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Stefan Fina
University of Applied Sciences Augsburg

Christian Gerten
ILS - Research Institute of Regional and Urban Development, Dortmund

Brian Pondi
ILS - Research Institute of Regional and Urban Development, Dortmund

See next page for additional authors

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Authors
Stefan Fina, Christian Gerten, Brian Pondi, Lorraine D'Arcy, Niamh O' Reilly, David Sousa Vale, Mauro Pereira, and Samuele Zilio

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OS-WALK-EU: An open-source tool to assess health-promoting residential walkability of European city structures

Stefan Fina [a,*], Christian Gerten [b], Brian Pondi [b], Lorraine D'Arcy [c], Niamh O'Reilly [c], David Sousa Vale [d], Mauro Pereira [d], Samuele Zilio [e]

[a] *University of Applied Sciences Augsburg, An der Hochschule 1, 86161 Augsburg, Germany*
[b] *ILS - Research Institute of Regional and Urban Development, Brüderweg 22-24, 44135, Dortmund, Germany*
[c] *Technological University Dublin, Bolton Street, Dublin 1, D01 K822, Ireland*
[d] *University of Lisbon, Lisbon School of Architecture, CIAUD, Rua Sá Nogueira, Pólo Universitário, Alto da Ajuda, 1349-063, Lisboa, Portugal*
[e] *Institute for Renewable Energy, Eurac Research, Drususallee 1, Viale Druso 1, 39100, Bolzano/Bozen, Italy*

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ABSTRACT

Introduction: This paper introduces OS-WALK-EU, a new open-source walkability assessment tool developed specifically for urban neighbourhoods and using open-source spatial data. A free and open-source tool, OS-WALK-EU is accessible to the general public. It uses open data available worldwide and free online services to compute accessibility, while at the same time allowing users to integrate local datasets if available. Based on a review of existing measurement concepts, the paper adopts dimensions of walkability that were tested in European city environments and explains their conceptualization for software development. We invite the research community to collaboratively test, adopt and use the tool as part of the increasing need to monitor walkability as part of health-promoting urban development.
Methods: Tool development is based on spatial analysis methods to compute indicators for five dimensions of walkability: residential density, weighted proximities to amenities, pedestrian radius of activity, share of green and blue infrastructure, and slope. Sample uses in the cities of Dublin, Düsseldorf and Lisbon test the validity of input data and results, including scenarios for target groups like older people.
Results: Overall, application of the tool in Dublin, Düsseldorf and Lisbon shows conclusive results that conform to local knowledge. Shortcomings can be attributed to deficiencies in open source input data. Local administrative data, if available, is suitable to improve results.
Conclusions: OS-WALK-EU is the first software tool that allows free and open walkability assessments with pedestrian routing capacities for 'proximity to facilities' calculations. Large scale implementation for 33 German city regions in an online application shows the value of comparative assessments of walkable neighbourhoods between urban and suburban neighbourhoods. Such assessments are important to monitor progress in a mobility transition towards improved walkability and public health.

* Corresponding author.
E-mail address: stefan.fina@hs-augsburg.de (S. Fina).

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Table 1

Overview of existing measurement approaches with selected examples and their strengths and weaknesses.

Type	Description	Strengths	Weaknesses	Examples
Audit-based walkability surveys	Questionnaire-based data collection on qualitative criteria (e.g. attractiveness, safety, comfort) along predefined routes (Clifton et al., 2007; Millington et al., 2009; Bucksch and Schneider, 2014; Lee and Talen, 2014; Department of Transport, 2017)	• Designed to inform local authorities about deficiencies in pedestrian infrastructure (Bucksch et al., 2012) • Complementary qualitative information for quantitative measurement concepts	• Requires trained personnel to capture data along predefined routes in street audits • Costly and time-consuming • Not readily available to evaluate the walkability of several cities at once	• Walkability audit tool capturing the quality of routes, considering their comfort, safety, directness and coherence for pedestrians (Department of Transport, 2017) • Evaluation of walkability following seven dimensions - the 7Cs (Moura et al., 2017) based on work previously developed by the London Planning Advisory Committee (Gardner et al., 1996). Evaluation of the walkability of the pedestrian network of an urban district in terms of Connectivity, Convenience, Comfort, Conviviality and Conspicuousness (the original 5Cs) as well as its Coexistence and Commitment
Multi-criteria indices on urban structure	Approaches that follow a comprehensive framework and measure walkability as a composite index of several built environment variables (Frank et al., 2010; Dobesova and Krivka, 2012; Buck et al., 2011; Koohsari et al., 2016)	• Assessment based on secondary data sources without the need to capture additional data in the field • Quite flexible in the operationalisation of key indicators (e.g. land use composition or land use mix, street connectivity, population or residential density	• The design aspect considered important by other researchers as a complementary aspect is frequently missing due to difficulties in finding adequate source data (e.g. visibility and safety, but also green infrastructure and other attractions) (Frank et al., 2006, 2010) • Sourcing input data requires access to datasets frequently not available to the research community (e.g. retail floor space) • Resulting assessments do not yield high correlations with actual travel behaviour (Reyer et al., 2014; Shashank and Schuurman, 2019)	• A representative example is the IPEN walkability index (known as WAI or WI). Its wide use is closely related to the publication of a free and easy-to-use software extension for the popular ArcGIS software package (Dobesova and Krivka, 2012). It identifies street connectivity, land use mix, residential density and the amount of retail floor space as the dimensions to measure.
Proximity of amenities	Concepts that conceive walkability mainly as the proximity of facilities for pedestrians. Proximity is modelled as a function of pedestrian accessibility of specific representative amenities (Kim et al., 2019)	• Straightforward due to a focus on the proximity of selected destinations, with all other dimensions not measured at all • The main idea is that pedestrian-friendly infrastructure attracts shops and businesses that people are motivated to walk to, and that high levels of pedestrian movements follow. These interrelationships mean that it is sufficient to simply measure the presence and pedestrian accessibility of shops and amenities to get an accurate picture of the supporting infrastructure from a user perspective. • Can either give one score per street address or city-wide walkability assessments (Kim et al., 2019)	• Requires a refined weighting methodology based on routing calculations and distance decay functions • Design aspect is missing • The algorithm can be biased towards an appreciation of urban areas with extensive shopping facilities (e.g. downtown and suburban business centres), but not necessarily where people live and access neighbourhood resources on foot.	• An example that stands for a *proximity to facilities* assessment method is the Walk Score® methodology with a copyright from a company of the same name based in Seattle, WA, United States (Walk Score®, n.d.). • The selection of amenities considered includes grocery stores and supermarkets, restaurants and bars, shopping facilities, schools, bakeries and cafés, entertainment facilities like cinemas and theatres, banks, recreational facilities, parks and bookstores. • Each amenity contributes to the final score with a weighting mechanism based on walking distance and number of choices.

1. Introduction

The idea for this paper arose from the inconclusive results produced by existing tools for monitoring the pedestrian friendliness of urban neighbourhoods in European cities. We found that our own perceptions of influencing factors were not fully covered by existing monitoring concepts, most of which were specifically designed for cities in the United States, Canada, Australia and New Zealand and did not capture the complexity and diversity typical of European city structures (Reyer et al., 2014).

An assessment of the tools currently available concluded that indicator-based measurement concepts needed to be enhanced and made more accessible to city planners. Urban planning initiatives that promote walking for health reasons benefit from measurements focusing on residential walkability at neighbourhood level, i.e. the level at which most assessments of the pedestrian friendliness of neighbourhood resources can inform policymakers about potential improvements. The overall aim of this study is therefore to develop a prototype walkability tool that is initially validated for applications in European cities, addressing the shortcomings of existing tools and making use of innovative open and free software and data. The software is designed to be transferable for application in other world regions.

This paper presents an overview of the resultant tool, as well as case studies from three European cities (Dublin, Lisbon and Düsseldorf) to test its practical application for developing health-promoting strategies in urban settings. A brief review of the literature introduces the concept of walkability as a theoretical construct for measuring the pedestrian friendliness of urban neighbourhoods. Based on this knowledge, we enhance concepts for measurement tools with emerging technologies in the area of open-source and open-data options. The paper explains how researchers can access the tool in a web-based open-software versioning repository for application and adaptation. Case study applications in Dublin, Lisbon and Düsseldorf helped evaluate the results for practical application.

2. Neighbourhood walkability: accessibility vs. proximity

The centres of European cities are generally more compact than in the United States or Australia and New Zealand, countries from where much of the influential research on walkability assessments originates. In European metropolitan areas, car-oriented peripheries surround historically grown centres in many different constellations, where the cores have a higher level of mixed land uses and where historically grown small towns have fused into suburban neighbourhoods, forming subcentres (van Holle et al., 2012). In their systematic review of European studies, van Holle et al. have shown that the physical activity of European city residents correlates strongly with pedestrian and cycling possibilities, the accessibility of amenities and road safety. They also report inconsistent findings, stressing that the design of the built environment does not necessarily increase activity. In this context, other researchers like Nelson et al. (2008) and Rhodes et al., 2007 hypothesize that personal factors moderate the influence of infrastructure and accessibility in a significant way. From this perspective, walking as a form of preferred mobility behaviour is a result of possibilities and individual intrinsic motivation (Baumgart et al., 2018).

The 1986 Ottawa Charta stresses that physical activity is clearly related to behavioural settings to which residents are exposed on a daily basis (WHO, 1986). The United Nations Human Settlements Programme's (UN-Habitat) *New Urban Agenda* promotes healthy living and wellbeing, calling for the creation of inclusive, safe, resilient and sustainable cities (Giles-Corti et al., 2015; United Nations Habitat, 2016). In Australia, Higgs et al. (2019) include walkability as an objective giving effect to the New Urban Agenda, alongside employment, food, housing, public open space, social infrastructure and transport. Changes to city layouts are needed at a regional and local level. Regional transport planning should prioritize public transport options for day-to-day trips, especially for commuters. Local urban planning, however, should provide walking and cycling options that make common destinations accessible on foot or by bike, safely and securely. In addition, design aspects need to include streetscapes as part of liveable communities that support socially active lifestyles with a variety of transport options, at the same time promoting a sense of place and community cohesion amongst residents (Giles-Corti et al., 2015).

More recently, city walkability has received renewed attention in the light of climate adaptation strategies, as exemplified by the concept of the "15-min city" (FMC). FMC stands for the (pedestrian-friendly) accessibility of facilities either on foot or by bike, thereby reducing the need to travel by CO_2-emitting means of transport and leading to carbon neutrality. In a critical evaluation of this "new urban planning utopia", a study conducted by Pozoukidou and Chatziyiannaki finds links between this concept and other neighbourhood-centred approaches for the promotion of urban designs to "reconnect people to local areas and localize city life". Policy analysis in FMC-promoting cities (Portland, Melbourne and Paris) reveals that the main change in transport planning is the new emphasis of ***proximity to resources*** instead of ***accessibility to resources*** (Pozoukidou and Chatziyiannaki, 2021). In other words, *accessibility by proximity*, ensured by an efficient land use pattern, is seen as a better option for health-promoting lifestyles than *accessibility by mobility*, ensured by an efficient transport system.

Following this line of thinking, concepts to measure the walkability of urban neighbourhoods contribute substantially to the proximity aspect of health-promoting neighbourhoods and facilitate FMC analyses. Aspects of infrastructure quality (e.g. walking conditions) are left to the domain of local area development planning that requires additional surveying to assess the potential outcomes of interventions. Cyclists certainly also benefit from the proximity of destinations but can easily also access destinations beyond the neighbourhood level. For this reason, the paper focuses on walking as the form of mobility to evaluate quantitatively.

3. Advancing existing measurement approaches

A review of selected existing concepts reveals what can to be done to enhance walkability measuring (see Table 1). Additional evaluations can be found in meta-studies on the topic. van Holle et al., 2012 for example reported on the findings of over 70 papers on

Table 2
Concept to measure residential walkability in the EU along the five D's.

Dimension	Indicators and methods	Importance	Open Data /*Implementation*
Density	Residential density	Somewhat important, associated and subordinate to 'proximity to amenities'	Global Human Settlement Layer
Diversity	Proximity to (diverse) amenities	Very important, associated with population density	OpenStreetMap (OSM)
Design	Pedestrian radius of activity, share of green and blue infrastructure	Important but limited to infrastructure design (radius of activity for pedestrians, share of green and blue infrastructure)	OSM
Destination accessibility	*Distance decay functions; consideration of slope*	*Important but covered by a refined selection and weighting of amenities in the diversity dimension*	*Covered by 'diversity'*
Distance to public transport	*none*	*Not covered since we focus on neighbourhood-oriented residential walkability*	*Not needed, might be implemented in the future*

the relationship between the physical environment and health before 2012, with many more published since then.

On the one hand, the growing body of literature bears witness to the great interest in this emerging topic. On the other, there are many critical remarks in the literature calling for additional work to be done on refining measurement concepts. The main criticism is that walkability assessments lack validation procedures in terms of the actual share of pedestrian trips they produce (Shashank and Schuurman, 2019). Empirical evidence on this causality is rare and debatable (Stafford and Baldwin, 2017). As a consequence, practical guides on the design of walkable neighbourhoods might be ill-informed about the specific needs of local residents. Generic assumptions on pedestrian-friendly infrastructures dominate but do not automatically produce more pedestrian trips and health-promoting physical activity (Bucksch and Schneider, 2014).

Based on this finding, it is worthwhile looking at the history of walkability measurement concepts. One influential impetus came from critical debates on the impact of urban sprawl on travel demand. Leading scholars in this debate recognized the problems that post-war urban developments had created, with an ever-increasing number of people commuting from suburban residential areas to downtown business locations by car (Soule, 2006). In the 1990s and early 2000s, new concepts of urban design were postulated to mitigate this car dependency, backed by the emergence of sustainable development initiatives. One of the most influential concepts was the so-called three Ds - density, diversity and design (Cervero and Kockelman, 1997), later enhanced by destination accessibility and distance to public transport. The resultant five Ds have a combined impact on a neighbourhood's walkability (Ewing and Cervero, 2010).

The five Ds have influenced the development of methods to measure walkability in a variety of ways. In line with the findings of Vale et al. (2016) and Dunn et al., (2018), such methods can be classified into the three groups shown in Table 1. The first (audit-based walkability surveys) requires specific data to be collected in the field and is therefore much more time-consuming and resource-demanding. By contrast, the latter two work with secondary data sources, i.e. they use existing datasets collected for other purposes.

Alongside the scientific conceptualization of walkability, the measurement concepts shown in Table 1 are also closely associated with the technical possibilities and data options available at the time they were conceived. *Audit-based walkability surveys* are easy to conduct but not feasible for larger areas - not to speak of comparative analyses of many cities. *Multi-criteria indices on urban structures* can be calculated using basic GIS processing capacities that emerged in the early 1990s in the research community. *Proximity of amenities* requires advanced network routing capacities with dedicated software modules that only became accessible for wider use from 2000 onwards (Fischer, 2006). For both of the latter, data sourcing is difficult and time-consuming.

Based on this review, our enhancement aims to combine the strengths of the three approaches with a focus on residential walkability for comparable area-wide coverage for all cities in the European Union (EU). Due to its importance for walkability research, we structure our concept in Table 2 along the lines of the '3 + 2 Ds' of walkability, showing which indicators have been taken over and rearranged ('importance') from previous measurement approaches. The selection of indicators results from experiments with several candidates sourced from the literature and our own (preliminary) assessments in terms of explanatory power as well as free and open-data options.

As described above the 3 D's were later complemented by the 'destination accessibility' and 'distance to public transport' dimensions ('3 + 2 D's'). They are set in italics in the table to highlight that we do not cover them separately. This is justified as follows:

The **density** dimension is important since the provision of amenities as destinations to walk to follows demand, in turn moderated by population density. At the same time, density stimulates higher levels of social activity for local residents.

The implementation of the *'proximity of amenities'* indicator adopted from the Walk Score described in Table 1 integrates the **diversity** and **destination accessibility** dimensions into one new dimension. We decided to keep the term 'diversity' and remove the destination accessibility. This approach replaces previously used proxies for destination accessibility like the land-use mix, the aggregated business floor space, or the number of jobs in an area with a set of all relevant amenities on the ground, sourced from OSM and complemented by authoritative data. The categories we use (see also next section) have a varying importance for local residents. This importance is modelled with a refined weighting and distance decay function by category. In addition to the decreasing weight of amenities further away, it uses penalties to reduce the weight for hilly terrain and high slopes above a user-specified threshold value. In theory, this approach to calculate and weight distances to actual destinations is more accurate and conclusive than the use of proxy data assumed to be associated with trip attractors (e.g. land-use mix, business floor space, number of jobs). The case study on Dublin below assesses the performance of this indicator in a real-world setting in more detail.

Aspects of the **design** dimension are covered with the share of green (i.e. parks and recreational facilities) and blue (i.e. water

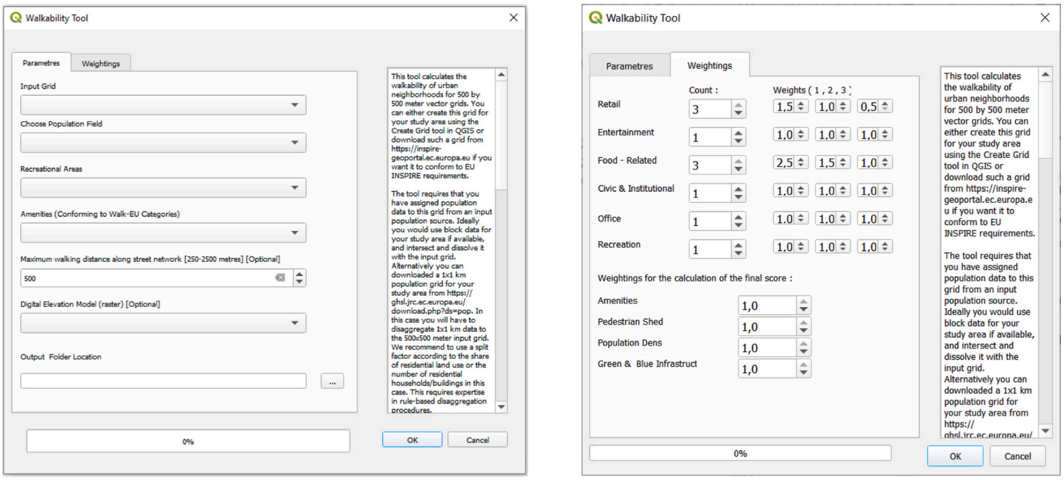

Fig. 1. OS-WALK-EU: An Open-Source Walkability Assessment Tool in QGIS. User interface to select input layers (left) and weightings for amenities (right).

Table 3
Overview of default inputs for OS-WALK-EU.

Data	Spatial accuracy and transformation	Source
Categorized amenities	Discrete points and polygon access points	OSM
Green and blue (water) areas	Polygons apportioned to grid cells	OSM
Digital elevation model	25-m resolution	Copernicus land cover service

surfaces) infrastructure as proxies for landscape design and recreational attractions that invite pedestrian trips. The existence and accessibility of green areas are relevant to creating a walkable environment, as they contribute to better living conditions and a healthy environment (Picavet et al., 2016; Ward Thompson et al., 2016). Urban green areas have also been found to improve social interaction and integration (Picavet et al., 2016; Ward Thompson et al., 2016). We also use the pedestrian radius of activity as a proxy to inform about the directness of routes in the pedestrian network. For a given pedestrian distance (default: 2000 m) this indicator compares the area reachable on foot with the area of a perfect circle. If the origin of both areas is the same, large deviations stand for a network that forces people to walk many detours to reach destinations along the network and vice versa. Please refer to Vale (2015) for more details about the methodology.

In the case of **distance to public transport,** we consciously decided not to include this dimension. Public transport stops show how people can extend their radius of activity to other areas, their inclusion would support an assessment of destination accessibility. In contrast, our approach aims to assess residential walkability at the neighbourhood level to assess the proximity of destinations in line with the FCM philosophy. We show in the case study on Dusseldorf how the inclusion of public transport stops potentially deflects from this perspective. At the same time, users are free to include public transport stops in their own customization of the software and its required data inputs. The software is designed to support such modifications.

Based on these considerations, we moved on to implement the concept in a new tool based on free and open data as well as on open-source software. Detailed infromation about installation, data and usage is available in an online documentation (‘wiki’). It is integrated as a submenu in the OS-WALK-EU software repository at https://gitlab.com/ils-research/os-walk-eu/and contains a list of amenities and their corresponding classifications from OSM tags that the author group of this paper recommends for usage.

4. OS-WALK-EU: A new tool to measure walkability in QGIS

We named the new tool *OS-WALK-EU* (pronounced ‘OS walk you’): an **O**pen-**S**ource **Walk**ability tool for **E**uropean **U**nion member states. This name refers to the tool software, the resulting index is the *OS-WALK-EU index*. The tool is available as a software extension (“plugin”) for the popular QGIS open-source desktop software.[1] OS-WALK-EU is therefore integrated into a fully functional GIS software package allowing users to load and prepare input data, run the tool (in different scenarios if required) and inspect the results in the form of maps and tabular output. Fig. 1 shows the user interface where users can select inputs and parameter settings (e.g. weightings, choice of amenities) to define scenarios.

[1] https://www.qgis.org/de/site/, last accessed 10 February 2022.

The tool works with a standardized grid of 500 x 500-m cells conforming to the European INSPIRE Grid[2] as the basic assessment geography. Grids have the advantage that they are not subject to changes in the delineation of administrative units as often occurs in local government settings. On the downside, all required inputs have to be transformed into the grid. In the case of open and free data this would also have been the case for any other geometry, meaning that rule-based transformation algorithms are needed anyway. Another consideration is that routing algorithms to calculate distances between residences and amenities as well as a pedestrian's radius of activities ("isochrones") on a pedestrian network require points as inputs. Such points are easily extracted from grids when taking the geometric central point ("centroid") of a grid cell. Although these grid cells and points are the geometries for input and also the default output, results can still be transformed into administrative units using standard GIS geoprocessing tools or visualization techniques like heat-mapping. Table 3 describes the datasets and procedures used to populate the grid cells for the conceptual considerations explained in the previous section.

Data on amenities and facilities was sourced from OSM data repositories. The online documentation of the tool shows an example of a possible categorization of OSM categories for points of interest (POIs) to six OS-WALK-EU amenity groups (retail, entertainment, food-related, civic and institutional, office, sports and recreation) in a sample spreadsheet. This categorization can be used as a default or modified for special purposes as showcased in the case studies below. The default was defined by the author group based on a literature research and experience with other walkability assessment tools where amenities are categorized as attractors of pedestrian trips with varying influence (e.g. Walkscore). The importance of an amenity category can be higher if it is for example a daily errand (e.g. grocery shops) as compared to generally less frequented amenities (e.g. medical services). It can also vary along the pedestrian radius of activity where amenities further away experience a reduced importance with increasing distance. The default threshold defined in the tool is 2000 m. This value stands for a maximum trip distance along which the attractivity of destinations decreases. The case study of Dusseldorf explains the construction of this weighting logic in more detail.

The spatial and thematic completeness of the POIs in OSM differs across countries and rural and urban areas (see the detailed assessment in the section on Dublin below). Green and blue infrastructures can also be sourced from OSM, while slopes can be derived from Copernicus digital elevation models with a 25-m resolution that is available for free (and can be replaced with higher resolution versions if available). The implementation penalises slopes in the calculation of accessibilities, in line with Waldo Tobler's 'hiking function' (Daniel and Burns, 2018). One major advance is the emergence of free OSM data for online pedestrian routing. For the development of OS-WALK-EU the *OpenRouteService*[3] software developed at the University of Heidelberg was installed on a dedicated server at ILS. This software comes with a QGIS plugin and an application progammers interface (API) to allow online routing along the pedestrian street network. OS-WALK-EU uses the OpenRouteService to calculate the network distances between cell centroids and the location of nearby amenities in the travel mode "by foot". This mode uses street links declared as walkable by OSM contributing members.[4] The installation at ILS allows online pedestrian routing in the three citywide case study areas as well as for the whole of Germany. It is extensible for any other region if the necessary hardware to support this can be provided.

The limitation we cannot overcome with the aim to potentially use OS-WALK-EU in all European cities is the lack of information on design aspects of pedestrian infrastructure as perceived by local residents and social groups (e.g. safety and comfort aspects). Required to fully cover the five Ds, this information is frequently available in data repositories for city administrations, but not freely available in a standardized way for everyone. In addition, costly audit-based walkability surveys are necessary to qualify such data for the purpose of walkability assessments. We compromise by allowing users to overwrite walkability scores generated by our tool with values derived from audit surveys if available. This is done by selecting the cells of interest and editing the corresponding attributes in the resulting tables of the OS-WALK-EU grid layer in QGIS, where the values for each assessment dimension are available as outputs in the attribute table. In order for this process to work, users will have to familiarize themselves with the weighting logic and value ranges in the script. Based on this knowledge, the same operations can be performed using the QGIS user interface. The software provides a range of functionalities to edit the outputs in the required fashion. Sample data is provided in the online repository to learn about format requirements.

Another consideration is that walkability is not the same for everyone. Age, health, lifestyle or cultural preferences moderate the choice of routes and the distances people are willing to walk. We therefore allow users to define the importance of amenities that pedestrians walk to as trip destinations, in addition to default settings we specify. Weightings can be applied to certain types of amenities according to preferences (e.g. schools for children, medical services for older people). Based on empirical data, so-called distance decay or impedance functions can be used to model the attractiveness of destinations to be accessed on foot. We use a cumulative Gaussian function as the generic default for the average population. The function is described in detail in Vale and Pereira (2017), p. 12 Fig. 3. It can be modified by users in the code of OS-WALK-EU if preferences for social groups require such adjustment. The added value of this possibility will be shown in the case study for Düsseldorf where the pedestrian needs of older people inform respective parameter settings for OS-WALK-EU.

5. Sample applications and results

Application of the tool requires basic knowledge on how to operate QGIS plugins from the official QGIS repository of plugins. Tutorials and documentation are available on the QGIS homepage https://www.qgis.org/. There is additional documentation for

[2] see https://inspire.ec.europa.eu/Themes/131/2892, last accessed 10 February 2022.

[3] see https://openrouteservice.org/and https://github.com/GIScience/openrouteservice (last accessed 10 February 2022).

[4] see https://wiki.openstreetmap.org/wiki/Key:foot (last accessed 10 February 2022).

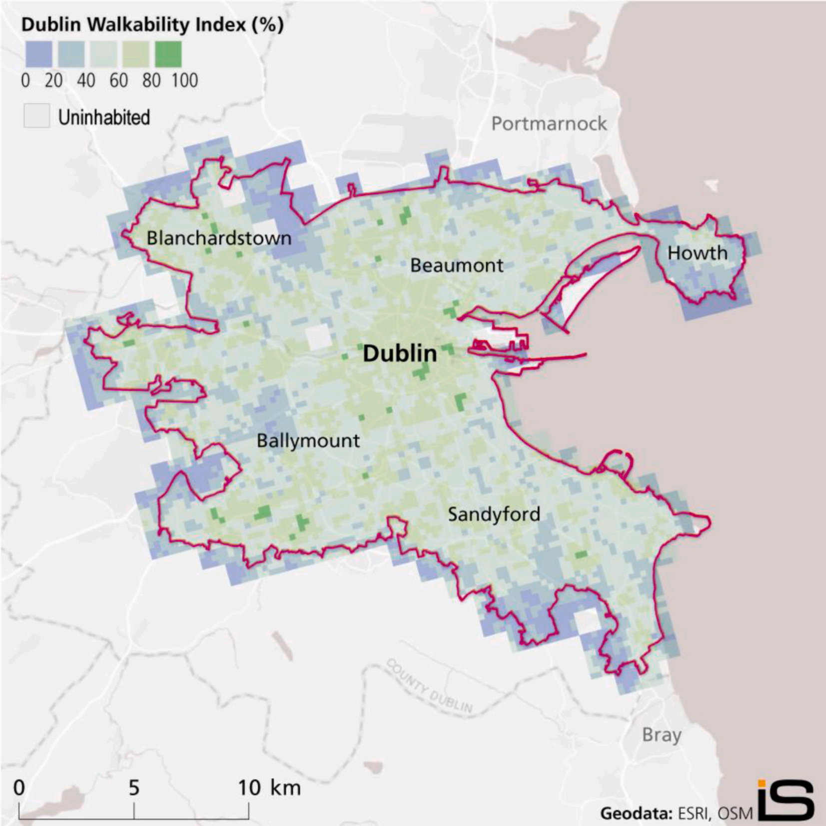

Fig. 2. OS-WALK-EU walkability assessment for Dublin (https://ils-geomonitoring.de/maps/327/view, last accessed 4 August 2022).

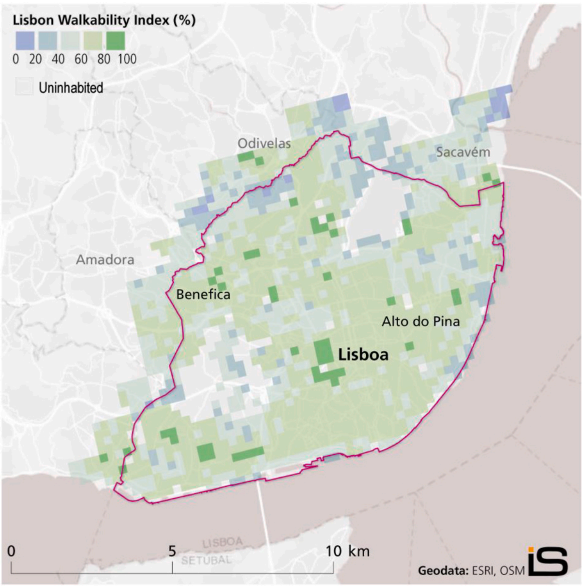

Fig. 3. OS-WALK-EU walkability assessment for Lisbon (https://ils-geomonitoring.de/maps/336/view, last accessed 4 August 2022).

developers wanting to modify the source code for their own purposes in a publicly accessible software repository at https://gitlab.com/ils-research/os-walk-eu/.

Once the tool has been successfully activated, data needs to be prepared according to the user documentation available in the tool's

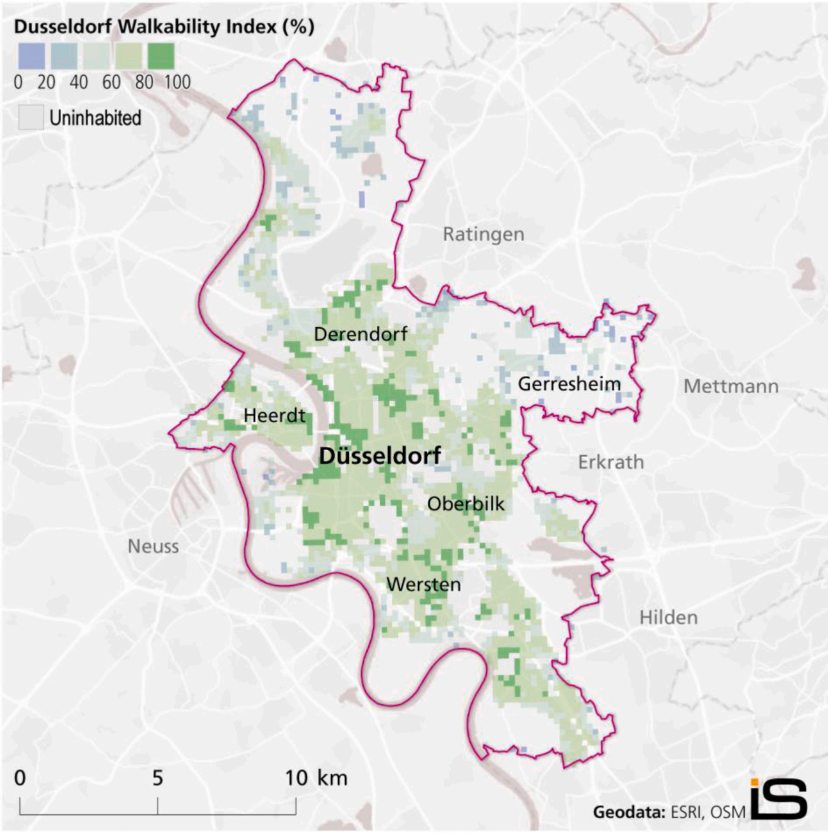

Fig. 4. OS-WALK-EU walkability assessment for Düsseldorf (https://ils-geomonitoring.de/maps/360/view, last accessed 4 August 2022).

Table 4
Comparison of amenities data between authoritative data and OSM in Dublin.

Amenity Type	OSM Data vs. Administrative Data		
	Average No. Amenities in the Areas' 800m Buffers		
	OSM	Adminis-trative Data	Coverage (OSM/Administrative)
A corner shop/newsagent	1.44	4.63	31%
A church or place of worship	3.88	4.44	87%
A park/pitch	36.63	53.50	68%
A local school	17.44	7.44	234%
A community centre or recreation centre	5.25	1.06	495%
A creche or childcare facility	0.63	12.94	5%
A chemist (or pharmacy)	0.44	4.50	10%
A supermarket	2.13	2.88	74%
A bank or credit union	0.69	4.31	16%
A post office	0.13	2.13	6%

graphical user interface. Default settings can either be accepted or modified for special interest groups. Locally sourced data can replace the default data options. The documentation in the GitLab repository (available as a submenu named 'wiki') specifies the required formats for data inputs. For performance reasons cells with no population can be removed from the inputs since the algorithm would skip them anyways. There can be no residential walkability assessment in uninhabited places. Blank cells therefore need be labelled accordingly in the legend of map outputs.

Figs. 2–4 show implementations for the cities of Lisbon, Dublin and Düsseldorf with a scale of 0 (lowest walkability) to 100 (highest walkability). The captions and the figures include links to the interactive representation of these maps including inputs (amenities, green and blue areas, elevation) and tabular outputs for scores of each cell. Low walkability scores are coloured in shades of blue, higher walkability scores are shown in shades of green.

For these cities, the results were evaluated by the local experts from this paper's author group. Assessments differed: (1) In the Dublin case study we looked at the quality of OSM amenity data in comparison to administrative datasets; (2) the Lisbon case study

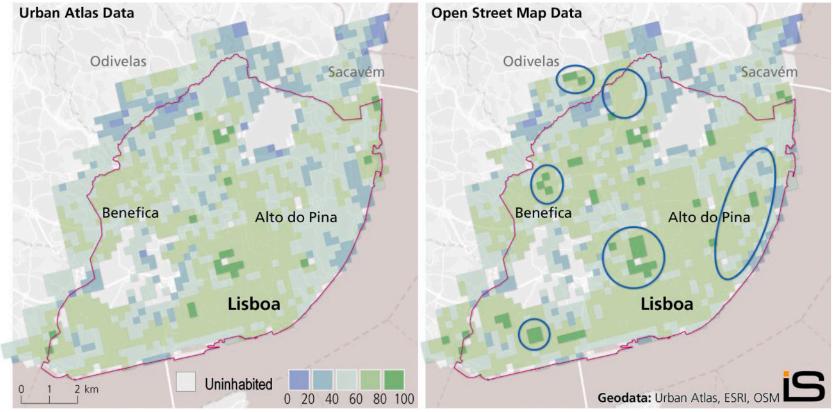

Fig. 5. Inspection of green area data options for OS-WALK-EU in Lisbon (data source: OSM, European Environment Agency).

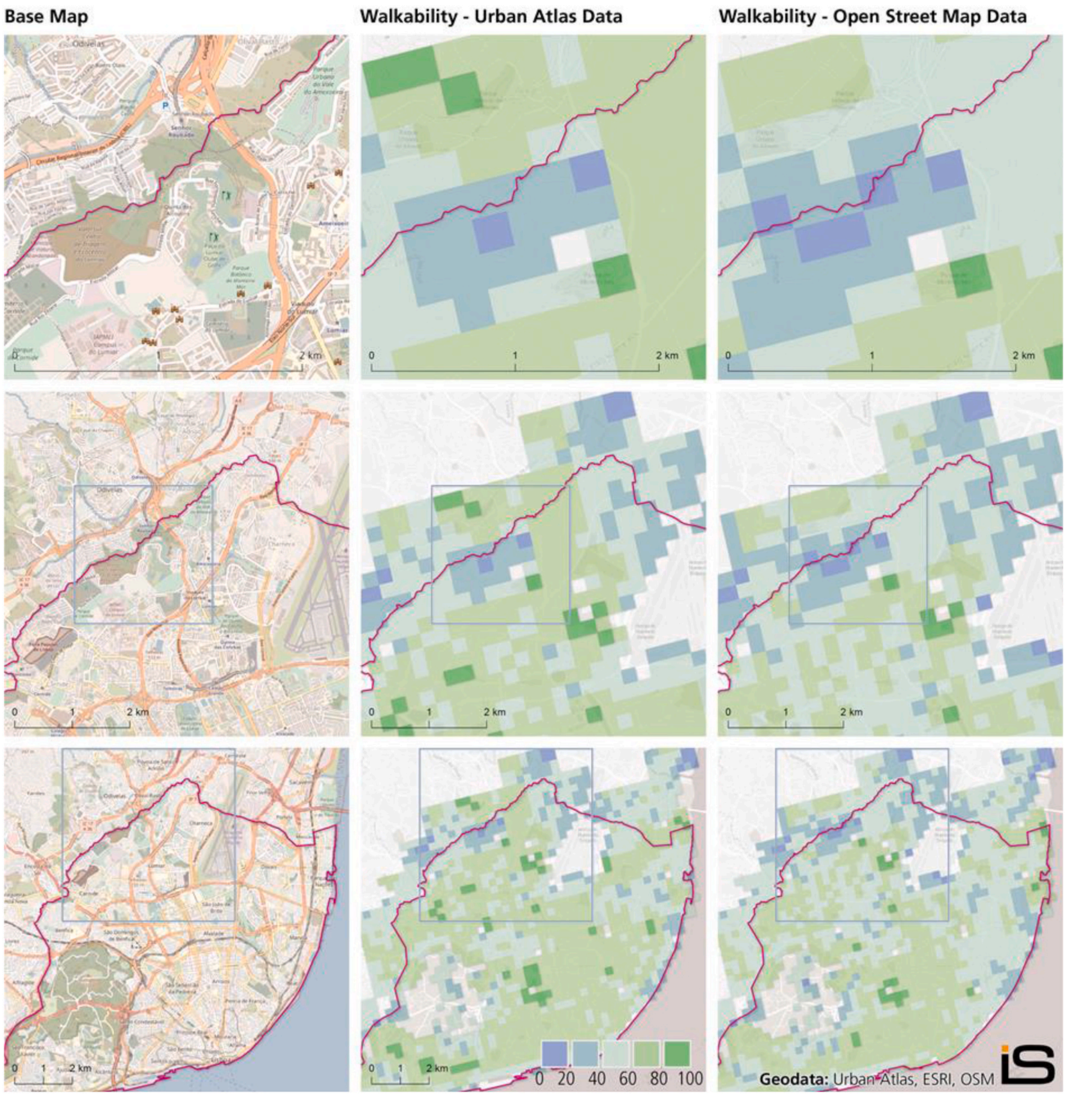

Fig. 6. Selected close-ups for the visual inspection of green data options in Lisbon on three scales (with increasing scale from bottom to top; data source: OSM, European Environment Agency).

Table 5
OSM tags (key and value) considered to measure green areas in Lisbon.

Key	Value	OSM Description
Boundary	National_park	*Area of outstanding natural beauty, set aside for conservation and for recreation (Other languages).*
Landuse	Cemetery[a]	*Place for burials. You can add religion=* (values listed in the place of worship page). Smaller places (e.g. with a church nearby) may use amenity=graveyard instead.*
Landuse	Allotments	*A piece of land given over to local residents for growing vegetables and flowers.*
Landuse	Recreation_ground	*An open green space for general recreation, which may include pitches, nets and so on, usually municipal but possibly also private to colleges or companies*
Leisure	Garden	*A place where flowers and other plants are grown in a decorative and structured manner or for scientific purposes.*
Leisure	Nature_reserve	*A protected area of importance for wildlife, flora, fauna or features of geological or other special interest.*
Leisure	Park	*A park, usually municipal.*

[a] Not used for Lisbon.

analysed the validity of green and blue area data as recreational attractions for pedestrians, while (3) the Düsseldorf case study compared scenarios of walkability assessments for the general population with adjusted parameters for the special interests of older people.

6. Dublin case study

For Dublin, OSM data quality was assessed in terms of completeness for POIs via a comparison of amenity data from official websites for 16 selected cells in the study area and amenities within an 800-m buffer around these cells. Table 4 shows the results of the comparison in percentage (column on the very right). If we accept that the collection of authoritative data is a good proxy for the ground truth, community centres and local schools are overrepresented in OSM. All other amenity types in the sample show lower numbers, in varying degrees. Their underestimation reflects the subjective nature of crowdsourcing data where volunteers assign building amenity information which can be subjective. By contrast, the overestimation of schools suggests that this type of amenity is easier for volunteers to identify when capturing OSM data (Elwood et al., 2012). However, the number of points collected for local schools in OSM is approximately five times greater than official sources. One explanation may be that within the perimeter of a school there may be more than one building captured in OSM, whereas an official source will show only one point for the school. Although this could be the case in this study, the number in OSM is much higher, suggesting that volunteer mappers consistently capture all building points within the perimeter of an area, unlike official sources where only one point is captured.

One key takeaway for the design of OS-WALK-EU from this case study is that OSM features for schools need to be merged into single ones if they belong to the same organisational unit. The case study also confirms that the OSM dataset has limitations when extracting POI data for Dublin. Sample sizes were sometimes rather low, and this finding does not necessarily reflect on OSM data quality for other cities, as the quality is dependent on volunteers mapping cities to achieve better coverage. Quality thus varies between cities, with POI density ranging from a couple to hundreds of points per square kilometre (Hochmair et al., 2018). For the future we expect OSM data repositories being filled with more and higher quality data if the trend of increasing numbers of contributing users continues.

6.1. Lisbon case study

The city of Lisbon is frequently called “the city of the seven hills” due to its topographic characteristics. This feature makes walking and cycling difficult. Until recently there was little research on walkability in Lisbon (Morais, 2013; Moura et al., 2017). A few studies have since appeared assessing the pedestrian potential of the street network based on predicted pedestrian flows (Morais, 2013). One study evaluates the influence of municipal interventions on individuals’ perceptions (Cambra and Moura, 2020). One approach to measuring walkability in Lisbon is the work of a co-author of this article, Pereira et al. (2020). Evaluating walkability for all parishes in Lisbon, the results show walkable characteristics in Lisbon as part of the EURO-HEALTHY project, including stakeholder perspectives (Freitas et al., 2020). The dimensions evaluated in this project aimed to assist the promotion of a walkable environment, not only from a utilitarian perspective, but also from that of leisure activities, with a comprehensive view of a good environment for a more sustainable and healthier city.

Evaluated from the point of view of a local expert, the focus in the Lisbon case study was to evaluate green areas using two potentially free datasets: the Urban Atlas from the European Environment Agency and OSM. We calculated walkability using both datasets and evaluated the results based on comparisons with reference studies on walkability in Lisbon, visual inspections and local knowledge. The Urban Atlas includes major green areas such as parks and gardens but misses other smaller but important green areas (see Figs. 5 and 6). Therefore, we chose to test OSM as an alternative data source for green areas, due to its finer granularity. Nevertheless, and again taking into consideration the cultural differences existing between the cities considered, cemeteries were excluded from the calculation, as in Portugal cemeteries are normally walled in and not used as leisure destinations.

The resulting assessments were more conclusive when basing OS-WALK-EU on OSM green and blue areas. We therefore defined the so-called tags, i.e. the nomenclature for classifying OSM objects for the user community to represent green areas for inclusion in OS-WALK-EU. Table 5 provides an overview and description of the resulting list of tags. Based on this research, the list is used as the default in the distribution of the tool in the previously mentioned software repository at GitLab. We recommend its usage if there is no other alternative available. As with all inputs of OS-WALK-EU, it can be replaced by any type of green and blue area alternative if there

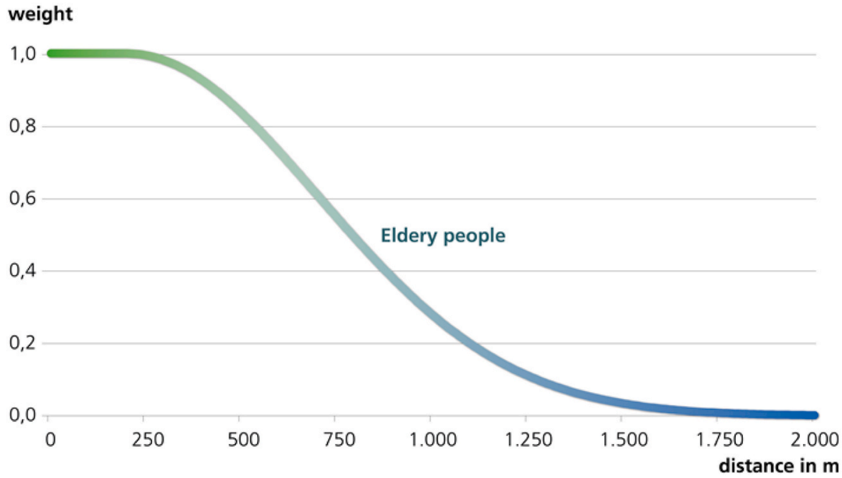

Fig. 7. Distance decay function for walking trips of people aged 65 and above.

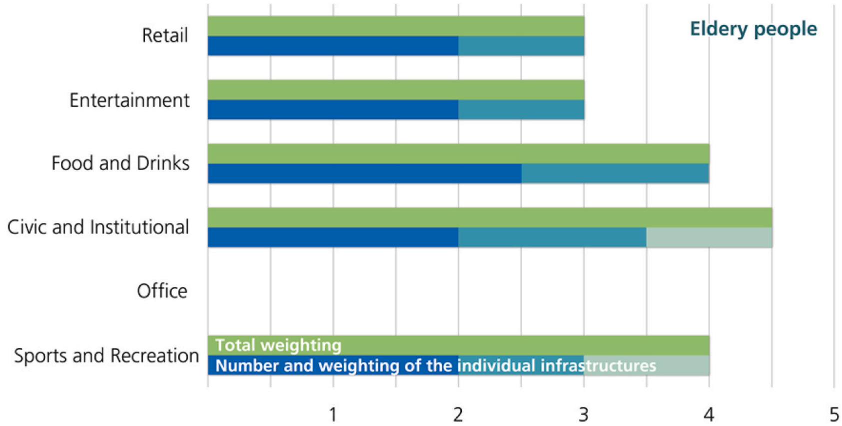

Fig. 8. Weightings and preferences for the variety of amenities for older people.

is (e.g. cadastral data, digial topographic maps).

6.2. *Düsseldorf case study*

In the case study of Düsseldorf, we compared tool results for population groups with specific needs against an assessment with default values for the general population. This is showcased for older people who, on average, walk shorter distances than the population at large. In addition, destinations differ. An example are office workplaces that are usually not a regular destination for walking trips of retired people, so the weighting is set to zero. The daily needs of older people are more closely associated with essential grocery shopping, health-related services and recreational activities in the residential neighbourhood (Distefano et al., 2021; Guida and Carpentieri, 2021). For this reason, the general assessment presented for the whole population is modified with higher weights for these amenities on the one hand and an adjusted distance decay function on the other.

Fig. 8 shows which facilities are most important to the 65+ population, and for which trip purpose the variety of facilities motivates more people to walk. The weightings were defined by the author team in an explorative exercise to test the tool for the typical preferences of older people. Civic and institutional includes retirement homes and health services (pharmacies, chemists, drugstores, general practicioners) with the highest weightings, followed by grocery shopping ('food and drinks'). For both of these categories the variety of options also plays an important role to satisfy different needs and preferences. This is especially the case when facilities specialize in products tailored to the needs of specific customer profiles (e.g. organic supermarkets, discounters, delis, etc.). OS-WALK-EU allows usage of variety as an additional parameter for the weighting algorithm (see also the online documentation in the GitLab wiki). Parks and recreational facilities also receive a high weighting, although with a lower importance for variety: Visiting a park for daily recreation depends more on nearby opportunities than a variety of options. Retail and entertainment receive a value similar to the one for the general population.

The weightings in Fig. 8 are further modified by the distance decay shown in Fig. 7. OS-WALK-EU uses a generic function where

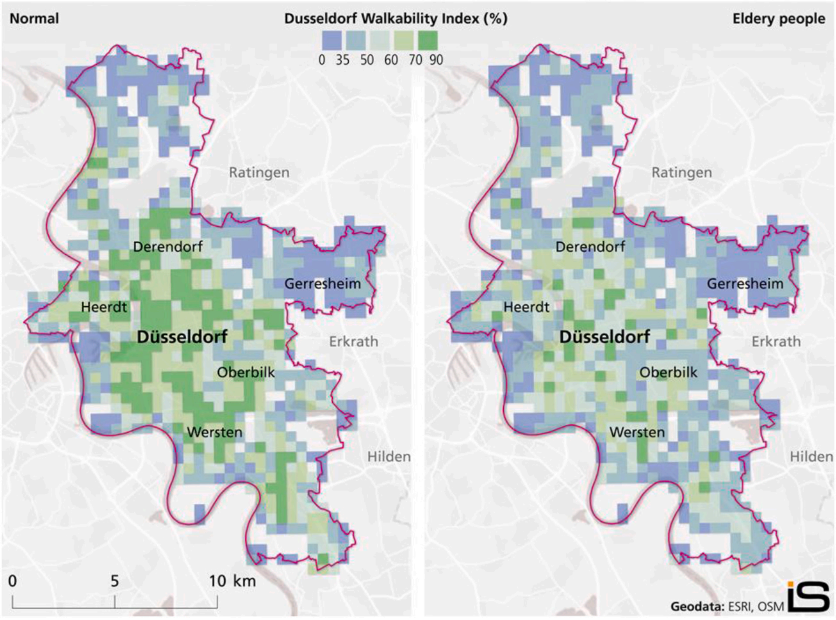

Fig. 9. Comparison of tool results for generic settings ("normal", i.e. settings typical for the requirements of all people) and modifications for the 65+ target group ("elderly people") (Source: OS-WALK-EU tool).

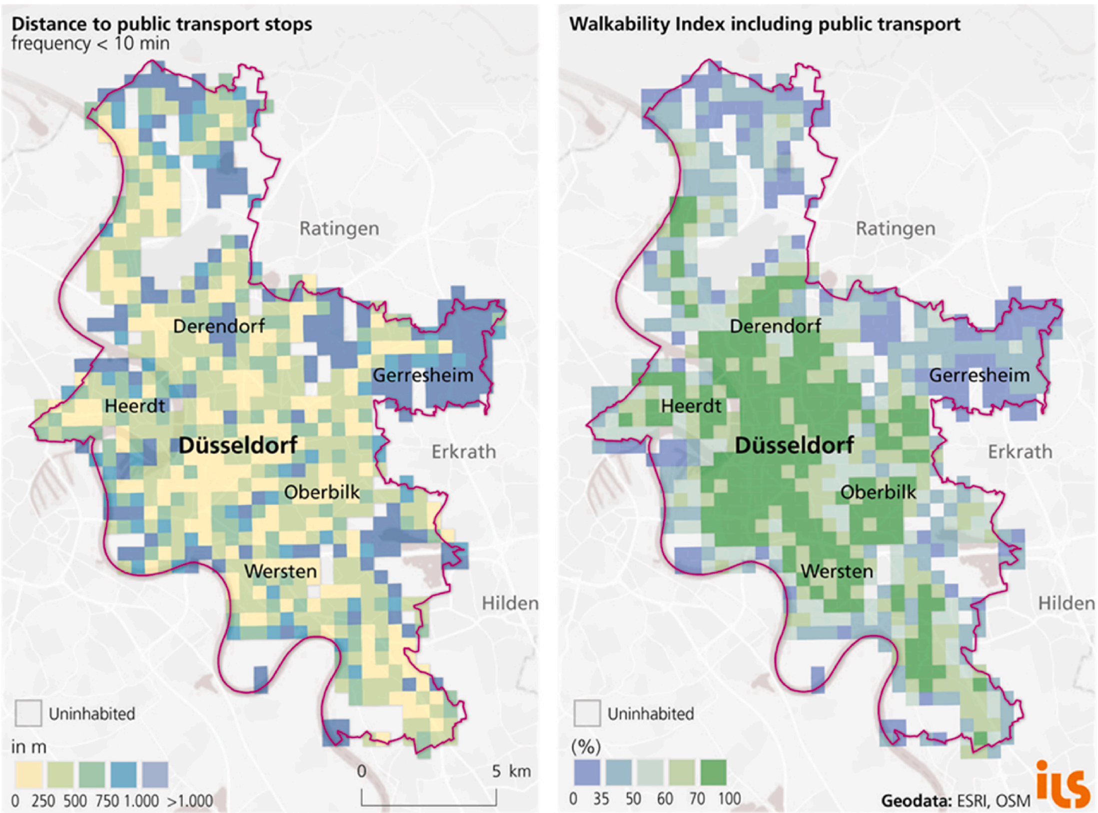

Fig. 10. Sample tool results to showcase the effects of the inclusion of public transport stops (with a minimum service frequency of 10 min) in the city environment (Source: OS-WALK-EU tool).

amenities in closer proximity to the assessed cell receive full weight. Amenities further away received a decreasing weight (y-axis) according to distance (x-axis). For older people the distance decay decreases sharper with a reduced radius of activity. It is applied as a factor range between 0 and 1 to the contribution of an amenity to the final OS-WALK-EU index, and therefore complements the weighting logic. Further information is available in the online documentation.

The modification of default tool settings with these weightings results in the maps shown in Fig. 9. The comparison highlights two main patterns for Düsseldorf where the tool was applied with default values (left) and for older people (right): (1) For older people areas of very poor (below 35) and poor accessibility (35–50) extend further on the outskirts of Düsseldorf. (2) Areas of very and high walkability (above 60) in the city centre are smaller in the map for older people.

This result is not surprising. The modifications to the aforementioned distance decay function ("older people walk shorter distances than the average population") and the selection of a subset of facilities of high importance to older people result in logically lower walkability ratings. At the same time, urban planning and public health can clearly benefit from such assessments. In a demographically ageing society, the needs of the older require due attention. The results presented here can deliver initial assessments of areas in need of adaptation for truly walkable neighbourhoods for older residents.

In an additional analysis we also showcase for Dusseldorf how tool results react to the inclusion of public transport stations (here: stops that are serviced at least every 10 min) as destinations for people to walk to. The results show that this leads to an amelioration of results from the core to the outskirts, with a generally extended range of higher values (see Fig. 10 right in comparison to Fig. 9 left). This approach can be seen as an important addition for pedestrians that extend their radius of activity with public transport options (e.g. commuters). The downside, however, is a reduced influence of other walkability dimensions that inform planners about local deficiencies. Since we focus on residential walkability in this article, we therefore decided to not include public transport as a default dimension in the tool.

7. Conclusion

In general, we conclude that OS-WALK-EU upgrades existing walkability measurement concepts via the following conceptual aspects:

1. OS-WALK-EU provides an easy-to use tool building on the strengths of existing measurement approaches for city- and region-wide walkability assessments, based on free and open data.
2. OS-WALK-EU allows default data to be replaced by local information better reflecting local realities (e.g. locally sourced datasets on amenities) and enables users to incorporate locally available information on walkability in map outputs (e.g. from audit-based walkability surveys).
3. OS-WALK-EU provides parameters for users to define social group preferences (e.g. choice of amenities) and deviations from theoretical assumptions that might not apply locally.

The theoretical foundation of OS-WALK-EU is based on a re-interpretation of the literature on walkability and pedestrian-oriented urban development. This re-interpretation searches for potential improvements based on newly emerging technologies and data options, and leads to a refinement of measurement concepts. The provision of pedestrian routing capacities to destinations and leisure facilities of varying attractivity are the main innovation in this respect. Potential shortcomings concern missing OSM data on amenities and green areas as seen in the Dublin and Lisbon case studies. At the same time, the case studies show how to overcome these shortcomings using data mining strategies that complement or replace open-data repositories like OSM. For the time being, users of the tool are required to learn about the weighting logic in order to customize the tool for their own needs. Looking to the future, we expect that new data fusion techniques and new sources will improve the quality of open source data, and that default profiles for social groups can be added to the tool for ease-of-use. The article posits that open and free availability of walkability tools such as OS-WALK-EU has the potential to reach users who have so far not been able to apply it for their own work, be it planning practice or academic research. The tool integrates routing possibilities which is a major improvement. Previous tools have frequently resorted to the use of proxies (i.e. employment share, land use mix, retail floorspace) with limited empirical knowledge on their actual explanatory factors for the walkability in European cities. Routing to actual walking destinations, categorized and weighted by importance, are preferable in comparison to such proxies.

The limitation of open data repositories like OSM is another aspect for discussion. The amenities in OSM are not complete but the trend shows that it is increasingly being used by contributors and is likely to become a more solid data base over time. For the time being, it can be complemented with other data sources to fill remaining gaps. In general, the use of open source and free official data for European countries provides an entry point to compare results from different cities across Europe, even if some data gaps remain. Such a comparison can be used to benchmark European cities, for example with regards to the emerging concept of the 15-min city in urban planning. Moreover, it might be possible in the near future to obtain user-generated data on walking trips in a standardized way, e.g. when smartphone-based mobile sensor networks fill data repositories available to the research community. At the moment, however, such data is only available in specialized empirical research settings.

The Düsseldorf case study illustrates how the inherent subjectivity of walkability can be objectified to a certain degree. Quantitative measurements inform urban planners on the 'person-environment' fit between urban structures and group preferences, though planners require additional insights based on street-level information when planning interventions. The case study helps to highlight areas with potential deficits and shows the effects if public transport is included as a dimension of walkability. The value of the results for planning can be that deficient areas are prioritized for subsequent analysis of infrastructure and walking conditions, e.g. with audit-

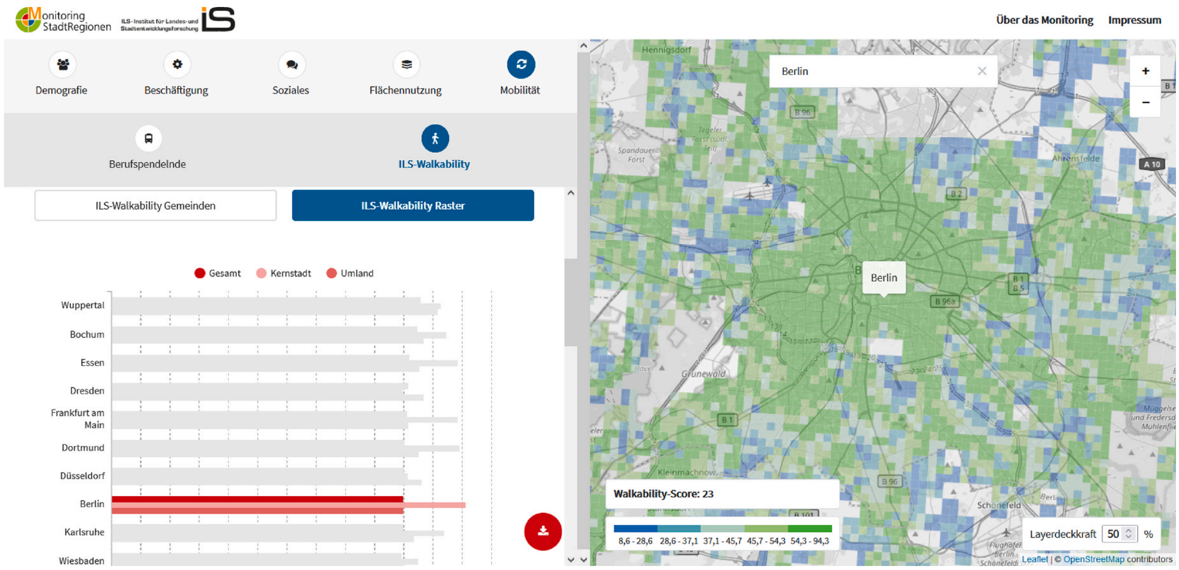

Fig. 11. Walkability assessments for German city regions using OS-WALK-EU at https://ils-stadtregionen.de (closeup for Berlin, last accessed 4 August 2022).

based methods. A planning outcome can be to retrofit structures to make them more walkable, both as an imperative for sustainable mobility and for improving quality of life.

At the same time, strategies to retrofit car-oriented city structures to walkable neighbourhoods are no guarantee that local residents will immediately walk more. Validation attempts to find high correlations between OS-WALK-EU results and actual pedestrian trips are bound to fail, as experienced in a running project on walkability in Stuttgart, Germany, where OS-WALK-EU was used to measure walkability (unpublished). Aspects like community cohesion and social activities, the lifestyles and activity patterns of local residents or perceptions of safety and comfort (including the weather) moderate people's motivation to walk. Spatial walkability assessment tools like OS-WALK-EU can therefore only be a starting point to inform urban planning and policy action about areas of interest that require more detailed analysis.

One early adopter of tool results is the spatial development platform https://ils-stadtregionen.de [5] where the ILS authors of this paper have helped conduct walkability assessments for 33 German city regions. The results have been aggregated to provide information on averages among core cities, commuter sheds and entire city regions in interactive graphs and maps for local administrations, as well as more detailed grid-based assessments (see Fig. 11). Helping to monitor initiatives for health-promoting walkable neighbourhoods, such assessments are part and parcel of the governance of sustainable mobility futures.

We very much hope that the strategy to present an open and free, easy-to-use publication of OS-WALK-EU motivates other walkability researchers to use and – above all – to contribute to the further development of the tool.

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[5] Currently only available in German, last accessed 10 February 2022.

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