**Methods & Data**

**Study region**

We applied our analysis to 832 European cities.

To account for the ability of city dwellers to leave their city if they live in proximity to a city border, we included UGS from a buffer of 1 km surrounding the city boundary (Wolff et al 2020).

The city delineation stems from the Urban Audit dataset of the European Union (<https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units/urban-audit>)

**Data**

For the analysis of the walkable environment of European cities, we needed available and comparable data on public green spaces and residential buildings and their respective entry points.

Additionally, the analysis required information on the population living in each residential building and a network that connects the buildings with the green spaces.

We aimed to incorporate publicly accessible data and open source software in order to allow i.) reproduction (e.g. with more recent data) and ii.) comparative approaches covering a large sample of cities.

We used Urban Atlas (UA) 2018 and OpenStreetMap (OSM) as our main data sources.

All analysis was carried out and tested in R 4.1.3 using RStudio version 1.4.1717 and are made available on the GitHub repository www.github.com/blabohm/MA

To ensure the best possible coverage, we downloaded the latest version possible of OSM (April / May 2022).

Urban Atlas (UA): UA is a land use / land cover (LULC) product from the Copernicus program of the European Union.

The 2018 UA version provides Europe-wide comparable data for 788 Functional Urban Areas with more than 50.000 inhabitants.

It represents 17 urban and 10 rural LULC classes with a MMU of 0.25 and 1 ha, respectively.

In addition to the spatial data, UA contains information on the population for the residential land use classes.

Since Copernicus does not offer an API, we downloaded the latest UA version available at the time of this study (c13) by hand.

OpenStreetMap (OSM): OSM is a community-based project that provides free geospatial data.

The OSM community seeks to create a database of the entire planet that is free and editable.

For the analysis we downloaded the OSM data with the identifiers ‘building’ and ‘highway’.

Since OSM is a community-based mapping service, the latest version of OSM data is expected to have the most information.

We acquired the OSM data via the OSM API, which we accessed via a custom-made tool that heavily relies on the R package ‘osmdata’.

For information on the OSM download tool see Appendix ...

**Data processing**

*Street network:* The network, in this analysis, represents the walkable environment of a city, which connects the entry points of the UGS with those of the residential buildings.

To acquire information on the street network of a city, we downloaded OSM data with the identifier ‘highway’, which represents all linestrings in the OSM database that are associated with streets and paths.

To secure comparability across European countries, we used all OSM highway classes, except for the class ‘highways’ as not being suitable for walking.

Linestrings identified with the string ‘highway’ represent motorways which are reserved for motorized use only.

To ensure network connectivity and reduce overlap, we cleaned the resulting network following the tutorial on network data pre-processing and cleaning by Lucas van der Meer (<https://luukvdmeer.github.io/sfnetworks>, May 2022).

Further information on the network pre-processing and cleaning steps can be found in Appendix ...

*Residential buildings:* The following analysis requires information on a cities’ residential buildings, their entry points and on how many persons inhabit each building.

We filtered the OSM ‘building’ polygons for residential buildings.

We only kept those OSM buildings whose centroids were contained inside of urban atlas residential areas (UA class code starting with: 11).

*Residential building entries:* To detect building entries, we first calculated the centroids of each building.

Centroids had to satisfy the constraint, that the point has to lie inside the polygon (see st\_point\_on\_surface).

We snapped the centroids to the closest point on the cleaned street network and assumed the resulting points to be the building entries.

*Population per building:* To assign each OSM building a reasonable population count, we used a simple area weighting disaggregation approach (Li et al. 2007).

The UA dataset provides information on population mostly on a city block level.

We disaggregated this data to the building level by distributing the population proportionally to a buildings base area.

This workflow follows the assumption, that the building structure, and thus the population per base area inside one city block is similar.

For buildings that were contained inside UA residential polygons that erroneously did not have population values, we used the mean population per square-meter of the corresponding UA residential class in the city.

*Green spaces:* The last data point required for the analysis is information on publicly accessible UGS and their entry points.

We filtered the UA data for the classes ‘green urban areas’ (code 14100) and ‘forests’ (code 31000) to ensure that all green spaces that are used in the analysis are publicly accessible.

All green spaces in the UA dataset come with information on area, which we double checked for consistency.

*Green space entries:* To detect green space entries, we intersected the outline of the UA green spaces with the cleaned network.

Furthermore, we applied different buffer sizes to the green space polygons as sensitivity analysis.

We used the resulting points as entry points of the green spaces for the further analysis.

In case a green space did not receive any entry points, we incrementally increased the buffer sizes.

Further information on the method and the validation / sensitivity analysis can be found in Appendix ...

*Network blending:* In the process of network blending, the entry points of the residential buildings and the UGS (now called ‘nodes’) are being ‘blended’ into the network.

During this process, the lines (now called ‘edges’) will be broken at every node location.

The node location now represents the new starting / ending points of the newly created edges.

For more detailed information on this process see Appendix ...

**Analysis**

%Analysis to achieve Objective 1:

Our first objective was to develop a modeling approach that applies the Detour Index (DI) and Local Significance (LS) walkability indices.

For computational considerations, we limited the catchment area around each building to 500 meters network distance.

We calculated the Detour Index (DI) and the Local Significance (LS) index for each UGS inside the city core plus a buffer of 1 km.

We accounted for the maximum walking distance by calculating both indices for the residential buildings within a network distance of 500 m between a building entry and the nearest entry point of a UGS.

**Detour Index (DI):** The DI is an indicator of barriers in a network.

It accounts for the efficiency of the routes that residents take on their way to the nearest UGS (Wolff 2021). The DI combines the Euclidean distance, i.e. the direct connection between two points, with the network distance (Esch 2014):

Where *DI* is the Detour Index, *D* is the Euclidean distance between points *i* and *j*, and *ND* is the network distance between the points *i* and *j*.

In the case of this analysis, the two points are the entry points of a residential building and the nearest entry point of a UGS.

The DI can assume values between 0 and 1.

A DI value of 1 represents a straight line between building entry and UGS entry, while a DI value closer to 0 means that the inhabitants of the building have to take a sub-optimal route to the nearest UGS.

If one building has access to several UGS within a network distance of 500 m, we decided to use the mean DI value.

**Local Significance (LS):** The LS is usually used as an indicator of edge importance in a network analysis (Esch, 2014).

We use a modified version from Wolff 2021 as an indicator of how many people have access to an UGS.

The LS also accounts for the size of an UGS as well as the distance between people’s homes and the UGS entries (Wolff 2021):

Where *LS* is the Local Significance, *p* is the population of building *i*, *A* is the area of UGS *j* and *ND* is the network distance between the entry points of building *i* and UGS *j.*

This indicator can assume infinite values.

A higher population and area, as well as a lower network distance lead to higher LS values.

We attached the LS values to each segment (edge) of the path between building and UGS entries.

We summed the LS values of overlapping paths from multiple buildings, leading to higher values on higher frequented edges.

A more detailed summary on index building can be found in Appendix …

To demonstrate application possibilities of the indices, we visualized the DI and LS values for the area surrounding the Lene-Voigt-Park (LVP) in Leipzig.

The city of Leipzig is the largest city in Saxony, Germany. After a massive population loss in the 1990s, the city faced a major regrowth since 2012. Rising population numbers led to increased pressure on the open spaces of the city.

The LVP was a former train station area and has been out of use since 1942.

In the 2000s, it was converted to a public park and is fully open since 2004 (Leipzig website).

Its diverse history and the population dynamic make the LVP an interesting test case for the demonstration of our results.

Since LS values tend to grow exponentially, we chose to use a logarithmic scale for visualization.

%Analysis to achieve Objective 2:

In our second objective, we wanted to compare the indices on a European level and assess in which cities the OSM data availability would facilitate our analysis.

%European comparison

For comparing the distribution of DI values in the European countries, we plotted the DI against the relative cumulative population in each city.

We aggregated the results to country level for easier visualization.

Furthermore, we mapped the percentage of people in a city that have a DI of 0.8 or higher.

To compare the LS values across European cities, we used the cities’ average of the summed LS values at the green space entries per UGS.

%OSM data coverage

We assessed the OSM data coverage for 834 European cities.

We did so by computing the percentage of UA residential polygons that are covered by at least one OSM building polygon.

As a compromise, we used a threshold of 85% OSM coverage (at least 85% of the UA residential Polygons have to contain at least one OSM building polygon) for the comparison of our results across European cities.

%Analysis to achieve Objective 3:

The final objective was to implement the two indices we developed to demonstrate possible use cases for city planners.

To describe the impact of changes in different model parameters, we tested three different scenarios and calculated the change of the index values to the base model.

**Alternative 1 – Unlimited access:** In the first scenario we demonstrated how the LS and DI indicators change if all barriers obstructing access to the LVP were removed.

To model unlimited access, we distributed hypothetical entry points every 5 meters on the network surrounding the LVP and applied the walkability indices to the changed conditions.

**Alternative 2 – Green space development:** In the second scenario we investigated the impact of a development of the green spaces surrounding the LVP to residential buildings.

We assumed the following green spaces in the north of the LVP to be developed to high density residential buildings: Reudnitzer Park, Staphaniplatz, and the green space between Täubchenweg, Perthesstraße and Gerichtsweg.

To implement this scenario, we converted the former green space entry points to building entries.

We multiplied the size of the parks by the 95th percentile of the population per square meter value derived from the urban atlas high density residential class in the surrounding two kilometers.

We distributed the outcome uniformly across the former green space entries and applied the two walkability indices.

**Alternative 3 – Population increase:** In the third scenario we modeled a population increase in the residential areas surrounding the LVP.

For each residential building in a distance of 2 km to the LVP, we increased the population value to the 95th percentile of the respective urban atlas residential class.

We then applied the DI and LS indices to the changed conditions.

**Alternative 4 – Ensemble scenario:** In the final scenario we applied the changes from the unlimited access, the green space development and the population increase scenarios and gathered them in one ensemble model.