Landsc Ecol (2024) 39:71
https://doi.org/10.1007/s10980-024-01871-7

RESEARCH ARTICLE

The green window view index: automated multi-source visibility analysis for a multi-scale assessment of green window views

Anna-Maria Bolte · Benjamin Niedermann · Thomas Kistemann · Jan-Henrik Haunert · Youness Dehbi · Theo Kötter

Received: 30 August 2023 / Accepted: 7 February 2024 / Published online: 11 March 2024

Abstract
Context Providing accessible urban green spaces is crucial for planning and ensuring healthy, resilient, and sustainable cities. The importance of visually accessible urban green spaces increases due to inner urban development processes.
Objectives This article proposes a new index, the Green Window View Index (GWVI) for analyzing and assessing visible vegetation, that promotes an integrated planning of urban green spaces and buildings at different scales and levels. It is defined as the proportion of visible vegetation area in a field of view when looking out of a specific window with a defined distance to the window.
Methods The method for estimating GWVI consists of three steps: (a) the modeling of the three-dimensional environment, (b) the simulation of the two-dimensional window views using modern rendering engines for three-dimensional graphics, (c) the computation of the GWVI. The method is proposed and tested through a case study of the urban area of Bonn, Germany, using a Digital Terrain Model (DTM), CityGML-based semantic 3D City Model at level of detail (LoD) 2, airborne Light Detection and Ranging (LiDAR) data, and 2D land use data from the official German property cadaster information system (ALKIS).
Results With an average processing time of 0.05 s per window view, an average GWVI of 26.00% could be calculated for the entire study area and visualized in both 2D and 3D.
Conclusion The proposed engine generates multi-scale visibility values for various vegetation shapes. These values are intended for use in participatory citizenship and decision-making processes for analysis by architects, real-estate appraisers, investors, and urban as well as landscape planners.

Keywords Visibility analysis · Urban green · Open source data · CityGML · LiDAR · ALKIS

A.-M. Bolte (✉) · B. Niedermann · J.-H. Haunert · T. Kötter
Institute of Geodesy and Geoinformation, University of Bonn, Nussallee 1, 53115 Bonn, Germany
e-mail: ambolte@uni-bonn.de

T. Kistemann
Institute for Hygiene & Public Health, GeoHealth, University Hospital Bonn, Venusberg-Campus 1, 53127 Bonn, Germany

T. Kistemann
Department of Geography, University of Bonn, Meckenheimer Allee 166, 53115 Bonn, Germany

Y. Dehbi
Computational Methods Lab, HafenCity University Hamburg, Henning-Voscherau-Platz 1, 20457 Hamburg, Germany

Introduction

Urbanization and the consequences of climate and demographic change are increasing the spatial pressure on cities worldwide (United Nations Human Settlements Programme, 2020, 2021). As defined in Sustainable Development Goal (SDG) 11.7, access to urban green spaces is essential for ensuring and developing sustainable, resilient, and healthy cities (United Nations 2017). Urban green spaces offer various ecosystem services to the urban population, depending on their spatial characteristics, location, and ecological features (Esperon-Rodriguez et al. 2020; Semeraro et al. 2021; Wang et al. 2022). These services include food provision, improvement of air quality, regulation of the microclimate in the city, water regulation, and prevention of erosion processes. In addition, green spaces offer socio-cultural benefits such as enhancing the aesthetic appeal of urban areas, increasing the potential for physical, mental, and cognitive recreation, providing cultural and artistic inspiration for urban populations, and enabling spiritual experiences for residents through access to urban open spaces.

Inner urban development processes aim to densify urban space and provide functional areas, resulting in two- and three-dimensional changes to urban morphology, access to urban green spaces, and the importance of visual access to these spaces (Angel et al. 2021; Eichhorn and Siedentop 2022).

The concept of biophilia explains the positive benefits of visible green spaces. It refers to people's innate affinity for nature, different life forms, habitats, and ecosystems (Fromm 1973; Wilson 1984). In this context, visible green spaces have multi-dimensional effects on residents, including economic, health, auditory perception, and cognition benefits (Söderlund and Newman 2015; Crompton and Nicholls 2019; Lindemann-Matthies et al. 2021; Trøstrup et al. 2019; Van Renterghem 2019; Williams et al. 2019).

Automatic-objective approaches for measuring visible urban green spaces are available for two different view positions: (1) street-level views, which describe the view of urban green spaces when the observer is standing on the street (Biljecki and Ito 2021), and (2) building-level views, which provide views of urban vegetation when the observer is standing inside a building and looking out of a window. However, existing approaches for window view assessment do not consider the window size (Yu et al. 2016; Wang et al. 2019) or the observer's position in the room (Yu et al. 2016; Wang et al. 2019; Li et al. 2022). Therefore, they do not fully address the potential for visual access that should be included in urban planning processes (Matsuoka 2010; Ko et al. 2021).

This article presents an automated implementation around the new Green Window View Index (GWVI), which considers the full potential of green visibility, including the window size and idealized indoor positions of the observer during the measurement. Figure 1 illustrates the operating principle of the GWVI.

The index and its implementation consider the spatial characteristics of the window, such as its size, the observer's vertical and horizontal fields of view (FOV), and the distance from the window, in order to quantify and evaluate the visual amount of urban green space in the window view. As a result, three-dimensional urban green structures can be observed within the window area. Possible spatial changes during densification processes and impacts on the visual access of urban vegetation can be identified to support and strengthen inner urban development processes and an integrated open space planning. The exclusive use of open data and open source software, as is common in planning practice, is intended to ensure reproducible results for the scientific community and to contribute to a transparent and cost-efficient analysis at a multi-scale level, providing practice-oriented findings for municipal planning departments, including participatory citizenship (Mobasheri 2021; International Smart Cities Networkt (ISCN) 2022; Yap et al. 2022; Henkel 2023). Thus, smart cities should be promoted (Bundesministerium des Innern, für Bau und Heimat (BMI) 2021; Moreira de Oliveira and Painho 2021).

The main contributions of this article are as follows:

1. A comprehensive literature review regarding the effect dimensions of green window views and previous methodological approaches to quantify a green window view,
2. The design and implementation of a new GWVI using exclusively open source software,
3. Feasibility demonstration using real world data from the case study in Bonn, Germany, including 3D and 2D visual assessment.

The article is organized as follows: "Literature review" section provides a literature review on effect dimensions and previous methods for quantifying green window views. "Index and technical

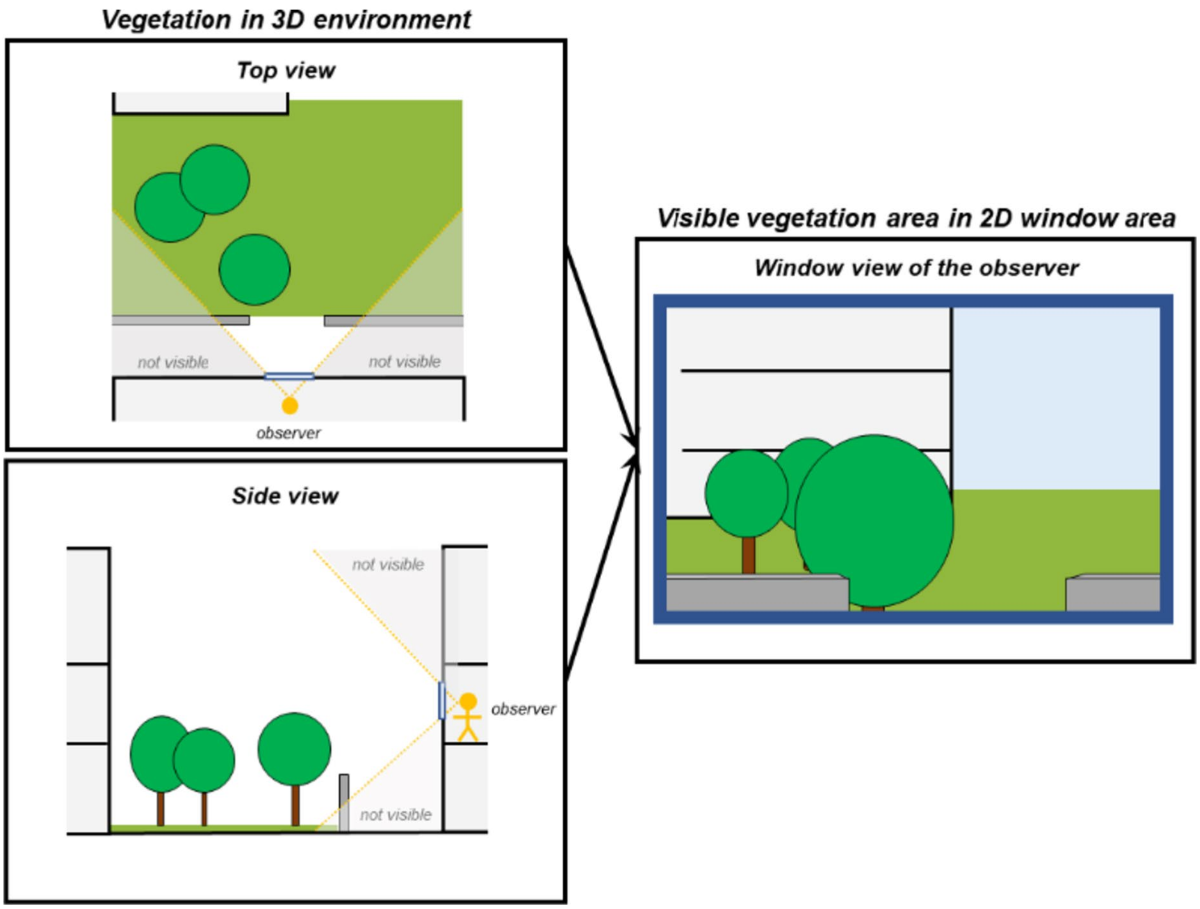


Fig. 1 Simplified visualization of the operating principle of the Green Window View Index (GWVI)

implementation" section introduces the index and its underlying principles, followed by two-dimensional window view simulations using bitmaps. The article presents a case study in Bonn, Germany, followed by the applied methodology in "Experimental setup" section. "Experimental results" section presents the results regarding different visualization opportunities of the index and visibility values of different vegetation types. The effect mechanisms of the window simulation are discussed in "Discussion" section. The article concludes with a summary and future perspectives in "Conclusion".

Literature review

Effect dimensions of green window views

The design of windows and their views plays a crucial role in architecture, which is influenced by factors such as the age of the building, architectural style, and function. Design standards have an impact on the window design to create a healthy indoor space with thermal comfort, sufficient brightness, and visual access to the outside (Aksamija 2013, pp. 69–71; ift Rosenheim GmbH, 2015; Jamshidi et al. 2020; Deutsche Gesetzliche Unfallversicherung e.V. (DGUV) 2022). During activities such as classes, work, clinical stays, or even while adhering to Covid-19 movement restrictions, window views may be the only way to access green spaces. A green window view can provide a variety of evidence-based multi-dimensional effects that influence health, auditory perception, cognition, and economics:

Regarding health effects, Ulrich (1984) and Raanaas et al. (2012) found that the view of green spaces, such as trees, positively affected patients during hospitalization, correlating with shorter hospital stays, less medication use, and fewer negative patient reports. Additionally, research has shown that viewing green spaces from a window at work or at home can lead to a decrease in human pulse and improvements in perceived restorativeness, self-esteem, well-being, and life satisfaction (Kaplan 1993; Chang and Chen 2005; White et al. 2010; McFarland 2017; Gao and Zhang 2020; Soga et al. 2021). Further, such exposure has been linked to a reduction in perceived loneliness and stress (Kaplan Mintz et al. 2021; Soga et al. 2021). Access to green window views of parks, gardens, trees, plants, bushes, or lawns has been shown to reduce the risk of depression and burnout (Brace et al. 2020; Mihandoust et al. 2021).

A positive influence on auditory perception based on the amount and quality of visible green in window views was also found in studies by Van Renterghem and Botteldooren (2016) and Sun et al. (2018), leading to changes in subjective noise perception.

Cognitive performance and cognitive recovery at work, school, and home have been linked to the existence or high amount of green structures such as trees, grass, or shrubs in the window view (Tennessen and Cimprich 1995; Taylor et al. 2002; Benfield et al. 2015; van Esch et al. 2019; Engell et al. 2020; or Lindemann-Matthies et al. 2021). Additionally, Matsuoka (2010) found a negative correlation between the size of windows with a view of trees, shrubs, and forest and the level of criminal activity in schools.

Moreover, several studies have examined the economic impact of windows overlooking public or private green spaces and have found that they have a positive effect on real estate prices and the willingness to pay higher prices for real estate or rent (Bishop et al. 2004; Chen and Jim 2010; Jim and Chen 2010; White et al. 2010; Hui and Liang 2016; Crompton and Nicholls 2019).

In summary, the existence and high proportion of visible three-dimensional green structures in the window view show a high number of various positive effects. This also illustrates the increased need to assess visual access to heterogenous green spaces for ”smart allocation to intensify visibility and visual quality” of urban green spaces for “saving and providing green space of high quality” (Haaland and Konijnendijk van den Bosch 2015). The significant insights emphasize the need to incorporate the existence and amount of visible urban green spaces as an alternative access form into urban and landscape planning at different scales, including individual apartments and buildings, neighborhoods, or city districts. This is necessary to ensure sustainable, resilient, and healthy urban development on a holistic basis, and to integrate green view information into necessary inner urban development processes (Angel et al. 2021; Eichhorn and Siedentop 2022). Here, various forms of two- and three-dimensional visualization are required for a clear and impartial communication of the results with stakeholders like planners, politicians, and citizens throughout the entire planning process (Mobasheri, 2021; International Smart Cities Networkt (ISCN), 2022).

Assessments of green window views

Studies on visible green spaces in window views have been conducted using either automatic-objective approaches or manual-subjective methods. These methods differ in terms of vegetation types investigated, characterization of window views, resolution, and visualization of assessment results (see Table 1):

Automatic-objective methods combine various two- and three-dimensional geo-analytical methods and data to enable assessment visualization in the forms of numerical plots, two-dimensional maps, or three-dimensional heat maps. They focus on quantitative assessment without qualitative effect evaluation of the green view. Among these methodologies are Yu et al. (2016), Wang et al. (2019), and Li et al. (2022). The Floor Green View Index (FGVI) measures the areal size of visible urban vegetation areas seen from buildings (Yu et al. 2016), while the Building Visual Greenness Index (BVGI) measures the ratio of visible green space to a defined areal view buffer around the building (Wang et al. 2019). Both approaches focus on two-dimensional vegetation structures and do not consider characteristics of a window view. However, the green view is automatically determined for different view directions (Yu et al. 2016), building floors, or entire buildings (Yu et al. 2016; Wang et al. 2019).

Table 1 Automatic-objective and manual-subjective approaches for green window view analysis

Approach	Type of visible vegetation	Spatial dimension of visible vegetation	Windows considered	Assessment resolution	Assessment visualization	Advantages and disadvantages
Automatic-objective methods						
Window view index (WVI)	Trees, bushes, and grasses	3D	Yes	Single views	View images, 3D heat maps, numeric plots	+ Consideration of view height, vertical FOV, and amount of visible vegetation in window view –Without consideration of horizontal FOV, observer's distance to window, 2D map visualization, or qualitative evaluation of visible vegetation
Building visual greenness index (BVGI)	Vegetation	2D	No	Floors, buildings	2D maps, numeric plots	+ Consideration of view height and amount of visible vegetation –Without consideration of 3D vegetation, window characteristics, 3D heat map visualization, or qualitative evaluation of visible vegetation
Floor green view Index (FGVI)	Vegetation	2D	No	Floors, buildings, observation direction	2D maps, 3D heat maps, numeric plots	+ Consideration of view height, observation direction, and amount of visible vegetation –Without consideration of 3D vegetation, window characteristics, or qualitative evaluation of visible vegetation
Isovist analysis/ space syntax analysis	Vegetation	3D	Yes	Single views, floors, buildings	2D maps, 3D heat maps, numeric plots	+ Consideration of view height, vertical, and horizontal FOV –Limited access to area-wide geo data and without consideration of qualitative evaluation of visible vegetation

Table 1 (continued)

Approach	Type of visible vegetation	Spatial dimension of visible vegetation	Windows considered	Assessment resolution	Assessment visualization	Advantages and disadvantages
Viewshed analysis	Parks, gardens, agricultural crops, meadows, forests, vineyards	3D	Yes/No	Single views	2D maps, numeric plots	+ Consideration of vertical and horizontal FOV –Without consideration of observer's distance to window, 3D heat map visualization, or qualitative evaluation of visible vegetation
Line of sight analysis	Forests, urban parks	3D	Yes	Single views	Numeric plots	+ Consideration of view existence –Without consideration of window characteristics, observer's distance to window, or qualitative evaluation of visible vegetation
Manual-subjective methods						
Photo evaluation	Late fall nature with leafless trees, naturalness such as trees, vegetation	3D	Yes	Single views	Qualitative results, numeric plots	+ Consideration of view existence and amount of visible vegetation –Without consideration of comparable evidence of the amount of visible vegetation and diverse result visualization
Questionnaire	Urban park, trees, green e.g., trees or lawn, plants, bushes, lawns	3D	Yes	Single views	Qualitative results, numeric plots	+ Consideration of view existence, amount, and qualitative evaluation of visible vegetation –Without consideration of comparable evidence of the amount of visible vegetation and diverse result visualization

Table 1 (continued)

Approach	Type of visible vegetation	Spatial dimension of visible vegetation	Windows considered	Assessment resolution	Assessment visualization	Advantages and disadvantages
Door-to-door household survey	Green space (parks or residential gardens)	3D	Yes	Single views	Qualitative results, numeric plots	+ Consideration of view existence, amount, and qualitative evaluation of visible vegetation –Without consideration of comparable evidence of the amount of visible vegetation and diverse result visualization
Face-to face interview	Green spaces, greenspace, green	3D	Yes	Single views	Qualitative results, numeric plots	+ Consideration of view existence, amount, and qualitative evaluation of visible vegetation –Without consideration of comparable evidence of the amount of visible vegetation and diverse result visualization

The Window View Index (WVI) quantifies the visible green of two- and three-dimensional vegetation types for single window views, taking into account the observer's vertical FOV. However, WVI does not consider the window size or the observer's distance to the window. As a result, it is not possible to ensure the entire "potential access to nature" (Matsuoka 2010) or the "availability of view[s] in [different][…] spaces" (Ko et al. 2021) during the assessment. Additionally, this approach only provides a limited visualization for assessment purposes.

Approaches such as three-dimensional isovist (Fisher-Gewirtzman et al. 2013; Suleiman et al. 2013) or space syntax analysis (van Nes and Yamu 2021) enable Building Information Modeling (BIM)-based virtual reality (VR) approaches to consider horizontal and vertical FOV (Motamedi et al. 2017; Ostwald and Dawes 2018) and visualize assessment results in diverse ways. However, the studies mentioned mainly refer to visibility analyses in indoor spaces. Therefore, they require a 3D City Model at level of detail (LoD) 4, which is mostly not available or freely accessible in Germany for a city-scaled analysis (Kolbe et al. 2005; Bundesamt für Kartographie und Geodäsie 2021).

Other automatic-objective approaches are based on viewshed analysis (Hilal et al. 2018; Wang et al. 2019; Kara et al. 2020) or line of sight analysis (Hellmanns et al. 2019; Pluta and Mitka 2019; Gu et al. 2021). These approaches exclude the observer's distance to the window and the window sizes, and therefore do not consider the visible amount of three-dimensional vegetation structures in the window view, as well as the whole visibility potential of the view.

Studies based on manual-subjective approaches utilized photo evaluations (Felsten 2009; van Esch et al. 2019; Lindemann-Matthies et al. 2021), questionnaires (Kaplan Mintz et al. 2021; Kley and Dovbishchuk 2021; Mihandoust et al. 2021), door-to-door household surveys (Chen and Jim 2010; Brace et al. 2020), and face-to-face interviews (Jim and Chen 2007; Van Renterghem and Botteldooren 2016; Torres Toda et al. 2020). Due to the subjective bias of the evaluation process, these approaches may not always provide comparable results for window views. However, these methods do offer highly detailed qualitative assessment information of green window views and the visible three-dimensional vegetation, including the phenological status of the vegetation and the description of the effect dimensions of green window views.

To summarize, there are various automatic and manual approaches available to measure and evaluate visible green spaces in a window view. Automatic-objective methods can provide quantitative information about the existence and amount of visible vegetation in the view at different resolution scales and in different types of visualization. Manual-subjective methods, on the other hand, can provide qualitative information about the view. However, they lack a comparable operationalization of the green view characteristics.

This article addresses these research gaps and presents an approach for assessing green window views, taking into account window size and observer's distance to the window. Consequently, it is possible to investigate the entire potential window view and determine the existence and amount of visible vegetation in the window view can be investigated. Using open data and open source software is common practice in planning practice, and enables the provision of reproducible results for the scientific community and the contribution of transparent and cost-efficient analysis at multiple scales, providing practical insights (Mobasheri 2021; International Smart Cities Networkt (ISCN) 2022; Yap et al. 2022; Henkel 2023;). The visualization of our methodological approach should facilitate intersubjective communication of our findings for planning processes (Mobasheri 2021; International Smart Cities Networkt (ISCN) 2022).

Index and technical implementation

Definition of green window view index

We introduce the GWVI as follows:

$$GWVI_{id} = \frac{Visible\ Vegetation\ Area\ in\ Window_{id}}{Area\ (Window_i)} * 100 \tag{1}$$

where the GWVI indicates the proportion of a visible vegetation area in the total FOV when looking out of a specific window i with a distance d to the window. The possible value range is from 0 to 100%.

The GWVI quantifies the visibility of green spaces through a specific window in a building. Window sizes vary depending on the building's architecture, age, function, etc. For instance, public buildings like schools or hospitals, or office buildings, where activities are primarily sedentary, may have larger windows as a design feature. This ensures sufficient brightness and thermal comfort in the room, while also allowing a possible window view from a seated position (Aksamija 2013, pp. 69–71; ift Rosenheim GmbH 2015; Deutsche Gesetzliche Unfallversicherung e.V. (DGUV) 2022). The same also applies to medical or care buildings, where a window view should also be possible from a lying position in the room (Jamshidi et al. 2020). Residential buildings frequently feature varying window sizes based on the architectural style and construction period (Siegele 2011). This makes windows a common stylistic element for horizontal facade design, resulting in different window sizes on different floors (Freie und Hansestadt Hamburg et al., n.d., pp. 5–6).

To enable the comparability of the GWVI even with different window sizes in buildings with the same main function, we present the following modifications:

- The Floor Green Window View Index (FGWVI):

$$FGWVI_h = \sum_{i=1}^{m(h)} GWVI_{id} * \frac{1}{m(h)} \tag{2}$$

  where the FGWVI indicates the average value of the GWVI for a specific floor h. The number of windows m depends on h. The possible value range is also from 0 to 100%.
- The Building Green Window View Index (BGWVI):

$$BGWVI_b = \sum_{i=1}^{m(b)} GWVI_{id} * \frac{1}{m(b)} \tag{3}$$

  where the BGWVI indicates the average value of the GWVI for a specific building b. m depends on b and the value range is again from 0 to 100%.

An automated three-step application including window view simulation using bitmaps

In order to automatically implement the presented indices, we use a rendering approach that utilizes 3D graphics rendering. The three-step procedure combines (1) modeling a three-dimensional environment in front of the window with (2) simulating the two-dimensional window view to finally quantify (3) the proportion of visible vegetation in the window view (Kaplan and Kaplan 1989; Bishop et al. 2000; Bishop 2003; Shreiner et al. 2013) (refer to Fig. 2).

The implementation is written in C++and includes OpenGL, a cross-language application programming interface (API) for rendering two- and three-dimensional vector graphics (Shreiner et al. 2013). GLEW (OpenGL Extension Wrangler Library), GLFW (Graphics Library Framework), and GLM (OpenGL Mathematics) are included.

For our case study area in Germany, we used multi-source open data sets, which are provided free of charge to model the three-dimensional environment. The Digital Terrain Model (DTM) represents the topography, while buildings are modeled using a semantic 3D City Model CityGML to serve as viewpoints and view obstacles (Kolbe et al. 2005). At level of detail 2 (LoD2), “all buildings are mapped with standardized roof shapes and oriented according to the real ridge lines” (Bundesamt für Kartographie und Geodäsie 2021). CityGML can also provide qualitative information, such as building function, which is commonly used for Smart Cities, Urban Digital Twins, or BIM (Open Geospatial Consortium, n.d.). Both data sets must be available as a triangulated mesh to determine precise localizations with x-, y-, and z-coordinates.

The 2D land use data utilized in this study was obtained from the official German property cadaster information system, known as the “Amtliches Liegenschaftskatasterinformationssystem”, ALKIS. This data was used to identify property borders and to derive flat vegetation areas. With this data set, it was possible to distinguish between private and public green space and to determine their ownership. Our assumption for private properties was that the undeveloped areas were greened. After selecting appropriate layers in GIS, the data must be provided in.gml format for modeling. Three-dimensional shrubs and trees are modeled using semantically segmented Aerial Light Detection and Ranging (LiDAR) Point Clouds. If required, the point clouds should be classified and clustered using 3D point cloud processing software.

To simulate the two-dimensional window view, we must assume the number and position of windows on

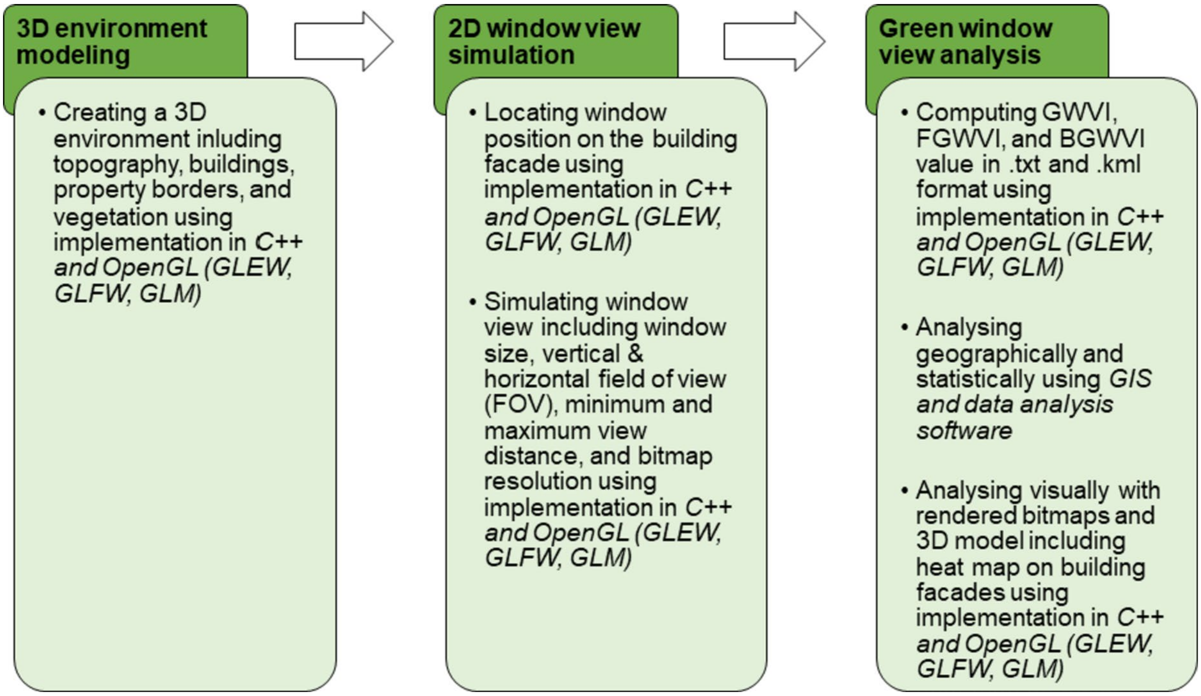


Fig. 2 Pipeline of our automated technical approach for automated visibility analysis including window view simulation using bitmaps

the exterior facade of the modeled buildings. This is necessary because the 3D City Model at LoD2 does not provide any information about the number, size, or position of windows. After localizing the windows, a virtual camera representing the observer is initially placed at the window centers. It is oriented into the three-dimensional environment in front of the building considering the pitch, roll, and yaw and moved by length d in the opposite direction to its orientation. Figure 3 illustrates the simulation principles.

Assuming a simulated window view, we consider w_{np} and h_{np} to be equivalent to the simulated window's aspect ratio. The vertical FOV of the observer is represented by α_v. If the observer is located inside the building with a window-centered view and a known d, α_v can be calculated using:

$$\alpha_v = 2 * \arctan\left(\frac{0.5 * h_{np}}{d}\right) \tag{4}$$

The observer's horizontal FOV is represented by α_h. If α_v is less than 180° respectively d is greater than zero meter, α_h can be derived using following equation:

$$\alpha_h = 2 * \arctan\left(\tan(0.5 * \alpha_v) * \frac{w_{np}}{h_{np}}\right) \tag{5}$$

By defining the near plane np and far plane fp to represent the minimum and maximum view distance, the visible area in front of the corresponding window can be rendered. This simulates the view for different windows while maintaining a window-centered view from inside the building. Anything outside this simulation space is not rendered and is therefore not part of the simulated window view. To transform the three-dimensional environment into a two-dimensional bitmap, we apply perspective projection (Shreiner et al. 2013).

Figure 4 demonstrates the impact of varying observer distances to the window on the spatial characteristics used in the window view simulation, based on Ko et al. (2023).

By utilizing the presented approach to quantify the GWVI we can consider:

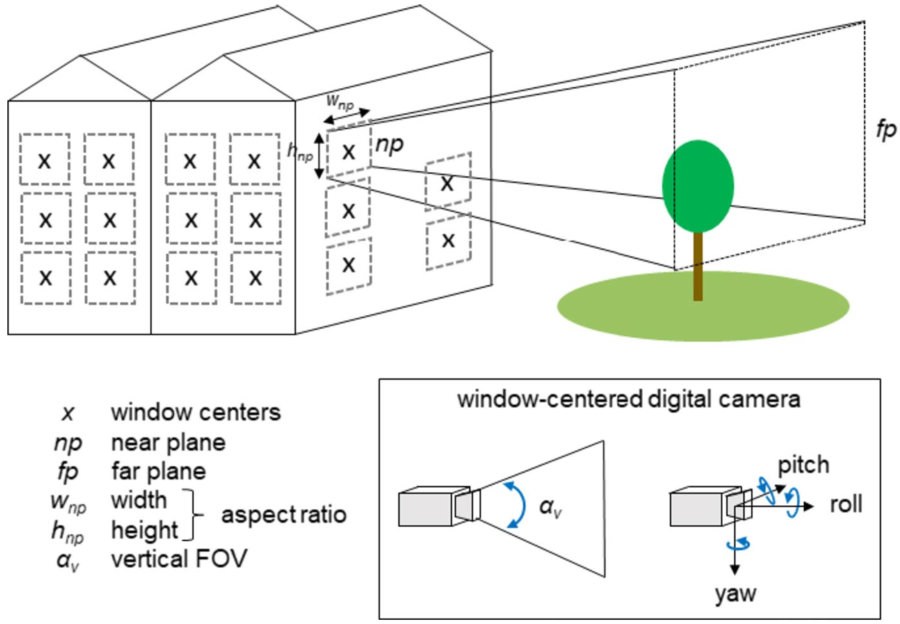


Fig. 3 Visualization of window view simulation principles

- the three-dimensional characteristics of vegetation, such as its depth d_v, width w_v and height h_v,
- the three-dimensional position of the vegetation including the distance of the window to the vegetation di_v and the height of the window h,
- the three-dimensional characteristics of objects obscuring the vegetation, such as their depth d_o, width w_o, and height h_o,
- the three-dimensional position of objects obscuring the vegetation, including the distance of the window from the obscuring object di_o and the height of the window h,
- the observer's distance to the window d assuming a window-centered view including the vertical and horizontal FOV α_v and α_h, and the two-dimensional aspect ratio of the window.

In the final analysis step of the technical implementation, GWVI and FGWVI values are computed in.txt format using the information of the window locations on the building exterior facade and the corresponding visibility values. Similarly, BGWVI values are computed in.kml format using the window locations on the building exterior facade, the corresponding visibility values, and the information of the building layout polygon derived from the 3D City Model CityGML. The data sets can be analyzed statistically and geographically using data analysis software and GIS. During the simulation step, visual analysis is possible as the window views are rendered in bitmaps. A large-scale visual analysis can be conducted by visualizing the three-dimensional model that is generated in the modeling step.

Experimental setup

The feasibility of our approach is demonstrated by the following experiment. It is designed to test the effectiveness of the presented indices and methodology on a real case study. Therefore, visibility values of various vegetation structures are calculated at different scale levels throughout an urban area.

Analysis of green window view index in Bonn, Germany

Bonn is an administrative district-free major city in the south of the federal state of North Rhine-Westphalia and has a population of approximately 336,000 of early 2022 (Bundesstadt Bonn, n.d.-a). It serves as the second seat of government for the Federal Republic of Germany and is located in the Rhineland, Rhine-Ruhr, and Cologne/Bonn metropolitan regions (Bundesstadt Bonn, n.d.-c;

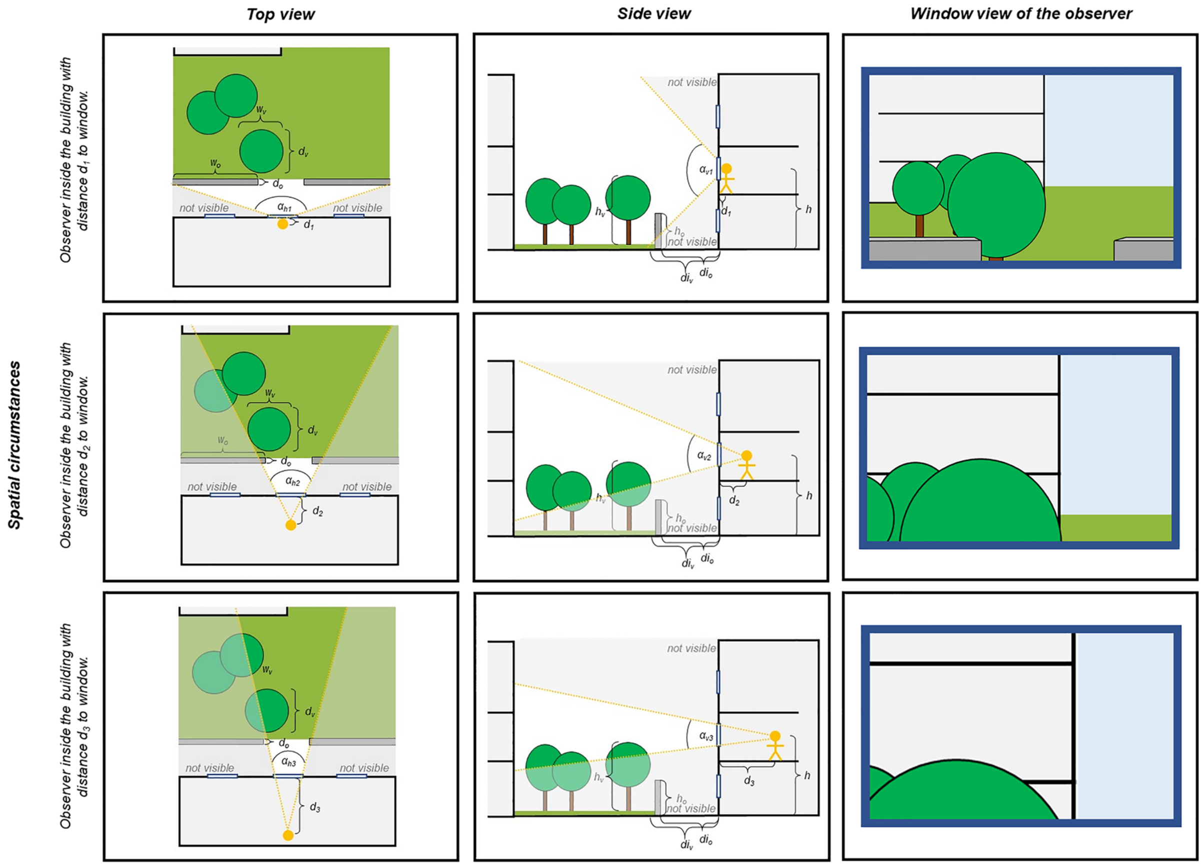


Fig. 4 Factors considered during window view simulation with different indoor positions of the observer resulting in a wide, middle, and narrow field of view (FOW)

Metropolregion Rhein Ruhr, n.d.; Metropolregion Rheinland e.V., n.d.; Region Köln/Bonn e..V., n.d.).

Approximately one third of the city's 141.1 square kilometers is built-up and is divided into four boroughs and 51 districts. The undeveloped areas in Bonn are characterized by private gardens, green spaces, the banks of the Rhine, and 39.8 square kilometers of forest areas, mainly located in the southern part of the urban area. Additionally, there are 16 public parks, 20 meadow orchards with 750 fruit trees, and over 100,000 trees in the urban area of Bonn, of which 36,000 are integrated into roadside greenery and public squares (Bundesstadt Bonn, n.d.-b).

Open data and open source software

Four open data sets were utilized to model the urban environment. For the sake of replicability, Table 2 lists all technical specifications of the used data sources.

The data sets were projected into the Universal Transverse Mercator (UTM) coordinate system. The LiDAR data set was from 2019, while all other data sets were from 2020.

We used Q-GIS 3.16 and CloudCompare 2.11.1. for preprocessing, Q-GIS 3.16 was used for geographical analysis, and GNU Octave 6.4.0 was used for statistical analysis. The workstation ran on a 64-bit operating system, specifically Ubuntu 18.04.6 LTS. It was equipped with an Intel® Core™ i7-3770K CPU @ 3.50 GHz×4

Table 2 Multi-source open data sets to model the three-dimensional environment

Modelling target	Topography	Buildings	Property borders	Flat vegetation	Tall vegetation
Data	Digital terrain model	3D Semantic city model LoD2	ALKIS 2D land use data	ALKIS 2D land use data	Aerial LiDAR point clouds
Source	www.open.nrw.de	www.open.nrw.de	www.geoportal.nrw.de	www.geoportal.nrw.de	www.bezreg-koeln.nrw.de
Coordinate system	ETRS89/UTM	ETRS89/UTM	ETRS89 geographic	ETRS89 geographic	ETRS/UTM
Height	DHHN2016	DHHN2016	–	–	DHHN2016
Spatial resolution	1m	2m	–	–	4–10 points/sqm
Accuracy	20cm (height)	1m (height); Cadaster (cm) (area)	Cadaster (cm) (area)	Cadaster (cm) (area)	15cm (height); 30cm (area)
Format	.gz format	.gml format	.gml format	.gml format	.laz format

processor, a NVIDIA GeForce RTX 3080/PCIe/SSE2 graphics card, and a 220.8 GB hard drive.

Multi-step implementation procedure of the green window view index

Figure 5 illustrated the multi-step procedure for estimating the Green Window View estimation in the case study. The three main steps of the approach are explained in detail below.

During the first implementation step, the data sets were preprocessed to model the three-dimensional urban environment: To improve data distribution, the DTM data set was reduced and triangulated, and the semantic 3D City Model was also triangulated. The vegetation was divided into flat and tall vegetation structures based on their height. ALKIS 2D land use data was utilized to model the flat vegetation areas. The first step was to select land use layer that contained vegetation, such as residential area, mixed use area, sports, leisure, and recreation area, cemetery area, agriculture area, forest area, and grove area. It was assumed that these areas have either a fully private or a fully public ownership. The layers' coordinate system was transformed into UTM and divided into private and public flat vegetation layers based on their ownership. To identify and model tall vegetation, LiDAR point clouds were additionally processed. Linear support vector machine (SVM) was used as a classifier leading to a point-wise classification of the following classes: Tall vegetation (trees and shrubs) and all non-vegetated objects (buildings, cars, etc.). Herewith an average accuracy of 97.8% was achieved. Based on the point-wise classification, a clustering step was perfomed in order to yield aggregated components representing single vegetation objects, e.g. tree, or groups of neighboured vegetations. For this unsupervied learning task, K-Means was applied on our 3D pre-classified vegetation points. Afterwards, the centroids of the clusters were projected into the two-dimensional horizontal plane to derive the object geometries from the point cloud of the trees and shrubs. Here, the object height was determined by the average height of the outermost 10 points and the object width was determined by the average distance between the center of the mass to the 10 farthest points. The object width was projected into the xy-plane. Using the determined object height, the objects were subsequently divided into trees and shrubs. All objects with a height of more than two meters above DTM were assigned to trees, remaining objects with a height of up to two meters above DTM to shrubs. The last step was the determination of the ownership status of the tree and shrub objects using the overlapping of the objects with an ALKIS land use layer (residential area).

The second step of the implementation involved simulating the window view: Firstly, all components of the urban environment were loaded. Then, the window centers were then positioned on the exterior facade of the buildings taking into account the DTM and the semantic 3D building model (refer to Fig. 6). An initial simplified assumption was made for all buildings, regardless of age, architectural style, function, and floor height, to determine the actual number of windows. Therefore, an on-site inspection was conducted in the urban area of Bonn.

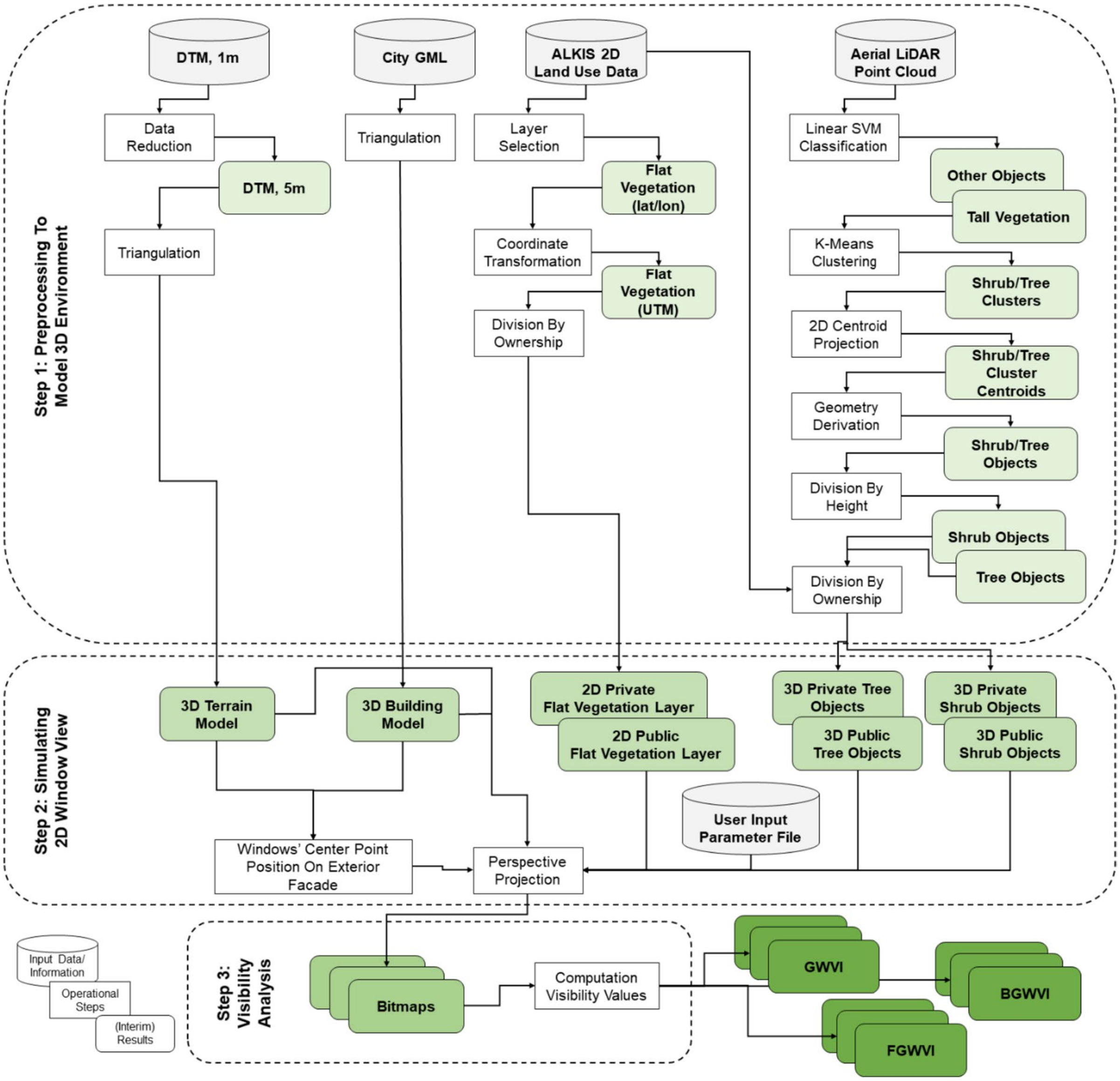


Fig. 5 The structure of the implemented engine and framework for the Green Window View Index (GWVI) estimation

The window centers were spaced three meters apart horizontally and vertically. The first window center was 1.5m away from the edge of the exterior building facade in both horizontal and vertical directions. If the exterior building facade was between one and three meters in length, a window center was placed in the middle of the building facade. The simulation of the window view was performed by taking into account the DTM, the 3D building model, and the requested flat and tall vegetation, based on the user input parameters provided in Table 3.

Finally, in the third step, visibility values were estimated for the different defined scales.

Experimental results

Our method was applied to process the open source data sets for estimating the GWVI, the FGWVI, and

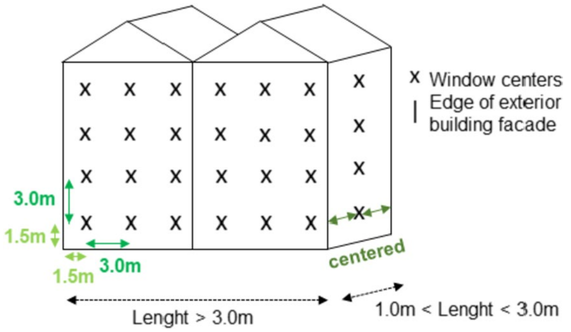


Fig. 6 Positioning of window centers on the exterior building facade

Table 3 Exemplary user input parameter for window view simulation

Input parameter	Experimental value
Assumed window size	1.0m
Distance to window	0.80m
Vertical FOV	64°
Aspect ratio of window	1/1
Minimum view distance	0.81m
Maximum view distance	8,000m
Bitmap resolution	512×512 pixel
Rendering colors	Individual RGB-values

the BGWVI over the entire urban area of Bonn. A total of 2,531,369 window views in a total of 87,592 buildings were automatically simulated, and their indices were calculated for private and public trees, shrubs, and flat vegetation, respectively. Additionally, we determined visibility values for the sky and sealed surfaces or the built-up structures. The calculation, 2D, and 3D visualization took a total of 135,169 s to complete the entire urban area of Bonn. This resulted in an average calculation time of 0.05 s per window view.

The approach provides four types of result visualizations for a visual, descriptive statistical, and geographical analysis of the calculated results on different scales (see Fig. 7).

This includes (a) the rendering of individual simulated window views via a two-dimensional bitmap using green and turquoise for vegetation, grayscale for sealed surfaces or the built-up structures, and blue for sky, (b) the three-dimensional visualization of GWVI values via heat maps in the three-dimensional model, (c) the.txt files of GWVI and FGWVI values that can be transformed into numerical plots or tables, and (d) the.kml files that can be cartographically visualize into two-dimensional maps thematizing BGWVI values.

During the simulation of window views, bitmaps were rendered for each individual view. These can be visually checked and analyzed during the second processing step. It is also possible to save these bitmaps as image files in order to subsequently perform a visual comparison or to carry out an accuracy assessment of the simulation approach using an intersection over union metric. Due to the very large data volume of over two million generated image files, an export and subsequent accuracy assessment were not carried out in this case study. However, in the current follow-up case study in Cologne, Germany this target is being attempted. Results for individual floors can be visualized based on three-dimensional modeling and window localization using heat maps. This tool is ideal for visualizing changes in visual access to urban green spaces during inner urban development processes or landscape planning. It can be used to demonstrate these changes to various stakeholders, including those in politics, planning, municipal authorities, and the local population. Results can be presented in numerical plots, tables, and geodata. The GWVI, FGWVI, and BGWVI values were exported to files in.txt and.kml format, allowing for tabular and cartographic representations using common data analysis software and GIS. This facilitates a targeted visualization with additional semantic data and subsequent analysis.

Regarding the visualization results, it should be highlighted that our approach provides multidimensional representation of the visibility values at different scales. Exporting to common data formats enables further processing and utilization of the results by various stakeholders.

Figure 8 illustrates the amount of visible vegetation classes (in total six different classes, named private and public trees, shrubs, and flat vegetation, respectively) and the distribution of GWVI for all vegetation over the urban area of Bonn. The majority of windows have a diverse vegetation view, with one to four different vegetation classes. The arithmetic

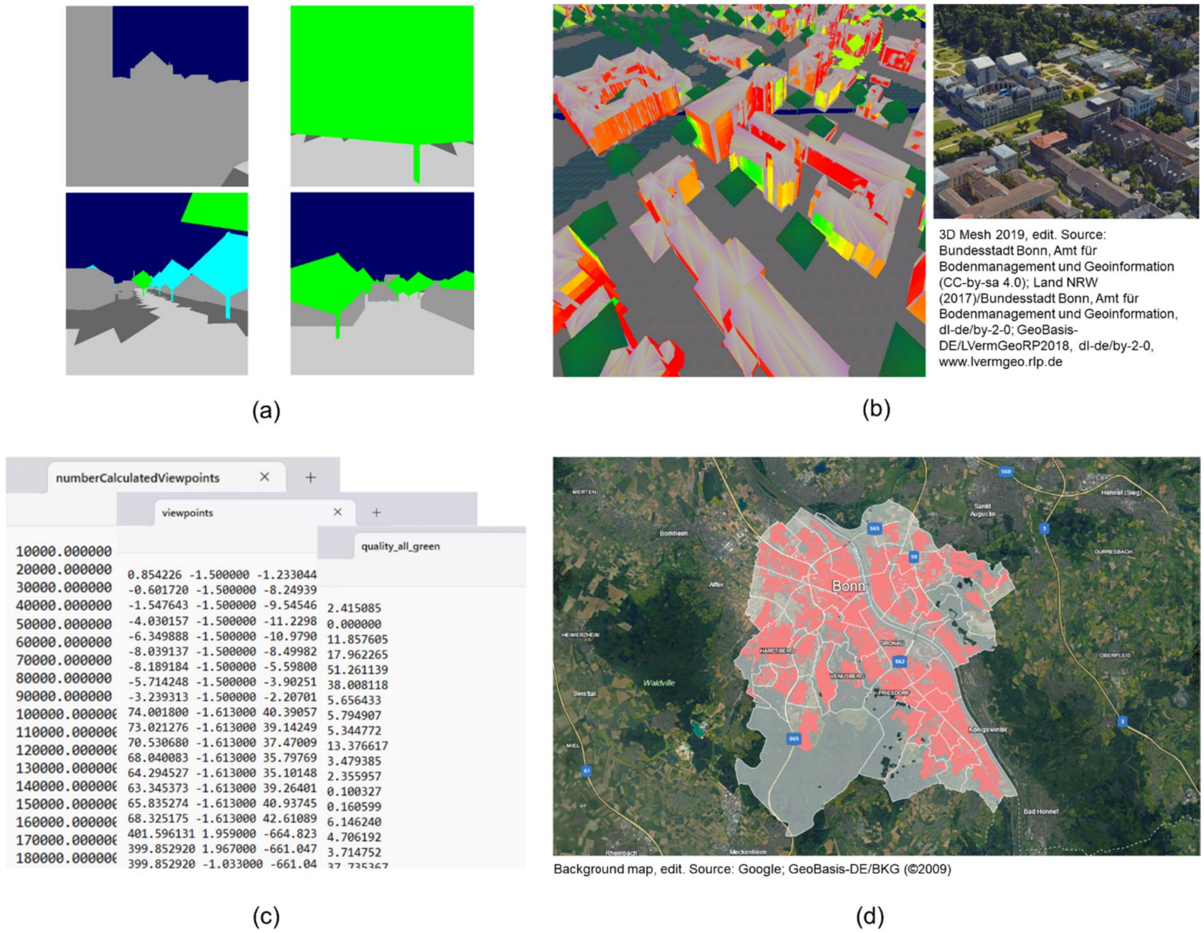


Fig. 7 Examples of result visualization for Green Window View Index (GWVI), Floor Green Window View Index (FGWVI), and Building Green Window View Index (BGWVI) estimation: **a** 2D bitmaps of simulated window views, **b** heat map in 3D model, including reference screenshot from 3D mesh, **c** numeric export files in.txt format, **d** geographic export files of single buildings and city districts in.kml format uploaded in Google Earth

mean of GWVI for all vegetation in the urban area of Bonn equals 26.00%.

The results show that the city of Bonn generally has a heterogeneous green window view.

Figure 9 distinguishes the locality, spread, and skewness of the average GWVI for districts based on visible vegetation type.

In detail, the average GWVI of flat vegetation has a minimum of 8.72%, a lower quartile of 15.51%, a median of 19.63%, an upper quartile of 21.43%, and a maximum of 24.54%. With the exception of the maximum of 1.42% and an upper quantile of 0.63%, the other values of the average GWVI for shrubs are below 0.5%. For visible trees, a minimum of 0.85%, a lover quantile of 5.23%, a median of 7.45%, an upper quantile of 9.38%, and a maximum of 13.12% are given. For the visibility of all vegetation in the window view, the highest values result with a minimum of 15.52%, a lower quartile of 22.58%, a median of 27.81%, an upper quartile of 30.18%, and a maximum of 35.13%.

At first glance, these results appear positive, as observers prefer complexity in the visual perception of nature (Kaplan and Kaplan 1989). However, the fact that the average proportion of visible greenery is less than 30% suggests that there may not be a general satisfaction with the green window view. Studies on the preferences of natural views and their effects on restorativeness have shown a significant positive

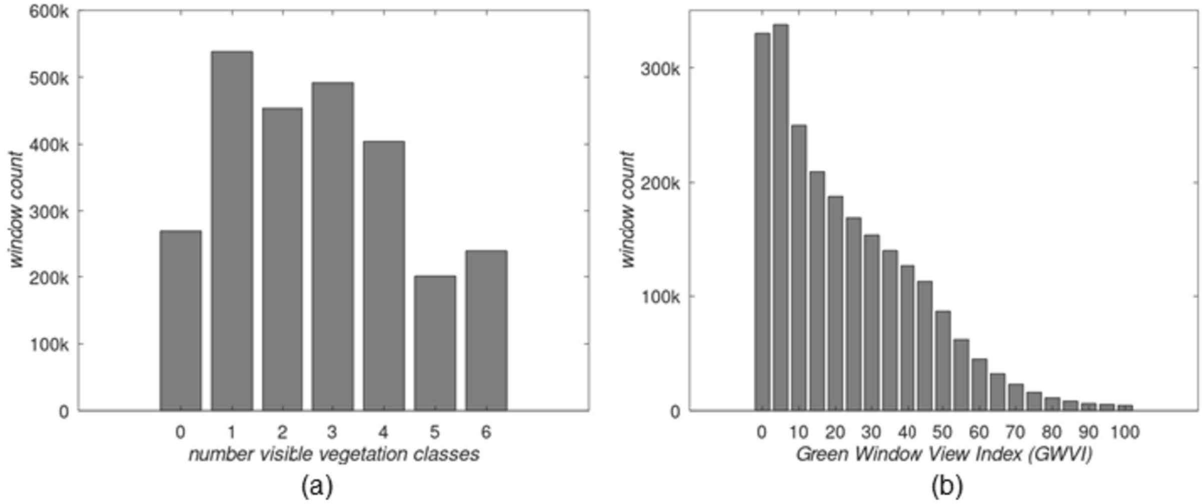
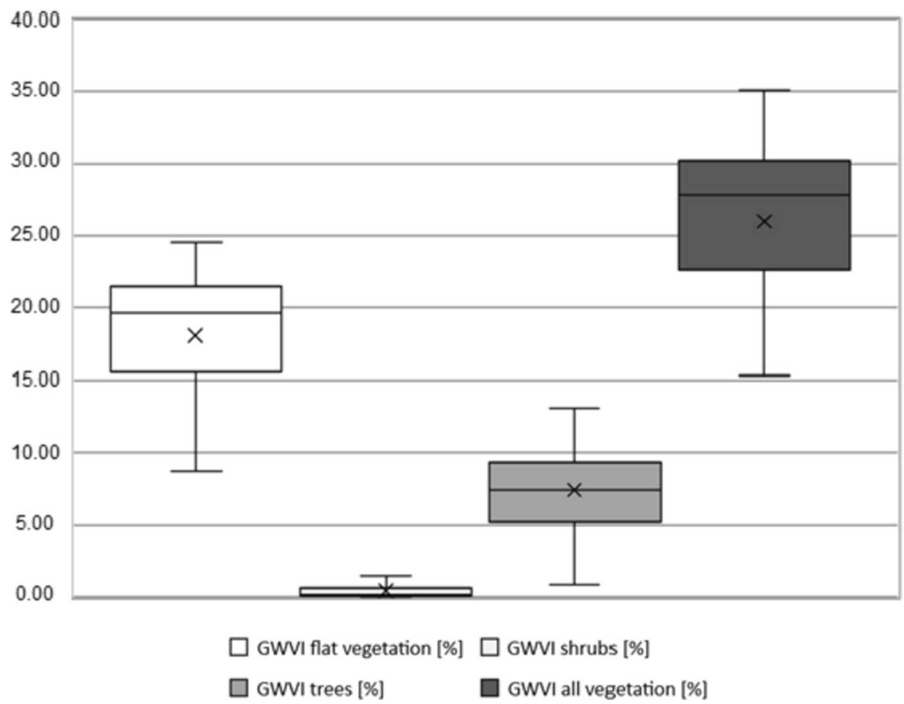


Fig. 8 Characteristics of GWVI in urban area of Bonn: **a** amount of visible vegetation classes, **b** distribution of GWVI for all vegetation

Fig. 9 Locality, spread, and skewness of average GWVI for districts, based on visible vegetation type



influence on the observer if at least 30% of the overall view is green (Aoki 1991; White et al. 2010).

Figure 10 shows the geographic distribution of the average GWVI for individual districts for trees, flat vegetation, and all vegetation. The legend scaling is based on the results of a picture image appraisal method (Aoki 1991). The average GWVI for shrubs is not included due to the very low value of 0.43% throughout the urban area.

The analysis of vegetation visibility in Bonn, as determined by the GWVI, confirms the diversity in both the type and quantity of visible vegetation.

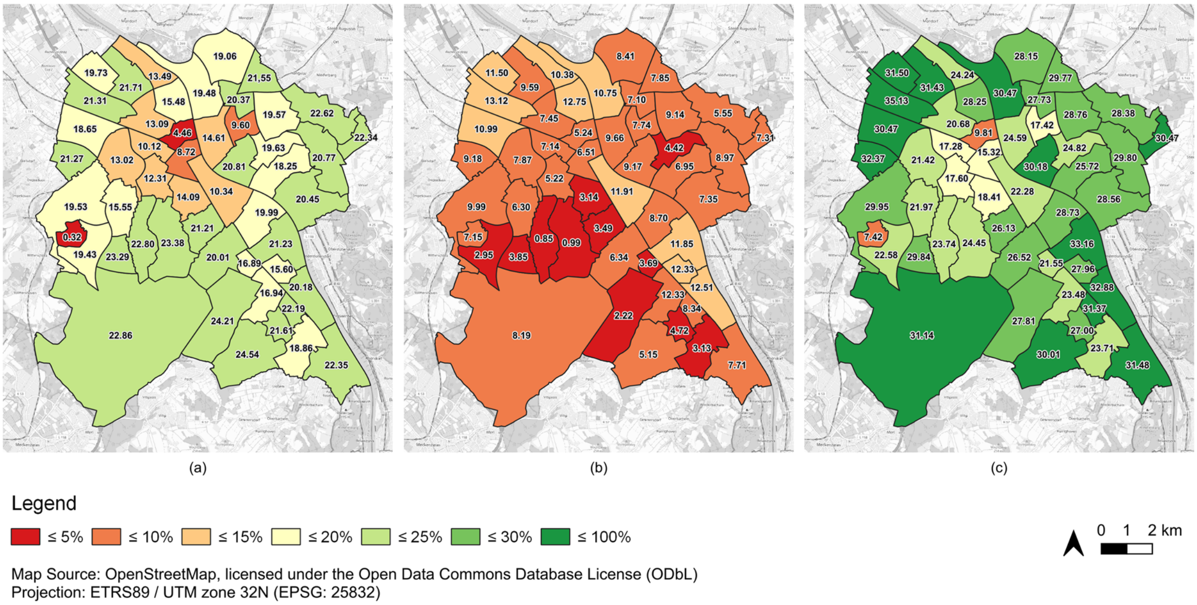


Fig. 10 Average GWVI for districts in Bonn for **a** flat vegetation, **b** trees, **c** all vegetation

However, it also reveals a spatial differentiation in the distribution of visible greenery. The average GWVI decreases towards the city center, suggesting a correlation with urban density values. Notably, the district of Hardthoehe stands out with an average GWVI of 7.42% for all visible vegetation. The area is exclusively occupied by the barracks area of the first headquarters of the Federal Ministry of Defense. Furthermore, it is evident that certain districts of Bonn have an above average GWVI exceeding 30%. The district of "Tannenbusch" has the highest average GWVI at 35.13%. This district is mainly characterized by residential areas with varying building densities including semi-detached houses, terraced houses, and high-rise apartment buildings. The open spaces consist mostly of private gardens or distant areas and a special landmark is the inland dune in the nature reserve, covering an area of approximately seven hectares.

To clarify these suggestions statistically, further analysis is required for buildings with a similar functions and comparable architectural conditions. A follow-up study will investigate the BGWI for health/care and educational buildings in Bonn.

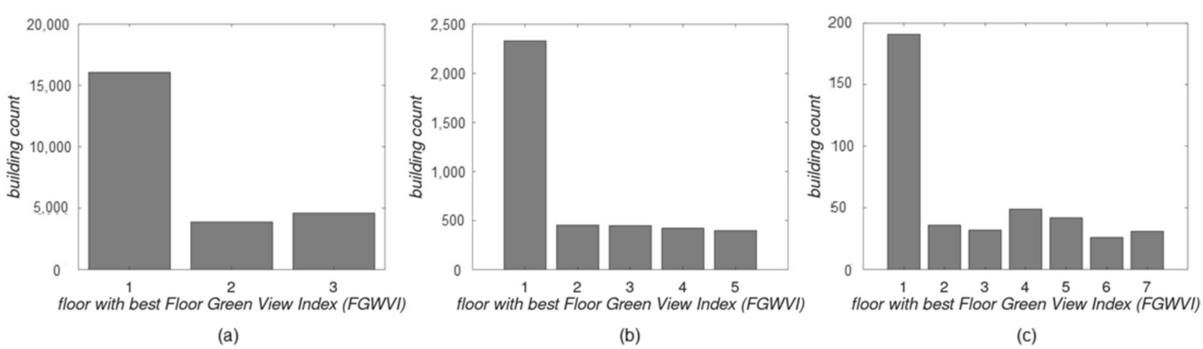


Fig. 11 Distribution of FGWVI for all vegetation according to height for buildings with a total of **a** three floors, **b** five floors, **c** seven floors

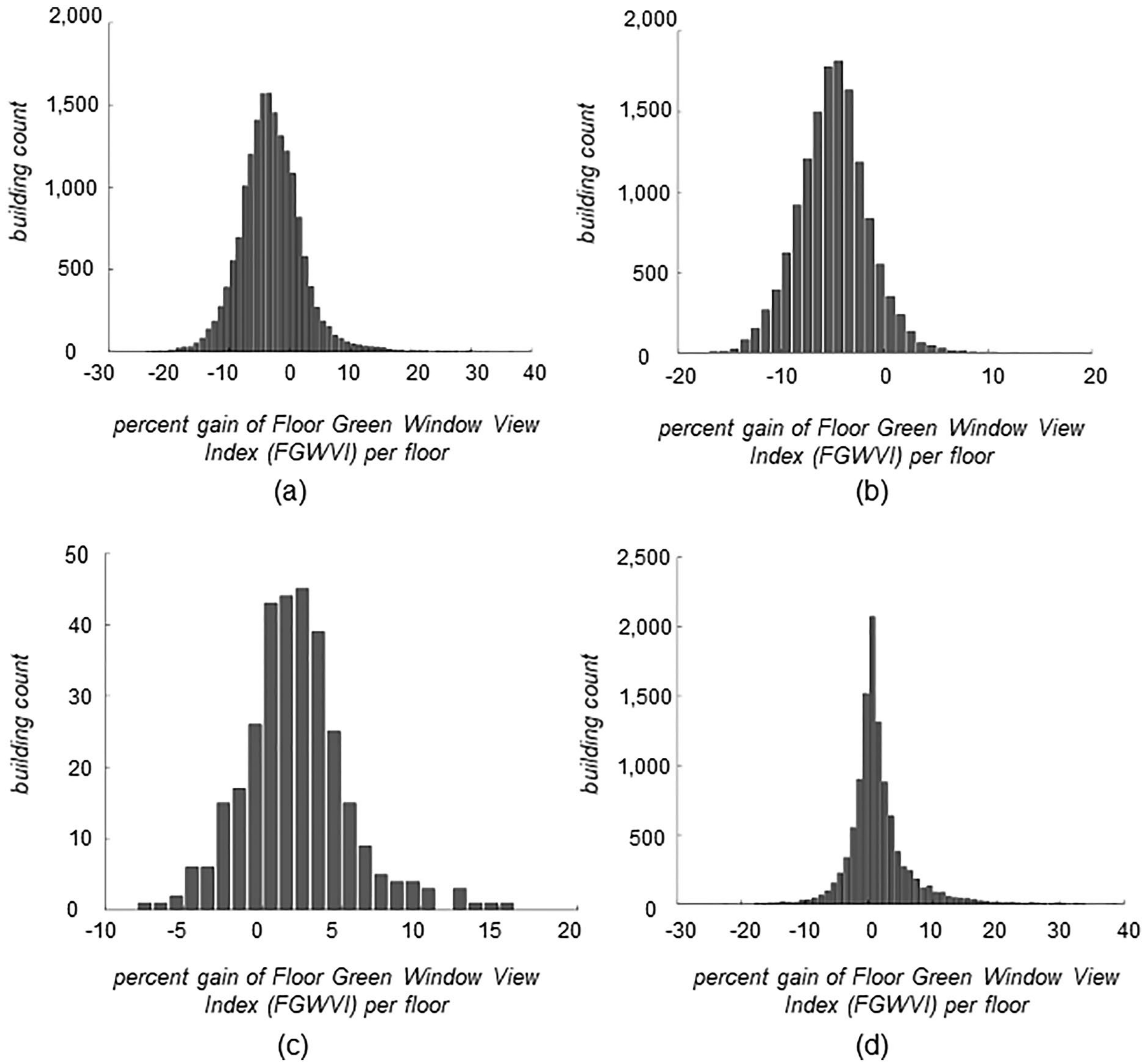


Fig. 12 Percent gain of FGWVI according to height for **a** all vegetation, **b** flat vegetation, **c** shrubs, **d** trees

By analyzing the results geographically, we were able to identify district-wide variations in the distribution of GWVI in Bonn, Germany.

To detect smaller-scale distribution patterns, we assessed the FGWVI of all vegetation based on the corresponding floor height. We only considered floors with at least 5% FGWVI. The first floor of all buildings, with an average window height of 1.5m above ground, had the highest FGWVI. A slight increase was also observed on the fourth and fifth floors (average window height of 10.5m and 13.5m above ground level, respectively) for buildings with a total of seven floors (see Fig. 11).

This phenomenon is also reinforced by the results in Fig. 12. This figure shows the percentage gain in FGWVI per floor for different vegetation types. Buildings with at least three floors and a FGWVI of 5% or more were examined.

The FGWVI decreases on average by 3.13% (median -3.37%) for all vegetation. A stronger decrease is visible with flat vegetation, where the FGWVI decreases by an average of 5.02% (median

-5.01%). An increase in the FGWVI occurs with visible shrubs (average 1.98%, median 1.91%) and trees (average 1.41%, med. 0.64%).

The results suggest that, on the one hand, the FGWI on the ground floor can be attributed to the diversity of the visible vegetation, as flat vegetation, shrubs, and trees can be seen. On the other hand, the measurable amplitude on the 4th floor allows possible conclusions regarding existing tree crowns in front of the windows, which can dominate the green window view.

Discussion

Green window view potential in Bonn, Germany

The descriptive results of the case study show that Bonn has a diverse visual access to urban open spaces. It is recommended to conduct follow-up studies on buildings with specific main functions or urban structure types and examine the correlation between green visibility and planning parameters. This will enable a targeted and evidence-based investigation of visibility potential (Arlt et al. 2005; Meinel et al. 2022).

To ensure a clear geographical demarcation, we limited the environmental modeling and visibility range to the administrative boundaries of the Bonn urban area. Therefore, we did not included areas from neighboring municipalities in our analysis. This may have affected the visibility values in the outer districts of the case study, resulting in values that are too low. In order to eliminate measurement bias and verify the methodological procedure and results of this case study, it may be beneficial to include surrounding municipalities. Additionally, a spatio-temporal analysis of land use or land cover changes caused by urbanization or redensification processes could also be considered to identify inter-regional relationships and different forms of urban green access (Ren et al. 2017; Dong et al. 2020; Yu et al. 2023; Zhang et al. 2023).

Multi-dimensional visibility analysis of green window views

The three-dimensionality of the viewed environment and the two-dimensionality of the window view must be considered when investigating visual access from a window view, according to Bishop (2003), Bishop et al. (2000), and Kaplan and Kaplan (1989). By modeling a three-dimensional environment to simulate a two-dimensional window view while considering the window size, the observer's distance to the window, and their horizontal and vertical FOV (Matsuoka 2010; Abd-Alhamid et al. 2023; Ko et al. 2023), we were able to consider all necessary spatial dimensions. In addition, a sideways examination of the urban green spaces allowed quantification of various three-dimensional vegetative structures in the window views. By implementing this "human-oriented analysis" (Yu et al. 2016), the GWVI supports a spatially-centered analysis of green spaces that focuses on human experience (Xiao et al. 2021). In doing so, our approach differs from classical landscape metrics and satellite-based vegetation indices, which use an area-centered and vegetation-oriented approach to quantify surface characteristics and assess land cover quality (Larkin and Hystad 2018; Dong et al. 2020; Gaw et al. 2022; Zhang et al. 2023).

Thus, our approach fills the research gaps identified by Yu et al. (2016) and Wang et al. (2019), who both focus on visible two-dimensional vegetation structures. Li et al. (2022) also quantify the visible green of two- and three-dimensional vegetation shapes, but their approach excludes the window size, the horizontal FOV, and makes no reference to the distance of the observer to the window. While the GWVI is closely related to their method, our method includes the previously missing parameters in the visibility analysis and is therefore able to simulate the full visual potential of the window view for idealized positions in the building.

However, our approach is also limited by our assumptions about the idealized position in the room. It does not take into account the average height of the observer or the actual position and direction of the observer in the room (van Nes and Yamu 2021; Abd-Alhamid et al. 2023; Ko et al. 2023). Therefore, we could not simulate all spatial usage scenarios inside the building, including the observer's visual perception during different activities while sitting and lying down. To test the simulation of a window view under different activity circumstances, individual buildings or apartments should be investigated with 3D city models at LoD4. This data resolution enables a modeling of interior spaces including precise information on window position and size.

Additionally, assumptions were made about the number, position, and size of windows on exterior building facades due to the limited LoD2 of the 3D City Model. Therefore, the simulation and the final statement regarding the amount of visible vegetation in the window view may not be entirely accurate. The results approximate reality. A future accuracy assessment of our approach using intersection over union metric will clarify the window view simulation and the spatial interaction of 3D environment modeling and window positioning. Once city-scale 3D City Models at LoD3 are available, our approach can be easily extended with real-world window positions and sizes. These limitations should to be addressed in follow-up studies to improve our approach.

Approach applicability for the practice

Multiple studies have demonstrated that the presence and quantity of visible greenery in window views significantly impact the quality of stay in buildings such as schools, hospitals, and workplaces, as well as the economic value of real estate (Felsten 2009; Van Renterghem and Botteldooren 2016; van Esch et al. 2019; Mihandoust et al. 2021). The GWVI values can be generated in various forms, such as bitmaps for individual window views, 3D heat maps for building floor and total building levels, 2D maps for aggregated results at the neighborhood, district, or municipal level, and numerical plots and tables for raw data analysis. These results can be used by architects, real estate appraisers, investors, and urban and landscape planners to evaluate building status-quo situations as well as different planning scenarios (Crompton and Nicholls 2019; Williams et al. 2019; La Rosa and Izakovicová 2022; Umweltbundesamt 2022).

By implementing our approach in OpenGL, we were able to calculate and visualize the vegetation visibility of an entire urban area with a population of approximately 336,000. The average calculation time per window view was 0.05 s. Our method is faster than those of Yu et al. (2016), Wang et al. (2019), and Li et al. (2022), who only tested their methodologies on individual buildings or blocks of buildings. This article discusses the usefulness of this feature for data analysis and visualization in participatory citizenship and decision-making processes for urban, landscape, or transportation planning. It follows current trends in integrating VR and gaming engines into planning processes, as well as integrating planning visualization into urban digital twins (Herwig and Paar 2002; Cristie and Berger 2017; Kalberer 2021). However, it is important to note that this result was achieved on a high-performance workstation. Using smaller workstations may result in a slower overall process.

In addition, the exclusive use of open data and open source software enables transparent advancement and adaptation of our approach, allowing for multi-functional and multi-disciplinary use in both private and public institutions (Bundesministerium des Innern, für Bau und Heimat (BMI), 2021; International Smart Cities Networkt (ISCN), 2022; Mobasheri, 2021; Moreira de Oliveira and Painho 2021; Yap et al. 2022). It enables public participation and communication with planning authorities, and facilitates cooperation between authorities and planners in different fields. It involves the use of freely accessible data and adaptable software systems that ensure data quality assurance throughout the decision-making process (Henkel 2023).

Methodological openings for qualitative window view analysis

Our method automatically quantifies both the proportion and the existence of visible vegetation in the window view. This information is crucial for multi-dimensional and multi-disciplinary research, enabling consistent and comparable investigations and evaluations of urban green space access (Söderlund and Newman 2015; Crompton and Nicholls 2019; Trøstrup et al. 2019; Van Renterghem 2019; Williams et al. 2019). This also creates the possibility of developing an evaluation index that includes all visible structures in the window, such as vegetation, water, sky, built-up areas. These structures can be individually evaluated through questionnaires or interviews, as suggested by Hellinga and Hordijk (2014) and Kent and Schiavon (2022), to analyze the quality and effect dimensions of the window view. This includes the integration of further semantic information of the visible structures, such as phenology status (Yu et al. 2016; Wang et al. 2019; Li et al. 2020; Ko et al. 2021; Kent and Schiavon 2022; Abd-Alhamid et al. 2023).

Conclusion

The Green Window View Index (GWVI) and its methodological approach, written in C++, utilizing OpenGL and multi-source open data input, are presented based on a literature review of existing methodologies' strengths and weaknesses. Floor Green View Index (FGWI) and Building Green View Index (BGWI) modifications are used to consider various window sizes on a building facade. The GWVI implementation procedure consists of three main components: (1) modeling of the three-dimensional environment, (2) simulating the two-dimensional window views, and (3) computing the visibility value in commonly used data formats. This allows a further processing and analysis of the results with universally available software.

The feasibility of the new indices and methodology is demonstrated using real-world data from a case study in Bonn, Germany. The visibility values for flat vegetation, shrubs and trees are calculated for approximately 2.6 million window views in over 87,500 buildings, with an average calculation time of 0.05 s per window view.

Our engine addresses previous research gaps by utilizing an innovative methodological approach and an open data basis. It enables the consideration of three-dimensional vegetation structures, two-dimensional window characteristics, and idealized indoor positions of the observer in the visibility analysis at the building level. Additionally, this approach provides the opportunity to develop additional quantitative and qualitative window view analysis methods and allows for versatile use across multiple functions and disciplines in practical applications.

However, like many new approaches, our method also has limitations. The limited data available from 3D city models forces us to simulate window sizes and positions. Additionally, the simulated window view further does not consider air pollution, weather, or time of day on resulting visibility values. These limitations will be the subject of future research.

In an ongoing case study, we are specifically investigating the GWVI for residential buildings and addressing the aforementioned challenges.

Our new approach around the GWVI complements previous research on building level vegetation visibility analysis and allows to fill previous research gaps. The use of open data and open source software for visualization and analysis has the potential to support multi-functional and multi-disciplinary research, planning, and participatory citizenship, and to provide new insights in the field of access analysis.

Acknowledgements We gratefully acknowledge the open data sets from Open NRW, GEOportal NRW, and the Regional Government of Cologne. We also gratefully thank Daniel Thomas Kubsda and Martin Obersheimer for their work on the first version of the methodological approach.

Author contributions AMB: Conceptualization. AMB, BN, YD: Methodology. AMB, YD: Formal analysis and investigation. AMB: Writing - original draft preparation. AMB, BN, TKi, JHH, YD, TKö: Writing - review and editing. All authors have read and approved the final manuscript.

Funding Open Access funding enabled and organized by Projekt DEAL.

Declarations

Competing interests The authors declare no competing interests.

References

Abd-Alhamid F, Kent M, Wu Y (2023) Quantifying window view quality: a review on view perception assessment and representation methods. Build Environ 227(2):1–23

Aksamija A (2013) Sustainable Facades: Design Methods for High-Performance Building Envelopes, 1st edn. Wiley, Hoboken
Angel S, Lamson-Hall P, Gonzalez Blanco Z (2021) Anatomy of density: measurable factors that constitute urban density. Build Cities 2(1):264–282
Aoki Y (1991) Evaluation methods for landscapes with greenery. Landsc Res 16(3):3–6
Arlt G, Hennersdorf J, Lehmann I, Thinh NX (2005) Auswirkungen städtischer Nutzungsstrukturen auf Grünflächen und Grünvolumen (Effects of urban utilization structures on green spaces and green volumes) 1st ed., vol 47
Benfield JA, Rainbolt GN, Bell PA, Donovan GH (2015) Classrooms with nature views: evidence of differing student perceptions and behaviors. Environ Behav 47(2):140–157
Biljecki F, Ito K (2021) Street view imagery in urban analytics and GIS: a review. Landsc Urban Plan 215:104217:1-104217:20
Bishop ID (2003) Assessment of visual qualities, impacts, and behaviours, in the landscape, by using measures of visibility. Environ Plann B Plann Des 2003(30):677–688
Bishop ID, Wherrett JR, Miller DR (2000) Using image depth variables as predictors of visual quality. Environ Plann B Plann Des 2000(27):865–875.
Bishop ID, Lange E, Mahbubul AM (2004) Estimation of the influence of view components on high-rise apartment pricing using a public survey and GIS modeling. Environ Plan b, Plan Des 31(3):439–452
Bundesstadt Bonn. (n.d.-b). *Parks. Gärten (Parks. Gardens)*. https://www.bonn.de/bonn-erleben/aktiv-und-unterwegs/parks-und-gaerten.php?sp%3Apage%5Bsearch-1.form%5D%5B0%5D=1andaction=submit
Bundesstadt Bonn. (n.d.-a). *Bonn in Zahlen (Bonn in numbers)*. https://www.bonn.de/service-bieten/aktuelles-zahlen-fakten/bonn-in-zahlen.php
Bundesstadt Bonn. (n.d.-c). *Politisches Bonn (Political Bonn)*. https://www.bonn.de/bonn-erleben/besichtigen-entdecken/politisches-bonn.php
Brace O, Garrido-Cumbrera M, Foley R, Correa-Fernandez J, Suarez-Caceres G, Lafortezza R (2020) Is a View of green spaces from home associated with a lower risk of anxiety and depression? Int J Environ Res Public Health. https://doi.org/10.3390/ijerph17197014
Bundesamt für Kartographie und Geodäsie. (2021) 3D-Gebäudemodelle LoD2 Deutschland (LoD2-DE) (3D Building Models LoD2 Germany). https://gdz.bkg.bund.de/index.php/default/3d-gebaudemodelle-lod2-deutschland-lod2-de.html
Bundesministerium des Innern, für Bau und Heimat (BMI) (Ed.). (2021). Open-Data-Strategie der Bundesregierung. Open data strategy of the Federal Government of Germany.
Chang C-Y, Chen P-K (2005) Human response to window views and indoor plants in the workplace. HortScience 40(5):1354–1359
Chen WY, Jim CY (2010) Amenities and disamenities: a hedonic analysis of the heterogeneous urban landscape in Shenzhen (China). Geogr J 176(3):227–240
Cristie V, Berger M (2017) Game Engines for Urban Exploration: Bridging Science Narrative for Broader Participants. In: Nijholt A (ed) Playable Cities: The City as a Digital Playground. Springer, Cham, pp 87–107
Crompton JL, Nicholls S (2019) The impact of park views on property values. Leisure Sci. https://doi.org/10.1080/01490400.2019.1703125
Deutsche Gesetzliche Unfallversicherung e.V. (DGUV) (Ed.). (2022). DGUV Information 215–211—Tageslicht am Arbeitsplatz und Sichtverbindung nach außen (Daylight at the workplace and line of sight to the outside) (215th–211th ed.). MAXDORNPRESSE GmbH and Co. KG.
Dong Y, Ren Z, Fu Y, Miao Z, Yang R, Sun Y, He X (2020) Recording Urban land dynamic and its effects during 2000–2019 at 15-m resolution by cloud computing with landsat series. Remote Sens. https://doi.org/10.3390/rs12152451
Eichhorn S, Siedentop S (2022) Inside before outside? An estimate of inner urban development in North Rhine-Westphalian municipalities, 1979 to 2011. Raumforsch Raumordn. https://doi.org/10.14512/rur.178
Engell T, Lorås HW, Sigmundsson H (2020) Window view of nature after brief exercise improves choice reaction time and heart rate restoration. New Ideas in Psychol 58:100781
Esperon-Rodriguez M, Rymer PD, Power SA, Challis A, Marchin RM, Tjoelker MG (2020) Functional adaptations and trait plasticity of urban trees along a climatic gradient. Urban Forest Urban Green 54(2020):1–9.
Felsten G (2009) Where to take a study break on the college campus: an attention restoration theory perspective. J Environ Psychol 29(1):160–167.
Fisher-Gewirtzman D, Shashkov A, Doytsher Y (2013) Voxel based volumetric visibility analysis of urban environments. Surv Rev 45(333):451–461.
Freie und Hansestadt Hamburg, Bezirksamt Eimsbüttel, Dezernat für Wirtschaft, Bauen und Umwelt, and Fachamt Stadt- und Landschaftsplannung (Eds.). (n.d.). *Eimsbüttel: Gestaltungsleitfaden für das Bauen im Bestand (Eimsbüttel: Design guide for construction in existing structures)*.
Fromm E (1973) The Anatomy of Human Destructiveness, 1st edn. Holt, Rinehart and Winston
Gao C, Zhang S (2020) The restorative quality of patient ward environment: tests of six dominant design characteristics. Build Environ. https://doi.org/10.1016/j.buildenv.2020.107039
Gaw LY, Chen S, Chow YS, Lee F, Biljecki F (2022) Comparing street view imagery and aerial perspectives in the built environment. ISPRS Annals Photogramm Remote Sens Sp Inform Sci X-4/W3-2022:49–56
Gu J, Wang X, Liu G (2021) Rediscovering the amenity value of urban landscapes in the mountainous areas with high-rise buildings from the perspective of 3D vertical urban systems. Urban Forest Urban Green. https://doi.org/10.1016/j.ufug.2021.127018
Haaland C, Konijnendijk van den Bosch C (2015) Challenges and strategies for urban green-space planning in cities undergoing densification: a review. Urban Forest Urban Green 14(4):760–771.

Hellinga H, Hordijk T (2014) The DandV analysis method: a method for the analysis of daylight access and view quality. Build Environ 79:101–114.
Hellmanns J, Schiewe J, Kistemann T, Höser C (2019) A planning tool for the automated quantification and visualization of blue space. KN - J Cartogr Geogr Inform 2019(69):63–71.
Henkel M (2023) Befreit eure Daten! Attraktivere Städte durch offene Daten. (Free your data! More attractive cities based on open data.). Forum Wohnen Und Stadtentwicklung 1:21–24
Herwig A, Paar P (2002) Game Engines: Tools for Landscape Visualization and Planning? In: Buhmann E, Nothhelfer U, Pietsch M (eds) Trends in GIS and virtualization in environmental planning an design: Proceedings at Anhalt University of Applied Sciences. Wichmann Verlag, pp 162–171
Hilal M, Joly D, Roy D, Vuidel G (2018) Visual structure of landscapes seen from built environment. Urban Forest Urban Green 32:71–80.
Hui ECM, Liang C (2016) Spatial spillover effect of urban landscape views on property price. Appl Geogr 72:26–35.
International Smart Cities Networkt (ISCN). (2022). Data Strategies for a Common Good-oriented Urban Development. International.
Jamshidi S, Parker JS, Hashemi S (2020) The effects of environmental factors on the patient outcomes in hospital environments: a review of literature. Front Archit Res 9(2):249–263.
Jim CY, Chen WY (2007) Consumption preferences and environmental externalities: a hedonic analysis of the housing market in Guangzhou. Geoforum 38(2):414–431.
Jim CY, Chen WY (2010) External effects of neighbourhood parks and landscape elements on high-rise residential value. Land Use Policy 27(2):662–670.
Kalberer P (2021) *Using game engines for 3D geospatial development* [FOSS4G]. https://www.youtube.com/watch?v=9O1J_8eKovc
Kaplan R (1993) The role of nature in the context of the workplace. Landsc Urban Plan 26(1–4):193–201
Kaplan R, Kaplan S (1989) The Experience of Nature: A Psychological Perspective. Cambridge University Press, Cambridge
Kaplan Mintz K, Ayalon O, Nathan O, Eshet T (2021) See or Be? Contact with nature and well-being during COVID-19 lockdown. J Environ Psychol 78:101714:1-101714:13
Kara A, van Oosterom P, Çağdaş V, Işıkdağ Ü, Lemmen C (2020) 3 Dimensional data research for property valuation in the context of the LADM valuation information model. Land Use Policy 98:104179:1-104179:1
Kent MG, Schiavon S (2022) Predicting window view preferences using the environmental information criteria. LEUKOS J Illum Eng Soc 19(2):190–209.
Kley S, Dovbishchuk T (2021) How a lack of green in the residential environment lowers the life satisfaction of city dwellers and increases their willingness to relocate. Sustainability 13(7):3984:1-3984:15
Ko WH, Kent MG, Schiavon S, Levitt B, Betti G (2021) A window view quality assessment framework. LEUKOS J Illum Eng Soc 18(22):268–293.
Ko WH, Schiavon S, Santos L, Kent MG, Kim H, Keshavarzi M (2023) View access index: the effects of geometric variables of window views on occupants' satisfaction. Build Environ 234:110132.
Kolbe TH, Gröger G, Plümer L (2005). CityGML – Interoperable access to 3D city models. In: Proceedings of the Int. Symposium on Geoinformation for Disaster Management, pp 1–16
Region Köln/Bonn e.V. (n.d.). Region Köln-Bonn (Region Cologne/Bonn). https://www.region-koeln-bonn.de/
La Rosa D, Izakovicová Z (2022) Visibility analysis to enhance landscape protection: a proposal of planning norms and regulations for Slovakia. Land 11(9):1–16.
Larkin A, Hystad P (2018) Evaluating street view exposure measures of visible green space for health research. J Eposure Sci Environ Epidemiol 2019(29):447–456.
Li M, Xue F, Wu Y, Yeh AGO (2022) A room with a view: automatic assessment of window views for high-rise high-density areas using city information models and deep transfer learning. Landsc Urban Plan 226:104505.
Li, M., Xue, F., Yeh, A. G. O., and Lu, W. (2020, November). Classification of photo-realistic 3D window views in a high-density city: The case of Hong Kong. In: Proceedings of the 25th International Symposium on Advancement of Construction Management and Real Estate (CRIOCM2020). 25th International Symposium on Advancement of Construction Management and Real Estate (CRIOCM2020), Wuhan, China. https://doi.org/10.1007/978-981-16-3587-8
Lindemann-Matthies P, Benkowitz D, Hellinger F (2021) Associations between the naturalness of window and interior classroom views, subjective well-being of primary school children and their performance in an attention and concentration test. Landsc Urban Plan 214:104146:1.
Matsuoka RH (2010) Student performance and high school landscapes: examining the links. Landsc Urban Plan 97(4):273–282.
McFarland AL (2017) The relationship between the use of green spaces and public gardens in the work place on mental well-being, quality of life, and job satisfaction for employees and volunteers. Hortatechnology 27(2):187–198
Meinel G, Krüger T, Eichler L, Wurm M, Tenikl J, Frick A, Wagner K, Fina S (2022) Wie grün sind deutsche Städte? (How green are German cites?) (p. 131) [Projektbericht]. Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR) im Bundesamt für Bauwesen und Raumordnung (BBR).
Metropolregion Rhein Ruhr. (n.d.). *Urlaub im Ruhrgebiet and am Rhein (Vacation in the Ruhr and Rhine area)*. https://www.rhein-ruhr-region.de/
Metropolregion Rheinland e.V. (n.d.). Mitglieder (Members). https://metropolregion-rheinland.de/mitglieder/
Mihandoust S, Pati D, Lee J, Roney J (2021) Exploring the relationship between perceived visual access to nature and nurse burnout. HERD 14(3):258–273.
Mobasheri A (2021) Open Source Geospatial Science for Urban Studies. The Value of Open Geospatial Data. Springer, Cham
Moreira de Oliveira TH, Painho M (2021) Open Geospatial Data Contribution Towards Sentiment Analysis Within

the Human Dimension of Smart Cities. In: Mobasheri A (ed) Open Source Geospatial Science for Urban Studies. The Value of Open Geospatial Data. Springer, Cham, pp 75–95

Motamedi A, Wang Z, Yabuki N, Fukuda T, Michikawa T (2017) Signage visibility analysis and optimization system using BIM-enabled virtual reality (VR) environments. Adv Eng Inform 32:248–262.

Open Geospatial Consortium. (n.d.). *CityGML. Overview.* www.ogc.org/standard/citygml/. Accessed 24 May 2023

Ostwald MJ, Dawes MJ (2018) The Mathematics of the Modernist Villa. Springer, Cham

Pluta M, Mitka B (2019) V-factor indicator in the assessment of the change in the Attractiveness of view as a result of the implementation of a specific planning scenario. ISPRS Int J Geo Inf 8(2):78.

Raanaas RK, Patil GG, Hartig T (2012) Health benefits of a view of nature through the window: a quasi-experimental study of patients in a residential rehabilitation center. Clin Rehabil 26(1):21–32.

Ren Z, Pu R, Haifeng Z, Zhang D, He X (2017) Spatiotemporal analyses of urban vegetation structural attributes using multitemporal Landsat TM data and field measurements. Annals Forest Sci. https://doi.org/10.1007/s13595-017-0654-x

ift Rosenheim GmbH (2015) Einsatzempfehlungen für Fenster in Schulbauten; Anforderungen, Planungsgrundlagen, Konstruktion und Ausführung (Recommendations for the use of windows in school buildings; requirements, planning principles, construction and execution) (FE-16/1). Fraunhofer IRB Verlag.

Semeraro T, Scarano A, Buccolieri R, Santinoano A, Aarrevaara E (2021) Planning of urban green spaces: an ecological perspective on human benefits. Land 105(10):1–25.

Shreiner D, Sellers G, Kessenich J, Licea-Kane B (2013) OpenGL Programming Guide: The Official Guide to Learning OpenGL. Addison-Wesley, Boston

Siegele K (2011) Historische Fenster – Konstruktion und Form: Vom Stock zur Sprosse (Historic windows—Construction and form: From the stick to the muntin). In *Www.db deutsche bauzeitung.de*. https://www.db-bauzeitung.de/bauen-im-bestand/historische-bautechniken/historische-fenster/

Söderlund J, Newman P (2015) Biophilic architecture: a review of the rationale and outcomes. AIMS Environ Sci 2(4):950–969.

Soga M, Evans MJ, Tsuchiya K, Fukano Y (2021) A room with a green view: the importance of nearby nature for mental health during the COVID-19 pandemic. Ecol Appl 31(2):e2248:1-e2248:10

Suleiman, W., Joliveau, T., and Favier, E. (2013). A New Algorithm for 3D Isovist. In 15th International Symposium on Spatial Data Handling Geospatial dynamics, geosimulation and exploratory visualization, 22-24th August 2012 in Bonn, Germany. Advances in Spatial Data Handling. Handling, Advances in Geographic Information Science, pp 157–173

Sun K, Echevarria Sanchez GM, De Coensel B, Van Renterghem T, Talsma D, Botteldooren D (2018) Personal audiovisual aptitude influences the interaction between landscape and soundscape appraisal. Front Psychol 9:780:1-780:15

Taylor AF, Kuo FC, Sullivan WC (2002) Views of nature and self-discipline: evidence from inner city children. J Environ Psychol 22(1–2):49–63

Tennessen CM, Cimprich B (1995) Views to nature: effects on attention. J Environ Psychol 15(1):77–85.

Torres Toda M, Miri M, Alonso L, Gómez-Roig MD, Foraster M, Dadvand P (2020) Exposure to greenspace and birth weight in a middle-income country. Environ Res 189:109866.

Trøstrup CH, Christiansen AB, Stølen KS, Nielsen PK, Stelter R (2019) The effect of nature exposure on the mental health of patients: a systematic review. Qual Life Res 28(7):1695–1703.

Ulrich R (1984) View through a window may influence recovery from surgery. Science 224:420–421

Umweltbundesamt (2022) Dreifache Innenentwicklung—Definition, Aufgaben und Chancen für eine umweltorientierte Stadtentwicklung (Triple inner urban development—Definition, tasks, and opportunities for environmentally oriented urban development). https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/221208_uba_hg_dreifacheinnenentwicklung.pdf

United Nations Human Settlements Programme (Ed.). (2020). World Cities Report 2020 The Value of Sustainable Urbanization. https://unhabitat.org/sites/default/files/2020/10/wcr_2020_report.pdf

United Nations Human Settlements Programme (Ed.). (2021). *Annual Report 2020*.

United Nations. (2017). Resolution adopted by the General Assembly on 6 July 2017 Work of the Statistical Commission pertaining to the 2030 Agenda for Sustainable Development.

van Nes A, Yamu C (2021) Introduction to Space Syntax in Urban Studies, 1st edn. Springer, Cham

van Esch E, Minjock R, Colarelli SM, Hirsch S (2019) Office window views: view features trump nature in predicting employee well-being. J Environ Psychol 64:56–64.

Van Renterghem T (2019) Towards explaining the positive effect of vegetation on the perception of environmental noise. Urban Forest Urban Green 40:133–144

Van Renterghem T, Botteldooren D (2016) View on outdoor vegetation reduces noise annoyance for dwellers near busy roads. Landsc Urban Plan 148:203–215

Wang W, Lin Z, Zhang L, Yu T, Ciren P, Zhu Y (2019) Building visual green index: A measure of visual green spaces for urban building. Urban Forestry and Urban Greening 40:335–343.

Wang C, Ren Z, Dong Y, Zhang P, Guo Y, Wang W, Bao G (2022) Efficient cooling of cities at global scale using urban green space to mitigate urban heat island effects in different climatic regions. Urban Forest Urban Green 74(2022):1–13

White M, Smith A, Humphryes K, Pahl S, Snelling D, Depledge M (2010) Blue space: The importance of water for preference, affect, and restorativeness ratings of natural and built scenes. J Environ Psychol 30(4):482–493

Williams KJH, Lee KE, Sargent L, Johnson KA, Rayner J, Farrell C, Miller RE, Williams NSG (2019) Appraising the psychological benefits of green roofs for city residents and workers. Urban Forest Urban Green 44:126399:1-126399:23.

Wilson EO (1984) Biophilia, 1st edn. Harvard University Press, Cambridge

Xiao L, Wang W, Ren Z, Fu Y, Lv H, He X (2021) Two-city street-view greenery variations and association with forest attributes and landscape metrics in NE China. Landscape Ecol 2021(36):1261–1280.

Yap W, Janssen P, Biljecki F (2022) Free and open source urbanism: software for urban planning practice. Comput Environ Urban Syst 96(2022):1–20.

Yu S, Yu B, Song W, Wu B, Zhou J, Huang Y, Wu J, Zhao F, Mao W (2016) View-based greenery: a three-dimensional assessment of city buildings' green visibility using floor green view index. Landsc Urban Plan 152:13–26.

Yu S, Leichtle T, Zhang Z, Liu F, Wang X, Yan X, Taubenböck H (2023) Does urban growth mean the loss of greenness? A multi-temporal analysis for Chinese cities. Sci Total Environ 898(2023):1–13.

Zhang P, Dong Y, Ren Z, Wang G, Guo Y, Wang C, Ma Z (2023) Rapid urbanization and meteorological changes are reshaping the urban vegetation pattern in urban core area: a national 315-city study in China. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2023.167269