Indicators for Assessing the Supply, Demand and Accessibility of Urban Green Spaces in the Context of a Planning Instrument

Linda Hänchen[1], Robert Hecht[1], Denis Reiter[1], Theodor Rieche[1], Elias Pajares[2], Sebastian Seisenberger[3], Johannes Gnädinger[4], Andreas Plail[4], Lisa Bareiss[4]

[1]Leibniz Institute of Ecological Urban and Regional Development, Dresden/Germany · l.haenchen@ioer.de
[2]Plan4Better GmbH, Munich/Germany · elias.pajares@plan4better.de
[3]Technical University of Munich, Munich/Germany · sebastian.seisenberger@tum.de
[4]Prof. Schaller UmweltConsult GmbH, Munich/Germany · j.gnaedinger@psu-schaller.de

Abstract: The design of urban green spaces is an essential part of urban planning and development. GIS-supported tools utilizing data-based indicators help to facilitate this process and identify deficits in the supply of urban green spaces (UGS). This paper introduces a comprehensive set of GIS-based indicators designed to assess the supply, demand, and accessibility of UGS within the framework of the planning instrument Geo Open Accessibility Tool 3.0 (GOAT 3.0). Recognizing the vital role of UGS for public health and the well-being of urban populations, the study focuses on the city of Munich, Germany, as a pilot region. The indicators, categorized into supply, accessibility, and supply-demand ratio, are implemented and tested, showcasing their applicability and relevance. Utilizing a hexagonal grid and routing-based methods, the indicators provide an objective depiction of UGS on various scales. The study contributes to digital landscape planning by bridging the gap between simple indicators and more complex, routing-based approaches. It highlights the need for high-quality data, particularly in relation to UGS and population, and suggests parameterizable accessibility indicators for planning purposes. The indicators presented provide a valuable tool for monitoring, planning, and managing UGS, with potential applicability to cities worldwide, where comparable data is available. The paper concludes by discussing future developments, including the refinement of indicators and the incorporation of additional parameters that describe the quality of UGS.

Keywords: Urban green space, indicators, accessibility, GIS, planning

1 Introduction

Green infrastructure contributes to human well-being (HEILAND et al. 2017). Research from the United Nations reported in 2017 that by 2050 the world's urban populations is expected to nearly double (UN 2017). Urbanization and pressure on land tends to significantly reduce the quantity and quality of remaining urban green spaces. Especially in inner-city areas, there is often a lack of sufficient and easily accessible green spaces (BERTRAM & REHDANZ 2015).

Previous studies attempting to assess the supply of urban green spaces in Germany usually use simple indicators such as the proportion of UGS area per city (BBSR 2018) or per capita (NOHL & ZEKORN-LÖFFLER 1994). Thereby, the accessibility of urban green spaces is mainly considered for larger analysis units such as city boundaries, regions or even entire countries. So far, there have only been a few studies on accessibility and recreation at a small-scale and neighbourhood level (WEBER et al. 2023). Accessibility is typically calculated using a Euclidean distance-based approach (BBSR 2018, GRUNEWALD et al. 2019). This approach ignores the topology of the street network in cities, such as bodies of water or railroads, which make access to green spaces more difficult. As a more realistic approach, studies suggest

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network-based methods to assess accessibility (OLIVER et al. 2007, WANG et al. 2021). Measuring accessibility by different modes of transport to a diverse set of destinations is not trivial, particularly in the case of UGSs that are heterogeneous and typically modeled as polygons. The main challenge lies in defining the accessibility to urban green spaces as unlike other urban amenities which can be represented as points, UGS needs to be represented as polygons. An additional challenge is that not all cities have geospatial data on urban green spaces available at the needed spatial or semantic resolution, requiring extensive data engineering to derive them (LUDWIG et al. 2021, RIECHE & HECHT 2022).

The digital planning instrument, Geo Open Accessibility Tool (GOAT), was developed to provide practitioners with a planning aid that has a low barrier to entry. GOAT is an interactive, web-based planning tool initially developed to carry out accessibility analyses for pedestrians and cyclists (PAJARES & BÜTTNER et al. 2021). The tool is open source and is being developed in a co-creative open development environment. The focus of development is on indicators that measure the supply and demand of services of general interest, the “15-minute city” (MORENO et al. 2021), public transport, and urban green spaces.

As part of GOAT's co-creative research and development, this paper therefore presents the assessment of UGS indicators, focusing on both already widely used indicators and more complex network-based indicators. One key objective is finding indicators that realistically reflect human behaviour while remaining simple to interpret. Special emphasis is on urban green spaces with a recreational function. The city of Munich in Germany will serve as a pilot region to demonstrate the indicators.

2 Method

This section describes indicator development process and then explains the prototype implementation.

2.1 Indicator Concept

UGS indicators are divided into three groups based on BBSR (2018): supply (quantity of UGSs), accessibility (travel costs like travel time or travel distance to the UGSs), and supply-demand-ratio. The first step involved researching indicators already utilized in urban planning. The literature research was mainly carried out using Google Scholar and relevant keywords. The result was a list of the most frequently used indicators. This list was expanded to include new, experimental indicators which should better account for the requirements of planners. This included a routing-based approach for the accessibility of UGS and approaches that map the relationship between supply and demand (supply-demand-ratio). This process resulted in a total of 10 indicators.

The research revealed that a large number of studies propose accessibility indicators that use a radius approach instead of a routing-based approach for the accessibility of UGS (BBSR 2018, FINA 2021, GRUNEWALD et al. 2019). This also applies to indicators that measure the supply. The indicators on supply-demand-ratio make up the largest share of the studies examined. The calculation is based on the division of green areas by the number of inhabitants as described in: (GRUNEWALD et al. 2019, IÖR 2023, MEINEL et al. 2022). To further develop this indicator the Two-Step-Floating-Catchment-Area-Method (2SFCA) (JÖRG et al. 2019, LUO and WANG 2003, H. ZHANG et al. 2013) was adapted and applied. This method offers the possibility to express the relation between supply and demand. It is a recognized method in the supply of services of general interest (SEISENBERGER et al. 2023). WANG et al. (2021) showed that combined network- and entrance-based methods provide a more realistic park accessibility measure. We therefore used a routing service method (see section 2.2) utilizing pre-processed entrance points of the UGSs.

Following the technical implementation, processing, and visualization of the indicators, the results were presented to planners for feedback. Five of the indicators were discussed with six experts in an online workshop in February of 2023 (RIECHE et al. 2023). Additionally, during an online meeting with two planners on July 2023, qualitative feedback was collected on the 10 indicators. The feedback indicated a preference for retaining simple indicators while also expressing an interest in incorporating routing-based indicators for more realistic analyses. There was a specific request for a comparison between established and new indicators. The literature research and the results of the discussion with practice partners suggest that the indicators in Table 1 have a high utility.

Table 1: Suggested indicators for the planning instrument GOAT (3.0)

Indicator Group	Indicator Description	Unit
Supply	Total area of UGSs per spatial reference unit (BBSR 2018)	%
Accessibility	Shortest travel distance or fastest travel time to the closest UGS entrance from centroid	m or min
Accessibility	Accessibility of at least one UGS in a defined travel distance or travel time from centroid	yes/no
Supply-demand-ratio	Total area of UGS per inhabitant within spatial reference unit (IÖR 2023)	$\frac{m^2}{inhabitant}$
Supply-demand-ratio	Average of accessible UGS area per inhabitant based on 2SFCA-method and defined travel distance or travel time. First, for each UGS the supply-demand-ratio is calculated within specific geographic catchment zones. Second, starting from each population location (buildings), all accessible supply-demand-ratios are aggregated. Additionally, the value is averaged within higher-level spatial reference units.	$\frac{m^2}{inhabitant}$

2.2 Implementation

The Esri GIS software ArcGIS Pro including the Python packages "ArcPy" and "Geopandas" were used for the prototypical implementation of the indicators and their visualization. The open-source routing service "openrouteservice" (ORS) from the Heidelberg Institute for Geoinformation Technology was used for the routing-based accessibility analysis (HEIGIT 2023). The data were collected within the pilot region, taking into account a buffer zone of 6km around the study area. This buffer zone was selected to provide maximum coverage for cycling at the highest route speed of 18 km/h according to the ORS. Even though the concept of the "15-minute city" was the basis, a 20-minute distance was chosen, which corresponds to the buffer of 6km. Publicly accessible UGSs designated for recreational purposes, regardless of the presence of vegetation, are referred to as recreation areas in this paper. The accessibility of UGSs for routing and isochrones was implemented in this work by considering the UGS entrance points. To create these points, the UGSs were buffered inwards by 2m to extract the in between line segments of the street network. Entrance points were only generated if the line segments have an intersection angle greater than 30°. In case there is no network segment intersecting the UGS, the centroid of the UGS polygon is used. The ORS processes OpenStreetMap (OSM) data to calculate routes between two locations or isochrones from a location. The ORS allows switching the mode of transportation (e. g. walking, cycling). Routing rules (e. g. speed) can be customized for the different routing operations. For this paper the mode was set to six minutes of walking or the equivalent of an average speed of 5km/h (500m walking distance). The spatial reference units are only a representation and not a delimitation area for the analysis. The prototype implementation forms the basis for a future migration to GOAT, which is based on other technologies.

3 Pilot Region and Data Used

The city of Munich in Germany was selected to implement and test the indicators. The following data was obtained for this purpose.

1) UGS: The UGSs polygons are derived from the Digital Landscape Model (ATKIS Basic DLM) as well as OpenStreetMap data. In the process, six semantic classes are taken into account, which are shown in Table 2. With OSM, it was possible to add smaller polygons, particularly for sport and leisure, that are not mapped in ATKIS. The geometries were created by fusion and without overlaps (Figure 1).
2) Spatial reference units: city districts and a hexagonal grid (UBER H3- resolution 9; average edge length ~200m). The city district geometries were provided by the City of Munich (MÜNCHEN 2018).
3) Population data: A dataset from the German Federal Office of Cartography and Geodesy in the form of point coordinates (buildings) and an attribute for the number of inhabitants was used.
4) Routing network: The ORS processes data using the OSM street network.

Table 2: Selected urban green spaces from ATKIS Basic DLM (ADV 2018) and OSM (2012)

	Parks	Sport & Leisure	Cemetery	Urban Gardening	Forestry	Other
ATKIS	**41008** • park • green area	**41008** • golf course **42009** • pedestrian zone • square	**41009** • cemetery	**41008** • allotment	**32002** • forest	**43003** • shrubland **43007** • unvegetat-ed area • riparian area • succession area
OSM	**Leisure** • park	**Leisure** • playground **sport** • soccer • skateboard • volleyball • basketball		**Leisure** • garden & gaden: type= community		

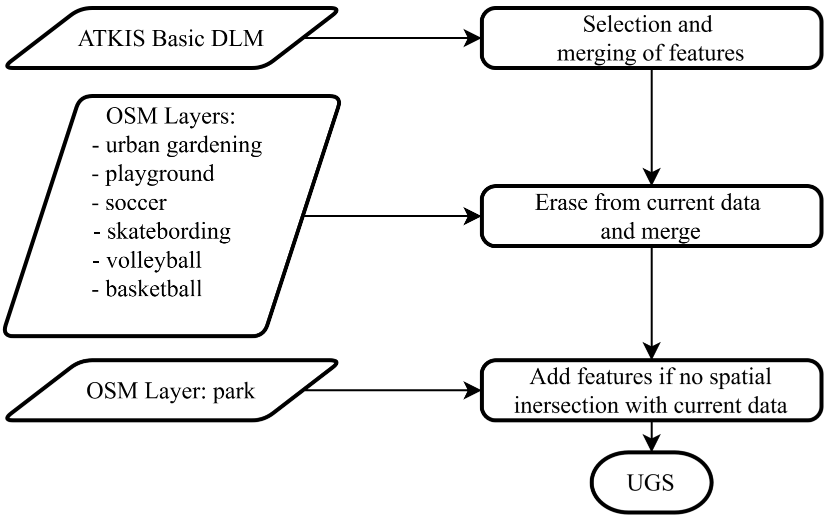

Fig. 1: Data fusion of urban green space data

4 Results

In the following section, the results of the prototypical indicator calculations for Munich are presented, specifically the supply, accessibility and the supply-demand-ratio. The supply indicator of UGS, defined as percentarea, gives an overview of the general supply-side distribution of UGS in the city (Figure 2). The representation based on the hexagonal grid (H3 Uber grid) makes small-scale patterns more visible. The larger reference units, city districts (on the right in Figure 2), makes the extremes in the districts disappear and the differences in values become smaller.

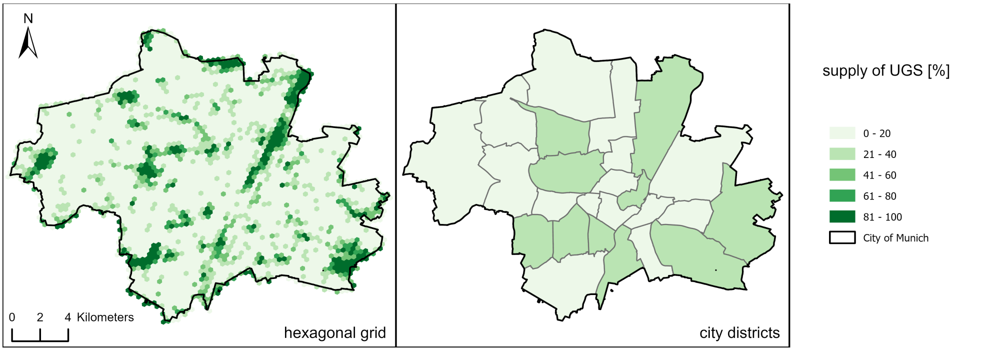

Fig. 2: Supply indicator: total area of UGS per spatial reference unit

Figure 3 shows the accessibility indicator, which is measured by the shortest travel distance (left) or the fastest travel time (right) to the nearest UGS. This is particularly useful when planning new residential buildings or even workspaces. The difference between these two is caused by background processes of the ORS variable walking speeds for different slopes. It highlights the importance of differentiating between travel time and travel distance as the former allows for sensitivity to the mobility characteristics of the population.

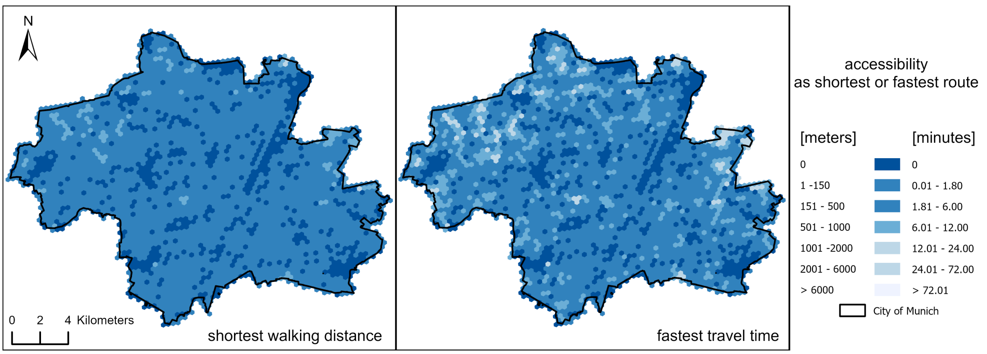

Fig. 3: Accessibility indicator: shortest travel distance or fastest travel time to the closest UGS entrance from centroid

The accessibility indicator in Figure 4 is a simple measure that is easy to communicate. It is useful for visualizing thresholds and quickly identifying where the accessibility of UGSs has potential to be improved.

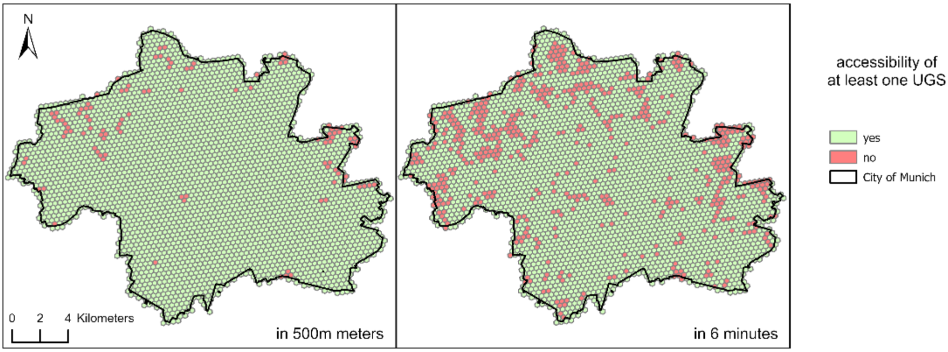

Fig. 4: Accessibility indicator: accessibility of at least one UGS in a defined travel distance or travel time from centroid

Indicators measuring the supply-demand ratio are most effective for highlighting deficits. The values cannot be calculated for all hexagons as some have no demand due to a lack of inhabitants. Nonetheless, for the comparability of previous calculations, it is important to integrate these as well. The total area of UGS per inhabitant within a spatial reference unit (Figure 5) is an indicator that is easy to interpret and communicate. However, given that the accessibility of UGS plays an increasingly important role in planning, the indicator based on the 2SFCA method (Figure 6) is considered an essential development because the UGSs are divided by all inhabitants who have access. The difference between the two indicators is most evident on the hexagonal grid level. The supply-demand-ratio within 6 minutes reach is generally higher.

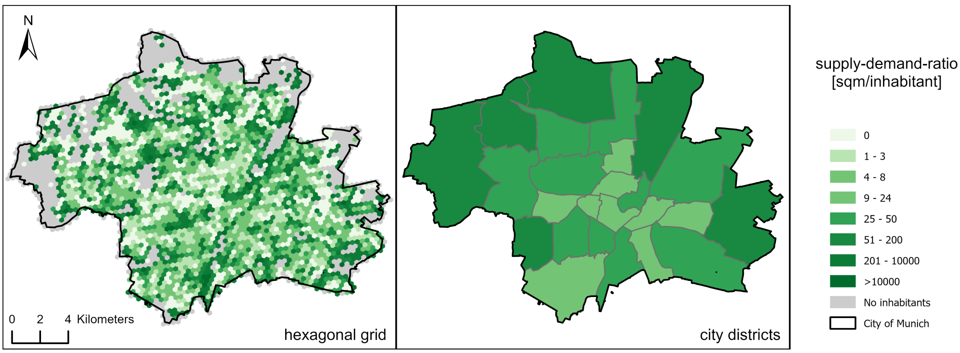

Fig. 5: Indicator on supply-demand-ratio: total area of UGS per inhabitant within spatial reference unit

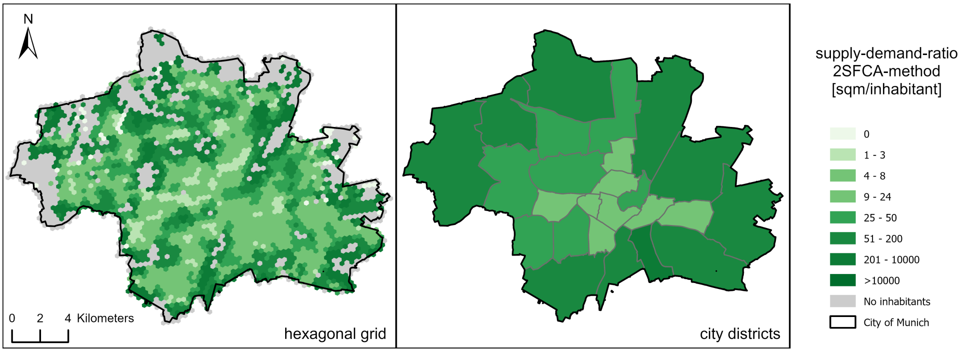

Fig. 6: Indicator on supply-demand-ratio: average of accessible UGS area per inhabitant based on 2SFCA-method and defined travel distance or travel time

The advantage of a fine hexagonal grid is that higher detail results can reveal deficits that would be hidden at the scale of administrative units. The five proposed indicators cover various aspects relevant to planning and managing UGS. The simple indicators are easy to understand and communicate, making them well-suited for applications such as monitoring over time. Furthermore, the results show that the indicators that leverage a routing-based approach provide a more realistic representation of accessibility at the micro level.

5 Discussion

The basic prerequisite for processing the proposed indicators is the availability of data of sufficient quality (completeness, positional accuracy, up-to-dateness), particularly with regard to the UGSs and population. In general, local authorities maintain this data within their jurisdictions. Difficulties can arise when looking at a supra-regional perspective or when comparing several cities. A standardized database could be useful for storing all relevant data in a suitable structure. As a planning tool, the selection of UGSs should be customisable depending on the use case. As an alternative to population data, a small-scale estimation approach (HECHT et al. 2018, PAJARES and MUÑOZ NIETO et al. 2021) can be used. Regarding the accessibility indicators, it is also important to know the OSM data quality. In some places, the positioning accuracy in large cities can be better than with other providers. Furthermore, with respect to routing, it can be assumed that the data quality of the road network is almost complete (BARRINGTON-LEIGH & MILLARD-BALL 2017). The efficiency of accessibility analyses through a routing service is constrained by its processing time. This limitation becomes particularly evident when computing all possible route combinations within a city and linking the centroid of each spatial reference unit to the entrance points of UGSs. Another challenge is the interpretability of indicators. Simple indicators are easier to communicate, while more complex and advanced indicators are more difficult to understand but aim to be more theoretically sound.

The indicators presented in this paper have been selected to demonstrate the potential of new approaches for the development of neighbourhoods and urban areas. Further research that incorporates feedback from mobility planners, urban planners or landscape architects for specific use cases should be carried out in the future. It is also worth investigating whether planners and local residents can utilize these new indicators to compare perceived accessibility with measured accessibility (J. ZHANG & TAN 2019).

6 Conclusion and Outlook

A set of GIS-based indicators is presented which can be processed using commonly available geodata. Visualizing the indicators via maps has shown that a combination of a hexagonal grid and a routing-based approach enables a realistic image to be depicted on a small scale. New indicators can potentially provide benefits for planning decisions, since they offer deeper insights into real world problems than conventional indicators. Results suggest that composite indicators that combine individual indicators into a single score should also be tested in the future. Likewise, a fourth indicator group tackling aspects of "attractiveness" should be looked into as well (GUGULICA & BURGHARDT 2023). For example, single indicators of beauty, silence, cleanness or safety.

In general, the indicators presented are also applicable in other regions and contexts if comparable data and comparable definitions of UGSs are used as a basis. The parameterizable accessibility indicators offer a high degree of adaptability to the planning requirements of UGSs.

The proposed approach could be refined by taking into account the qualities of the UGSs, such as their size, their amenities or specific ecosystem services (KRELLENBERG et al. 2021). In this way, a user group-specific assessment could be carried out with the indicators, for example to assess the provision of green spaces for vulnerable population groups (STANLEY et al. 2022). The indicator processing could be preceded by a filter function in order to take planning-specific requirements into account in the analysis. Finally, the indicators within the planning tool should also be applicable to small towns and rural areas. The user should therefore be able to select suitable spatial reference areas (e. g. administrative units, city blocks, hexagonal grids) for the indicator calculation and visualization.

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