**Results**

**1. Applying walkability indices**

* Figure 1: *The network colors depict the cumulative LS. A higher LS value is depicted by a darker red color, representing i.) more people taking this path, ii.) the people taking this path are living in closer proximity to the green space, and / or iii.) the path is leading to a larger green space. Since the LS values are cumulative, a higher value might also mean more paths from different buildings overlapping (See Appendix … for further information). The building colors represent average DI calculated for all green spaces in a network distance of 500 meters from a building. The dark blue the color of a building is, the closer to one the DI value, the more direct can its residents travel to the closest green spaces. The opposite is the case if the color tends towards orange.*

In this section, we present the results of applying the two walkability indices to the test case, the Lene Voigt Park (LVP) in Leipzig, Germany.

Figure Xa displays the local significance (LS) values that we calculated for the city of Leipzig, Germany.

The map shows the area east of the city center (top right corner of the map).

In the center of the map, highlighted with a darker green, is located the LVP.

Other green spaces are depicted in a lighter green, buildings and the network in white and gray, respectively.

Lower LS values are displayed in blue shades, higher values in red shades.

Due to the high density of green spaces and residential buildings in the area, an overall high level of LS values can be observed.

In general, LS values tend to grow towards green space entry points – i.e. higher LS values can be observed in closer distance to UGS.

Due to the cumulative nature of our LS representation, this effect symbolizes street segments with the potential for overcrowding.

Furthermore, high LS values are associated with direct connections between parks and residential buildings.

The highest LS values can be found at park entries adjacent to streets which connect UGS to areas with high population, indicating street segments that are highly visited for routes towards UGS.

The eastern part of the LVP close to the *Riebeckstraße* is a good example for this (marker A on the map).

Here, we find high LS values at those parts of the streets that lead to the residential areas in the north, east and south-east.

At the same time, we see that the Riebeckstraße in this area is actually a bridge with two Tram and two car lanes and few possibilities for crossing (see picture …).

This circumstance is not represented in the street segment´s LS values.

Furthermore, the *Josephinenstraße* (marker B) which connects the center of the LVP to the next larger park in the south, the *Friedenspark* (marker C), displays high LS values.

On the other hand, we can make out lower LS values at streets with residential buildings that are close to the cut-off threshold of 500 meters distance to the nearest green space.

For example, in the southeast of the map, in many streets, the blue shade is getting brighter with each street segment until it switches over to red shades.

With each building entry, more inhabitants are expected to take these routes towards the nearest green space.

This increases the LS values of the street segments.

Figure Xb displays the detour index (DI) east of the city center of Leipzig.

Higher DI values are depicted in blue shades, lower ones in red shades.

High DI values can be found at buildings that are located at streets which lead directly to a green space entry.

Along these streets there are straight formations of buildings with high DI values as can be seen in the south of the LVP.

In contrast, there occur clusters of low DI values in areas where larger detours have to be taken to reach a park entry. Such areas can be found in the northeast of the map.

Furthermore, we can observe low DI values at buildings that are close to several UGS but whose routes towards one or more UGS are inefficient.

Some buildings that are directly adjacent to one UGS, but have to take small detours to the nearest green space entry point, also show low DI values.

Lastly, we see that there are buildings close to UGS with high DI values but that have to cross larger streets or other obstacles to reach the green space entry point.

**2. Comparing walkability indices**

Figure 2 Percentage of urban atlas residential class polygons that contain at least one OpenStreetMap building polygon. Red colors represent a higher coverage. Yellow and blue colors represent lower share of covered polygons.

Here, we present the results of the OSM data coverage assessment and, later, compare the two walkability indices across Europe.

Figure x depicts the OSM coverage, i.e. the relative share of UA polygons that are covered by at least one OSM building polygon.

Most cities in central Europe – in particular in Poland, the Czech Republic, Austria, Northern Italy, Switzerland, France, Belgium and the Netherlands – exhibit a very high OSM coverage of nearly 100 percent.

In the UK, northern Spain and the southeast of Europe, we see more cities with an OSM coverage of around 50%.

In Portugal and the south of Spain few cities express an OSM coverage above 50%, and most cities are around 25% OSM coverage.

In figure x we see two exemplary cities – Vienna as an example for a high OSM coverage and Lisbon as an example for a low OSM coverage.

The city of Vienna, Austria is a prime example for a high OSM coverage with 98.7% of the UA residential building polygons covered by at least one OSM building.

A source of error explaining a fraction of the imperfect coverage in most cities are misclassified UA polygons (see Appendix 1b).

In another share of UA polygons, the population values might have been so small that none of the OSM buildings received a population count, so they got filtered out during the data cleaning process (see Appendix 2b).

In contrast, in Lisbon, Portugal 55.6% of the UA polygons are covered by OSM buildings.

As we see in figure …a, most of the low coverage can be explained by a lacking digitalization of buildings in the OSM dataset.

Additionally, the OSM building coverage in Lisbon is declining with higher distance from the city center.

Where OSM buildings are present, the workflow of generating LS and DI indices was functional.

On the other hand, large parts of the residential areas of Lisbon have no OSM coverage and, thus did not get index values.

This lack of DI values for a large part of the population would complicate a comparison with other cities that have a more complete coverage.

Also, comparing the LS values could prove unreliable, even though we use the average value at green space entry for the above analysis.

Missing residential buildings in the service area of green spaces would lead to LS values that might be lower than expected.

Due to these inconsistencies, we decided to exclude all cities with an OSM coverage of less than 85% from our analysis.

Most of Europe’s capital cities feature a high OSM coverage and by choosing a threshold of 85%, we only had to exclude 5 of them from our analysis (Lisbon, Athens, Budapest, London and Madrid).

Figure 3 Top: share of population with DI values of 0.8 or greater (in cities with OSM coverage > 85%, n = 533). Bottom: DI values per share of population.

In this section we compare the DI and LS indices in 533 European cities with an OSM coverage of 85% or higher (see previous section).

To compare the DI of European cities, we will have a look at the cities’ DI per relative cumulative population.

For the example of the LVP, a share of roughly 45% of the population in the surrounding area has a DI of 0.8 or higher:

DI\_plot\_small

In figure x (DI MAP) we demonstrate this share of population for each city.

Here, we can observe a clustering of cities with mid- to high shares of population with DI values above 0.8 in northern and central European countries.

This cluster consists especially of cities in the Netherlands, Belgium and Germany, as well as the western parts of Poland and the Czech Republic.

In France, the UK, Italy and the eastern part of Poland, we see a larger share of cities with a lower percentage of population with DI values greater than 0.8.

Most Balkan countries, as well as Ireland have no cities with a > 20% share of population in the highest DI segment.

As we can see in figur­­­­e x, the distribution of DI values plotted against the cumulative, relative population varies strongly across countries.

The ending points of the lines show the percentage of people with green spaces in a network distance of 500 meters.

The slopes of the lines indicate how direct the inhabitants of a country can travel to the green spaces they have access to.

On the top end there are mostly northern and central European countries where more than 85% of the urban population can reach green spaces in 500 meters network distance.

On the lower end there are mostly southern and south eastern European countries where less than 30% of the population or less live in 500 meters network distance of green spaces.

It is notable, that on both ends of the spectrum, the sample size is limited to only a few cities (top: FI = 3, SE = 5, LU = 1, bottom: AL = 2, XK = 1, RS = 3, RO = 5).

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%).

Additionally, there are countries with large city samples and a lower percentage of people in proximity to green spaces like France (84 cities, 58%) and Italy (56 cities, 57%).

In France, for example, we see a higher share of population with a more direct access to UGS in the north-eastern part of the country and a lower one towards the south-western part.

Generally, a curve that has a late onset and a steep slope means that more people have a more direct route to the nearest green spaces and vice versa.

An example for this would be Finland, where about 32% of the urban population have an DI of more than 0.8.

On the contrary, the curve of Norway has an early onset and a lower ending point, resulting in a smaller share of people (23%) having a DI in the highest 0.2 margin.

Figure 4 (top): Mean LS at green space entry points per city (color) and LS coverage – i.e. percent green spaces in a city that have been reached by inhabitants (size). (bottom): Mean LS values at green space entry points per city. Aggregated by country.

The average LS values at green space entry of the European cities also show a large variation.

For example, in figure X (LS MAP) we can observe above average LS values at the green space entries in mid- to southwestern Germany.

According to our results, in these areas the street segments at the UGS entries are highly visited, UGS are large and / or the population lives close to the UGS.

In contrast, most of the cities in France or at the eastern coast of Italy feature rather low LS values.

In Poland or the Netherlands, we find a mixed picture of cities with higher and lower LS values at green space entry.

In figure x we see the LS values aggregated on a country level.

Every point that is plotted behind the box-plots represents the average LS value at green space entry of one city.

Accordingly, we see that the differences in the number of cities where our analysis was feasible vary substantially between countries.

At the bottom and top ends of the chart, there are countries where relatively few cities are included in the final analysis, like Greece, Luxembourg or Norway.

From the countries with a larger share of cities that were eligible for our analysis, Italy has the largest spread of LS values.

Like France and the Netherlands, Italy’s mean LS at UGS entry is at the line indicating the lowest 25% of cities, while the mean values of Germany and Poland are in the middle of the 25% and the 75% lines.

Again, a high average LS at UGS entry might indicate more people at the UGS entries, larger UGS and / or population living closer to UGS.

**3. Implementing walkability indices**

In this section we want to demonstrate how local planners can use the two walkability indicators that we applied before.

Therefore, we return to the example of the LVP as outlined in section X.1.

We explore three potential alternatives in which we reshape the built environment as an expression of applied planning tools.

In each alternative, we alter one of the core variables that are used to calculate LS and DI.

In the first alternative, “unlimited access”, we assume that the LVP can be accessed from all around the park.

For the second alternative, “densification”, we selected a number of UGS north of the LVP and replaced them with residential buildings.

In the last alternative, “population growth”, we assume a certain increase in residents in the area surrounding the LVP.

Alternative 1 – Unlimited access

*Figure? Delta values for local significance (left) and detour index (right). Streets and buildings that expressed no change are not colored. An increased LS is mapped in red, a decrease in blue. Increasing LS values depict street segments that are higher visited. An increasing DI is mapped in blue, a decrease in red. Higher DI means that the trajectories from a building to the nearest UGS entry have become more efficient. The top two maps show the unlimited access alternative.*

In the first alternative we demonstrate how the LS and DI indicators change if all barriers obstructing access to the Lene-Voigt-Park (LVP) were to be removed.

We do so by assuming a park entry every 5 meters on the network surrounding Lene-Voigt-Park.

As can be seen in figure x\_a, a decrease in LS values occurs on all streets that are adjacent to the LVP.

On most of the remaining streets, we observe an increased LS.

Thus, according to our model, removing the barriers along the edges of the LVP would result in less crowded streets surrounding the park, which may be a desirable effect for city planners.

On the other hand, more people could reach the LVP, increasing the overall amount of people traveling through net network and towards the park.

Accordingly, removing entry barriers could also be a pull factor for an UGS.

Figure x\_b shows the change of the DI values in the first alternative.

When the DI of a building increases, the routes towards the nearest UGS have become more direct, representing a facilitated access to the nearest UGS for the residents of the building.

Overall, we mostly observe minor changes of DI values (delta-DI < 0.1) when providing unlimited access.

We filtered out any delta-DI values that were smaller than +/-0.05 to place emphasis on the more significant changes.

It appears as though the change of DI values is mostly limited to buildings that are either very close to the park or that were not reachable before, but are now inside the threshold network distance of 500 meters.

A few buildings adjacent to the eastern part of the LVP express an increase larger than 10%.

A larger area to the northeast and smaller areas to the east and south of the center of the LVP show a minor increase of DI values.

These buildings may now be able to take a more efficient trajectory towards the LVP.

In the northwest of the map we see a cluster of buildings that seems to have gained access to the LVP via a direct path, which increased their DI values.

Contrary, in the southeast there is a couple of buildings that have gained access as well, but on a less direct path.

For these buildings the DI values decreases, meaning the average trajectories towards the nearest UGS have become less efficient.

Alternative 2 – Densification

In the second alternative we intended to see how the indices behave if the green spaces in the city blocks north of the LVP were to be developed into residential areas.

To apply these changes, we switched the former park entries into building entries and distributed among them population according to the former park’s size.

Figure x-c shows that overall, most of the LS values appear to decrease substantially.

Since the UGS disappeared, the trajectories of the people that traveled to them have disappeared as well, leading to decreased LS.

Only on the paths connecting the newly built residential areas to the LVP and the former *Johannes-cemetery* in the west (marker A) can we see a substantial increase of LS values.

Overall, the reduction of the number of parks in the area seems to have a larger effect on the LS-index than the increase in population due to the newly “constructed” residential buildings.

In Figure X-d we see DI values mostly increasing in the area.

Especially the buildings along the *Heinrichstraße* (marker B) that leads from the center of the LVP north experience a substantial DI increase.

Again, a higher DI means more efficient routes to the nearest parks.

Some areas in the east and north of the map express a decrease of DI values, representing less efficient trajectories towards the nearest UGS.

South and west of the LVP we observe a mixed picture of minor de- and increases.

The five green spaces that we intended to change into residential areas are comparatively small and, thus, “hard to reach”.

Taking them out of the equation seems to leave the surrounding buildings with more efficient trajectories towards the larger parks.

Alternative 3 – Population increase

The third alternative is designed to demonstrate how a population increase would affect the DI and LS indices.

In this alternative, we assumed for each residential building a population increase to the 95th percentile of the population per area according to its urban atlas residential class.

Since we did not change the locations of any green spaces or building entries, the DI index did not change, either.

As we can see in figure x, the delta-LS is positive in the entire area.

In contrast to the other alternatives, changes are now scattered across the entire map, since we also applied the population growth all buildings in the area.

In this alternative, we see a similar pattern as in the basic LS map (see figure x).

LS tends to grow larger, the closer a street is to one of the large parks, specially along those streets, where the population flows from multiple areas combine on their way towards the UGS.

For example, we can observe high LS values between the LVP and the Friedenspark in the south of LVP.

The further away a street is from the larger parks, the lower the increase of the LS.

Close to LVP we now observe a large cluster with high LS values in the west.

If we have a look at the population data that is attached to the residential buildings, we can see that the area in the northwest of the LVP has several buildings with very high population (see appendix for larger version of the image).

Most of these buildings can reach the LVP only via the entry point at the northwest, which causes the high LS values in this area.

Alternative 4 – Ensemble model

In the final alternative, we applied all the changes of the previous three alternatives at once.

The joint effects of removing barriers, developing the green space in the north and a population increase can be seen in figures x a and b.

Figure x a, shows that the change of the LS index is mostly influenced by the population increase and the green space development alternatives.

Due to the population increase, we see a general increase of LS, except for those streets that experience a decrease of LS due to the removed green spaces.

This makes the changes of the LS appear more diffuse than in the other alternatives.

Similar to the population increase alternative, we see a large area with high LS increase in the northwest of the LVP.

In this alternative we can simultaneously observe the effects of the population increase and the unlimited access alternatives.

The nearest entry point for the area with the high population residential buildings in the northwest has been shifted to the northernmost corner of the LVP in contrast to the third alternative.

As we can observe in figure x b, change of DI is restricted to those buildings that either reached one of the now developed green spaces before or that can reach the LVP through one of the new entry points.

In the fourth alternative we can still see an overall increase in DI from removing the small and hard-to-reach green space in the north of the LVP.

Also, the mixed effects from removing the entry barriers to the LVP can still be observed in the south or the northwest of the LVP.

For both, LS and DI, the overall changes in this alternative appear more gradual than e.g. in the densification scenario and are most apparent where we applied intense constructional changes.