**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**

%LS

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 representation of the DI enables users at first glace to see which buildings have access to UGS, and weather they can reach UGS in and unobstructed manner.

In some cases, the DI can be misleading, though.

Low DI values may occur in close proximity to UGS 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 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.

Our application of the LS and DI fails to account for obstacles people have to overcome on their ways to the nearest UGS like traffic lights or large streets.

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, posing another factor for introducing uncertainties.

Lastly, 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.

**%Comparing indices**

Comparing the two walkability indices on a European scale has shown similar results as past studies.

Spatial patterns

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

%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%).
  + 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.

%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).

* + In areas with sub-optimal OSM data coverage, LS values might be lower than expected due to incomplete residential building digitization.

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**

To demonstrate potential applications for the two walkability indices for city planners and researchers, we implemented the LS and DI in three alternatives at our model case, the Lene Voigt Park LVP in Leipzig.

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 e.g. physical exercise or being in the nature (QUELLE).

In contrast, an increase of the LS value of a street segment can usually be deemed negative.

If no larger changes in the built-up structure have been implemented, an increasing LS means more people traveling through the same network, resulting in more crowded streets which might have an adverse effect on UGS accessibility.

The implementation of the LS and DI may not only help to assess green space demands of a city.

The two indices might also help city planners to test the effects of their actions ragarding green and blue infrastructure on green space supply and demand before implementation.

Additionally, the LS and DI may facilitate planning the street network, as well as residential units of an area together with the green and blue infrastructure, enabling synergies between departments and avoiding potential pitfalls.

%Alternative 1: Unlimited access

%LS:

In the first implementation, we modeled an unlimited access to the LVP by adding green space entry points every 5 meters on the outline of the park.

At the immediate surrounding of the LVP, the LS index behaved as expected.

Here, removing the entry barriers resulted in a decrease of the index, representing less crowding taking place, which is desirable for city planners, as it might alleviate the effects of overcrowding.

Nonetheless, the implementation of the unlimited access alternative showed ambiguous effects.

A UGS with less barriers might be more attractive, and thus, pull more people from the surrounding residential areas, resulting in more traffic in the remaining network and a higher overall visitation of the park itself.

%DI:

The DI values of most of the residential buildings express only minor changes.

The small changes of the network distance that occur when the nearest green space entry point is shifted do not carry as much weight if network and Euclidean distance values are larger.

In contrast, close to the LVP the small changes have a larger effect on the DI values, resulting mostly in substantial increases of the index.

The contradicting effects on the DI values of those buildings that have ‘gained’ access through removal of barriers show that considering the DI alone might not yield a full picture on UGS accessibility.

%Alternative 2: Densification

%LS:

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

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 modeled, 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 cause the remaining UGS to be more crowded.

%DI:

Furthermore, the second alternative has shown that 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 two 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

The modeled population increase in alternative three resulted in a general increase of LS values in the entire area.

Where the population flows from multiple areas combine on their way towards the UGS we can visualize potential crowding effects that might occur if population increasing trends tend to continue (Cortinovis et al. 2022).

Alternative 4: Ensemble model

Finally, by uniting all changes, we see the complex interactions of built-up environment, population and UGS.

At the first glance, the population increase seems to dominate the other changes.

A closer look reveals the effects of converting the green spaces to residential area, as well as providing unlimited access to the LVP, though.

Overall, changing the build-up environment turns out to have higher impact on the flows of residents towards UGS than the population.

An increase in urban dwellers adds up to those crowding effects that are caused by other changes like in the densification alternative.

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.

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.