two raster layers it allows calculate a local correlation matrix of space.

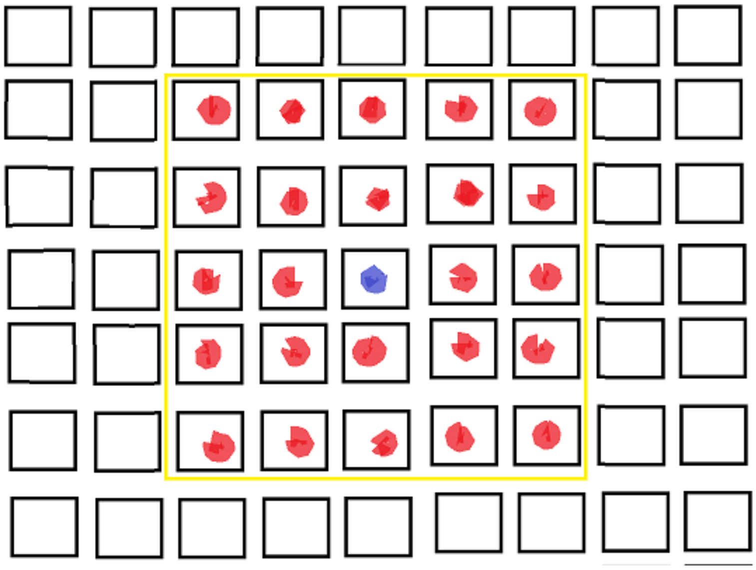


Figure 8: Example of the square 5x5 moving window

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 method and a correlation measure is then put inside an empty matrix. Results indicate where correlation is strong or weak spatially.

```r
#choice 800 - landuse
stackedch800 <- stack(ch800, landuse)
names(stackedch800) <- c("ch800", "landuse")

#Calculate local correlation using focal on two rasters at the same time
stackedch800_nb <- raster(stackedch800, 1)
values(stackedch800_nb) <- 1:ncell(stackedch800)

matrix_stackedch800 <- values(stackedch800) # stack as raster

cor_stackedch800 <- focal(
  x = stackedch800_nb,
  w = matrix(1, 5, 5),
  fun = function(x, y = matrix_stackedch800){
    cor(y[x, 1], y[x, 2],
        use = "na.or.complete", method="spearman")
  },
  filename = ("correlations/cor_stackedch800.tif"),
  overwrite = TRUE
)

plot(cor_stackedch800)
```

Figure 9: R snippet for local correlation using Rochette's (2018) method

During the implementation phase, a window 5x5 was chosen for all combinations of raster layers mentioned above (see subchapter 4.3). This decision was made after testing windows of 3x3 and 9x9. It was observed that there is no significant difference among them apart from the processing time so the intermediate solution of 5x5 window was chosen. The extent of the square moving window reaches up to $(5 \text{ cells } x100m)^2 = 0.25km^2$. This extent is a relatively walking distance and calculations have not a big effect in neighboring centers. In order to calculate correlations inside centers addressed by Finger Plan, zonal statistics were applied in which mean value of correlation cells is measured divided by number of cells within their boundaries.

5. Results

In this chapter, results of the analysis are explained and answers are provided to the research questions. Four main issued calculations are explored:

1. Diversity Index within municipalities (DIV)
2. Configurational and active centralities (KDE)
3. Kernel Density Correlation between configurational and active centralities
4. Spatial correlation between configurational and active centralities within Finger Plan centers in the study area

Results are interpreted for the entirety of the study area as stated in Copenhagen's Finger Plan and in centers designed or acknowledged by the Plan. Maps of the results are also provided in the *Appendix* of the study.

Diversity index calculates the land-use mix at a municipality level. Land-use data points are classified and represent non-residential use. Space syntax analysis calculates the Angular Choice (AC) values for each segment of the road network in the study area. These calculations are used to produce a KDE with configurational centralities. Kernel density correlation and spatial correlation are acquired for KDE raster layers produced for the configurational and geographical patterns of the road network and land-use point pattern, respectively. Land-use point pattern is entirely used during KDE, KDC and spatial correlation without any classifications. The aim is to proceed to an analysis which evaluates centralities created from the configurational and geographical analysis as well as to highlight their relation.

- Which is the character of active centralities based on their non-residential land-use mix within the study area?

Diversity index (DIV) was calculated for specified types of non-residential land-use. Results, as represented in the map below, appear to have mild differences among municipalities with most of them having over 50% diversity. The three most efficient municipalities in terms of land-use mix are Rudersdal, Glostrup and Lejre and the three least are Halsnæs, Ballerup and Solrød.

Municipalities ranking the least land-use mix are surrounded or are in proximity with municipalities ranking over 50% diversity. Copenhagen's municipality diversity reaches up to 0.5415 showing that it contains all kinds of functionalities at a decent level while it is surrounded by municipalities such as Herlev, Gladsaxe, Gentofte and Tårnby where office spaces, green spaces, healthcare and education institutions appear most and are more equally distributed as quantities.

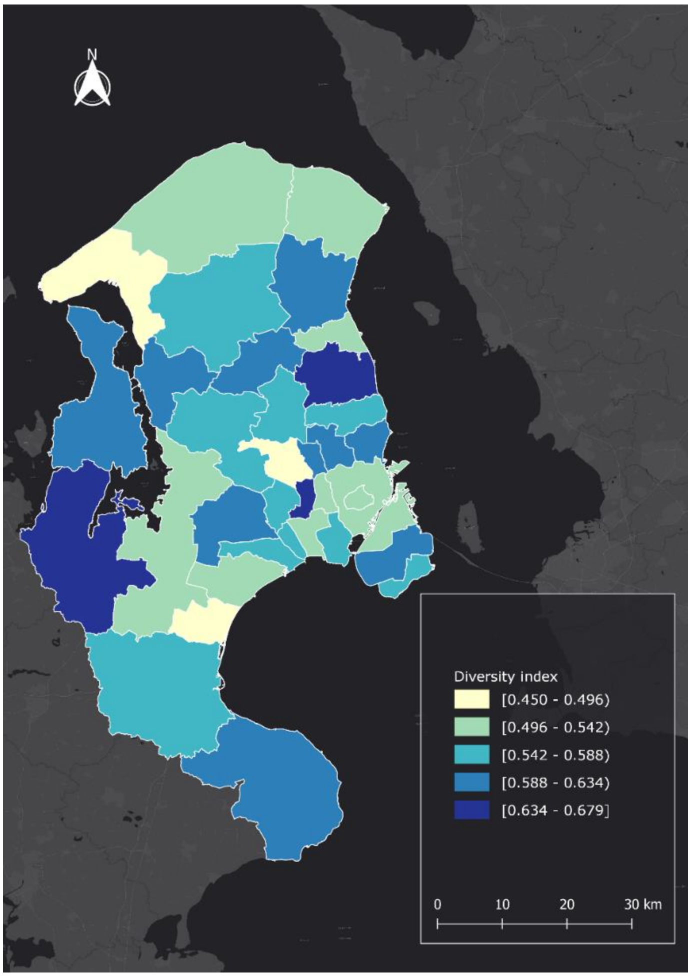


Figure 10: Diversity index of land-use within municipalities

- What kind of mobility do configurational and active centralities attract?

Angular choice calculations were acquired for various radii depicting local and global scales from 400 meters to 10 kilometers. The study focuses on pedestrian flows so 400m and 800m radius, which represent 5-minute walks and 10-minute walks respectively and are mainly compared to larger radii. As aforementioned, angular choice is the frequency of a segment to be used in angular shortest paths from a starting segment to an end segment for the entire network. Maps shown below, depict this frequency and boundaries of numbers are set with quantile classification. This may result to many values that seem to be high but are classified as low. However, numbers are classified based on the relativity of the entire network so they represent data as a whole and cannot be compared to other cities without adjustments.

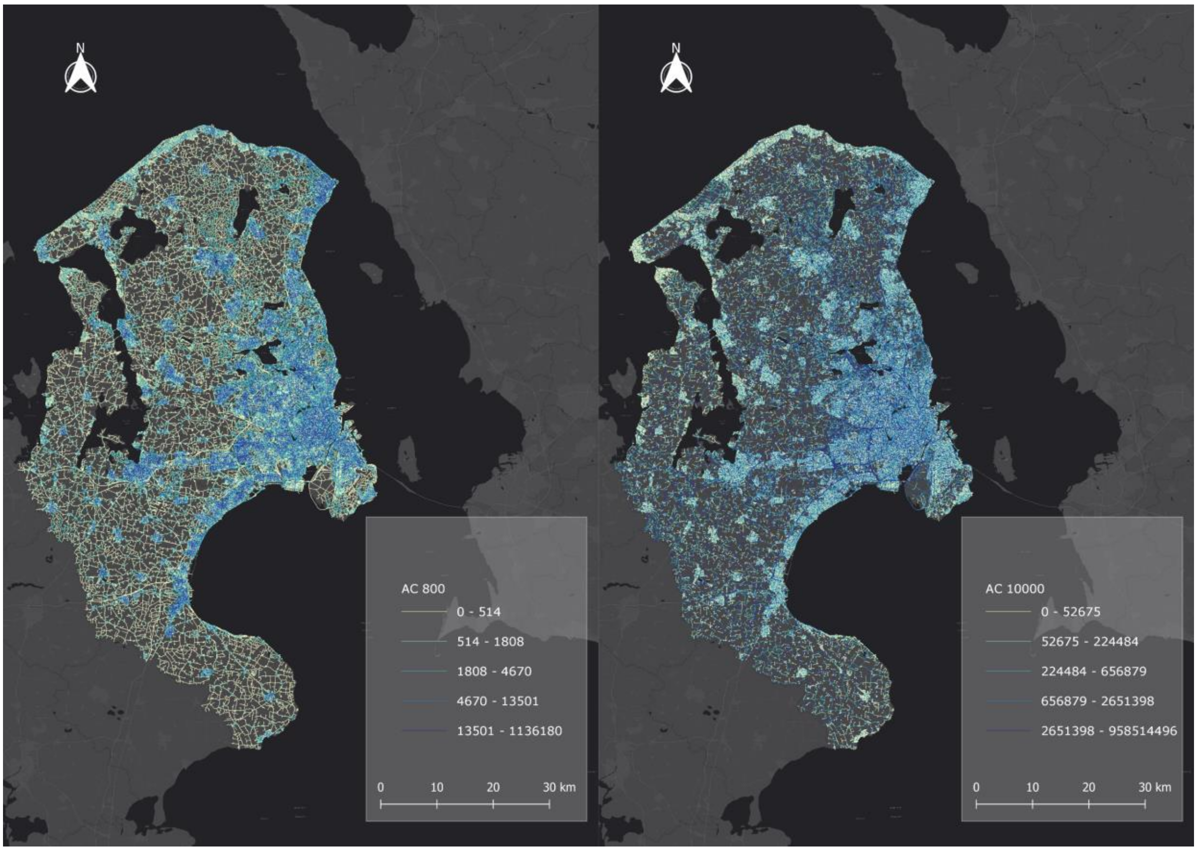
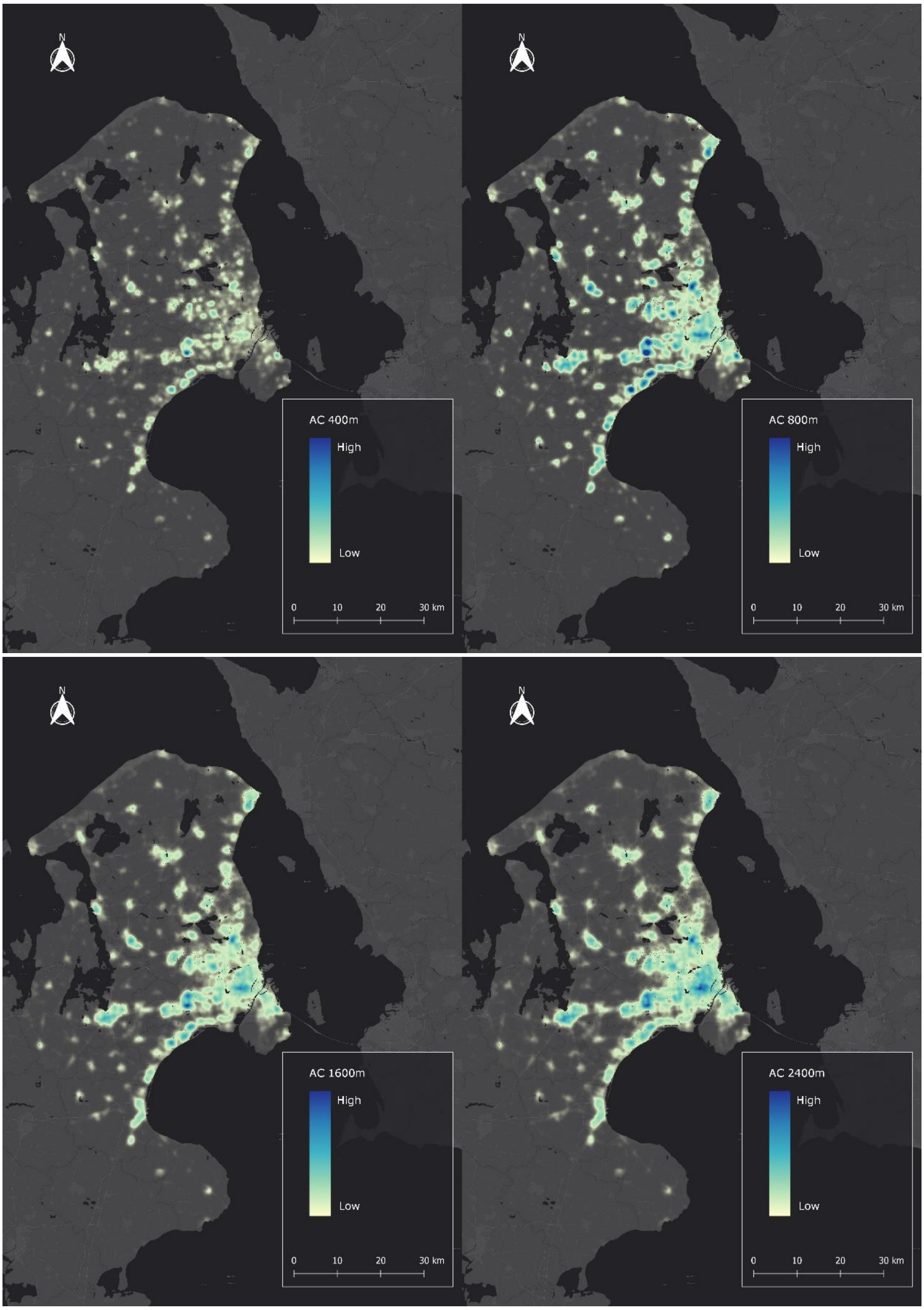


Figure 11: Examples of Angular Choice calculations for space syntax analysis

Maps following depict this frequency after KDE implementation and form the configurational centralities. Results indicate that configurational centralities for pedestrian usage are better for 800m radius corresponding to 10-minute walk. Moreover, in this radius centralities are close to the main axes of the Finger Plan and inside the city center. Radius of 400m highlights centralities at the western part of Copenhagen's city center and in Albertslund, Greve and Ishøj municipalities.

Radii of 1600m and 2400m which correspond to 10 and 20-minute cycling are better highlighted for areas around the main axes of Copenhagen's Finger Plan. This configurational type shows the polycentricity of metropolitan Copenhagen which focuses on main axes but not 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.

Global radius of 10km suggests that while moving towards the city center 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.


N
AC 400m
High
Low
0 10 20 30 km
AC 800m
High
Low
0 10 20 30 km
AC 1600m
High
Low
0 10 20 30 km
AC 2400m
High
Low
0 10 20 30 km

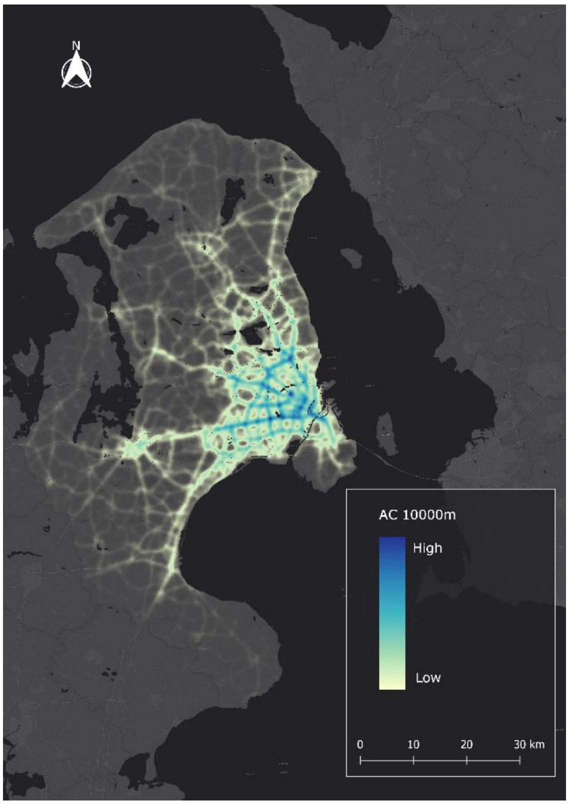


Figure 12: Angular choice calculations KDE for local and global scales

Map shown below highlights active centralities after KDE implementation for all non-residential land-uses without classifications. Active centralities are illustrated more intensely in areas of the city centre, 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 not close to 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.

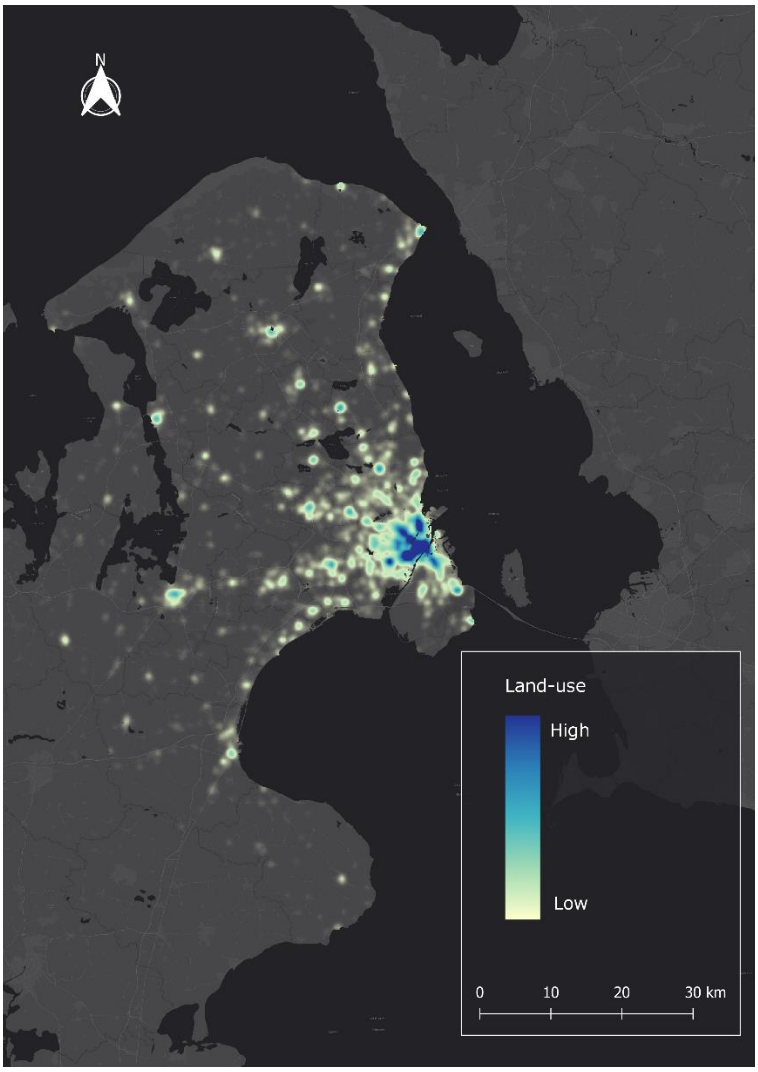


Figure 13: Land-use KDE

- Is there association of configurational and active centralities within metropolitan Copenhagen?

Implementation of kernel density estimation (KDE) for values of angular choice of each radius and the land-use pattern are a step towards proceeding to KDC. Resulting layers of KDE used bandwidth of 300m and 100m cell size in order to make them comparable. KDC was executed cell-by-cell as already described.

Spearman's rho correlation was calculated for combinations of raster layers as shown in *Table 2*. Local scales of angular choice (AC) have strong positive correlation with the land-use (LU) pattern. Only values above zero were taken 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.

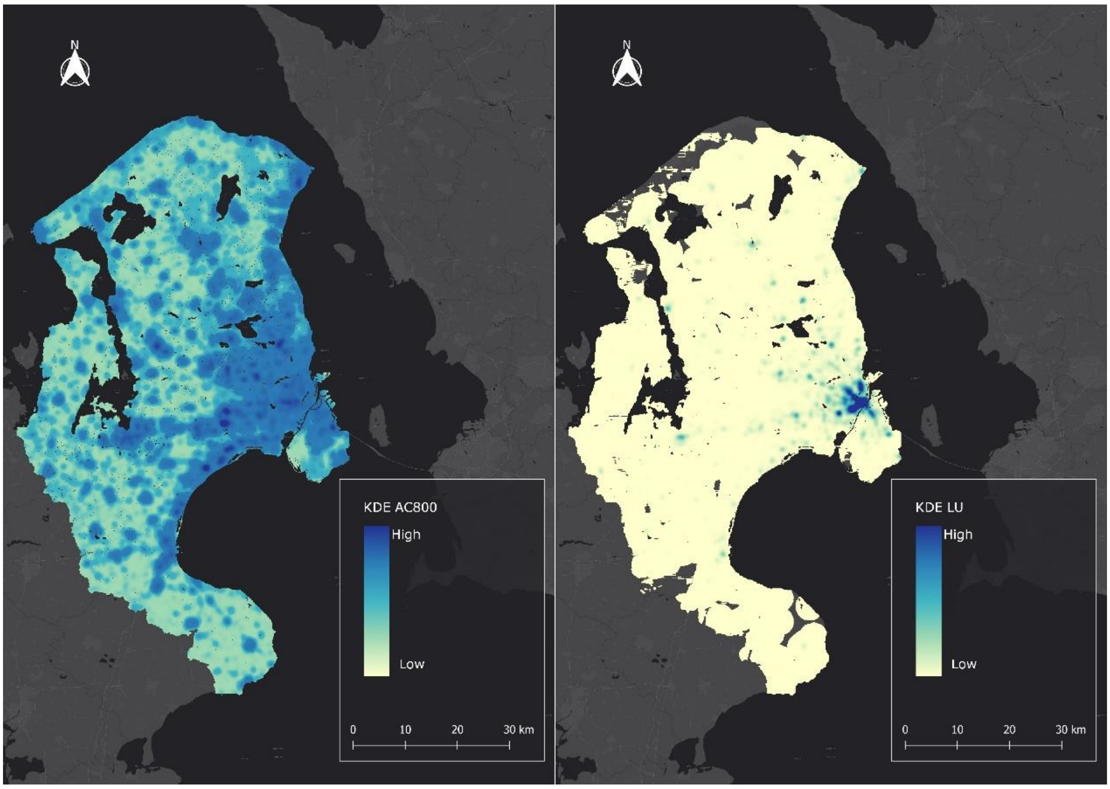


Figure 14: KDE for angular choice values and 800m radius (left), KDE for land-use point pattern (right)

There is association of global scale and land-use but not as strong as the local scales. This type of association might depend on the less car-oriented urban form. In other words, active centralities created by LU pattern are not totally concentrated around highways but also between them forming a convex shape.

As figure suggests below, there is similarity among different local scales for radii from 400m up to 2400. Global radius of 10km contains values which are more dispersed than in local scales. When it comes to comparison between AC and LU there is a repeated trend for local scale radii while in global radius values are not following the same trend. There are two explanations regarding the comparison between local and global scale with LU; there are several centers designed for pedestrians and cyclists but not as many as for cars.

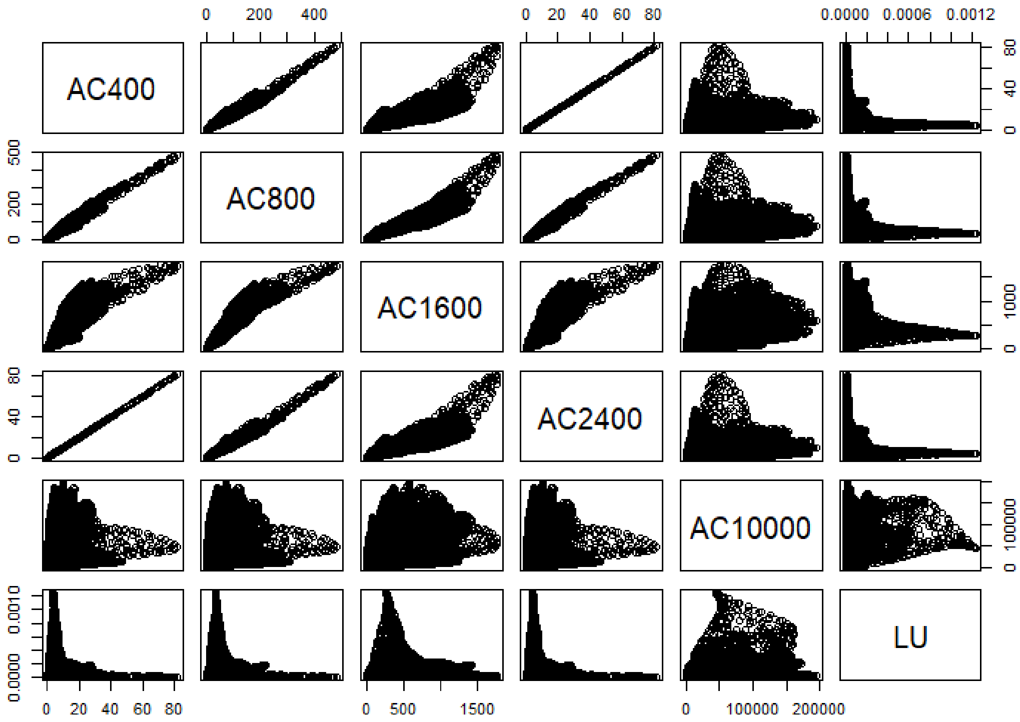


Figure 15: Pair plot of KDE values produced from AC and LU patterns

Correlation values of local scales show that urban planning promotes walking and cycling towards activities as well as it encourages co-presence in the public space. However, a not very strong positive correlation indicates that in some districts within the study area there is not easy access to centers by walking and cycling. Correlations for all combinations are resulted with a significance level of 1%.

		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 2: Correlation values among KDE of choice values and KDE of land-use

Further correlations needed to be applied in the combinations of the same layers as stated before so differences between configurational and active centralities patterns will be highlighted. Centers described by the Finger Plan within municipalities of the study area are chosen to be examined.

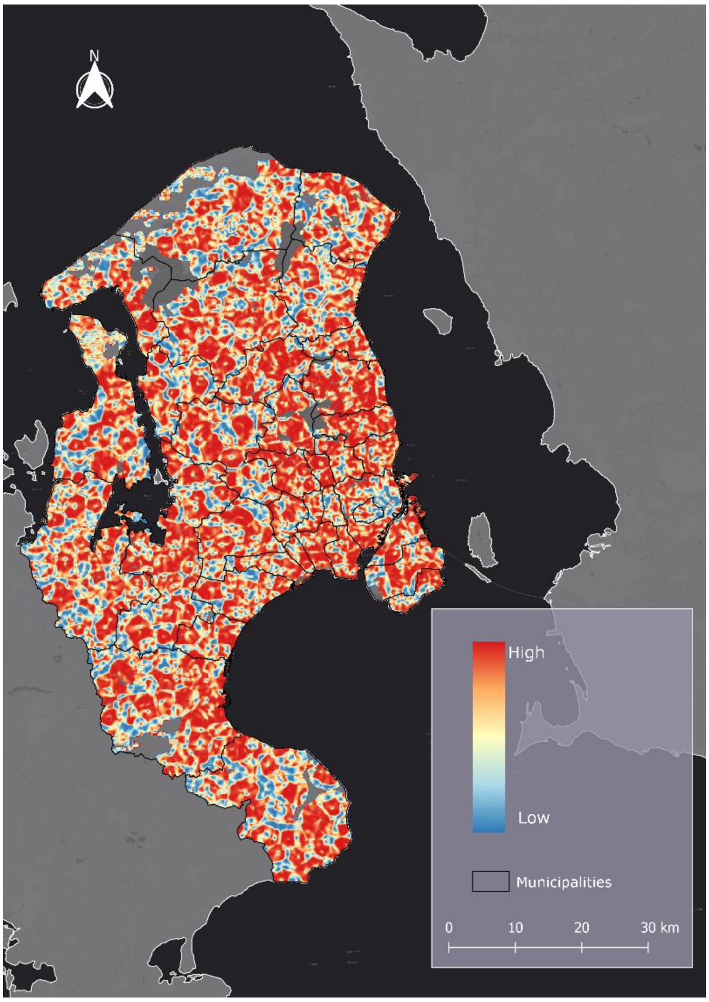


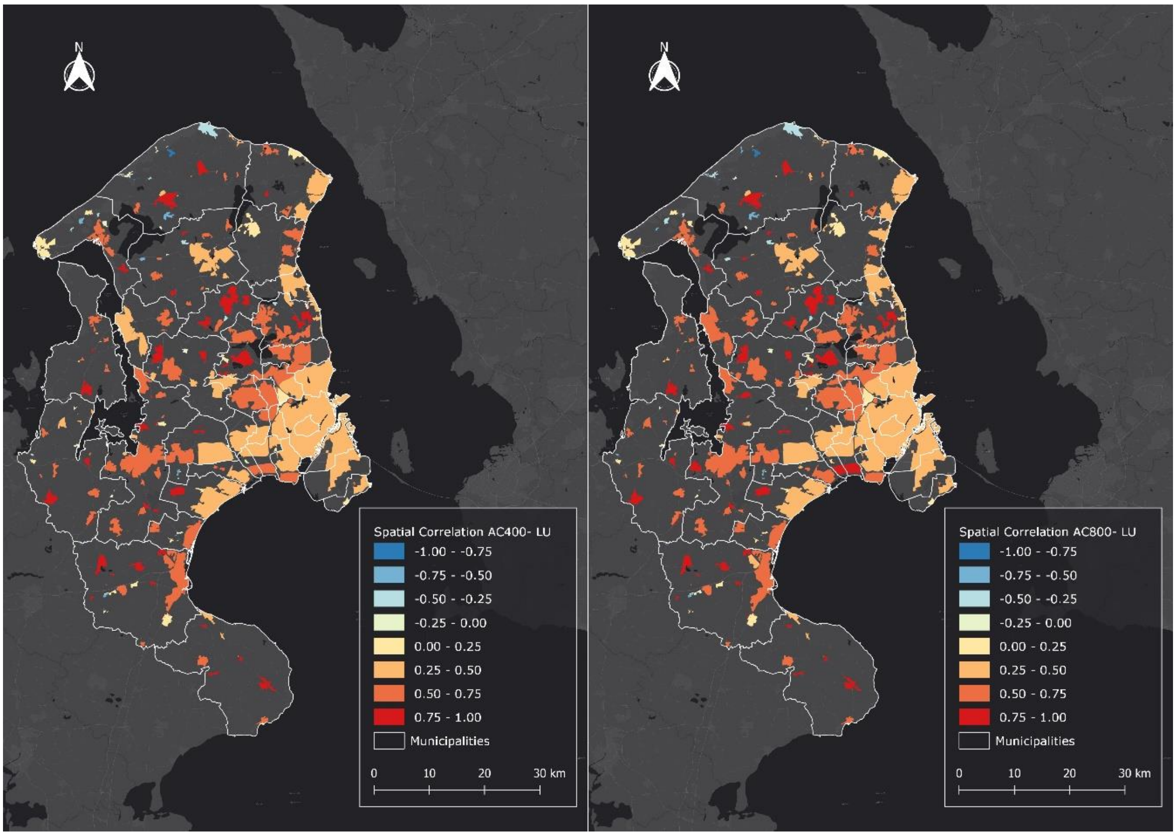
Figure 16: example of raster layer produced during spatial correlation of KDE of AC 800m and land-use

Maps shown below are the product of spatial correlation between configurational and active centers. Values of correlation flactuate from -1 to 1 since they are results of Spearman's rank correlation. Categories of correlation types are; no correlation, very weak, weak, strong and very strong.

As depicted in the maps below, centers in Copenhagen's suburban area starting from the edges of the city center 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 and 800m. Patterns for 1600m and 2400m are correlated similarly but centers created by the Finger Plan and urban centers in the Nothern-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 center 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 improvment the road network for pedestrians and vehicles or the land-use distribution.

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

Centers 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 centers around highways or roads designed for cars.



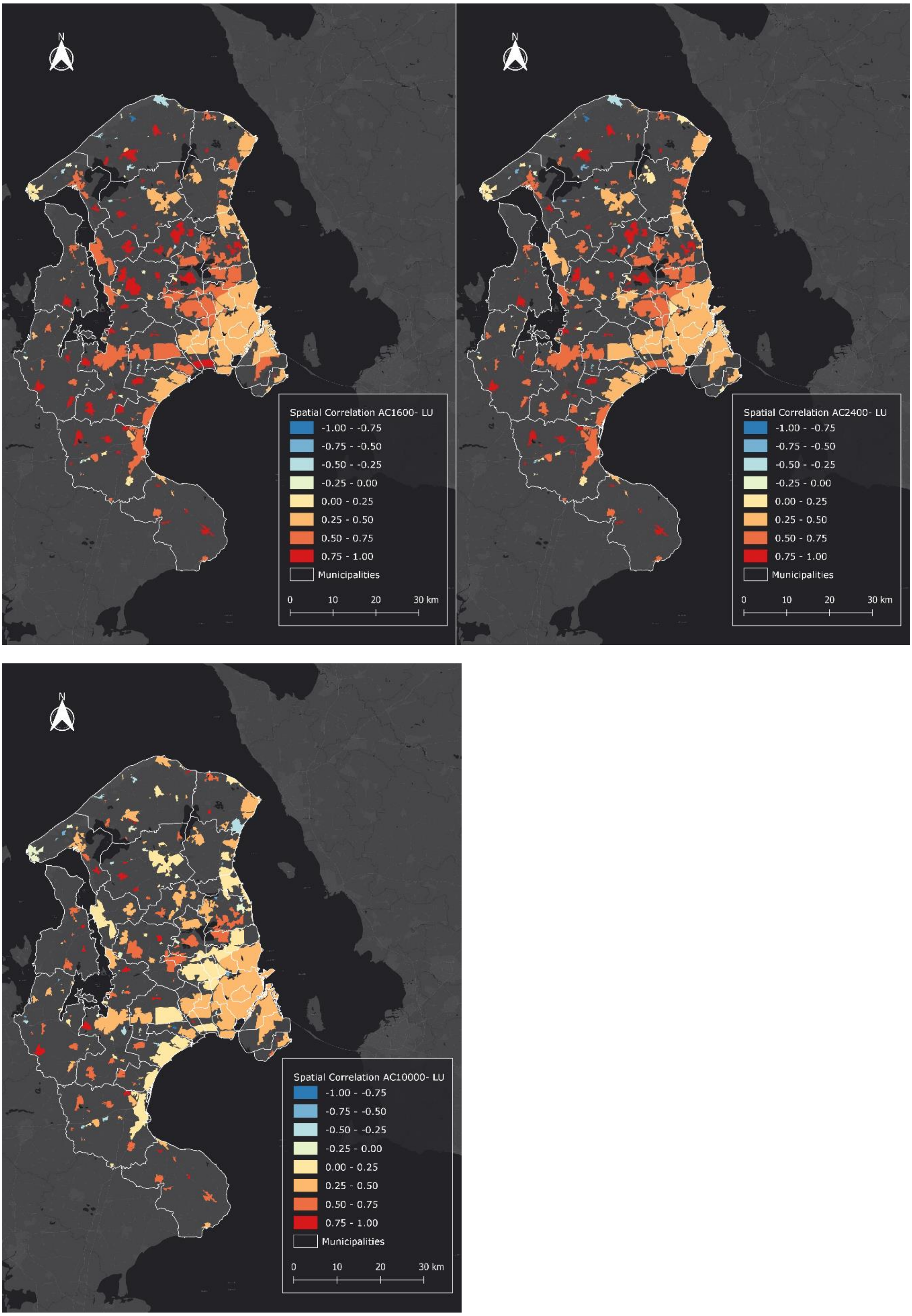


Figure 17: Spatial correlation of KDE for angular choice values and land-use KDE at municipality level

6. Discussion

This research is a contribution towards understanding configurational and active centralities in Copenhagen. A methodological framework is provided for visualizing and analyzing those areas to better explore urban mobility in the study area. The outcome can be a starting point towards exploring smaller areas more thoroughly such as specific municipalities.

Moreover, it explores walkability within centralities in the study area by comparing AC-400 and AC-800 with AC for larger radii. An additional study on how well centralities are connected is necessary for exploring accessibility to these areas. Angular Integration can help understand better suburban mobility. Additionally, implementation of various spatial analysis methods such as clustering analysis and geographically weighted regression (GWR) by combining more datasets such as Angular Integration calculations and census of population can contribute in analyzing the character of centralities in a more detailed way.

Calculation of diversity index is implemented for non-residential land-use points. Better results would be given if data about residential and non-residential use was provided by the authorities. Classes about the calculation of diversity index is according to other studies but also adjusted to the availability of data by OSM within the study area. Calculations can provide significantly different results for more classes of land-use and quantities of them.

KDE results for configurational and active centralities are calculated after choosing a 300m bandwidth and 100m x 100m cell size. The bandwidth was chosen after literature review. Similar studies chose this bandwidth by stating that this is the average size of a neighborhood and other similar studies compared bandwidths and selected 300m as the most realistic. Cell size could be changed to smaller one as in similar studies 10m x 10m was investigated. However, an adjustment was made because of the study area's extents. If an area with smaller extents is selected to be investigated, a smaller cell size is necessary.

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 be taken place in northern urban areas for walking and cycling as spatial correlation signified. 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.

Furthermore, centralities concentrated around Finger Plan´s axes are decentralized, more clustered and more continuous showing that its transit-oriented purpose has succeeded. 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, it will highlight areas which have potential of better centrality distribution.

In addition, OSM does not provide information about residential use and authorities do not provide detailed information about non-residential land-use. A dataset created by the same source either from the authorities or from OSM could help distribute better the quantities of the classified land-uses. As aforementioned, data missing from OSM may locate in distant areas from the city center since information collection is based on crowdsourcing or data imported might not be updated. These two factors have impact on the calculations of Diversity index, KDE, KDC and spatial correlation.

A different approach can be implemented based on network analysis which includes transit movement. Multi-modal analysis can help investigate the purpose of each centrality by comparing different ways of approaching spaces within the study area since Copenhagen’s Finger Plan is transit based.

7. Conclusion

The study is an attempt towards exploring the relation between configurational and active centralities in metropolitan Copenhagen, investigating the meaning of the configurational (syntactic) and active (geographical) centralities, and examining urban complexity by considering land-use mix within the municipalities.

Diversity index results show that land-use mix within municipalities is at a descent level. However, land-use mix has potential for improvment by starting from Halsnæs, Ballerup and Solrød municipalities. Diversity index signifies also that areas with lower mix are in proximity to areas with higher mix. It is important to note that a more reliable dataset of land-use points given by the authorities is essential.

Configurational centrality for AC-400 shows that Albertslund, Greve and Ishøj are planned for 5-minute walking distance and less highlighted centralities in the same radius are on the Finger Plan’s axes. Moreover, AC-800 shows that all centralities concentrated on the main axes of the finger plan are designed for 10-minute walking distance. Best centralities for cycling are also created 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 centre, especially those between the main axes and municipalities in the northern part of the study area, lack more equally distributed centralities. However, centralities existing in those areas are car-approached as AC-10000 highlighted. AC-10000 also shows that Copenhagen’s and Roskilde’s municipalities are used for intermunicipal mobility.

Kernel density correlation shows that configurational and geographical patterns have strong correlation for local scales and less strong for the global scale. This verifies the hypothesis 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 in the study area.

Additionally, spatial correlation indicates that certain centers have to be improved for pedestrian and cycling usage. Copenhagen's city center and centers between Finger Plan's main axes have potential for improvement regarding road network and land-use distribution for walking and cycling as found in the KDE analysis and the correlations implemented. When comparing local scales to the global there are particular suburban centers 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 highlighted. Central areas ranking less spatial correlation between the configurational and geographical pattern are also close to the nothern edges so there are two explanations for these results: these areas lack urban planning and are going to be developed later from the Finger Plan and the dataset of land-use points has many missing features.

Overall, analysis indicates that there must be better planning for northern municipalities regarding their land-use distribution and road network. Furthermore, Finger Plan is well established as configurational and active centralities show. However, it is neglecting areas between the main axes and the results are depicted on the KDE of active centralities; with dispersed and decentralized urban areas. A further research, taking into consideration population density and integration of areas in the entire study area is necessary.

8. Future development

As a future development of the current study Angular Integration calculations can be performed for the road network. These values can help understand better the accessibility from one place to another in the study area. Connections between areas such as different municipalities can be underlined and analyzed. This would result to a more holistic image on how vehicular mobility is perceived by urban planning in metropolitan Copenhagen. In order to include more sustainable mobility in the analysis such as means of transportation there is need for multi-modal network analysis. As a result, a multiple network centrality analysis would represent in a more detailed way how and why people move across Copenhagen.

Furthermore, population density should be taken into account in order to seek which centralities not located on the main axes of the Finger Plan must be developed. Finger Plan focuses on developing only those main axes by creating concentrated decentralized urban areas which are transit oriented. In addition to angular integration calculations, population density can highlight areas which must not be overlooked.

Additionally, proposed Place Syntax analysis can be used in order to examine distance from specified locations to others. For example, attraction distance and attraction reach are indices developed for supplementary analysis next to space syntax theory. More specifically, attraction distance can measure how far or close certain types of land-uses are and attraction reach is how much of the centers can be reached within a threshold. This analysis can be useful when analyzing the access to workspaces as Ann Legeby has investigated in her research which deals with segregation and its negative impacts on finding a job (Legeby, 2013). A study like this requires also residential land-use data.

Moreover, in case of using the research as an input for urban planning, interviews and pedestrian count for smaller scales of areas is essential in order to understand how local communities perceive and use the public space. This would give a helpful outcome on what is lacking from their neighborhoods and which alterations on land-use distribution and on road network should be done.

Bibliography

Bailey, T., & Gatrell, T. (1995). Interactive Spatial Data Analysis.

Basiri, J., Amirian, P., Sester, W., & Moore, Z. (2016). Quality assessment of OpenStreetMap data using trajectory mining.

Batty, M. (2008). The Size, Scale, and Shape of Cities.

Batty, M. (2012). Building a science of cities.

Batty, M., Besussi, E., Maat, K., & Harts, J. (2003). Representing multifunctional cities: density and diversity in space and time.

Batty, M., Couclelis, H., & Eichen, M. (1997). Urban Systems as Cellular Automata.

Buliung, R. N. (2011). Wired people in wired places: Stories about machines and the geography of activity.

Cervero, R., & Kockelman, K. (1997). Travel demand and the 3Ds: Density, diversity, and design. doi:10.1016/S1361-9209(97)00009-6

Cipeluch, B., Jacob, R., Winstanley, A., & Mooney, P. (2010). Comparison of the accuracy of OpenStreetMap for Ireland with Google Maps and Bing Maps.

Conroy Dalton, R. (2001). The secret is to follow your nose.

Fertner, C., Jørgensen, G., & Nielsen, T. S. (2012). Land Use Scenarios for Greater Copenhagen: Modelling the Impact of the Fingerplan.

Friedrich, E., Hillier, B., & Chiaradia, A. (2009). Anti-social behaviour and urban configuration using space syntax to understand spatial patterns of socio-environmental disorder.

Grazi, F., Waisman, H., & van den Bergh, J. (2009). Agglomeration economies and spatial sustainability.

Haklay, M. (2010). How good is OpenStreetMap information? A comparative study of OpenStreetMap and Ordnance Survey datasets for London and the rest of England. doi:10.1068/b35097

Hijmans, R. (202). focal - R Documentation. Retrieved from https://www.rdocumentation.org/packages/raster/versions/3.0-12/topics/focal

Hillier, B. (1999). Centrality as a process: accounting for attraction inequalities in deformed grids. doi:https://doi.org/10.1057/udi.1999.19

Hillier, B. (2003). The knowledge that shapes the city:the human city beneath the social city.

Hillier, B. (2007). Space is the machine: a configurational theory of architecture.

Hillier, B. (2009). Spatial sustainability in cities: organic patterns and sustainable forms.

Hillier, B., & Iida, S. (2005). Network effects and psychological effects: a theory of urban movement.

Hillier, B., & Sahbaz, O. (2009). Crime and urban design: an evidence based approach.

Hillier, B., & Vaughan, L. (2007). The city as one thing. Progress in Planning. doi:10.1016/j.progress.2007.03.001

Iranmanesh, A., & Atun, R. (2018). Exploring the spatial distribution of geo-tagged Twitter feeds via street-centrality measures. doi:10.1057/s41289-018-0073-0

Jane, J. (1961). The death and life of Great American cities.

Laerd statistics. (2020). Retrieved from https://statistics.laerd.com/

Lee, D., Dias, E., & Scholten, H. (2014). Geodesign by Integrating Design and Geospatial Sciences. doi:10.1007/978-3-319-08299-8

Legeby, A. (2013). Patterns of co-presence. Spatial configuration and social segregation.

Legeby, A. (2013). Patterns of co-presence: Spatial configuration and social segregation.

Mavoa, S., Eagleson, S., Badland, H. M., Gunn, L., Boulange, C., Stewart, J., & & Giles-Corti, B. (2018). Identifying appropriate land-use mix measures for use in a national walkability index. doi:10.5198/jtlu.2018.1132

Montello, D. R. (1991). Spatial orientation and the angularity of urban routes: A field study. doi:10.1177/0013916591231003

Paraskevopoulos, Y., & Photis, Y. (2019). The Athens Form: Exploring the spatial signatures of functional and configurational typologies of Athens Urban Area.

Perry, C. A. (1929). The Neighborhood Unit. Neighborhood and Community Planning.

Planloven - Erhvervsstyrelsen.dk. (2020). Retrieved from https://planinfo.erhvervsstyrelsen.dk/

Porta, S., Latora, V., Wang, F., Rueda, S., Strano, E., Scellato, S., . . . Latora, L. (2012). Street Centrality and the Location of Economic Activities in Barcelona. doi:10.1177/0042098011422570

Porta, S., Strano, E., Iacoviello, V., Messora, R., Latora, V., Cardillo, A., . . . Scellato, S. (2009). Street Centrality and Densities of Retail and Services in Bologna, Italy. doi:https://doi.org/10.1068/b34098

Rees, W., & Wackernagel, M. (1996). Urban ecological footprints: why cities cannot be sustainable and why they are a key to sustainability.

Sébastien, R. (2018). Spatial correlation between rasters. Retrieved from https://statnmap.com/2018-01-27-spatial-correlation-between-rasters/

Shen, Y., & Karimi, K. (2016). Urban function connectivity: Characterisation of functional urban streets with social media check-in data. doi:10.1016/j.cities.2016.03.013

Shen, Y., & Karimi, K. (2017). The economic value of streets: mix-scale spatio-functional interaction and housing price patterns. doi:10.1016/j.apgeog.2016.12.012

Stavroulaki, G., Koch, D., Legeby, A., Marcus, L., Ståhle, A., & Pont, B. M. (2019). Documentation PST 20191122. doi:10.13140/RG.2.2.25718.55364

Thurstain-Goodwin, M., & Unwin, D. (2000). Defining and delimiting the central areas of towns for statistical modelling using continuous surface representations. Retrieved from https://www.smog.chalmers.se/pst

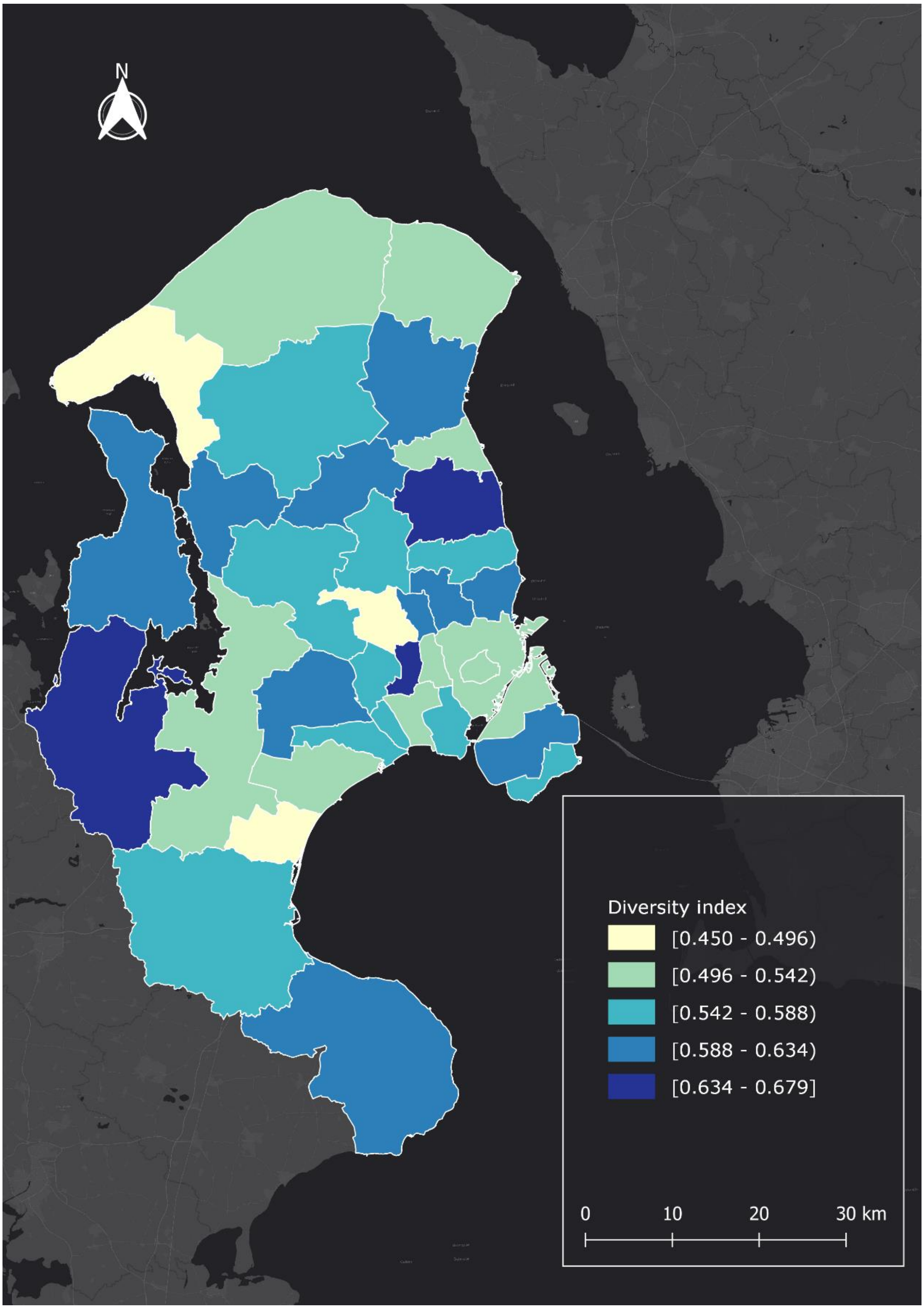
Van Nes, A., & Yamu, C. (2018). Space Syntax: a method to measure urban space related to social, economic and cognitive factors.

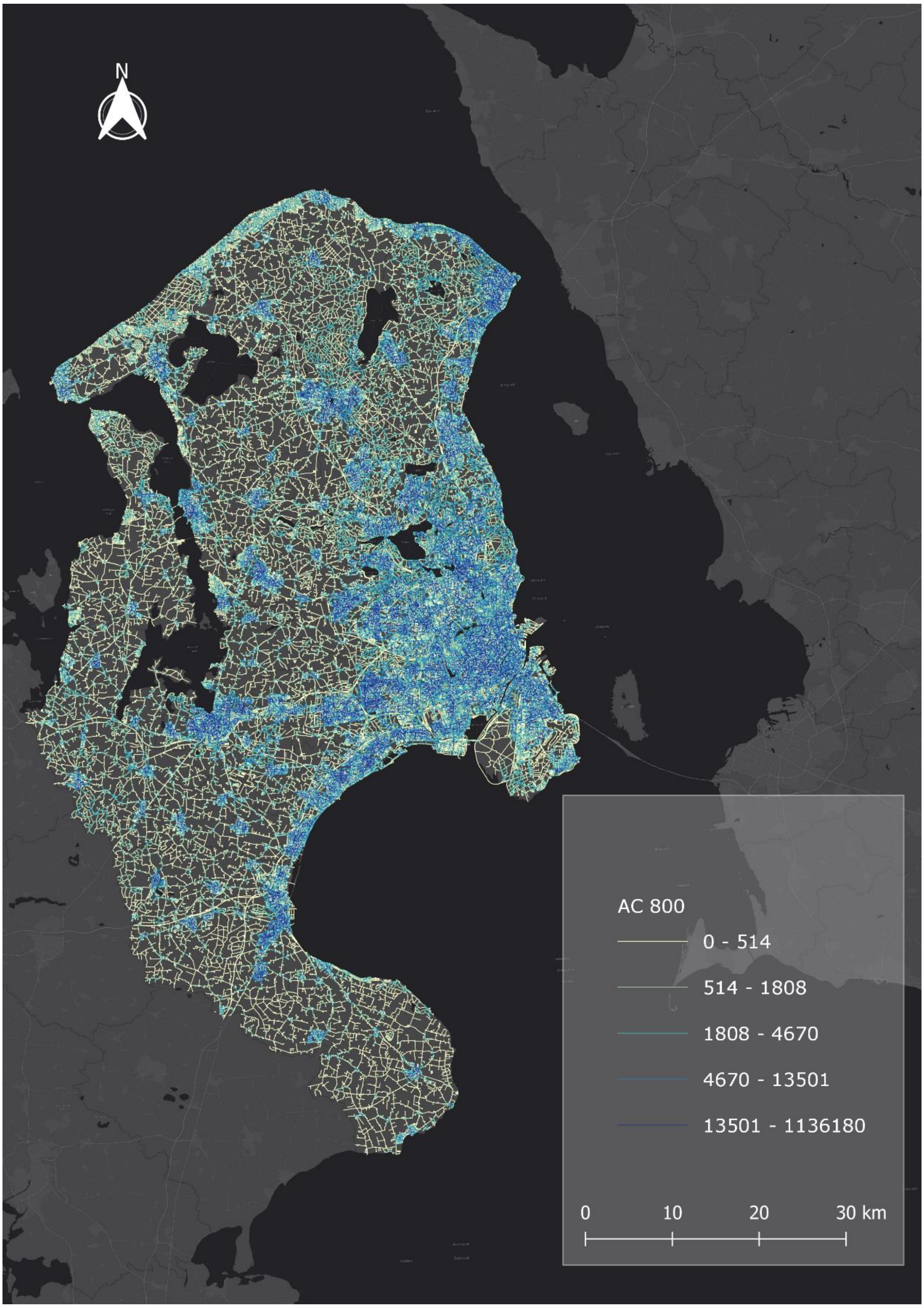
Vaughan, L., Jones, C., Griffiths, S., & Haklay, M. (2010). The spatial signature of suburban town centres.

Zhong, C. (2015). Revealing Centrality in the Spatial Structure of Cities from Human Activity Patterns.

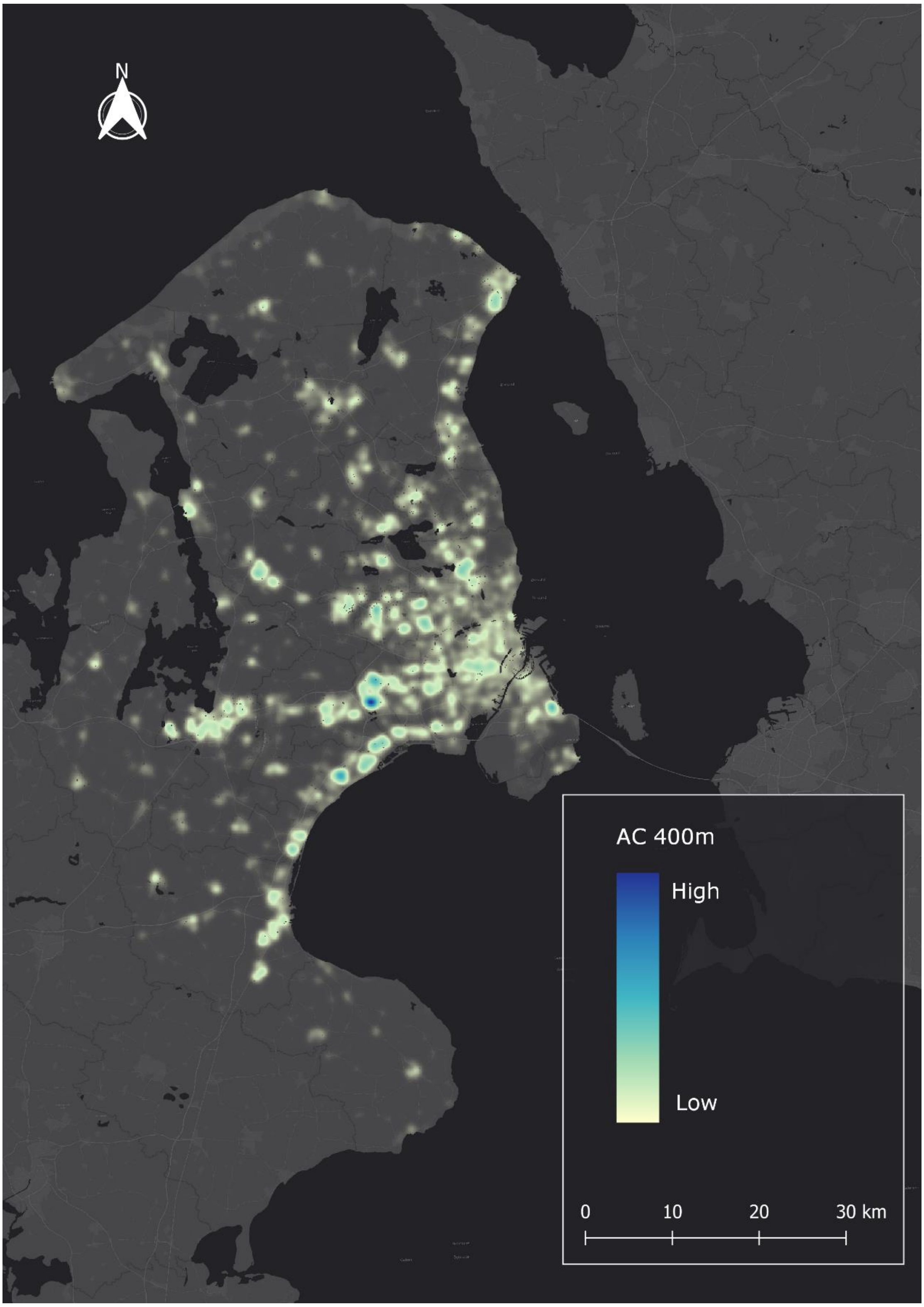
Appendix

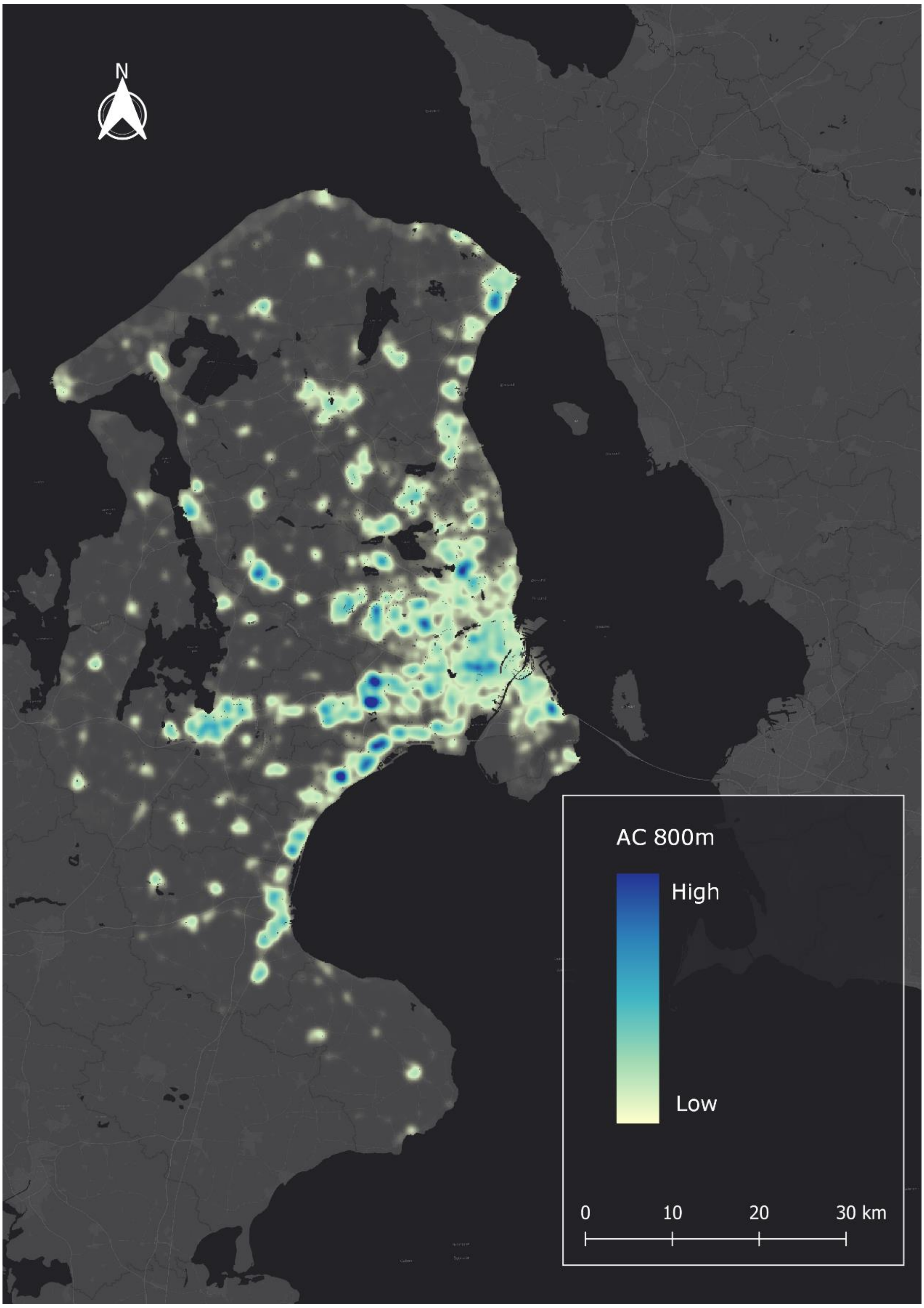
The code repository is: https://github.com/maryandplus/space_syntax_scripts_thesis

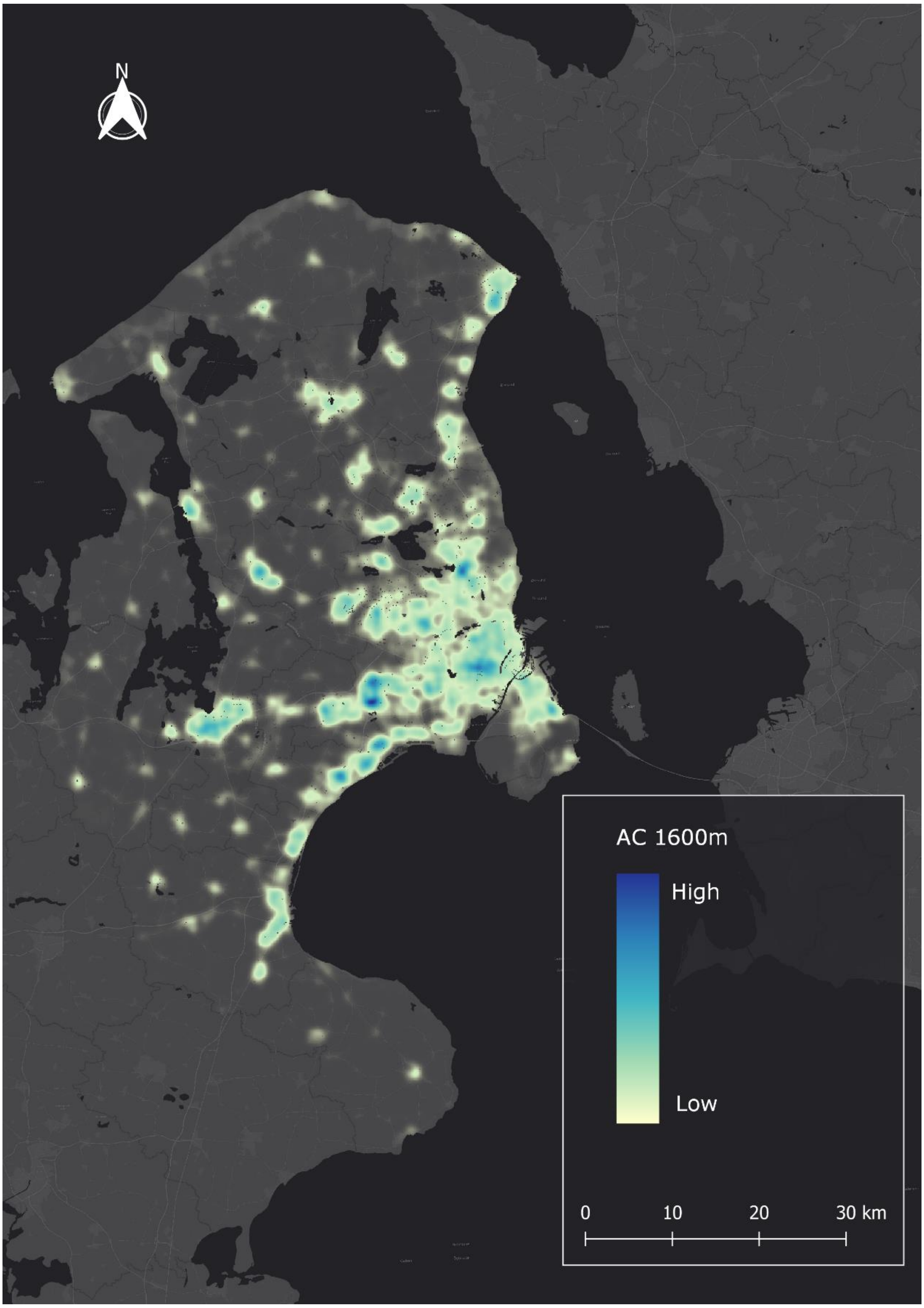


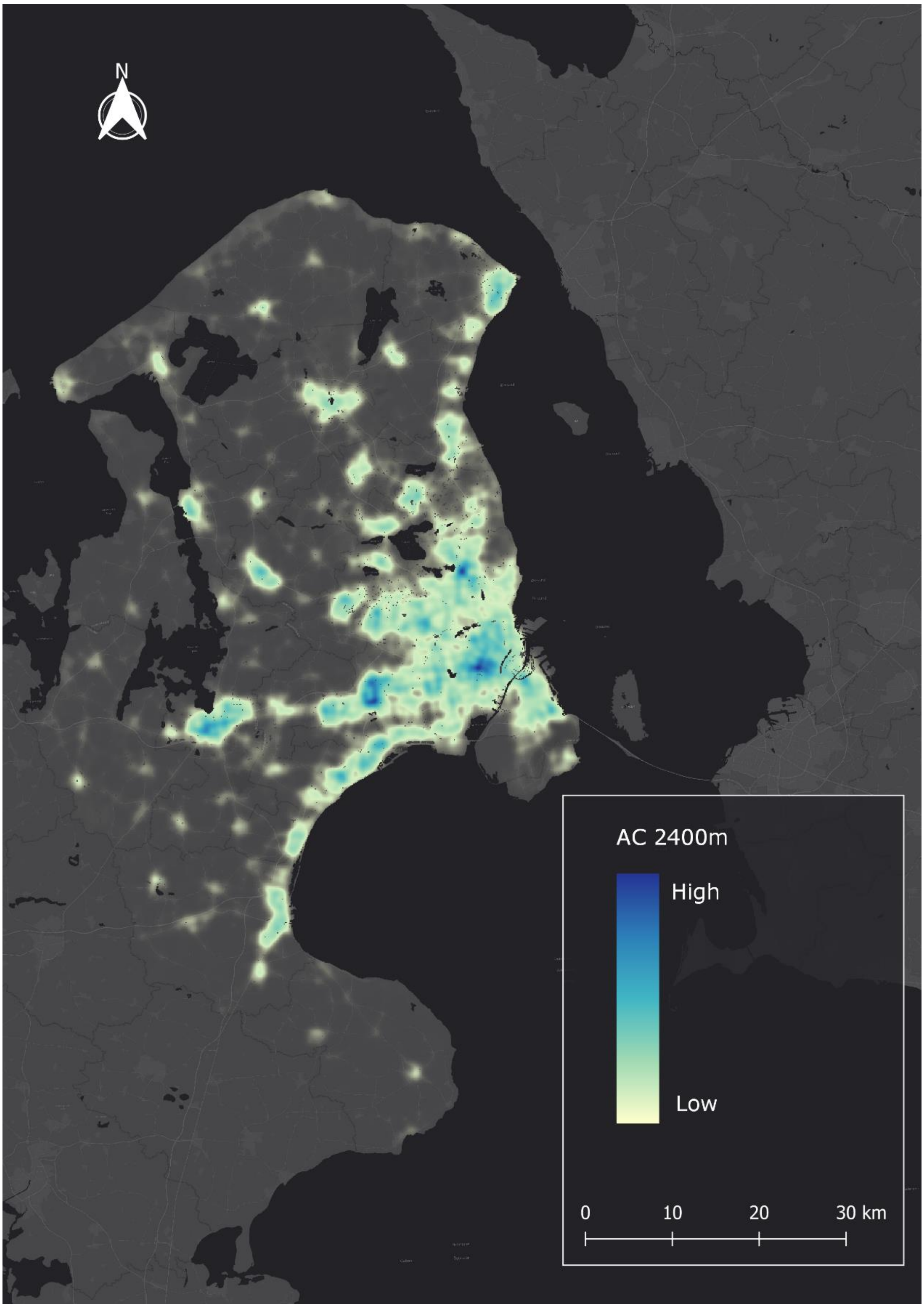

N
AC 800
0 - 514
514 - 1808
1808 - 4670
4670 - 13501
13501 - 1136180
0
10
20
30 km

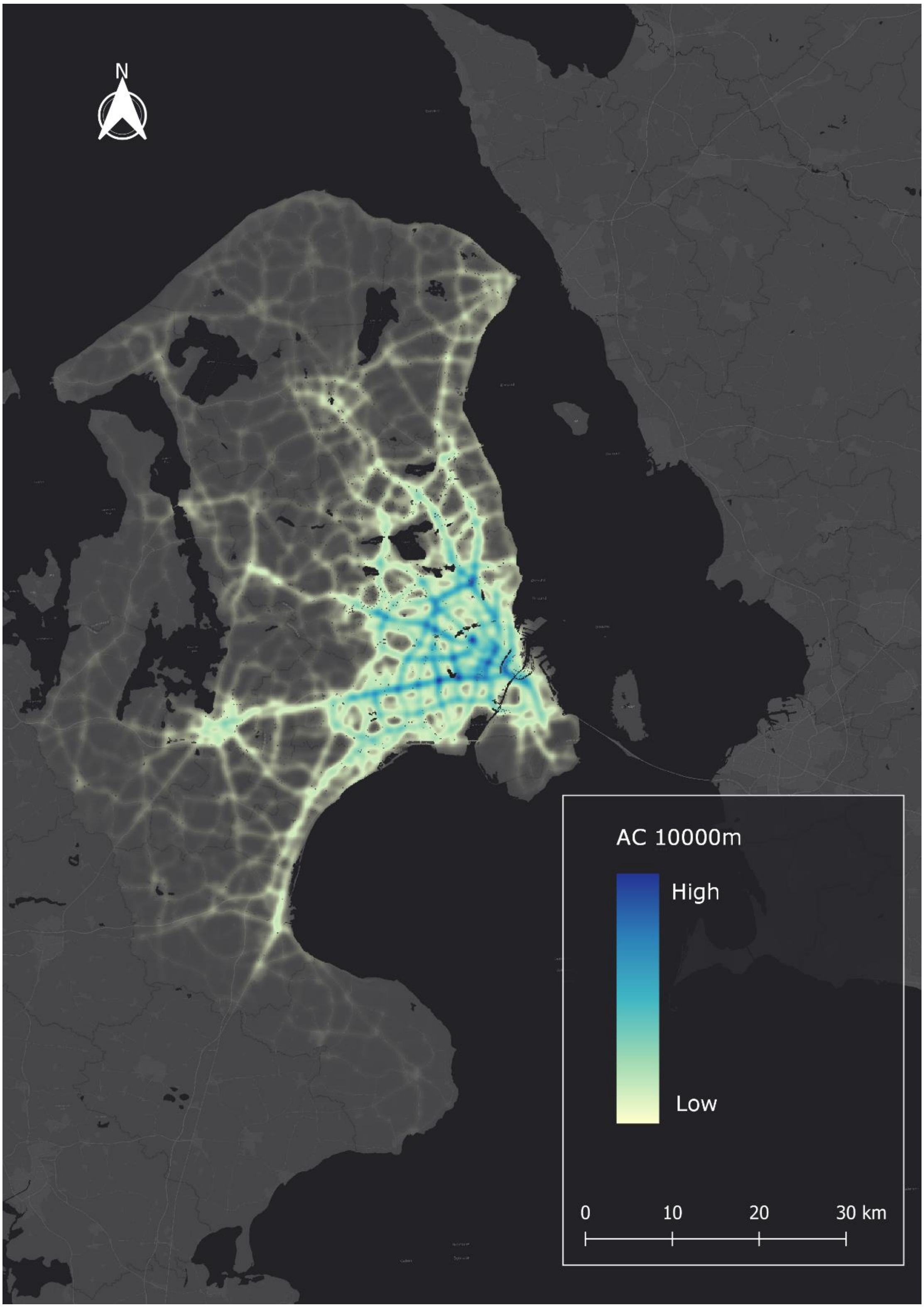

N
AC 10000
0 - 52675
52675 - 224484
224484 - 656879
656879 - 2651398
2651398 - 958514496
0
10
20
30 km

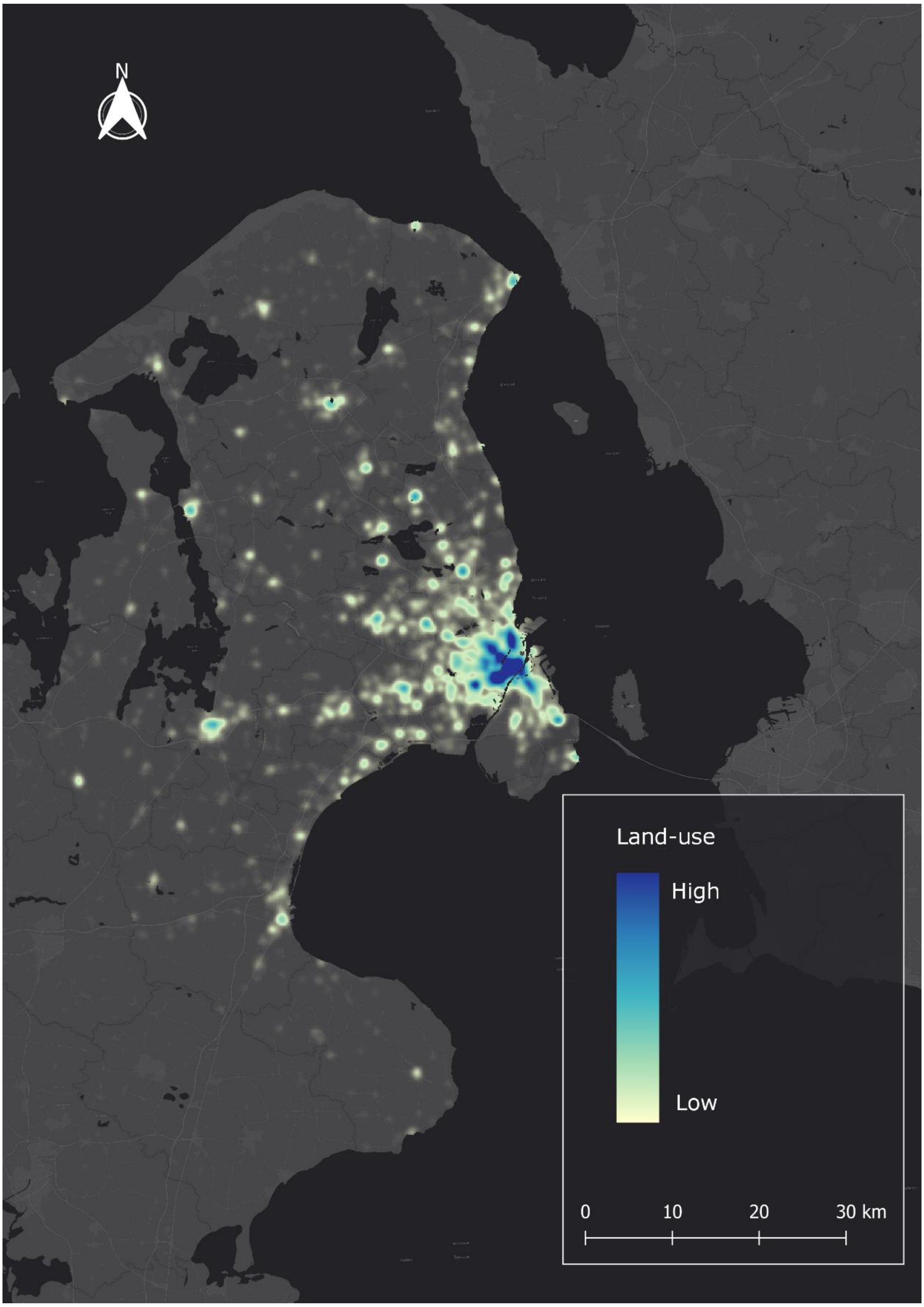

N
AC 400m
High
Low
0
10
20
30 km

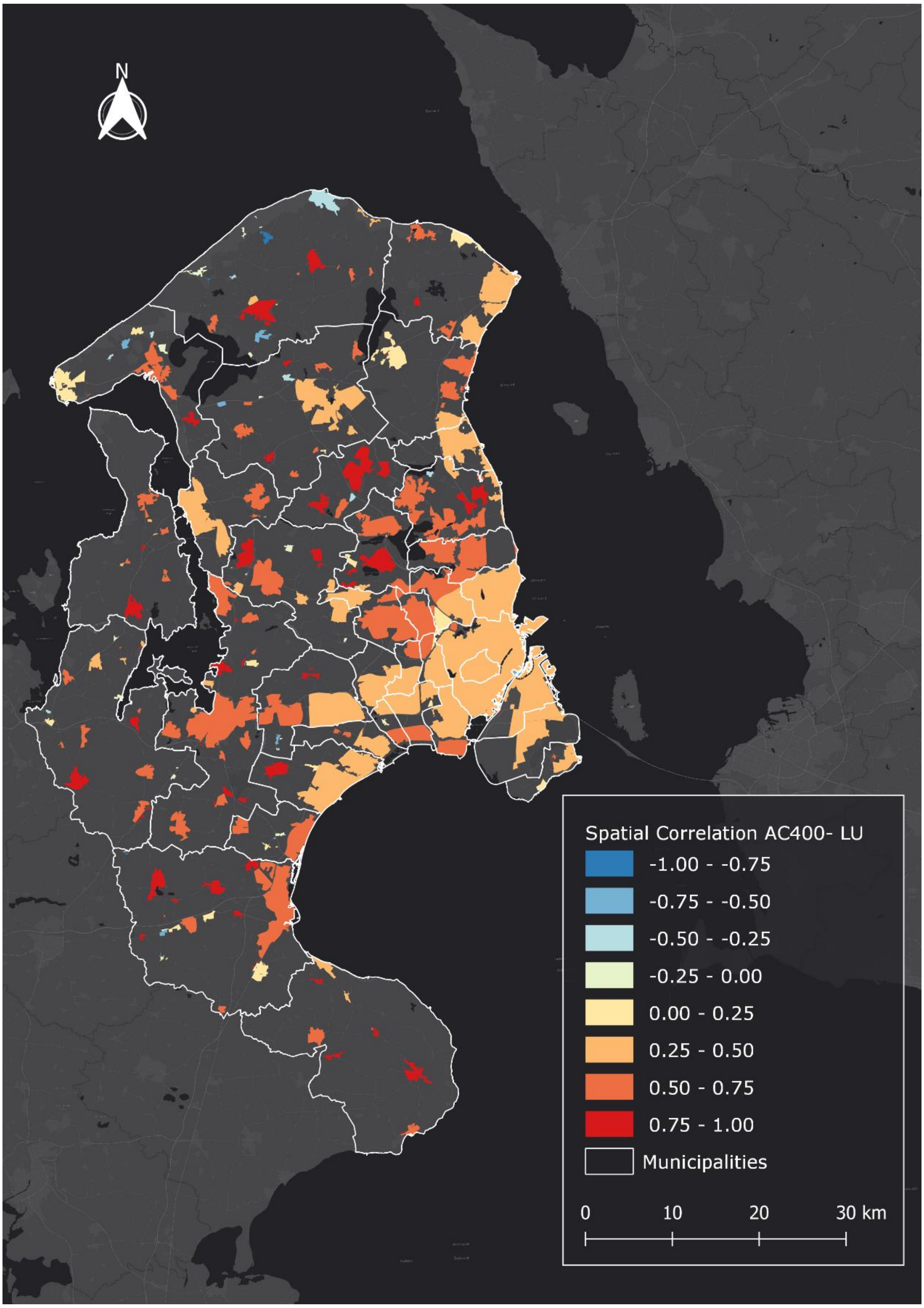

N
AC 800m
High
Low
0
10
20
30 km

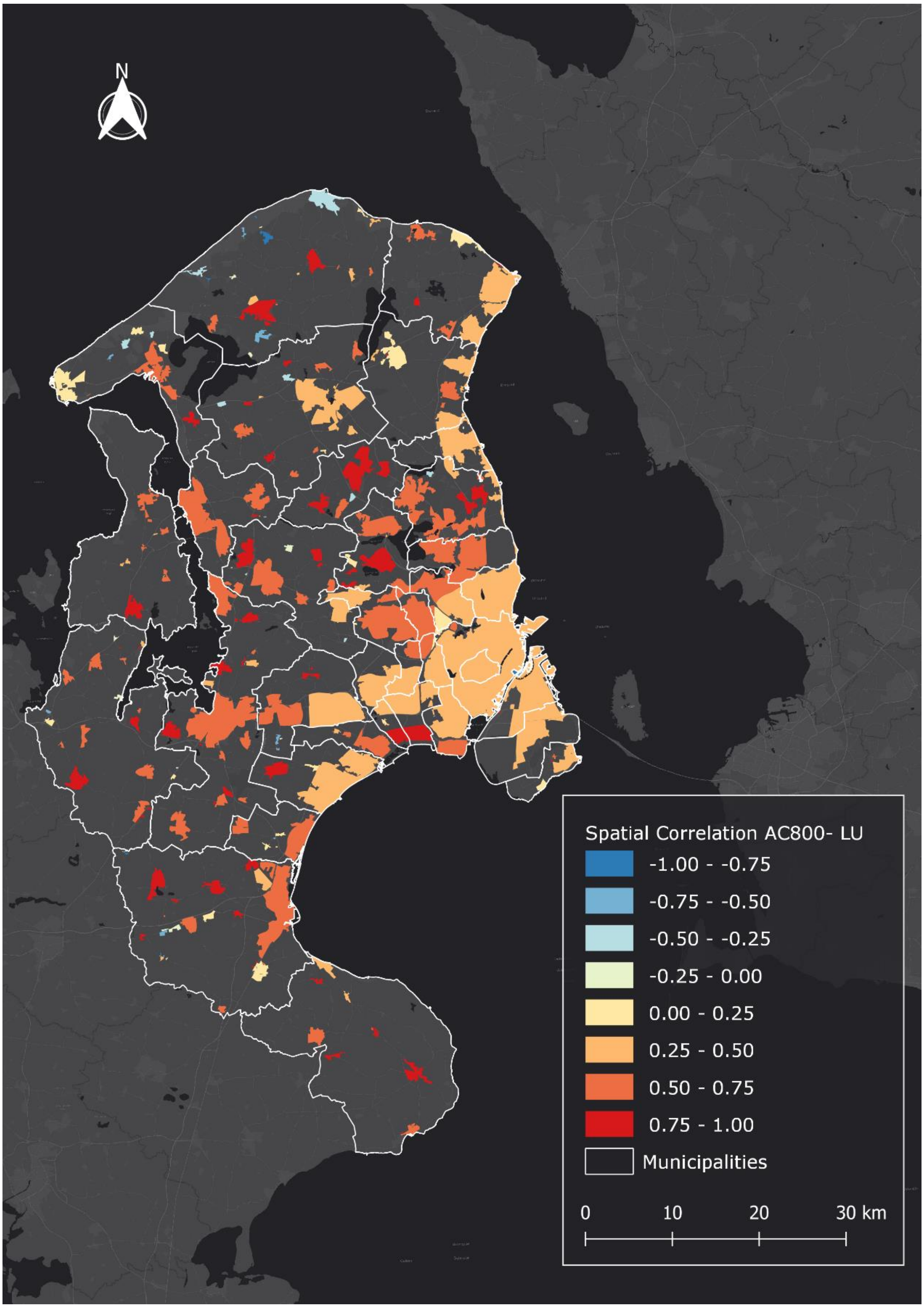

N
AC 1600m
High
Low
0
10
20
30 km

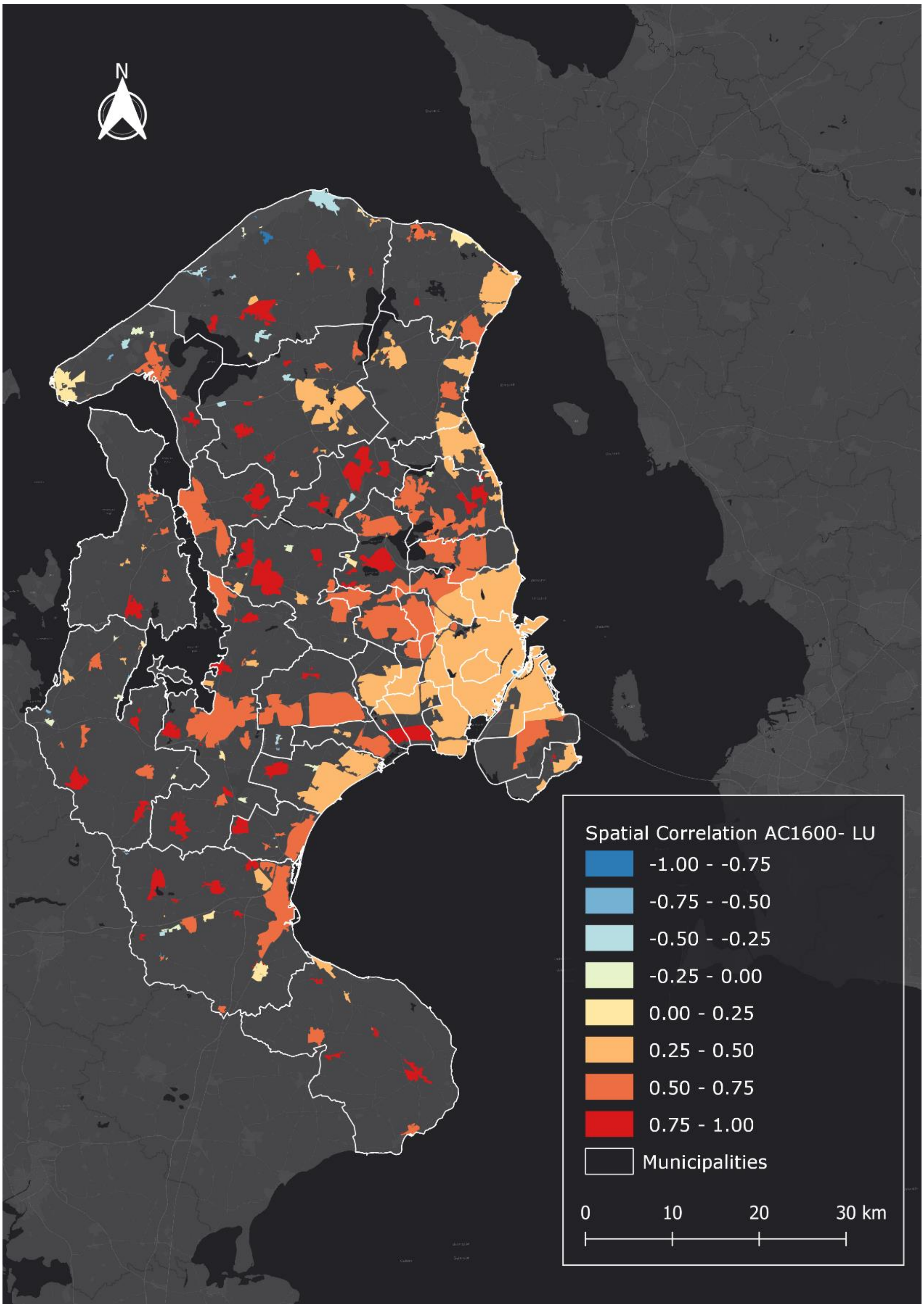

N
AC 2400m
High
Low
0
10
20
30 km

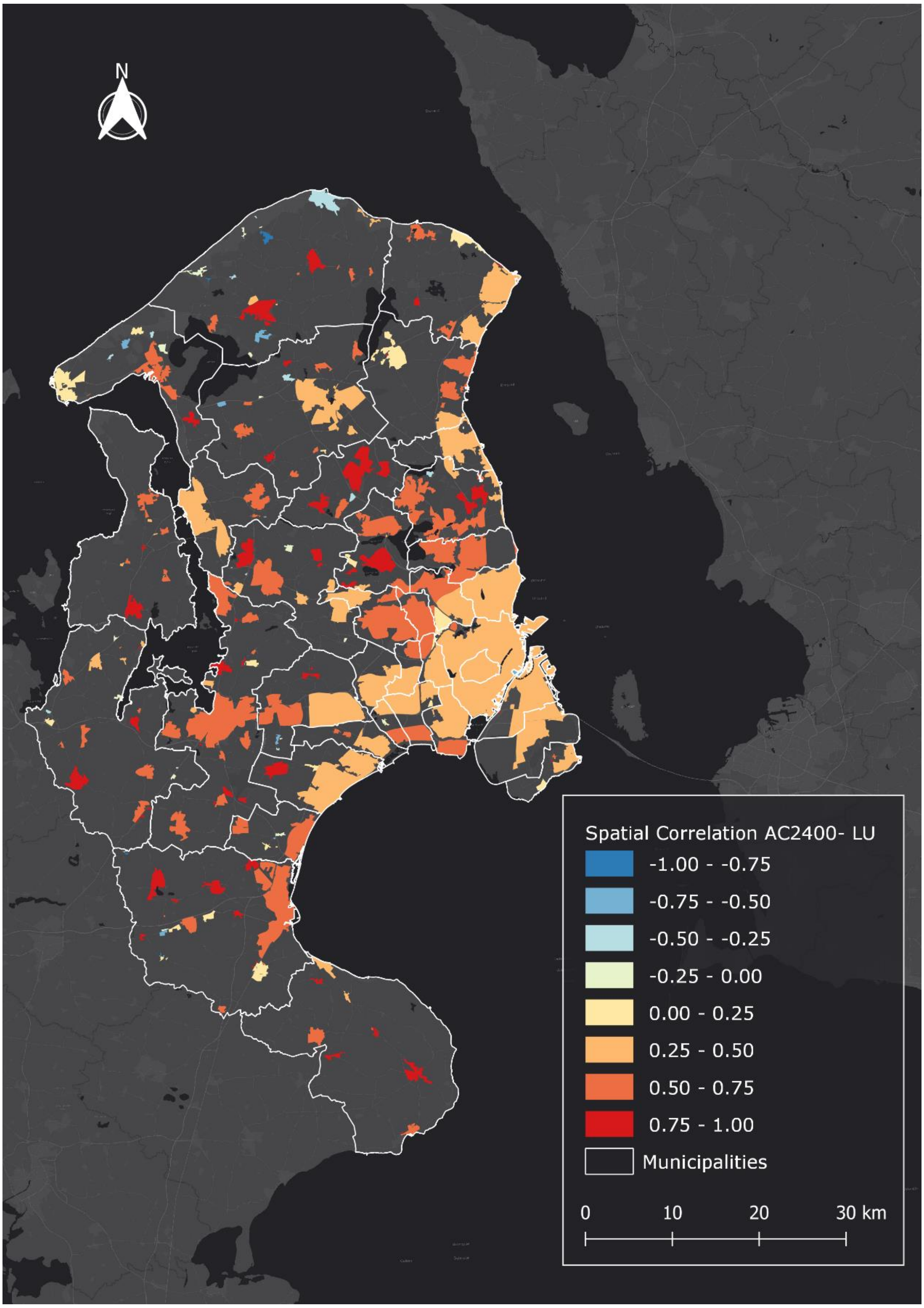

N
AC 10000m
High
Low
0
10
20
30 km

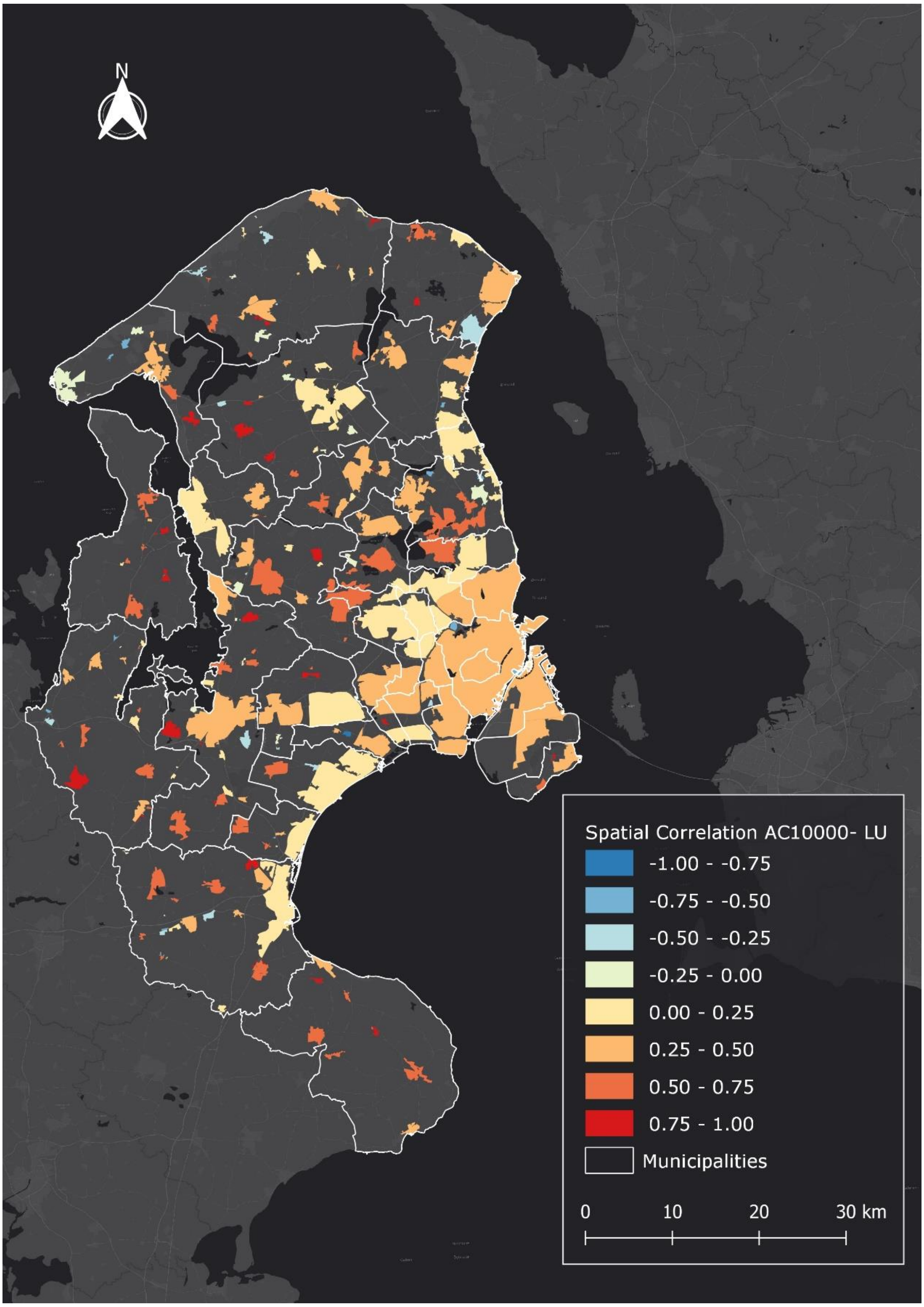

N
Land-use
High
Low
0
10
20
30 km


N
Spatial Correlation AC400- LU
-1.00 - -0.75
-0.75 - -0.50
-0.50 - -0.25
-0.25 - 0.00
0.00 - 0.25
0.25 - 0.50
0.50 - 0.75
0.75 - 1.00
Municipalities
0
10
20
30 km


N
Spatial Correlation AC800- LU
-1.00 - -0.75
-0.75 - -0.50
-0.50 - -0.25
-0.25 - 0.00
0.00 - 0.25
0.25 - 0.50
0.50 - 0.75
0.75 - 1.00
Municipalities
0
10
20
30 km


N
Spatial Correlation AC1600- LU
-1.00 - -0.75
-0.75 - -0.50
-0.50 - -0.25
-0.25 - 0.00
0.00 - 0.25
0.25 - 0.50
0.50 - 0.75
0.75 - 1.00
Municipalities
0
10
20
30 km


N
Spatial Correlation AC2400- LU
-1.00 - -0.75
-0.75 - -0.50
-0.50 - -0.25
-0.25 - 0.00
0.00 - 0.25
0.25 - 0.50
0.50 - 0.75
0.75 - 1.00
Municipalities
0
10
20
30 km


N
Spatial Correlation AC10000- LU
-1.00 - -0.75
-0.75 - -0.50
-0.50 - -0.25
-0.25 - 0.00
0.00 - 0.25
0.25 - 0.50
0.50 - 0.75
0.75 - 1.00
Municipalities
0
10
20
30 km