Bringing moral clarity to urban planning: Developing data-driven metrics of spatial justice for neighbourhood accessibility

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Summary

Recent research has focused on developing conceptual frameworks for spatial justice in accessibility analysis, but there remains a gap in its practical application at the neighbourhood level. We propose specific indicators based on the ethical principles of Egalitarianism, Utilitarianism and Rawls' Egalitarianism. To illustrate the approach, we evaluate the fairness of accessibility to places of employment, applied to urban network models of diverse cases, although in this abstract we focus only on Cape Town. The results emphasise how spatial justice is both scale and value reliant. Furthermore, the methodology contributes to an inclusive urban agenda, adapting to varying data availabilities.

Key words: spatial justice, urban science, network science, cities, employment accessibility

1 Introduction

Over the last fifty years, a profound shift in global urban development has seen most new urban growth being concentrated in the global South necessitating a more inclusive urban agenda for advancing urban science and theory (Parnell et al, 2009; Robinson, 2016). At the heart of the urban debate on sustainable development are ideas embedded in spatial justice, which require us to consider the fairness of urban resource distribution (Rocco et al, 2022; Soja, 2010).

The methodological innovation of this research introduces spatial justice metrics for neighbourhood accessibility based on different ethical theories, using a graph network approach. We examine the fairness of the distribution of employment opportunities in Monterrey, Cape Town, and the Hague/Rotterdam. Although, in this abstract, it is important to note that we only present results from Cape Town. By placing different cities into comparative juxtapositions, we highlight the shared universal and diverse contextual factors that give rise to spatial justice as iterations of a singular phenomenon.

2 Metrics of spatial justice for neighbourhood accessibility

Definitions of spatial justice vary, but broadly pertain to the equitable distribution of resources, fair decision-making processes, and the participatory rights of citizens (Pereira et al, 2017). We focus on distributive spatial justice, for which there is no universally accepted framework. Utilitarian principles might favour decisions that benefit the majority (Sandel, 2010), while Egalitarian theories advocate for

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equal consideration for all individuals and Rawls's approach focuses on resources aiding the most disadvantaged (Fainstein and DeFilipp, 2016:263). These diverse frameworks underscore the need for planners to understand justice concepts (Schmitt and Hartmann, 2016:44).

The lens of spatial justice provides a moral basis for assessing fairness within accessibility analysis. Recent research has focused on conceptually binding accessibility analysis with moral philosophy (Martens et al, 2012; Pereira et al, 2017) but there remains a gap in their practical application at the neighbourhood scale. This gap is exemplified by the use of metrics like the Gini Index, which is difficult to decompose. Whilst the definition of neighbourhood boundaries remains contentious (Shelton and Poorthuis, 2019), administrative boundaries are crucial for local governance resource management.

Developing indicators for spatial justice is important for integrating ethical considerations into urban decision-making. Historically, urban theory has been based on a limited number of Western cases, yet there's an urgent need for a more inclusive approach. Whilst data scarcity in certain contexts remains a challenge, urban network analysis from graph theory allows for the modelling of cities as complex networks and is adaptable to varying data conditions.

3 Methodology

There are four stages to our methodology, as depicted in Figure 1:

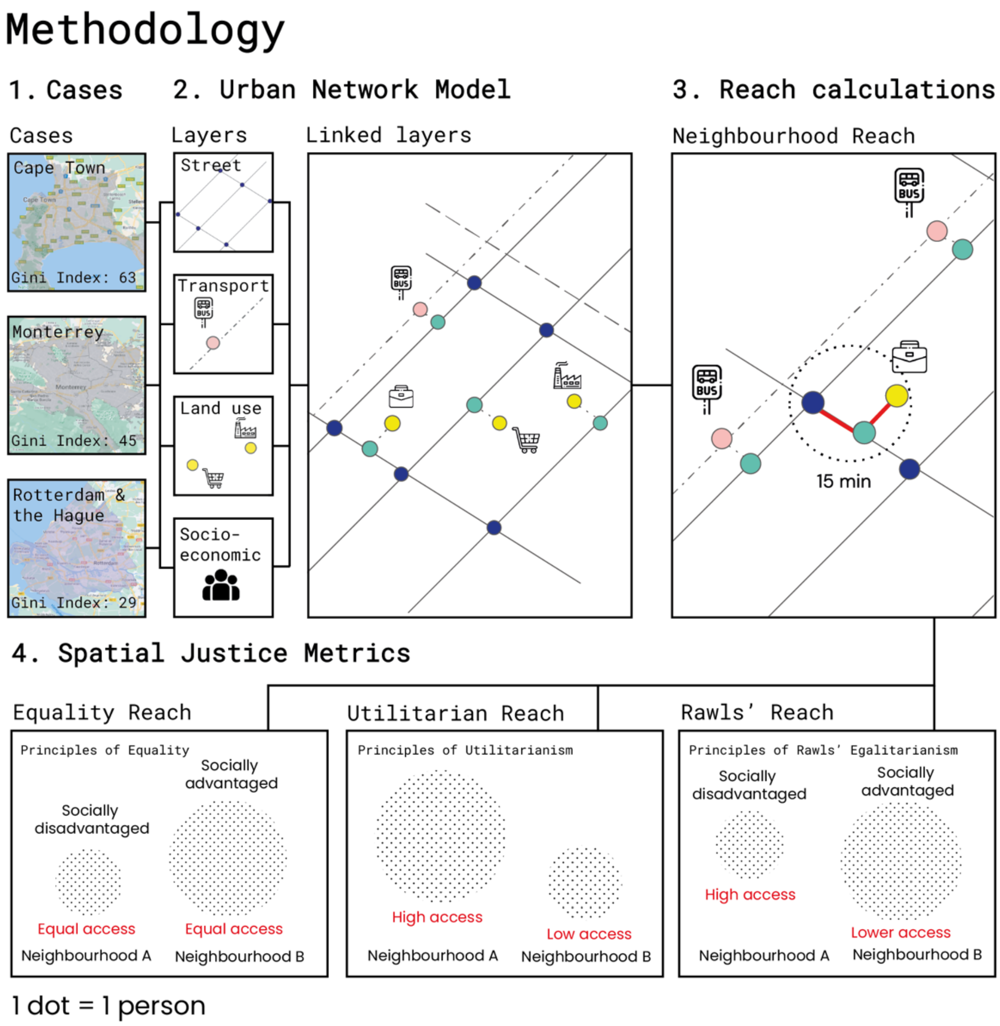

Figure 1: The methodology.

The first stage involves selecting diverse case studies, which are: Cape Town Metro (South Africa), Monterrey Metro (Mexico) and Rotterdam and the Hague (Netherlands), based on diverse levels of income inequality.

The second stage develops an urban network model (UNM) for each. Formally, a UNM is a large graph *G*, composed of a set of nodes *n* and edges *e*. The nodes represent the positions of street intersections, places of employment or transportation stops/stations. The edges represent the connections between the nodes: streets, transportation routes, or an interchange between a street node and a land use or transportation node. Each edge is weighted by the time *t* it takes to traverse it through walking or transportation. The UNM are created in Python using the libraries NetworkX and Snkit. For a summary of each dataset and their source, refer to Table 1 and 2 in the Supplementary Material.

The third stage quantifies how many places of employment can be reached within different time thresholds (15, 30, 45, 60 minutes) from each neighbourhood, by calculating Neighbourhood Reach Centrality (NRC).

The NRC of neighbourhood *a* is the sum of employment opportunities *j* that can be reached from nodes *I (*all street nodes in neighbourhood *a)* in the shortest distance *d* which is weighted by maximum walking and public transportation time thresholds *W* and an overall time threshold of *t*. We employ Dijkstra's Multi-Source Algorithm to find the shortest paths from nodes *I* to *j*.

$$R^t[a] = \sum_{\substack{d[Ij]^w \leq t \\ \begin{cases} W=(w1,w2) \\ w1=15 \\ w2=t \\ i\in a; \\ j\in Ge; \\ G=(Gs\cup Gt\cup Ge) \end{cases}}} O[j]$$

where:

$$O[j] = \{1 \text{ for } j \in Ge \tag{1}$$

The fourth stage develops ideal NRC indicators based on our interpretation of Egalitarian, Utilitarian and Rawlsian principles.

Equality Reach Centrality (ERC)

The ERC is based on the principle that all neighbourhoods should have equal access to opportunities *j*. The ERC for a neighbourhood *a* within time *t* is the sum of all neighbourhoods' actual reach $R^t[a]$ divided by the total number of neighbourhoods *A* in G.

$$Eq.R^t[a] = \frac{\sum_{a\in A} R^t[a]}{A} \tag{2}$$

where:

$$\{A \in G$$

We calculate the difference between the actual NRC and ideal ERC, referring to this as the **Equality Gap** (Δ Eq^t[a]) of *a*.

$$\Delta Eq^t[a] = R^t[a] - Eq.R^t[a] \tag{3}$$

Utilitarianism Reach Centrality (URC)

The URC is based on the principle that utility should be maximised for the greatest good and thus reach employment should be proportional to the percentage of a neighbourhood's working population. The URC for neighbourhood *a* within time *t* is the sum of all neighbourhoods' actual reach $R^t[a]$ divided by the sum of the working population *W* of all neighbourhoods, multiplied by the working population of *a*.

$$Ut.R^t[a] = \frac{\sum_{a \in A} R^t[a] \cdot W[a]}{\sum_{a \in A} W[a]} \tag{4}$$

where

$$\{A \in G$$

We calculate the difference between the actual NRC and the URC, referring to this as the **Utilitarian Gap** $\Delta\, Ut^t[a]$ of *a.*

$$\Delta Ut^t[a] = R^t[a] - Ut.R^t[a] \tag{5}$$

Rawls' Reach Centrality (RRC)

The RRC is based on the Rawlsian principle that resources should benefit the most vulnerable to the greatest extent and thus be proportional to a neighbourhood's vulnerability. We create a Vulnerability Score *V* for each neighbourhood *a* by summing the normalized indicators for vulnerability, then dividing this by the number of indicators and subtracting from 1.

$$V[a] = 1 - \frac{V1 + V2 + V3}{3} \tag{6}$$

RRC for a neighbourhood *a* within time *t* is the sum of all neighbourhoods' actual reach $R^t[a]$ multiplied by $V[a]$ divided by the sum of all the Vulnerability scores for all neighbourhoods *A* in G.

$$Ra^t[a] = \frac{\sum_{a \in A} R^t[a] \cdot V[a]}{\sum_{a \in A}} \tag{7}$$

where

$$\{A \in G$$

We calculate the difference between the NRC and its RRC, referring to this as the **Rawls' Gap** $\Delta Ra^t[a]$ of *a*.

$$\Delta Ra^t[a] = R^t[a] - Ra.R^t[a] \tag{8}$$

From all perspectives if the gap metrics are 0 or above, they meet the requirements for justice.

4 Results

We focus only on the results from Cape Town.

4.1 Neighbourhood Reach Centrality

The NRC outputs reveal that accessibility for shorter time limits tends to be higher in neighbourhoods with dense local employment opportunities, while for longer time limits a neighbourhood's proximity to the CBD and transportation are more important (refer to Figure 2). As time limits increase, only a few neighbourhoods gain significantly more opportunities in Cape Town.

4.2 Neighbourhood Reach Gap

Importance of temporal scale is emphasised as inequalities increase with time across all metrics between neighbourhoods with the highest negative and positive gaps, refer to the density plots in Figure 2. The way we define *fairness* has a significant influence on the outcomes which is highlighted by the changing percentages of neighbourhoods which meet the requirements for justice from each perspective.

4.3 Statistical Analysis

The Pearson correlations indicate that larger and more vulnerable neighbourhoods have a slight inclination to have better access, although this does not indicate fairness, refer to Table 3 in the Supplementary Material. From a Utilitarian perspective, larger neighbourhoods and a Rawlsian perspective, more vulnerable neighbourhoods are both more likely to have a negative gap and thus not meet the requirements for justice.

5 Discussion

The results presented highlight that spatial justice as a phenomenon is shaped by several factors:

- The first factor that influences spatial justice is the chosen ethical framework. Each gap metric yields markedly diverse outcomes.
- The second factor is temporal scale: the *NRC* and *NRG metrics* are highly time dependent.
- The third factor is spatial morphology: the topography shapes the spatial form.
- The final factor are specific sociological conditions. In some instances, wealthier neighbourhoods do not meet the requirements for justice, indicating issues of "forced" versus "chosen" exclusion.

6 Conclusion

Indicators are not absolute truths (Kitchen et al., 2015), but these ones can be applied to ensure the relevance of theoretical frameworks. Furthermore, we envision that within their application they may aid in providing moral clarity by requiring the decision maker to be clear on their ethical stance, highlighting *who and where* benefits the most from decisions in relation to urban resource distribution.

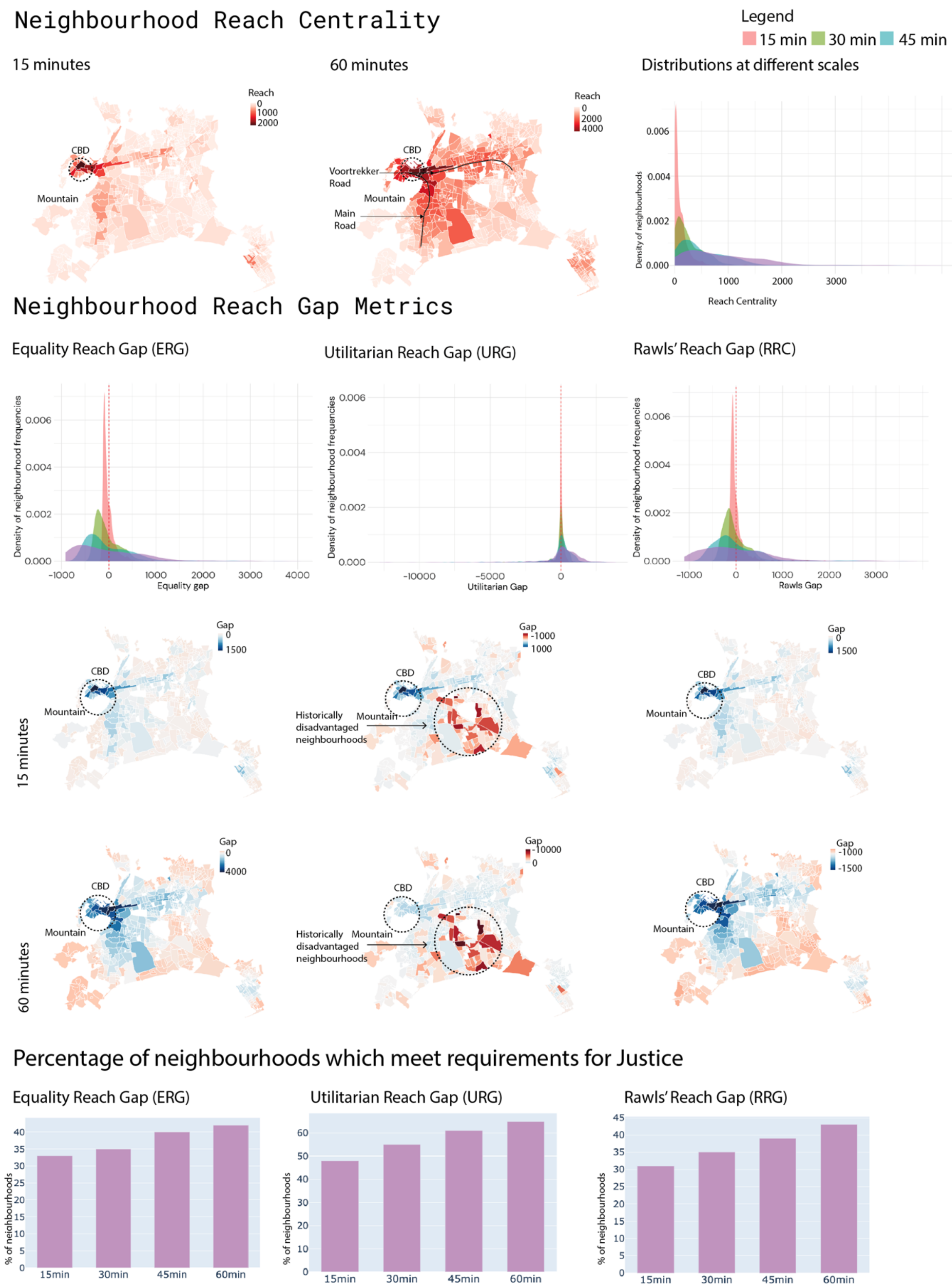

Figure 2: The maps highlight the spatial positioning of neighbourhoods, the density plots highlight the changing distributions.

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Supplementary Material

Table 1: Data set description and their Sources

Variable	City	Data set	Sources	Description
Transport	Cape Town	MyCiti BRT data	Cape Town Open Data Portal www.myciti.org.za	vertices: stations/stops Edges: routes
		Train data	Cape Town Open Data Portal https://capetowntrains.sitelio.me	Weight: travel time
Land use	Cape Town	Zoning data	Cape Town Open Data Portal	vertices: land use
Streets	Cape Town	Road centre lines	OpenStreetMap	vertices: street intersec. Edges: streets Weight: walking time
Socio-economic	Cape Town	Census 2011	Statistics South Africa	Data aggregated to admin boundary of neighb.

Table 2: Node and edge characteristics

Node category	Node dimension	Description
Street node	Street network	Each street node represents an actual street intersection
BRT node	Transport	Each BRT node represents an actual BRT stop
Train node	Transport	Each Train node represents an actual Train station
Land use node	Land use	Each Land use node represents an actual place of employment
Created street node	None	This represents a point on a street that is linked to a land use or transport interchange
Edge category	**Weight**	**Description**
Street edge	varies by length of street	Connects two street intersections
Train edge	varies by route length	Connects two train stations
BRT edge	varies by route length	Connects two BRT stations
BRT to nearest street	0.5 min	Connects a BRT node with a created street node
Land use to nearest street	0.5 min	Connects a Land use node with a created street node
Train to nearest street	1 min	Connects a train node to a created street node

Table 3: Cape Town Pearson Correlation Statistics

Name	Total	Av Income	Education %	Employment %	Vul Index %
Reach 15 min	0.1	-0.1	-0.1	-0.1	0.1
Reach 30 min	0.1	-0.1	-0.1	-0.1	0.1
Reach 45 min	0.1	-0.1	-0.1	-0.1	0.1
Reach 60 min	0.1	-0.1	-0.1	-0.2	0.1
Eq Gap 15 min	0.1	-0.1	-0.1	0.1	0.1
Eq Gap 30 min	0.1	-0.1	-0.1	0.1	0.1
Eq Gap 45 min	0.1	-0.1	-0.1	0.1	0.1
Eq Gap 60 min	0.1	-0.1	-0.1	0.2	0.1
Ut Gap 15 min	-0.7	0.2	-0.2	0.1.1	-0.2
Ut Gap 30 min	-0.8	0.2	0.3	0.1	-0.3
Ut Gap 45 min	-0.9	0.3	0.3	0.2	-0.3
Ut Gap 60 min	-0.9	0.3	0.3	0.2	-0.3
Ra Gap 15 min	0.1	0.1	0.1	0.0	-0.1
Ra Gap 30 min	0.0	0.1	0.1	0.0	-0.1
Ra Gap 45 min	0.0	0.1	0.2	0.0	-0.1
Ra Gap 60 min	0.0	0.2	0.2	0.1	-0.2

Biographies

Ruth Nelson

Ruth Nelson is spatial data scientist and PhD researcher at Delft University of Technology. She holds an M.Arch from NMMU and an MRes. in Space Syntax from the University College London. Both her practice and research are embedded in system thinking and evidence based methods that draw on data science, AI and urbanism. Her skills lie in linking data analysis and computational methods with decision making for strategic planning and policy.

Prof.dr. Martijn Warnier

Martijn Warnier is full Professor of Complex System Design at Delft University of Technology. His research addresses the design and management of large-scale socio-technical systems. His work focuses both on operational aspects, such as robustness and efficiency as well as on aspects such as empowerment and fairness of such systems.

Dr. Trivik Verma

Trivik Verma is an Associate Professor at Delft University of Technology. His research focusses on tackling challenges of urbanisation in an equitable and just manner. Specifically, he is using methods in spatial data science, complex network analyses and participatory mapping to develop computational tools for advancing the theories and practices of urban science.