**Discussion**

In this paper, we developed a modeling approach that applies two walkability indices, the Local Significance (LS) and the Detour Index (DI).

We demonstrated the application of both indices in a test case, the Lene Voigt Park in Leipzig.

Furthermore, we compared the two indices on a European scale and, in a final step, implemented them in different cases to demonstrate possible uses of LS and DI for city planners.

Our workflow is applicable, and – with limitations – comparable on a European scale.

**%Applying indices**

In his paper, Wolff mapped the LS with colored straight lines that directly connect residential areas with the respective UGS (Wolff 2021).

His representation of the index enables an overview of potential overcrowding in individual UGS and the direction from which people flow into the green spaces.

By plotting the LS in a cumulative way on individual street segments, we enable an even more targeted representation of the flows.

In an individual city, areas of high use intensity with potential for overcrowding can be identified at first glance as red clusters around the UGS’ in question.

Consequently, researchers and city planners can utilize our results to distinguish potential overcrowding effects that might limit accessibility of a specific UGS at individual street segments or green space entry points.

Our DI representation …

%Limitations:

* LS:
  + In areas with sub-optimal OSM data coverage, LS values might be lower than expected due to incomplete residential building digitization.
  + Furthermore, the LS does not account for obstacles people have to overcome on their ways to the nearest UGS like traffic lights or large streets.
* DI:
  + In data-scarce regions, the DI should be accurate for all buildings that are digitized in OSM and that are covered by the UA dataset.
  + One of the largest limitations of the DI is that the DI values do not account for further obstacles people have to overcome on their ways to the nearest UGS.
  + For example, there can occur high DI values in close proximity to UGS, even though the residents have to cross larger streets or pass traffic lights on their trajectory to the UGS.
  + Low DI values also occur in close proximity to the LVP as an artifact of small Euclidean and network distances values.
  + In these cases, a minor difference can lead to a low DI values even though the overall traveling distance to the next green space entry is relatively small.

* Both indices:
  + Both indices only account for the fasted route from A to B given the underlying network.
  + People might choose their trajectories towards UGS based on different factors than pure distance, though (Quelle).
  + Another important point is, that, by using the urban atlas classes 14100 and 31000, we have only accounted for publicly accessible green spaces.
  + The role of private or residential green cannot be underestimated, since a high share of residents might prefer the use of their private green space over publicly accessible ones (Chiesura 2004, Säumel et al. 2021).
  + This effect might cause the LS values to overestimate the flow of people from their homes to UGS.
  + Furthermore, by leaving private green out of the equation, we cannot account for institutional barriers of accessibility (Wolff 2021, Biernacka & Kronenberg 2018).
  + We did neither account for any measures for the attractiveness of the parks, or further barriers that affect accessibility like in Biernacka et al. 2020.
  + But combining the DI or LS with such measures might yield inference on a per building level instead of an UGS level, enabling quantitative and qualitative assessments with a higher accuracy than before (Biernacka et al. 2020).
  + Furthermore, our walkability indices may be combined with local demographic, socio-economic or environmental data, which can open up further opportunities for analysis (Poelmann 2018).
  + Reaching UGS by means of public transportation, private motorized transportation or cycling was not addressed by our study.

**%Comparing indices**

%OSM coverage:

* Mostly central European cities (Poland, Czech Republic, Austria, Northern Italy, Switzerland, France, Netherlands)
* Approach not really suited for a European comparison due to incomplete digitization of buildings in OSM it is mostly a central European comparison.
* UA polygons covered by at least one OSM polygon is only a proxy for the „real“ coverage. No real inference about the nature / quality of the OSM data.

%DI:

* + - Yet, there are countries with large city samples and a high percentage of population reaching green spaces in 500 meters network distance, like Germany (126 cities, 73%) or Poland (68 cities, 69%).

%LS:

In comparing the average LS index values at UGS entries of the European cities, we found a cluster of cities with above average and high values in mid- to and south-western Germany.

Wolff and Haase showed in their 2019 paper, that in this area most cities express high residential density as well as only average supply of UGS (Wolff & Haase 2019).

High population pressure and short distances to or an unequal distribution of UGS might lead to relatively high visitation rates at green space entries.

These results confirm regional studies by Xu et al. from 2018 and 2020, who stated that a higher housing demand increases the pressure on GS availability (Xu et al. 2018, Xu et al. 2020).

Kabisch et al. 2016:

* Per capita UGS availability in 300 meters or 500 meters,
* Enabling spatial assessment of unequal distribution of UGS in a city, or between cities on a European scale.
* Similar to our results: UGS availability gradient: higher values towards north and central Europe, lower values towards southern and eastern Europe
* Independent of OSM coverage: Southern European countries are better covered than in our analysis.

Poelman 2018:

* Population weighted median of UGS area that can be reached in 10 minutes walking time
* Proximity measure show distribution of access within cities: highlight disparities within and between cities

Wolff und Haase D. 2019:

* Below average supply of UGS in southern and south-eastern European countries
* High residential density + average supply of UGS in south-western Germany = explanation for high LS value in the area?

Cortinovis et al. 2022:

- European cities have shifted from a de-densification to a densification regime due to growth of urban population, decrease of land-take for residential use and higher immigration (Cortinovis et al. 2022)

**%Implementing indices**

(Es Hilft:

1. Bedarfe abzuchecken,
2. Verschiedene Planungen zusammenzudenken -> Straßen + Grünflächen
3. Auswirkungen von Veränderung hinsichtl. Bebauter und Grün/blauer Infrastruktur abzuleiten (green / blue infrastructure, built-up + demand)

In general, we can say that an increase of the DI value of a building is a desirable effect because the residents have a more efficient – or more direct – way to UGS.

As a result, people might be incentivized to visit UGS more often and reap the positive effects of physical exercise and being in the nature (Quelle).

In contrast, a decrease of the LS value of a street segment can usually be deemed positive.

If no larger changes in the built-up structure have be made, a decreasing LS means less people traveling through the same network, resulting in less crowded streets.

Alternative 1: Unlimited access

LS:

- Removing the entry barriers might have ambiguous effects:

- On the one hand, the streets around the UGS might become less crowded, which is desirable for city planners, as it might alleviate the effects of overcrowding.

- On the other hand, a UGS with less barriers might be more attractive, and thus, pulling more people from the surrounding residential areas, resulting in more traffic in the remaining network.

DI:

- In the first alternative, the DI values are very sensitive to small changes of green space entry locations.

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%Alternative 2: Densification

%LS:

The LS index reacts strongly on the changes that we have applied to the built-up structure in the area.

Replacing the UGS with residential areas would cause the absolute number of people to use the network to increase.

Our representation of the LS reacted contra intuitively to the changes, though.

Removing the UGS reduced the overall number of trajectories modelled, which in turn decreased the index values for most of the network.

Only did the values increase at those street segments that lead from the converted UGS to the remaining ones.

The strong LS decrease in most of the network, as well as its evenly strong increase at certain streets highlight the importance of the UGS that were changed into residential buildings: Many neighboring residents can potentially use these places for recreation, while converting them and bringing even more people in will increase the crowdedness of the remaining UGS.

%- DI:

Taking UGS that prove harder to reach out of the equation can increase the DI.

An increasing DI itself mean that residents travel along efficient trajectories towards UGS.

Thus, only considering DI values might implicate, that the green space accessibility for residents improves when green spaces are converted to build-up.

Since we are only looking at distances, the index lacks to account for an in- or decrease of the number of alternative green spaces.

Alternative 2 exemplifies one of the greatest weaknesses of our implementation of both indices: we merely account for the individual trajectories between residential buildings and green space entries without addressing the overall number of green spaces that are accessible per building.

Consequently, our representation of LS and DI might still need further improvement in future studies to better represent the green space accessibility of urban dwellers.

At the same time, our analysis highlights an acute lack of research in this regard.

Alternative 3: Population increase

Alternative 4: Ensemble model

Conclusions:

The Detour Index (DI) and Local Significance (LS) indicators not only enable small scale and high-resolution analysis of green space accessibility in single cities, but also allow for a large-scale comparison of cities and countries in Europe.

Nonetheless, in this study we only provide a broad overview – cities have grown over millennia and each data point in our graphs is an individual case study with challenges for itself.

It is not important to make the results accessible and available (e.g. on a website) for urban planners so they will actually use them for their specific contexts.

Both indices are only as good as the data that they are built on.

Errors in the UA or OSM data sets might propagate from data preparation to index building and multiply on the way.

To really model the walkability of a city in the future, we need to take the environment into account:

A more convenient walking experience on one street might cause people to change their trajectories and even take detours on their way towards UGS.

At the same time, a less pleasant walk may cause the opposite behavior (Quelle).

Furthermore, certain features that are not reflected in our network can turn out to be barriers for the accessibility of UGS, like large streets that have to be crossed.

Even though most of the data that is required to account for these features might be hard to get and to harmonize, an implementation can be easily realized by re-running our program, once the data is present.

Another point that the two indices are not sensitive for, is the fact that many residents have access to more than one UGS. Thus, building a new block of residential housing might not be as grave in a neighborhood with a plethora of alternative UGS. If the only park around is sealed and even more people are invited to live in the area, it can be a disadvantageous decision.

→ change index calculation process to account for this in future work.

Since the two walkability indices are only an approximation of the potential flows, GPS data as is produced by companies like e.g. Google or Apple could facilitate a far more sophisticated analysis.

Especially overcrowding effects could be modelled with higher detail and even on a temporal scale.