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Quantitative Approaches to Urban Imbalance: Accessibility Modeling and Spatial Clustering

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Introduction

- Urban planning has evolved significantly over the past decades:
- The emergence of **the compact city** model becoming one of the central paradigms in achieving sustainable and livable urban environments.
- Compact cities emphasize higher density, reduced sprawl, and **more efficient use of space**, promoting proximity between housing, workplaces, and essential services (see e.g. Boussauw et al., 2012; Dempsey et al., 2012; Guzman et al., 2024; Jenks & Jones, 2010; Holden & Norland, 2005).
- The central idea behind this model is that **proximity** - where residents can easily access most of their daily needs within short distances, promotes not only environmental sustainability but also **economic and social well-being** (Moreno et al., 2021; Allam et al., 2022a; Olivari et al., 2023; Silva et al., 2023).
- The **15-minute city model** advocates that urban residents should be able to access essential services - such as healthcare, education, groceries, and leisure activities - within a 15-minute walk or cycle from their homes (Moreno et al., 2021; Gaglione et al., 2022; Khavarian-Garmsir et al., 2023).

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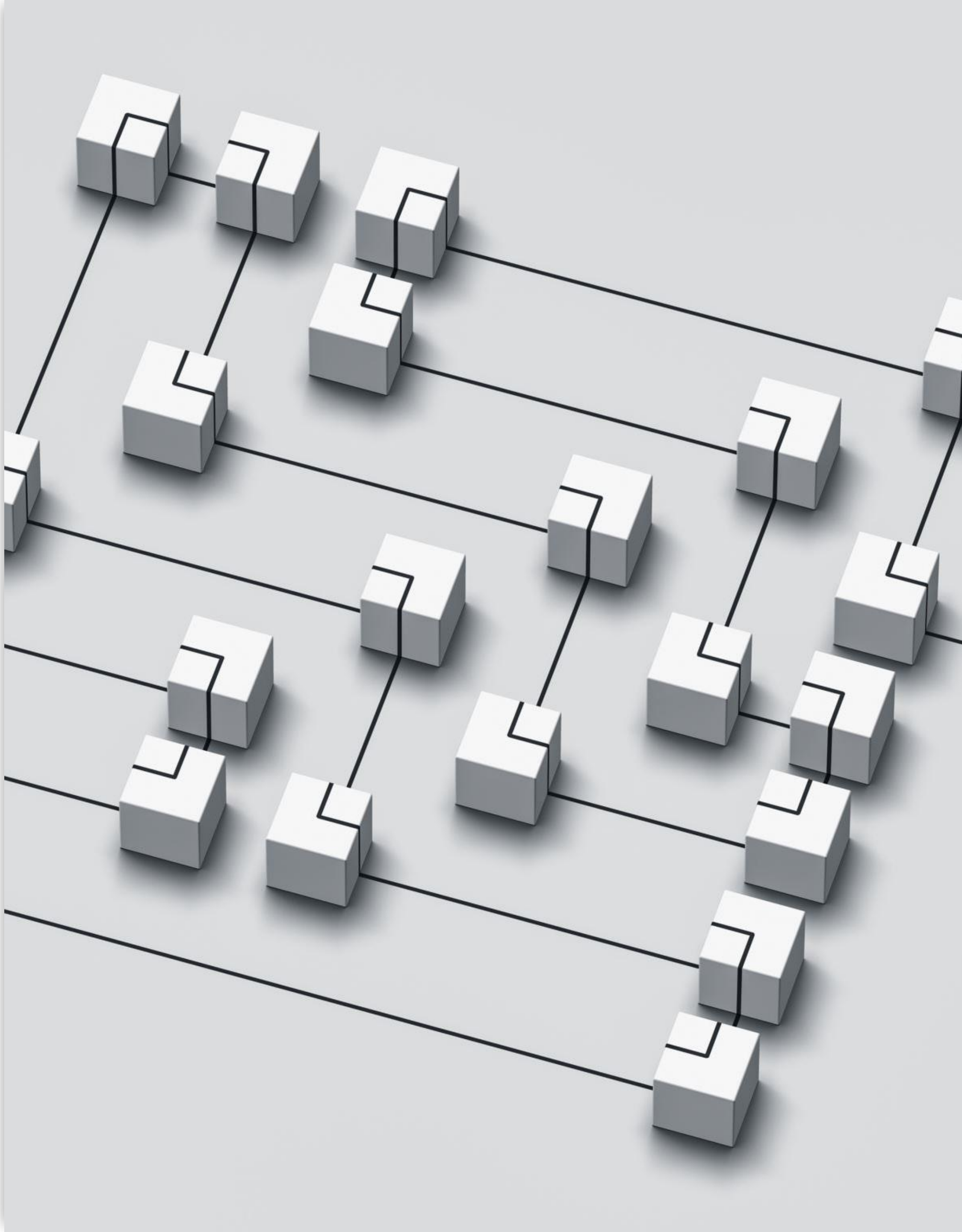
Introduction 2

- The **X-minute city** adapts the 15-minute city model, allowing **flexibility** based on local geography and transport infrastructure.
- While **15-minute cities** suit dense urban areas, suburban and rural regions may require **20- or 30-minute frameworks**.
- Many cities, including **Paris and Brussels**, have tested the 15-minute concept (Hadavi & Kaplan, 2016; C40, 2020; Jens & Gregg, 2021).
- Denmark and the Netherlands have long embraced **15-minute city principles** via policies supporting walking, cycling, and public transit.
- The **15-minute city has attracted attention of policy makers**, but academic **research lags behind practical implementation**.
- A **key research gap** is the operational analysis of transport and accessibility challenges, particularly regarding **inequality analysis** (Gaglione et al., 2021).
- In the Netherlands, an **X-minute city model** is better suited, allowing **flexible accessibility zones** based on local geography and urban density.

Objectives

- The goal is to develop a framework to analyze spatial accessibility in **overlapping** X-minute cities within the Dutch settlement system.
- The theoretical basis extends the 15-minute city **using Christaller's central place theo**ry for interconnected urban areas.
- Central place theory explains how settlements are distributed in a hierarchical pattern, where **first-order markets** provide basic goods, **second-order markets** offer more specialized services, and **higher-order markets** serve as major hubs with the most specialized goods and services.



CPT to Activity Spaces

- Christaller's model from 1933 is updated for modern urban mobility, defining daily activity spaces where residents access amenities through walking and cycling.

Activity Spaces

- The geographical area within which an individual can reasonably access essential services within a given time frame
- We reinterpret Christaller's "market areas" as **daily activity spaces** defined by walking and cycling distances.
- Instead of **central places**, we focus on **service accessibility from people's homes**.
- Services are no longer arranged in rigid hierarchies but exist in **overlapping accessibility zones**.
- Activity spaces vary by **transport mode** (e.g., 500m for walkers, 1000m for slow cyclists, 2000m for commuters).
- Accessibility is shaped by **micro-level geography**, not idealized hexagons —**real travel behavior**.

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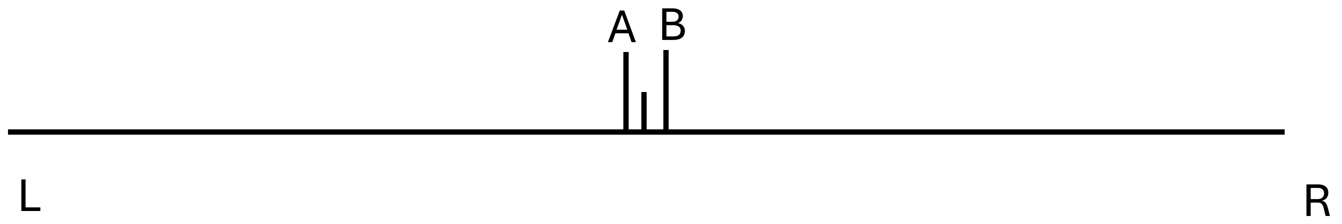
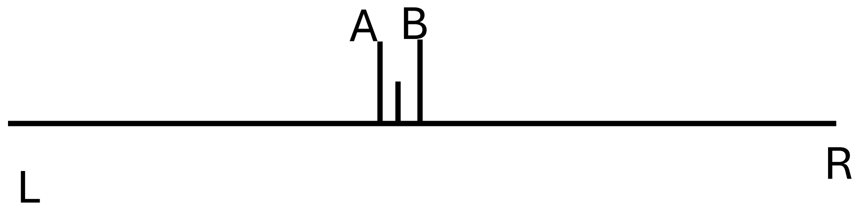
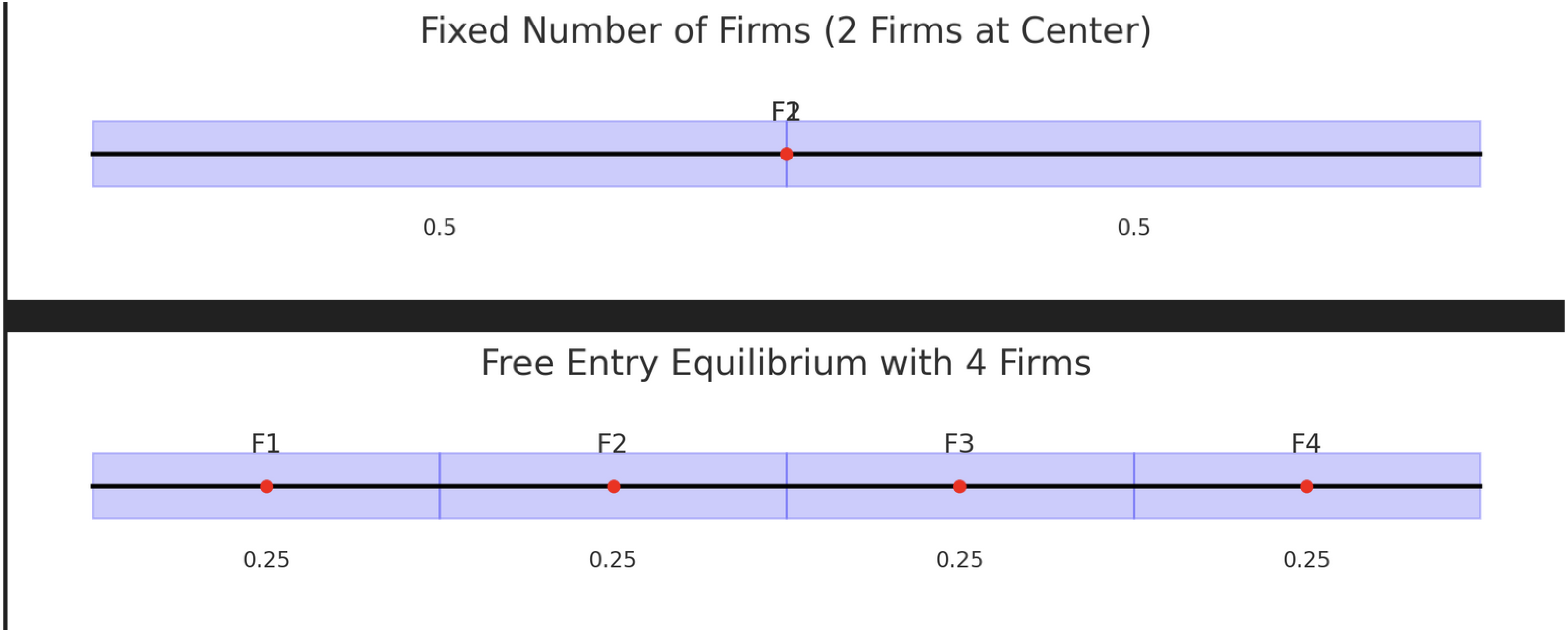
Understanding the Firm Behavior

The principle of minimum differentiation Hotelling (1929)







Fixed Number of Firms (2 Firms at Center)
F1
F2
0.5
0.5
Free Entry Equilibrium with 4 Firms
F1
F2
F3
F4
0.25
0.25
0.25
0.25

Free entry equilibrium

- $l\,max = \frac{2f}{M}$
- $lmax$ is the maximum length of the market a firm can cover without inviting further entry
- f fixed costs
- M population density
- **Reasons for clustering:** low fixed costs, high population density, entry bariers.

A test of Hotelling Model in the Netherlands

Table 1: Mean and Median Distances to Services by Percentiles

		Mean	Median	Percentile 05	Percentile 25	Percentile 75	Percentile 95
class	bakery	1616.74	1255.51	169.73	508.08	2338.40	4368.09
	bar	1987.62	600.64	29.95	127.31	3403.89	6975.84
	cafe	1091.21	806.10	42.22	146.27	1776.47	2992.75
	pharma	1384.70	958.86	179.32	467.93	1993.99	3714.77
	doctors	2248.08	1960.97	279.37	821.88	3194.75	5396.39
	fast_food	826.10	381.43	38.41	133.95	1155.38	2990.76
	hairdresser	971.69	447.33	52.86	144.99	1374.23	3483.23
	playground	1002.67	657.02	97.01	265.71	1454.32	2984.92
	pub	1314.24	607.65	26.18	111.38	2089.99	4434.54
	recycling	433.58	135.10	12.62	59.67	385.41	2058.56
	restaurant	552.49	210.69	19.16	55.64	821.58	2040.69
	school	1533.99	1089.35	264.00	547.79	2127.79	4144.85
	supermarket	1246.60	905.81	172.19	436.30	1808.63	3271.78

Table 2. Average nearest neighbor analysis of service clustering

SERVICE TYPE	OBSERVED MEAN DISTANCE	EXPECTED MEAN DISTANCE	NEAREST NEIGHBOR RATIO	Z-SCORE	P-VALUE
Recycling	183.6 m	959.0 m	0.19	-200	0
Pharmacies	458.9 m	1994.0 m	0.23	-91	0
Hairdresser	392.7 m	1656.8 m	0.24	-107	0
Fast-food	399.6 m	1438.9 m	0.28	-121	0
Restaurants	288.3 m	992.1 m	0.29	-171	0
Pub	744.5 m	2195.0 m	0.34	-71	0
School	752.0 m	2203.3 m	0.34	-70.3	0
Playground	528.9 m	1508.2 m	0.35	-101	0
Supermarket	672.6 m	1766.2 m	0.38	-83	0
Bakery	936.4 m	2280.3 m	0.41	-60.7	0
Café	936.4 m	2280.3 m	0.41	-60.7	0
Doctors	1542.8 m	3011.9 m	0.51	-38	0

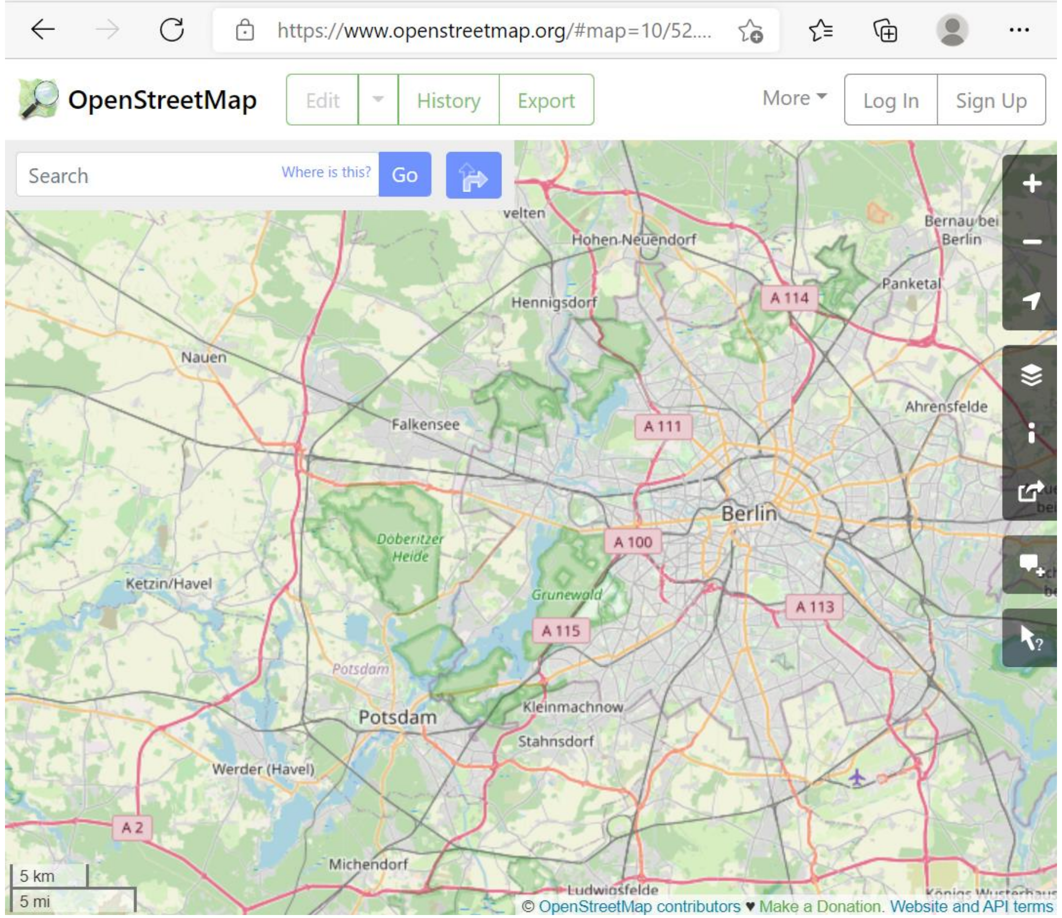
Challenges for X-minute city analysis

Incorporation of:

- "X" in the index
- Sociodemographics: different groups have different needs.
- Transportation mode: walking or cycling

Data Requirements

OpenStreetMap data



- The Wikipedia of maps
  - Global rules for mapping
    - i.e. same coding for shops, schools, etc. globally
    - Constantly updated

Dataset

- Data were sourced from OpenStreetMap (OSM),
- The dataset includes the locations of residential buildings and all relevant urban functions, such as education, healthcare, groceries, recreational facilities, and public services.
- Three radii—500 meters, 1000 meters, and 2000 meters—were used to define accessibility zones. For each radius, a composite index was calculated to measure walkability and cyclability, integrating both distance and the density of services within each zone.
- Contents and quality of OSM data vary substantially between countries, but the Netherlands is well represented when it comes to the match between factual and GIS-represented features utilized in this study.
- While OSM lacks information about population, it appears that nearly all buildings in the Netherlands are mapped
- Analyses were conducted at the **building** level.

Dataset

- From each of the buildings, access to various services can be estimated.
- The services considered include pubs, cafes, schools, pharmacies, chemists, restaurants, supermarkets, libraries, fast-food establishments, doctor practices, playgrounds, hairdressers, bakeries, and five different types of recycling stations (metal, paper, etc.).
- Some of the services, such as pubs, cafes, restaurants, and fast-food establishments, serve similar purposes (i.e. eating and drinking), and are, at a later stage of our analysis, treated groupwise.
- In a comparable way, groups are formed for health (pharmacists, chemists, and doctor practices), groceries (supermarkets and bakeries), and other public services (libraries and recycling stations).

Methods: Solutions to Challenges

- Defining activity spaces : K-NN approach for creating overlapping x-minute cities
- Method to calculate spatial accessibility of amenities: Hansen gravity index
- Introduction of spatial decay factor: exponential function for incorporating different transport modes, walking, slow biking and biking.
- Aggregation of different accessibility functions: Multi-criteria decision analysis (MCDA) for incorporating different demographic groups and their needs.
- Within and between inequality in x-minute cities: Gini index

Methods

- This study employs an object-based k-nearest neighbor (K-NN) approach (Fix & Hodges, 1989; Cove & Hart, 1967; Franklin, 2008)
- Building on Hansen's (1959) work, accessibility is defined as the potential for interaction with various opportunities.
- Most K-NN methodologies concentrate on the spatial proximity of k-nearest units, determined by the nearest spatial areas.
- A common challenge with traditional K-NN approaches is the requirement that spatial units be sufficiently large to encapsulate the measured variables.
- To overcome these limitations, this study shifts the focus from the traditional K-NN model, which relies on neighboring spatial units, to an object-based K-NN approach.

K-NN approach for defining the ”x” in x-minute city

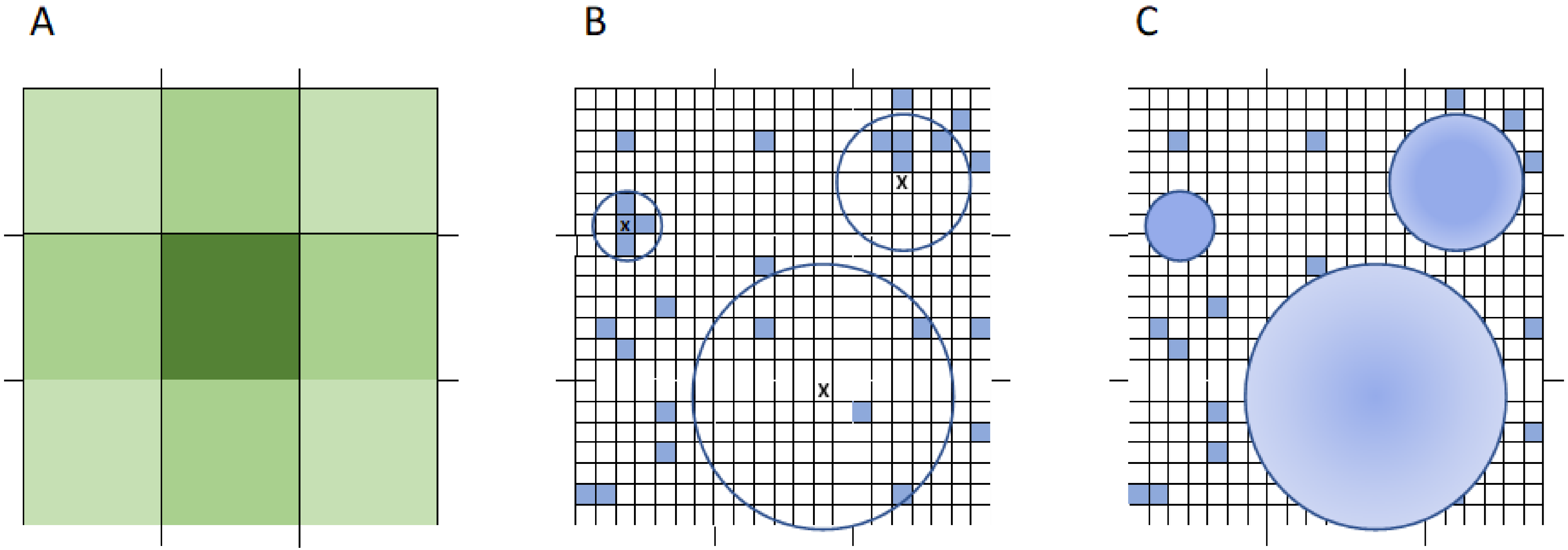


Figure 1. Difference between more common K-NN approach (Part A), and object based K-NN approach (Part B) and spatial decay in object based K-NN approach (Part C).

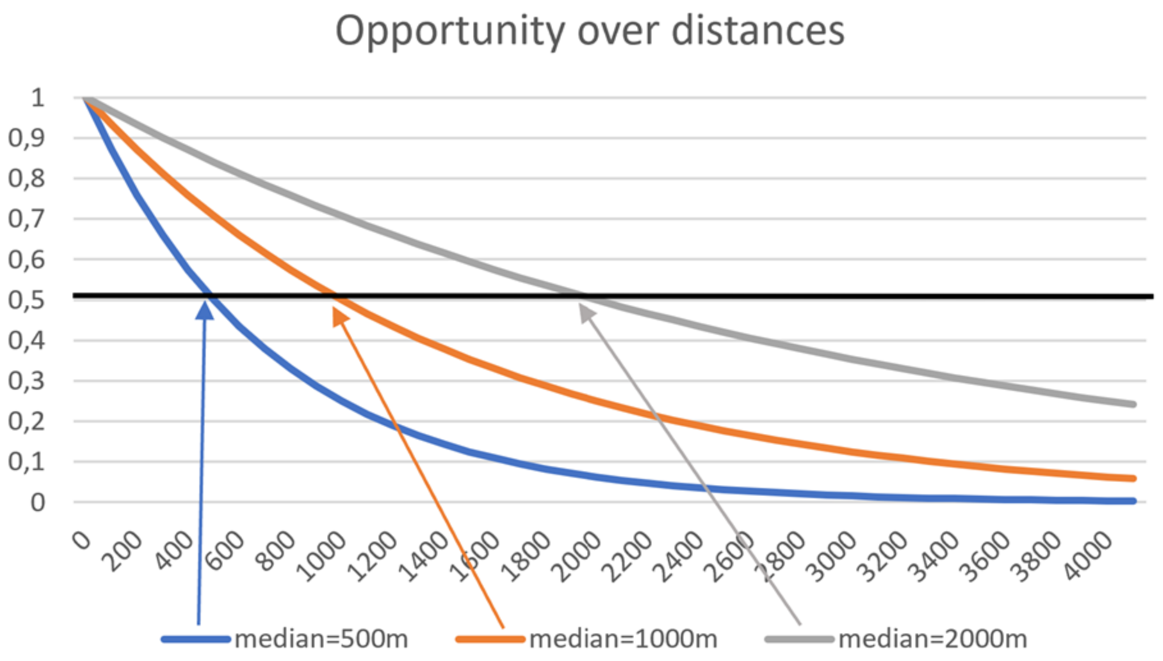
Spatial Decay for incorporating transport mode

- Spatial decay refers to **the gradual decrease in interaction**, accessibility, or influence of a location as the distance from a central point increases.
- Spatial decay is a critical concept in understanding accessibility and can be represented in various forms, including cost, time, and metric distances between features (see e.g. Hansen, 1959; Tobler, 1970, 2004; Wilson, 1970, 1981; Haynes, 1975; Nijkamp, 1975; Nijkamp & Reggiani, 1992; O'Kelly & Horner, 2003; De Montis et al., 2011; Reggiani et al., 2011; Östh et al., 2014a, 2016).
- Östh et al. (2014a, 2016) indicate that a **negative exponential function** is more appropriate for modeling mobility behavior within urban settings.
- Usually empirically derived : **Spatial interaction models**
- But for **super local level analysis**, it is difficult to have data on spatial interaction.
- An effective alternative is to compute a decay parameter value mathematically (see e.g. Östh et al., 2014a; 2016).

Spatial Decay

- By employing **travel survey studies that publish median travel distances for different transport modes**, it is possible to apply the median distance for each mode to calculate the decay parameter.
- The underlying assumption is that about **half of the population chooses their trip destinations at distances greater than the median distance, while the other half locates them at shorter distances.**
- $f(d_{ij}) = \mathrm{e}^{-\beta d_{ij}}$ -> distance function
- In this formulation, d*ij* represents the metric distance between any two locations. The parameter $-\beta$ in equation (2) is derived by dividing the natural logarithm of 0.5 (representing the median quantile) by the median distance:
  - $$-\beta = ln(0.5)/median(d_{ij}) \qquad (2)$$
- To calculate the total accessibility Acc_i for a given location *i*, we use the following equation:
  - $$Acc_i = \sum_1^j Opp_j e^{-\beta d_{ij}} \qquad (3)$$
- In this equation, Opp_j represents the opportunity values associated with destination *j*, while d_{ij} is the distance between location i and destination *j*. This formula aggregates the opportunity values from all accessible services, weighted by the decay function that accounts for the distance to each service, discounting access by distance.

Illustration



In this example, 500m, 1000m, and 2000m are selected as median distances traveled by individuals who walk, cycle slowly, or cycle-commute. y-axis line indicates the spatial opportunity, showing that for all curves, the y- and x-axes intersect at the specified median distances, each with an opportunity value of 0.5.

Distinct groups and modes of transport

- Research by Schneider et al., (2018) indicates that Dutch cyclists typically travel a median distance of 2000 meters from their homes. This distance corresponds to a decay value (β) of approximately -0.00034658.
- For elderly or less mobile cyclists, we also analyze accessibility measures based on a median cycling distance of 1000 meters.
- Furthermore, a median walking distance of 500 meters was incorporated, which aligns with previous findings that suggest walking distances often hover around this mark (Millar, 2012; Tennøy et al., 2007).

Incorporation of Demographic Groups: Aggregation

- Multi-criteria decision analysis (MCDA) approach is applied to weight amenities according to their importance for each demographic group.

The accessibility index is generated using an adapted version of the Weighted Sum Model (WSM), a robust conventional MCDA tool designed to sum and weight the best option values among several alternatives for each group. Using statistical notation, the aggregate accessibility index can be expressed as:

$$Agg_{igd} = \Sigma W_g \, max(Acc_{ikd}) \quad (4)$$

where Agg_{igd} represents the aggregate measure of accessibility from building i (or X-minute city index), for group g and for a median distance of d. W_g denotes the weights assigned to amenities based on the preferences of different demographic groups. Acc_{id} is the accessibility measure of amenity k at median distance d.

Distinct Groups:

Table 3. Socioeconomic groups and their rankings of city functions.

City Function	Families	Older Adults	Young Individuals
Eat and drink	2	1	3
Education	3	1	3
Groceries	3	3	2
Health	2	3	1
Recreational facilities	1	1	3
Other public services	1	1	1
Personal services (e.g. hairdresser)	1	1	1

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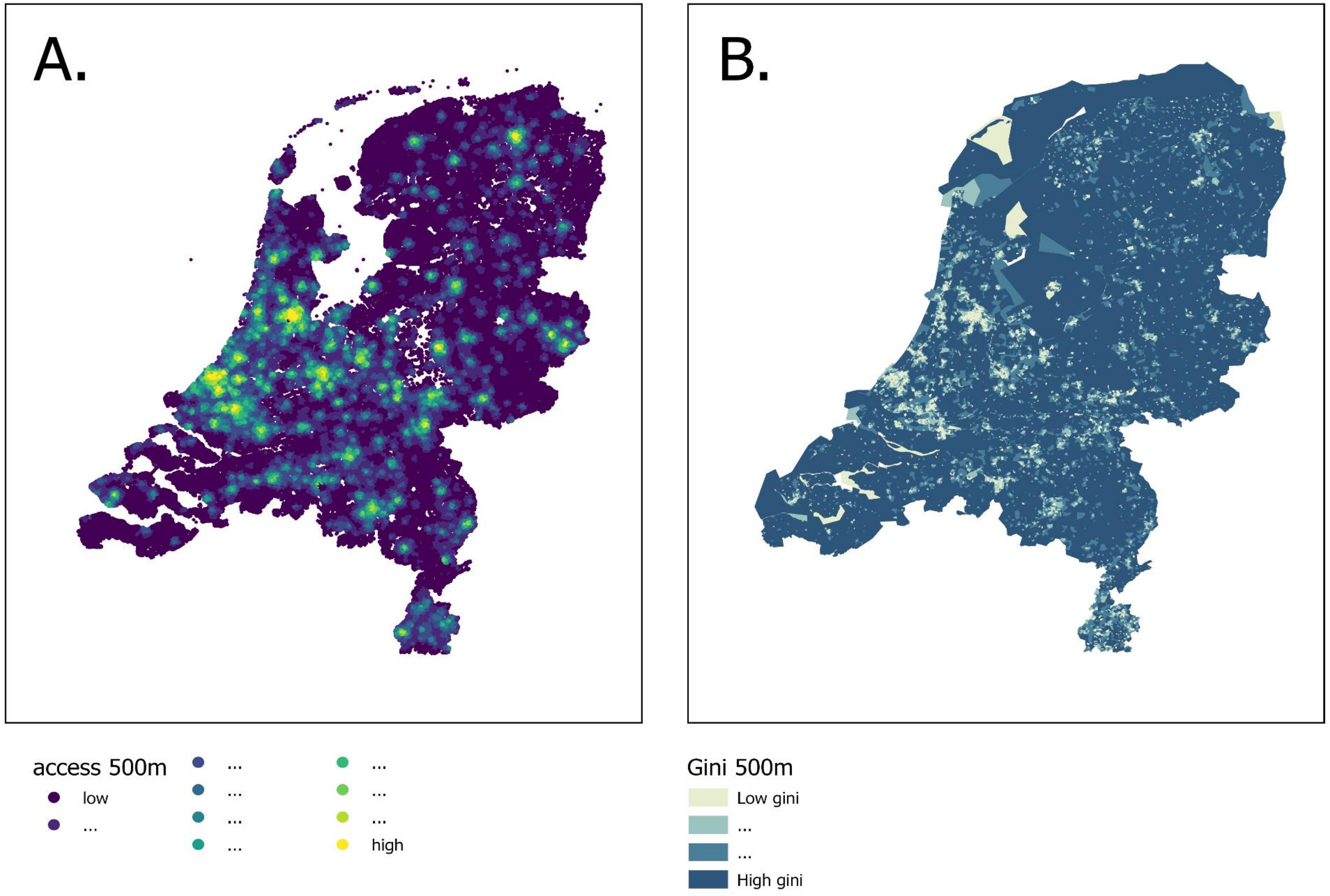
Results

Mapping the X-minute city index and within inequality in accessibility

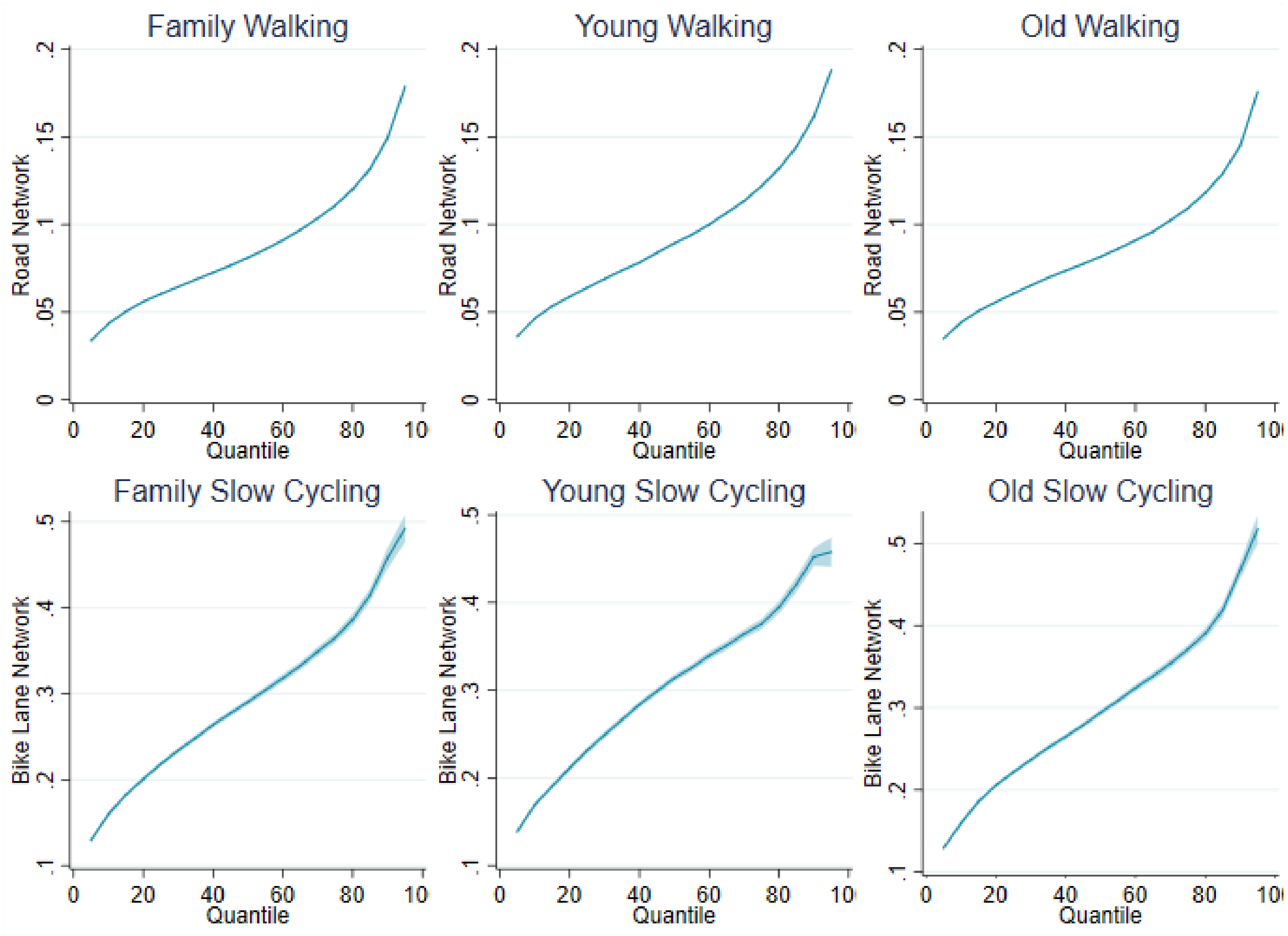


Visualization of spatial accessibility and Gini inequality index of accessibility

Table 2. Gini inequality measure (between) for the whole country at the building level.

Composite Index	Gini
Accessibility_500Decay (Old Walking)	0.47
Accessibility_500Decay (Family Walking)	0.46
Accessibility_500Decay (Young Walking)	0.45
Accessibility_1000Decay (Slow Old Cycling)	0.4
Accessibility_1000Decay (Slow Family Cycling)	0.39
Accessibility_1000Decay (Young Slow Cycling)	0.38
Accessibility_2000Decay (Old Cycling)	0.31
Accessibility_2000Decay (Family Cycling)	0.3
Accessibility_2000Decay (Young Cycling)	0.28

X-minuteness and spatial connectivity



What's New in Our Approach? Methodological Innovation

Traditional Approach	Our Approach
Polygon-based K-NN	Object-based K-NN at building level
Census-block averaging	True micro-level measurement
Distance cutoffs	Exponential spatial decay
Single-mode analysis	Mode- and group-specific accessibility functions

Conclusions

- Urban cores like Amsterdam and Rotterdam are accessibility strongholds — dense, well-connected, and service-rich.
- Rural areas fall behind — not because of roads, but because of service deserts and low population density.
- Infrastructure without demand = empty access. Services just don't "go" where fixed costs can't be recovered.
- The elderly lose out most — they walk more, drive less, and rely on close-by care that often doesn't exist.
- Youth and cyclists benefit from distance-resilient mobility, and cities cater to them better.
- In rural areas, adding bike lanes isn't enough if there's still nothing at the end of the lane.
- Quantile regression shows a sharp accessibility jump only after the 70th percentile — urban areas cross this line, rural ones don't.
- More infrastructure helps, but only **after** there's a critical mass of services and people.
- True "X-minute" cities are not just well-designed — they're **well-distributed**.
- Policy must go beyond networks — it must seed **essential services** where the market won't.
- The X-minute city is not one-size-fits-all — it should flex with local demographics, density, and mobility.

Thank You!

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