In this paper, we developed a modeling approach that applies two walkability indices, the Local Significance (LS) and the Detour Index (DI) based on publicly available data and software tools \citep{EuropeanUnion.2020, RcoreTeam.2022, OpenStreetMapContributors.2022}.

We further demonstrated possible uses of LS and DI for city planners by using an urban park as a test case, the Lene Voigt Park in Leipzig.

In a final step, we compared the two indices for a set of European cities in order to detect variations between different cities.

The application of our workflow was feasible, and the results were – with limitations – comparable on a European scale.

In a consistent method reflection we report on the benefits and limits of the applied procedure.

**%Applying indices**

%LS

Wolff mapped the LS with colored straight lines that directly connect residential areas with the respective UGS.

His representation of the index enables an overview of potential overcrowding in individual UGS and the strength of expected recreational flows towards the green spaces \citep{Wolff 2021}.

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 in order to display crowding effects of the corresponding Service Connecting Areas (SCA) \citep{Dworczyk.2021, Barthelemy.2018}.

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

The index provides an estimation of potential detours people have to take in order to reach and UGS: the closer the route towards the UGS is to a straight line, the higher is the index DI suggesting a better accessibility. \citep{Esch.2014}.

Consequently, this index is a good proxy showing discontinuous accessibility options of people without suggesting an artificial dichotomous differentiation between having and not-having access like indicated by fixed-distance buffers or isochrones. (e.g. \cite{Poelman.2018, Kabisch.2016}).

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 value even though the overall traveling distance to the next green space entry is relatively small.

Nonetheless, both walkability indices may be combined with local demographic, socioeconomic or environmental data, which can open up further opportunities for city planners.

For example, traffic, air pollution or -temperature or vegetation parameters along the street network might help in the decision process for intervention \citep{Poelmann.2018}.

**%Comparing indices**

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

The spatial patterns of high accessibility in central and northern Europe, and low accessibility in southern and eastern Europe, match those found in past studies.

For example, Kabisch found a lower UGS availability in south-eastern Europe within, both 300 and 500 meters \citep{Kabisch.2016}.

Poelman found similar results when using a proximity approach in 10 minutes walking distance for calculating a population weighted median of UGS area \citep{Poelman.2018}.

Both studies enabled a spatial assessment of unequal distribution of UGS in a city, or between cities on a European scale.

%DI:

By comparing the relation of the DI and the cumulative population, we can add to these findings by showing potential barriers people have to overcome on their way to UGS.

Overall we could show a large variation across European countries.

While in southern and Eastern Europe, UGS availability in 500 meters network distance is comparatively low, the accessibility of the UGS seems to be low, as well.

In central and northern Europe, we observed not only high values of UGS availability, the routes people have to take to get there also seem relatively efficient.

In countries with similar percentages of UGS accessibility like Norway and Germany the DI / population curve in figure \ref{fig:lsmap} depicts that a larger share of urban dwellers have a more direct path towards UGS in Germany, because here, the onset of the curve happens later.

On the other hand a late onset of the curve can result in an overall low accessibility, like in Italy, while an early onset can still yield a relatively high accessibility as in Norway.

%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.

Cortinovis et al found that 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 \citep{Cortinovis.2022}.

Furthermore, Wolff and Haase showed in their 2019 paper, that in southern Germany most cities express high residential density as well as only average supply of UGS \citep{Wolff.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 \citep{Xu.2018, Xu.2020).

%OSM coverage:

Former studies relying on Urban Atlas (UA) were able to compare all 788 cities that are covered by this product in 2018 \citep{EuropeanUnion.2020}.

Enhancing the accuracy of the dataset by using OpenStreetMap (OSM) data has reduced the overall number of cities.

In this regard, we found a gradient of OSM coverage from north- and central Europe towards southern and south-eastern Europe.

Consequently, mostly central European cities exhibited a sufficient data coverage for effective comparison (Poland, Czech Republic, Austria, Northern Italy, Switzerland, France, Netherlands).

As long as the OpenStreetMap community is mostly active in central European countries, our approach is not really suited for a wholesome European comparison.

Due to the incomplete digitization of buildings in OSM it is mostly a central European comparison.

Furthermore, UA polygons that are covered by at least one OSM polygon is only a proxy for the potential coverage that may not yield inference about the nature and quality of the OSM data.

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.

**%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 \citep{Kabisch.2021}.

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 regarding 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 \citep{Cortinovis.2022}.

These results also enrich different more areal-based approaches as on different density patterns emerging from the constellation of population trajectories and built-up area changes \citep{Wolff.2017}.

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.

%Limitations

There are several factors that limit out appraoch.

First, 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.

Both indices only account for the fastest routes from residential buildings to UGS in a walking distance of 500 meters, given the underlying network.

People might choose their routes towards UGS based on different factors than pure distance. Elements of attractiveness such as equipment, events etc. might encourage people to approach UGS in greater distances \citep{Biernacka.2018, Biernacka.2020}.

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, large streets or other physical barriers (see \cite{Barber.2021}).

Another important point is, that, by using the urban atlas classes 14100 and 31000, we have only accounted for publicly accessible green spaces.

Furthermore, 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 \citep{Chiesura.2004, Säumel.2021}.

This effect might cause the LS values to overestimate the flow of people from their homes to UGS.

By leaving private green out of the equation, we can not account for institutional barriers of accessibility \citep{Wolff.2021, Biernacka.2018}.

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).

Lastly, reaching UGS by means of public transportation, private motorized transportation or cycling was not addressed by our study.

By including public transport into the model future research might remove further uncertainties of our approach.

%Conclusions:

In this study, we modeled the walkability of European cities – i.e. the quality of the routes people take to reach urban green spaces (UGS) – using publicly availability data and software.

The Detour Index (DI) and Local Significance (LS) indicators that we employed 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.

In adding to former research, we developed an approach for modeling the service connecting areas (SCA) between residents homes and UGS.

Instead of providing a dichotomous measure of having or not-having access to UGS, our approach enables inference about the SCA itself.

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.

Therefore, it is important to make the results accessible and available (e.g. on a website) for urban planners so they will actually use them in their specific contexts.

Augmenting our results with environmental variables or other local data might enable researchers and city planners to better account for overcrowding effects and barriers that limit accessibility of UGS.

To enhance modeling of 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.

Furthermore, certain features that are not reflected in the network we used, 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.

A change of our index calculation process should account for UGS alternatives in future reasearch.

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 modeled with higher detail and even on a temporal scale.