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A composite index for assessing accessibility in urban areas: A case study in Central Athens, Greece

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ABSTRACT

Effective transportation planning necessitates the consideration of all road network users and their needs. Towards this goal, the integration of accessibility in planning and the development of tools that enable the assessment and measurement of accessibility within urban areas becomes essential. This study aims to contribute to the accessibility assessment process of urban areas by developing two accessibility indices: the infrastructure and the opportunity accessibility index, which use an infrastructure-based and distance-based approach, respectively. Four types of users and their needs are considered: pedestrians, People with Disabilities (PWD), cyclists and public transport users. Data for modeling the accessibility indices are collected by: 1) an infrastructure audit, 2) a user survey, and 3) geographic information systems. The proposed method is applied in a district in central Athens, Greece, which is characterized by high population density and high level of activities. The Infrastructure Accessibility Index (IAI) measures accessibility for sidewalks, crosswalks, bikeways and public transport stops. The IAI results indicate moderate accessibility levels for pedestrians and PWD, for sidewalks and crosswalks. The Opportunity Accessibility Index (OAI) measures the share of different types of users that reach different opportunities within a time threshold. The accepted time threshold per user type is estimated based on the survey responds, for seven different opportunities: green spaces, recreational spaces, education buildings, health buildings, public service building, commercial uses and public transport stops. Compared to the IAI, the majority of users reach different opportunities within the estimated time threshold. The study concludes with recommendations to improve accessibility levels at local level.

1. Introduction

Modern cities face several challenges, including inaccessible public space and unattractive street environment (Cervero et al., 2017), intense traffic congestion (Rode et al., 2017), road accidents (Ziakopoulos and Yannis, 2019), urban sprawl (Rubiera-Morollón and Garrido-Yserte, 2020), noise, air pollution and health hazards (Bouguerra and Bhar Layeb, 2019). These insufficient conditions are partially a result of a car-oriented transport planning rationale (Marshall and Banister, 2007).

Transportation planning in cities has traditionally focused on improving efficiency and performance (Banister, 2005), however, new approaches consider accessibility as a key feature towards a sustainable planning rationale (Saghapour et al., 2016; Tiznado-Aitken et al., 2018). In this new reality, transportation is placed under a common framework with urban and land use planning, thus adopting integrated approaches (Melkonyan et al., 2020; Miller, 2018). Exploring new ways of measuring and illustrating accessibility both in macro and microscale, could be characterized as a necessity for urban areas, both at the present and in the future (Cui et al., 2020).

In this context, this research aims to develop accessibility metrics that integrate micro and macroscale features for assessing districts and neighborhoods by considering public perception. More specifically, the proposed framework uses an infrastructure-based and distance-based approach to model accessibility by considering four types of users: pedestrians, people with disabilities, cyclists, and public transport users. Two accessibility indices are developed: the infrastructure accessibility index, which assesses existing infrastructure, and the opportunity accessibility index, which integrates a spatial interaction model with the propensity to travel to different destinations. The accessibility indices may be aggregated or used individually, thus provide the flexibility to interested stakeholders to use either one based on data availability to provide a holistic accessibility assessment of an urban area. The

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proposed method is tested on the municipality of Kallithea, Greece, which is a highly populated municipality in metropolitan Athens, Greece. The urban and transport characteristics of the area (i.e., land uses, points of interest, road network structure, etc.) qualified Kallithea as a suitable case study.

The paper is structured as follows. In Section 2, the theoretical background, illustrating the basic concepts of accessibility that are used in this research, is described, while Section 3 employs the methodological framework. In Section 4, the application of the proposed methods and their outcomes are presented. The qualitative and quantitative outputs from the implemented methods are discussed in Section 5 to reveal insights for the future and potential policy recommendations. The last section draws conclusions from the study.

2. Background

The notion of spatial accessibility is a complex and multidimensional issue that cannot be described solely by using a single definition (Gutiérrez, 2001; Mościcka et al., 2019). The first attempt to discuss accessibility was made by Hansen (1959), who defined accessibility as the potential of opportunities for interaction. Another definition among the most important ones is found in Ingram's work (Ingram, 1971) mentioning that "accessibility is an inherent property of a place, associated with a certain form of overcoming the resistance of space (e.g., physical or temporal distance)". Similarly, Dalvi and Martin (1976) noted that accessibility is the ease of accomplishing any activity, from any place, making use of a specific transport system. Thirty years later, Bertolini et al. (2005) discussed the concept of accessibility as "what and how can be reached at a given point in space", while Handy (2020) in her most recent work, referred to accessibility as the way of characterizing the available choices (for multiple transport modes).

2.1. Measuring accessibility on macroscale level

Quantification and measurement of accessibility has been approached in several studies by using different methods and tools (Halden, 2002; Lei et al., 2012; Adhvaryu et al., 2019). The main methods of measuring accessibility on a macroscale are: a) Cumulative opportunity measures (Dovey et al., 2017; O'Sullivan et al., 2000), b) Gravity measures (Geurs and Van Wee, 2004; Bocarejo and Oviedo, 2012; Karou and Hull, 2014), c) Utility measures (Ben-Akiva and Lerman, 1985), and d) Distance measures (Talen and Anselin, 1998; Yenisetty and Bahadure, 2020). It is acknowledged that this variety of tools provides many perspectives through which someone may measure accessibility in the macroscale. Notwithstanding, according to El-Geneidy and Levinson (2022) two of them are the most common: a) the cumulative opportunities, and b) the gravity models. In this context, this research focuses only on these two methods and a brief analysis for each one follows.

Firstly, regarding the cumulative opportunity method, it should be stressed that it provides priority on the transportation network of the studied area. A particularly useful and simple tool for measuring accessibility, based on this approach, is the isochronous curve (Dong et al., 2006; Dovey et al., 2017). Based on these curves, the boundaries of areas are defined, which can be approached in a certain period of time (e.g., 30 min) by a transport mode or a combination of modes starting from an origin (O'Sullivan et al., 2000). After creating the isochronous curves different attributes may be measured, with the most common ones, being the area of the curves, the population within this area and the sum of the points of interest within it (e.g., squares, municipal centers, workplaces, shops, etc.). The clarity and immediacy of the cartographic representation of these curves contributes significantly to the extraction of findings.

Focusing on the second method (i.e., gravity or entropy models), spatial accessibility is determined as the potential of opportunities available for an individual (or group of people) located at a certain location for interaction (similar to Hansen's definition). Recent studies followed the same direction and mentioned that the accessibility of a zone in a (public) transport system is proportional to the spatial interaction between the origin trip zone and all other zones through a generalized (travel) cost decay (impedance) function (Geurs and Van Wee, 2004; Handy and Niemeier, 1997). Tellingly, the spatial interaction can be represented through multiple ways, referring to land use elements; for example, workplaces, points of interest, etc. (Bocarejo and Oviedo, 2012; Karou and Hull, 2014).

The above methods are highly connected to public transport users (that usually make inter-local trips). Notably, spatial accessibility is found to be one of the most significant factors influencing the attitude of public transport users (Chowdhury et al., 2016; Tiznado-Aitken et al., 2020). For this reason, if a spatial planning scheme intends to support the use of collective transport, then focusing on increasing the macroscale accessibility measures becomes an essential action.

2.2. Measuring accessibility on microscale level

Nonetheless, research interest is not only focused on macroscale, but also on microscale, where walking (including people with disabilities), cycling and micromobility users are the centerpiece of such methods. Hence, apart from traditional accessibility indices, suitability models, that are capable of displaying how suitable (or not) a road section is for active mobility, are incorporated as well (Macdonald et al., 2017).

In this context, Bartzokas-Tsiompras and Photis (2020) developed a walkability index that integrates residential density, land use mix, land use proximity and pedestrian network connectivity. Kalfa (2015) developed two walkability indicators. The first one is based on actual counting, such as the number of pedestrians, and reflects the level of flows, signifying the exact use of the area. The second one is a spatial walkability index that integrates proximity to land use mixes, population density, sidewalk network connectivity, existing infrastructure data (i.e., sidewalk width and condition, number of obstacles) and signage information along the routes. Another research by Singh (2016) examined the aspect of walkability in urban environments and found that the key factors were related to the built envelop on either side of the street. More specifically, factors like enclosure, block length and edge conditions seemed to be crucial for a walkable neighborhood. At large, walkability is greatly influenced by street connectivity, land-use diversity and proximity to walking attractors (Frank et al., 2005; Cervero and Kockelman, 1997; Owen et al., 2004).

In general, it should be strongly emphasized that walkability indices do not focus exclusively on (able-bodied) pedestrians. On the contrary, they aspire to include the needs of people with disabilities as well. In this context, many researchers employed different indicators that illustrate and analyze at what level and how the urban space facilitates or not the movement of this social group. For instance, the work of Paraskevopoulos et al. (2020) utilized a data-driven approach to measure the walkability level of PWD in a neighborhood in the city of Athens. Moreover, in the same direction, Campisi et al. (2021) evaluated walkability requirements of visually impaired people in urban spaces and found that infrastructural criticalities have a greater weight for PWD.

Walkability indices, additionally, address the needs of public transport users, especially, when assessing accessibility to/from transit stations (Zuo et al., 2018). Focusing on PWD it is noteworthy that a study conducted by Grisé et al. (2019) illustrated striking contrasts between the numbers of accessible jobs by public transport for wheelchair users compared to the general population. Similar results are also displayed by Park and Chowdhury (2018) who specified that the main barriers creating this contrast are related to the urban environment, terminals and stops, services, and quality of footpaths.

In addition to walkability indices, the literature presents research attempts on the development of bikeability indices. Bikeability is defined as "the ability of a person to bike", but also as "the ability of the urban landscape to be biked" (Guzman Mesa and Paez Barajas, 2013; Kang et al., 2019). Two indices that describe the bike-friendliness of street segments were developed by Emery et al. (2003) and Harkey et al. (1998). Both indices use multiple formulas to address different attributes measured by audits. Additionally, a "cyclability" or "bikeability" index was built and used in the US, Australia and Belgium, and integrated the proximity to destinations, walking and cycling facilities, parking difficulties near local shopping areas, and aesthetics (Van Dyck et al., 2012).

Recent approaches that focus on identifying the factors influencing accessibility related to cycling and building indices based on these details afterwards, are rather important for the concept of bikeability. Notably, the research work of Karolemeas et al. (2022) demonstrated through an expert based AHP approach that the most influential factors are the slope, junction density and activities coverage. However, their bikeability index involves several other parameters as well (traffic speed, urban environment quality, etc.). In the same context, the work of Ros-McDonnell et al. (2020) created a bikeability index adapted to Mediterranean cities, displaying as key parameters the following: 1) conditions of cycling infrastructure, 2) cycling crossings, 3) obstructions and barriers, 4) safety issues, 5) traffic signaling and 6) connectivity to points of interest. Porter et al. (2020) incorporated an integrated transportation bikeability index, including cycling lanes, residential density, population density, ozone level, distance to transit and parks as well as tree canopy coverage. Although, these attempts focus on single modes, a generic accessibility framework, capable of capturing different network users, infrastructure types and destinations (i.e., opportunities) does not exist.

2.3. Methods and tools for measuring accessibility

While the aforementioned methods are commonly used to measure accessibility, the data collection is a time-demanding process that may be accomplished by different tools. The most common ones are audits and Geographical Information Systems (GIS). Indices that are based on audits provide a time-demanding option, especially for large areas, however, they provide a detailed assessment of the existing infrastructure that may be also used for monitoring and decision-making of new projects. On the other side, GIS based tools allow for faster analysis and visualization of results in large areas.

The use of audit tools requires personal observation in the field to collect the necessary data. These tools may support policy makers and planners to pinpoint deficiencies and building walkable communities (Park et al., 2014; Gerike et al., 2021). One of the most used and applied audit tools, especially in the UK, is the PERS (Pedestrian Environment Review System) (Barman and Daftardar, 2010; Kartsidimas and Ronquillo, 2010). This well-established tool developed by the Transport Research Laboratory (TRL) (Allen and Clark, 2007), was taken as reference to assess the level of service and quality of various pedestrian environments (e.g., links, paths, public spaces, etc.) (Ignaccolo et al., 2020). PERS allows users to rate a range of factors about a pedestrian route, link or crossing (TRL, 2009). The aggregation of these results provides the opportunity to the operator to assess walking routes and highlight specific features that should be improved (Kelly et al., 2011).

This tool includes two phases, a) the completion of the audit forms for the collection of data (both quantitative and qualitative) in the field, and b) the use of software with which the data are processed and presented (Macdonald et al., 2017). The PERS uses a qualitative scoring method for reviewing the attributes of the pedestrian environment; it uses the auditor's judgement to score the priorities of the attributes (Naharudin et al., 2020). More specifically, the PERS scoring system ranges from -3 to $+3$ and the software assigns weights to each parameter to generate the final index.

It should be also mentioned that this tool has been incorporated in several studies that aim to evaluate walkability conditions. For instance, Nilles and Kaparias (2018) used PERS to assess walkability conditions in the local network in the commune of Lorentzweiler in Luxembourg, and particularly to identify design shortcomings around the network. Additionally, Ignaccolo et al. (2020), drew inspiration from PERS and developed a new index that could illustrate the existing quality of pedestrian infrastructure. Therefore, the contribution of this tool is rather important; thus, this research builds on PERS to develop a new index that also considers various user needs (pedestrians, people with disabilities, public transport users and cyclists).

Advanced GIS tools may be also used to create a reliable accessibility index, by processing and analyzing a large volume of spatial data for a study area. For example, there are several online applications that study walkability and how they affect the urban environment. The most important of these are www.walkonomics.com (Walkonomics, 2021) and www.walkscore.com (Walkscore, 2021). The Walkscore measures the walkability of any route, while it also depicts how friendly the area is in terms of bicycle use. It uses data sources, including Google, OpenStreetMap and Education.com, and locations that have been added by the user community. The score ranges between 0 and 100; with 0–24 representing complete dependence on the car, while 90–100 representing journeys that do not require a motor vehicle. The importance of the aforementioned indices has been underlined by several studies so far (Moura et al., 2017; Naharudin et al., 2020; Weng et al., 2019), indicating that these tools along with PERS, comprise a considerable toolset for preliminary walkability or even bikeability analysis.

Focusing on GIS methods, Bartzokas-Tsiompras and Photis (2020) presented the process of implementing a walkability index in GIS based on parameters presented in the literature, namely housing density, land use mix, land use proximity and pedestrian network connectivity. These parameters were weighted based on the results of an online questionnaire and the weighting method was used to derive the final values of the index, on a scale of 0–100. Svoronos (2014) utilized methods and techniques of geospatial analysis, and evaluated the walkability based on the parameters defined in the literature. The methodology included raster image management and three different weight distribution cases.

Our study utilizes three tools, 1) an infrastructure audit, 2) a survey of travel preferences, and 3) GIS, to integrate infrastructure attributes, opportunities, and weights to develop two indices for monitoring and enhancing accessibility at local level. Therefore, it employs a wide set of solutions that demonstrate a holistic approach towards a multi-level measurement of accessibility in urban areas. Notably, these indices are the following: a) the Infrastructure Accessibility Index (IAI) and b) the Opportunity Accessibility Index (OAI). The first index is related to walkability and bikeability indices. More specifically, this index measures and illustrates the suitability of sidewalks, crosswalks (this aspect derives from walkability studies and is destined to pedestrians and peopled with disabilities), bikeways (aspect deriving from bikeability studies and is destined to cyclists) and public transport stops (aspect originating from walkability studies but refers to public transport users). Next, the OAI is based on accessibility measures, but mostly on the cumulative ones. To be more precise, this index attributes the isochrones curves and measures how many activities are encountered in various curves for different time intervals and their diversity. Tellingly, this index is adjusted for every user type by changing the time thresholds. Therefore, these two indices are closely related to existing tools and methods and aspire to enrich the existing accessibility literature by proposing new insights on how to measure the urban environment with respect to different users.

3. Methodology

Data are collected by using an infrastructure audit (Subsection 3.1) and a survey of travel activities for residents and visitors of a specific area in central Athens (Subsection 3.2) Two accessibility indices are developed within the framework of this study, that may be also integrated into an overall accessibility index (Subsection 3.3). We propose an infrastructure-based and distance-based approach, to model accessibility for all users in an urban area. The methodological steps that we follow are summarized in Fig. 1. The method is generic; thus, it may be used for any district or area. In this paper an area within the Kallithea district is used, which is located in the central Athens, Greece.

3.1. Infrastructure audit

Conducting an audit requires a formalized process, which should be adapted to the nature and scale of the particular project (Karndacharuk and Hillier, 2019). In agreement to this process, an infrastructure-based audit is developed, which is suitable to assess the accessibility attributes of four infrastructure types: sidewalks, crosswalks, bikeways and public transport stops. The audit aims to record data within a study area and set the basis for developing an infrastructure attribute database.

Towards this goal, customized questions depending on the infrastructure type are used for recording accessibility-based attributes and assessing the degree of accessibility. All questions, thus developed indicators are based on Greek regulations on designing accessible infrastructure for public spaces in municipalities (Official Government Gazette, 2002; Official Government Gazette, 2009). This rationale ensures an easier implementation of these indicators in the policy making towards accessibility. The checklist that is formed is composed of questions, and the majority of them may be answered by Yes/No. Each question is converted into an indicator, and they are applied to all road sections. If a question is composed of multiple sub-questions, then it is defined as a composite indicator. Thus, a composite indicator is estimated as the sum of its sub-indicators, which they are assigned equal weights (i.e., equal significance).

For example, a composite question with three sub-questions (each one accounts for 0.33 or 33%) is applied to parking space for PWD:

- Is there an appropriate horizontal and vertical signage that clearly indicates the parking space for the PWD?
- Is the surrounding area free of permanent or temporary obstacles?
- Are the minimum space dimensions of 3.30 × 6.00 m. fulfilled?

All indicators are considered of equal importance for each infrastructure type. After completing the checklist, the percentage of checked-on attributes for each infrastructure type is calculated as the number of indicators checked-on divided by the total number of indicators for an infrastructure type. The infrastructure audit addresses accessibility aspects for different users. Thus, the infrastructure types, users and relevant indicators are:

- Sidewalk: Five indicators and two composite indicators are used to assess accessibility for pedestrians and PWD, resulting to a total of 11 questions. The five indicators are:
  - o Sidewalk width,
  - o Minimum available free width for pedestrians
  - o Minimum available free height for pedestrians,
  - o Parking markings along the sidewalk,
  - o Legally parked vehicles along the sidewalk,

  The two composite indicators (and sub-indicators) are:

o Safe parking space for PWD (the sub-indicators are mentioned above as an example),
o Accessibility for PWD (availability of tactile paving, even sidewalk without failures and cracks, uniform undisrupted tactile paving).

- Crosswalk: One indicator and four composite indicators are used to assess accessibility for pedestrians and PWD, resulting to a total of 11 questions. The indicator is:
  - o Availability of a crosswalk.

  The four composite indicators (and sub-indicators) are:

o Accessible crosswalk (minimum width for pedestrians, availability of on/off ramp),
o Safe crosswalk (even crosswalk without failures and cracks, free of obstacles),
o Marked crosswalk (availability of pavement markings, status of markings, availability of a flashing beacon),
o Accessible crosswalk for PWD (availability of audio warning, availability of a crosswalk button, availability of yellow truncated domes).

- Bikeway: Five indicators and one composite indicator are used to assess accessibility for cyclists, resulting to a total of 8 questions. The five indicators are:
  - o Minimum desired width for bikeway,
  - o Minimum desired separation of bikeway and motor vehicles,
  - o Parking and stop of motor vehicles along the bikeway based on provided regulations,
  - o Undisrupted movement along the bikeway,
  - o Appropriate bikeway materials to allow all active modes to move without vibration (e.g., electric scooters and bikes).

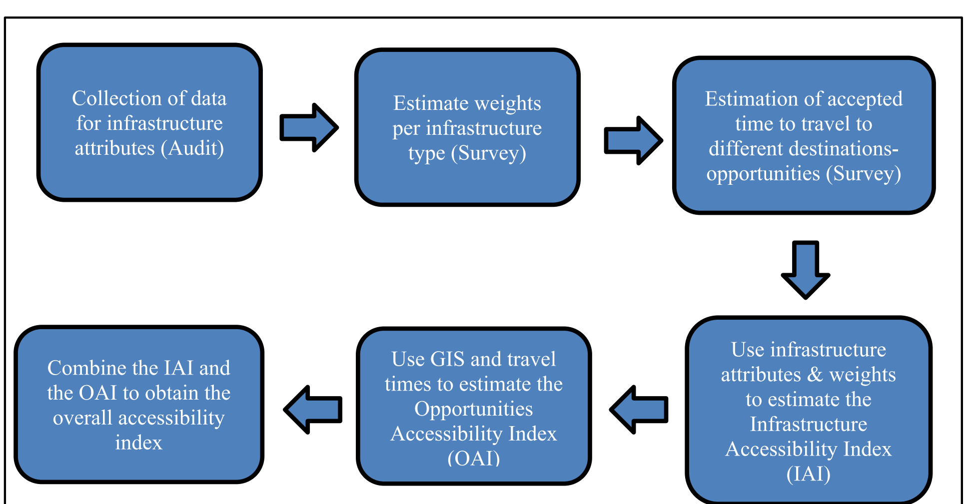

Fig. 1. Methodological steps for the development of the accessibility index.

The composite indicator (and sub-indicators) is:

o Availability of appropriate signs along the bikeway (median horizontal marking for two lane bikeway, vertical signs, painting condition of pavement markings).

- Public transport: Five indicators and one composite indicator are used to assess accessibility for public transport (PT) users, resulting to 9 questions. The five indicators are:
  o Availability of inclined curb cut,
  o Availability of yellow tactile warning strips to indicate PT stops,
  o Parking and stop of motor vehicles before and after PT stops based on provided regulations,
  o Availability of shelters,
  o Availability of bench or (perch) seats,

The composite indicator (and sub-indicators) is:

o Availability of other PT stop furniture (stop ID, route schedule, real time information, audio capabilities).

The developed audit is flexible enough to be used by various organizations that desire to assess the accessibility of different user and infrastructure types and desire to ensure fair access for people with physical disabilities. Moreover, this checklist can be used to create a database of infrastructure attributes for all local authorities.

3.2. Survey of travel activities

A survey was employed to identify the parameters that prevent people from moving in the city of Kallithea, as well as to estimate the time that people are willing to spend in order to approach specific land uses by different means of transport. The questionnaire was available to all residents and visitors of the study area in an online form due to COVID-19 restriction measures, and it was disseminated electronically through social media (Facebook groups) which can be an adequate pool of potential respondents (Ribeiro et al., 2020). These groups account approximately for 10,000 members, however, the response rate it is not possible to be estimated for this type of survey delivery because the population of users is unknown (i.e., the number of group members that accessed the link, thus the denominator) (Burruss and Johnson, 2021). It was addressed to all ages and it required 8 min on average to complete it. The questionnaire was composed of two parts, and a screening question regarding mobility needs was directing respondents to the respective part. The question was asking respondents if they consider themselves as a person with any form of disability. The respective part that it was addressed to respondents that they answered 'No″ contained 29 questions organized in five sections, as follows:

- The first section included questions on respondents' most used travel mode, vehicle ownership (yes/no), trip duration by car (<5 min, 5–10, 10–15, 20–30, 30–45 and >45 min), travel satisfaction level (Likert scale 1–5, with 5 being very satisfied).
- The second section focused on public transport and included questions on usage frequency for bus and fixed-guideway modes (every day, 3–5 times per week, 1–2 times per week, 3–5 times per month, rarely and never), travel satisfaction level (Likert scale 1–5, with 5 being very satisfied), acceptable time to walk to the nearest stop (<3 min, 3–5, 5–10, 10–15, 15–20, 20–30, >30 min), acceptable time to travel by public transport to six different destinations (i.e., opportunities). Seven-time cohorts were used: <10 min, 10–20, 20–30, 30–40, 40–50, 50–60 and >60 min.
- The third section focused on bike users and included questions on bike ownership, usage frequency, average bike travel time and acceptable time to travel my bike to six different destinations (i.e., opportunities). Six-time cohorts were used: <5 min, 5–10, 10–15, 15–20, 20–30 and >30 min. The last question concerned eight issues that may be faced when travelling by bike and respondents were asked to rate how important they consider the issues when travelling (Likert scale 1–5, with 5 being very important).
- The fourth section focused on pedestrians and included the same questions that were used for bike users. The only difference is that seven-time cohorts were used for the acceptable time to walk to six different destinations (i.e., opportunities): <3 min, 3–5, 5–10,10–15, 15–20, 20–30 and >30 min. Similarly, to bike users, for the last question, eight issues that may be faced when walking in urban areas were rated by respondents.

The respective part that it was addressed to respondents that answered 'Yes" in the screening question (i.e., if they consider themselves as a person with any form of disability), contained 18 questions organized in four sections, as follows:

- The first section included questions on respondent's most used travel mode, availability of driving license (yes/no), vehicle availability for daily use (yes/no), usual routing while travelling on foot or by a wheelchair in low traffic roads (on the pathway, on the right-hand side of the pavement, towards the middle of the road).
- The second section focused on public transport and included questions on usage frequency (every day, 3–5 times per week, 1–2 times per week, 3–5 times per month, rarely and never), modal choice (bus, metro, tram, sub-urban rail), trip purpose (work/education, errands/shopping/leisure, doctor/hospital/other health reasons, unexpected trip/other), issues that they face when using public transport (multiple answer to choose among 15 issues) and acceptable time to travel by public transport to seven different destinations (i.e., opportunities). Seven-time cohorts were used: maximum of 3 min, 3–5,5–10, 10–15, 15–20, 20–30 and >30 min.
- The third section focused on respondents' disabilities. If a respondent had a mobility issue, they were asked to rate their satisfaction (Likert scale 1–5, with 5 being very satisfied) when moving by a wheelchair in eight different areas (i.e., parking areas, public transport stops, boarding on and travelling in a bus, travelling on a pathway and a roadway, and crossing streets). If a respondent had a vision disability, they were asked to rate their satisfaction regarding audio assistance when crossing a road, waiting at a public transport stop, travelling by public transport, travelling on a sidewalk and a roadway, and crossing streets (Likert scale 1–5, with 5 being very satisfied).
- In the fourth section respondents were asked to rate how important they consider the issues that they face when travelling in their district (rate 10 issues in a Likert scale 1–5, with 5 being very important).

In the common last section, respondents were asked to rate how important (Likert scale 1–5, with 5 being very important) is the improvement of pedestrian crosswalks, sidewalks, public transport stops and bikeways, in their district. The last questions were addressing sociodemographic characteristics, such as home country, gender, age, educational level and professional status.

3.3. Accessibility indices

The methodology for modeling the Infrastructure and the Opportunity Accessibility Index (IAI and OAI, respectively) is presented in the following sub-sections.

3.3.1. Infrastructure accessibility index

The IAI contributes to accessibility by measuring how suitable an infrastructure type is for different user types to reach their destination. Thus, it depends on the infrastructure's condition and design, and the users' priorities for improving each infrastructure.

The infrastructure data is collected by auditing. Hereafter, a road section is defined as the segment that is located between two parallel roads; and a road is defined as the union of multiple sections with the same address name.

The audit is performed for each side of a road section (i.e., left and right) and infrastructure type k and the indices $I^k_{l,\ i}$ *and* $I^k_{r,\ i}$ (for left and right road section i, respectively) are estimated. The average of these two values is estimated as the road section infrastructure accessibility index ($I^k_{i,\ j}$) for road section i of road j for infrastructure type k (i.e., sidewalk, crosswalk, bikeway, and public transport stops).

The road section accessibility index ($I_{i,\ j}$) captures all available infrastructure types in a road section i ($i = 1\ldots n$) for road j ($j = 1\ldots m$) and is estimated by Eq. (1).

$$I_{i,j} = \sum_{k=1}^{4} I^k_{i,j} \times w_k \ (k = (1)\ \text{sidewalk}\ , (2)\ \text{crosswalk}\ ,(3)\ \text{bikeway}\ ,\text{and}\ (4)\ \text{public transport stops}\ ) \quad (1)$$

Where w_k: is the weight per infrastructure type, which shows the users' priorities to improve each infrastructure type (i.e., crosswalks, sidewalks, bikeways, and public transport stops). The relative weights for prioritizing infrastructure types are calculated by considering the respondents' answers and estimating the weights from respective ranks. We estimate the rank sum weights by assigning 1 to the most important infrastructure type, according to the survey results, and n to the least important in Eq. (2):

$$w_k = \frac{(n - r_k + 1)}{\sum_{k=1}^{4}(n - r_k + 1)} \ (k = (1)\ \text{sidewalk}\ , (2)\ \text{crosswalk}\ ,(3)\ \text{bikeway}\ ,\text{and}\ (4)\ \text{public transport stops}\ ) \quad (2)$$

Where r_k is the rank of the k^{th} infrastructure type.

The average value of $I_{i,\ j}$ for all road sections provides the IAI_j for each road j, and the average of all IAI_j provide the Infrastructure Accessibility Index (*IAI*) for the study area. IAI values may range between 0 and 100 (i.e., zero represents that none of the proposed indicators are met while 100 represents that all indicators are met) as follows:

- Not accessible (0);
- Poor accessibility (1–25);
- Moderate accessibility (26–50);
- Satisfactory accessibility (51–75);
- Excellent accessibility (76–100).

Quartiles are used in this case to split the IAI scale, for facilitating results' interpretation (i.e., a 5-level IAI would lead to "neither moderate or satisfactory accessibility" for middle level) and visual presentation (i.e., less coloring on maps), and be in line with similar research studies in transport and accessibility (e.g., Keall et al., 2018; Saraiva and Barros, 2022).

3.3.2. Opportunity accessibility index

The OAI is developed to supplement the IAI by capturing the ability of different users to reach to area destinations (opportunities). Thus, it depends on land use planning to accommodate adequately user needs. Seven different destinations (i.e., green space, recreational space, education building, health building, public service building, commercial uses and public transport stop) and four types of users (i.e., pedestrian, PWD, cyclist and PT user) are considered for modeling the OAI.

While a performance standard is usually set by responsible authorities and adopted locally, accessibility level targets are established locally. There is no universal performance standard for an acceptable level of accessibility to different destinations, such as jobs or stores. For example, there is not an agreed standard that within 30 min the residents of a district should be able to reach at least a specific number of jobs, or that within 15 min of walking the residents of a district should have access to two health centers. Some cities have long-range targets which plan all or most of their residents to have access to all basic necessities. Sydney, for example, is divided into three "30-min cities", with the nearest business areas being available within 30 min on foot, bicycle or public transport (Greater Sydney Commission, 2018).

For modeling the OAI we consider the maximum accepted time that each user is willing to travel to reach each one of the seven destinations (opportunities). The process is described in three steps: 1) Accepted travel times for each user type are estimated based on the survey results, 2) Estimated travel times are used to create isochrones in QGIS using ORS Tools, which is a free QGIS plugin that allows to create isochrones based on time or distance for various travel modes (i.e., driving, cycling, walking) by considering their speed, and 3) Isochrones curves are built around each destination (opportunity) with the aim to illustrate the area which is reachable within a certain travel time. The resulting curves are dissolved, thus creating a unified area. Afterwards, they are displayed in proper thematic maps, indicating the potential coverage of the study area. The OAI values may range between 0 and 100 (i.e., when none destination (opportunity) may be reached by any user within the estimated travel time and 100 when all desired area opportunities may be reached by a specific user group within the estimated travel time.

4. Application and results

4.1. Study area

A large Greek municipality was selected due to its urban identity that fits our research agenda and its strategic location in the center of Athens, but also due to data availability; however, the suggested method is flexible to be implemented in districts or cities with other characteristics. Additionally, a wide variety of land uses, points of interest and public transport stations are encountered within the district. This variety of attributes is considered useful for testing the proposed method.

Kallithea is an urban municipality next to the seafront with high population density (255 inhabitants/ha), which belongs to the South sector of Athens. It is considered as one of the most busy municipalities in the Athens Metropolitan Area (AMA), neighboring with the metropolitan centers of Athens and Piraeus. The Urban Plan of the Municipality envisages 21 urban units, depending on the population density. Regarding the existing land uses, they include retail, services, catering, education, sports, health, welfare, etc.

Although commuting is based on car, Kallithea - compared to other municipalities - has a fairly good transport infrastructure, mainly due to its close proximity to the center of Athens and its supra-local uses. Kallithea is served by Metro Line 1 (Electric Railway) and Tram. In addition, 26 bus and trolley lines connect Kallithea with many areas of the Region of Attica. The road network within the municipality is mostly characterized by limited road width. Moreover, there is an intense parking problem, as most households do not own private parking spaces and most people park along the streets. Regarding, the cycling network, on Ilissou Street, which is the western boundary of the municipality, there is a two-way cycling lane. This is the Southern part of the Metropolitan Bicycle Network of Athens "Faliro - Kifissia", which connects Faliro with Gazi. The existing road network classification is mainly car-oriented, thus allowing the penetration of the central area by major arterials (Zoika et al., 2021). Moreover, it undermines the role of sustainable transport modes (i.e., walking, cycling and public transport). However, Kallithea has in principle a great potential for shifting from conventional to alternative transport modes (i.e., high land use mix, high residential density, low car ownership levels, readable road network structure, etc.).

According to the 2011 census (ELSTAT, 2011), the Municipality of Kallithea has a permanent population of 100,641 inhabitants and represents 18.9% of the inhabitants of the Regional Unit of the Southern

Sector of Athens and 2.6% of the inhabitants of Attica Prefecture. The Municipality of Kallithea is considered the most densely populated municipality in the country, with a population density of 21,192 inhabitants per square kilometer (km), almost twice the average of the Peripheral Unit of the Central Sector of Athens (which corresponds to 11.66 inhabitants per square km). In terms of population structure by gender and age, women account for 53.5% and men for 46.5%. Regarding aging, over 50% of the Municipality of Kallithea inhabitants are up to 50 years old, with the highest share belonging to the age group 25–34 years. In total, there are 43,395 households in the Municipality of Kallithea. In terms of marital status, married account for 45.2% and unmarried for 41.2%. The municipality is characterized by an average standard of living.

Within the district of Kallithea, the study area is selected. The selection of the study area is based on geo-spatial certain criteria that relate to urban morphology, transport infrastructure, land uses and points of attraction. To be more precise, the study area should contain, a) the main central core of the municipality, b) at least one metro station and one bus station, c) at least two public spaces (parks or squares), d) at least two public service buildings (e.g., city town hall, tax office, post office, etc.), e) at least two educational facilities (primary, secondary schools or universities), f) cycling infrastructure and g) a diversity of street categories (e.g., primary, secondary, collector, local roads, pedestrian). All these criteria should be met to acquire a vibrant part of the city (meaning diverse flows like human or motorized traffic) that could be used as an adequate background for implementing the proposed accessibility indices. Notably, the exact boundaries of the study area were determined mostly arbitrarily, however, the scope of this study, does not imply to define this area strictly, since it functions as a pilot spatial setting.

Focusing on this specific area (a polygon of 74.1 ha and 4.17 km perimeter), 292 road sections and 64 roads were examined in detail. Fig. 2 depicts the boundaries and the street network that is recorded and analyzed. Furthermore, within the boundaries of the study area, there are 17 bus stops and 1 metro station, 5 public spaces such as parks and squares and also a plethora of points of interests, including the commercial center of Kallithea, the Harokopio University, primary and secondary schools, public service buildings (city hall, post office, tax office), recreational uses (e.g., cafe, restaurants, bars, etc.). All these features shape a diverse environment with multimodal mobility opportunities.

4.2. Survey results

The questionnaire was specifically designed for the purpose of this research; to study the accessibility for different user groups in the district of Kallithea. The sample consisted of 300 complete responses. All respondents live in the Metropolitan Area of Athens. A substantial share, approximately 74% of the respondents are residents of Kallithea, while another 16% live permanently in the Metropolitan Area of Athens. It should be noted that all respondents who do not live in Kallithea, have an actual experience of the area, since they have visited the area for various reasons. Concerning other sociodemographic features, the majority of the respondents are women (51.7%), private employees

Table 1
Sociodemographic and transport behavior results ($n = 300$).

Variable	Measure	Frequency	Percent
Gender	Male	141	47.0
	Female	155	51.7
	Not say	4	1.3
Age	18–24	39	13.0
	25–34	100	33.3
	35–44	94	31.3
	45–54	28	9.3
	55–64	28	9.3
	> 65	11	3.7
Occupation	Unemployed	16	5.3
	Prefer not to answer	11	3.7
	State/ Municipal employee	28	9.3
	Freelancer	75	25.0
	Private employee	106	35.3
	Household	4	1.3
	Retired	25	8.3
	Undergraduate student	35	11.7

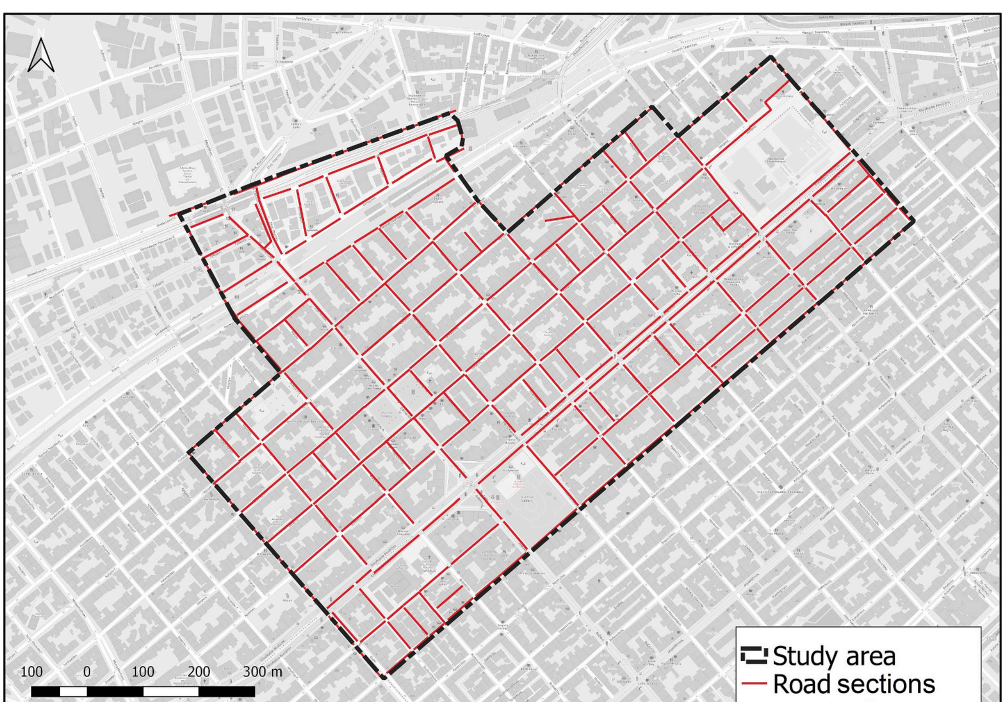

Fig. 2. Study area.

(35.3%) and freelancers (25.0%) and the dominant age groups are 25–34 and 35–44 accounting for 33.3% and 31.3%, respectively (Table 1).

Table 2 presents the travel behavior of respondents ($n = 250$) that answered that they do not have any form of disability, while Table 3 the behavior of respondents ($n = 50$) with a mobility disability. According to Table 2, the majority of the respondents (69%) own a private car, which is indicative for the mobility conditions in the study area. Regarding the mobility behavior a considerable share of the participants has mentioned that their typical travel time by using car ranges between 20 and 30 min. On the contrary, trips lasting <5 min account for only 6% of the respondents. This implies that a car-oriented culture is prevailing. The second and third most frequently used mode is the subway and the bus with 18% and 13%, respectively; while the bicycle accounts for only 3%. As a result, the respondents show a clear preference towards private car. When it comes to bicycle, the low share, reveals that this mode is not well integrated in the entire transport network.

Fifty responses were collected via an online questionnaire that was distributed to specific groups in social media related to people with disabilities (Table 3). Based on these responses, 36% of the participants need assistance for their daily mobility, which means that they cannot be independent in the complex environment of the study area. Furthermore, 28% of the respondents must use a wheelchair, implying a serious need for a properly accessible infrastructure. Additionally, only 32% of them use the public transport; this fact shows that public transport is not favored by people with disabilities, thus leading them to use the private car as a driver or a passenger, especially for long distance trips.

The sample size related to the area of Kallithea for a random sample is calculated to be 272 respondents for a confidence level of 90% and an error of 5%; in total 300 responses were collected in this research. As mentioned, the surveys were conducted through social media, which implies that the majority of respondents are older than 18 years old (in line with results of Ribeiro et al., 2020). However, the authors attempted to capture all population groups by focusing on generic pages (e.g., citizens of Kallithea) related to the municipality of Kallithea, rather than on pages with a specific focus (e.g., sport or activity). To assess that the sample is representative of the population in question, the authors compared the random sample characteristics to formal results from the Census 2011 in Greece. To some extent, this comparison may be inaccurate, because the random sample was restricted to community adults, whereas the census includes all residents.

The distribution of gender for male:female in the sample were 47.0%:51.7% versus the census with 46.5%:53.5%, respectively. Regarding age there are few differences in the distribution, since the sample is slightly younger than the general population, however the majority of them are below 45 years old in both cases. The distribution of the survey through digital means due to COVID-19 restrictions has likely resulted to a younger random sample. In terms of occupation, in the random sample 5.3% of respondents are unemployed, while the census data displayed a share of 9.3%, showing that unemployment percentage values are close. Lastly, car ownership distribution for the random sample was found to be 69% (i.e., older than 18 years old), and the census indicated a share of 58%, which includes all ages. In general, despite the possible limitations due to available data collection methods, the research has formulated a relatively representative sample that ensures the validity of the research outcomes. Detailed datasets about modal share or PWD are not available in the census records, thus comparison of such data is not possible.

Table 2
Transport behavior results ($n = 250$).

Variable	Measure	Frequency	Percent
Car ownership	Yes	172	69
	No	78	31
Typical travel time by car	<5 min	4	2
	5–10 min	9	4
	10–20 min	67	27
	20–30 min	87	35
	30–45 min	49	20
	>45 min	34	14
Main means of transportation	Car	141	56
	Bus	32	13
	Subway	46	18
	Motorcycle	24	10
	Bicycle	7	3

Table 3
PWD transport behavior results (n = 50).

Variable	Measure	Frequency	Percent
Need for transportation assistance	Yes	18	36
	No	32	64
Disabilities	Yes, I have difficulty walking, but I can move upright	25	50
	Yes, I only use a wheelchair	14	28
	No	11	22
Holder of a car or two-wheeler license	Yes	28	56
	No	22	44
A car or two-wheeler is available	Yes	27	54
	No	23	46
Use of public transport	Yes	16	32
	No	34	68

Apart from the above results, the survey incorporated questions aiming to explore the importance of issues when travelling by different modes (Table 4). Based on average estimated values of answers, for cycling, the most important challenges were the lack of exclusive bicycle infrastructure (4.4.) and the behavior of other road users (4.3). Concerning walking, the most important ones were the existence of obstacles on the sidewalks (4.1) and insufficient sidewalk width (4.0), while for PWD, the most important mobility issues were again obstacles on the sidewalk (3.8) and the dense parking that traps the disabled on the sidewalk (3.7).

Based on respondents' answers the estimated weights for prioritizing improvement of the infrastructure are: sidewalk (0.4), crosswalk (0.3), bikeway (0.2) and public transport (0.1). Therefore, improvements in sidewalks for improving accessibility are considered to be the most important.

4.3. Auditing and estimation of the IAI

The Municipality of Kallithea selected the audit team, which consisted of experienced transportation and urban planners and provided the necessary access in the study area. The team performed a commencement meeting, assessed the data and the documents, and performed the audit within seven working days. Following the collection and analysis of the data for all road sections, the accessibility indices are generated. The IAI specifically uses the infrastructure physical attributes as represented through the indicators in Section 3.1 by providing accessibility information regarding the design of these facilities based on national guidelines. Therefore, we use the method presented in sub-Section 3.1, and we estimate the road section infrastructure accessibility index ($I_{i,j}^k$) for road section i and road j, for infrastructure type k (i.e., sidewalks (Fig. 3a), crosswalks (Fig. 3b), bikeway (Fig. 3c), and public transport stops (Fig. 3d)). The collected data were inserted in a QGIS geodatabase for better spatial analysis and data visualization of the infrastructure accessibility index ($I_{i,j}^k$) per road section (Fig. 3a-d).

For sidewalks, the average value of the index equals to 37.2. The lowest value equals to 7.14 and the highest to 85.7. In respect to the spatial pattern of the index, the higher values are encountered in the northwest part of the study area where the only urban rail station is located, and where road traffic-calmed measures have been applied.

In total, twenty-five roads are recorded to have at least one crosswalk in one of their road sections. This is translated into 63 road sections that attribute at least one crosswalk. The results are presented in Fig. 3b. The

Table 4
Average estimated importance of issues for walking, cycling and PWD (1–5 scale).

Cycling	Importance	Walking	Importance	PWD	Importance
Lack of exclusive bicycle infrastructure	4.4	Existence of obstacles on the sidewalks	4.1	Obstacles on the sidewalk	3.8
Behavior of other road users	4.3	Insufficient sidewalk width	4.0	Dense parking that traps the disabled on the sidewalk	3.7
High Speed of vehicles	4.2	Lever of security during night hours	3.9	Absence of pathways for the blind people	3.6
Condition of crosswalks	4.1	Dangerous pedestrian crosswalks	3.9	Insufficient sidewalk width	3.6
Condition of bike lanes	3.9	Condition of sidewalks	3.8	Absence of a network of accessible routes throughout the city	3.4
Lack of parking spaces for bikes	3.9	High speed of vehicles	3.7	Inaccessibility of squares / green spaces / playgrounds	3.3
Weather condition	3.4	Behavior of road users	3.7	Feeling of insecurity when moving on the road or crossing it	3.3
		Weather condition	3.1	Absence of audible signals at the crosswalks	3.2
				Lack of information on points of interest	3.0
				feeling of insecurity due to a large number of bicycles	1.8

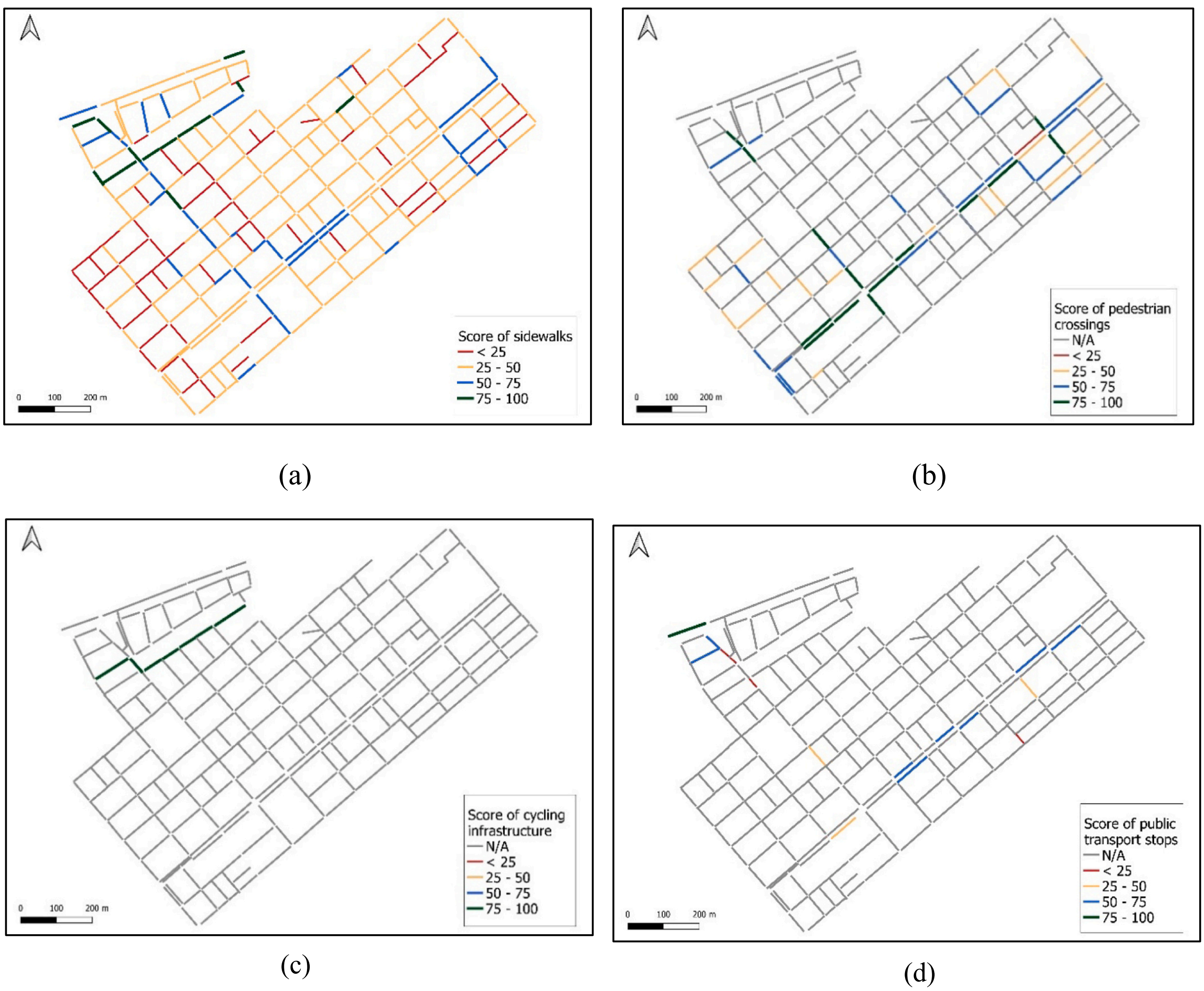

Fig. 3. Infrastructure accessibility index per road section and infrastructure type ($I_{i,j}^{k}$) for: (a) sidewalks, (b) crosswalks, (c) cycling infrastructure, and (d) public transport stops.

crosswalks are mainly encountered in arterial and collector roads or in neighborhoods near significant land uses (e.g., Harokopio University, Ilisos river, school buildings, etc.). The average value is estimated to be 12.45 and the median is 0, with minimum and maximum values of 0 and 86.7, respectively. Additionally, the standard deviation is approx. 25. However, when excluding sections without crosswalks (i.e., zero value), then the average value equals to 57.92 and the median to 56.70, with minimum and maximum values of 24.0 and 86.7, respectively. In general, it is highlighted that existing conditions imply a considerable contrast within the study area.

Fig. 3c presents the assessment of the cycling infrastructure (i.e., exclusive or not). During the auditing only 3 of the 64 roads, and specifically 7 road sections, were recorded with a cycling lane or a cycling track; this implies low coverage of bike lanes in the study area. These roads are located in the northwest part of the study area. The average accessibility index value is estimated to be 91.5, with minimum and maximum values of 76.7 and 98.9, respectively.

The developed index for bike infrastructure at its current form uses indicators that represent attributes of the bike infrastructure and national regulations; therefore, it becomes adjustable to local conditions. Its application, however, is limited to dedicated and shared bike lanes, for which design guidelines usually exists. Future work should expand the indicator set, to integrate within the assessment on-street cycling conditions when no specific cycling infrastructure exists. In this case, an expanded indicator set should include the speed limit, road hierarchy, and other factors that may affect bike route selection (e.g., Karolemeas et al., 2022; Ros-McDonnell et al., 2020).

The accessibility assessment for public transport stops is presented in Fig. 3d. Among the sample, public transport stops are only encountered in 8 roads and specifically in 12 road sections. In terms of their spatial pattern, these roads are located mainly along major arterials. The average accessibility index value is estimated to be 51.7, with minimum and maximum values of 8.3 and 83.3, respectively.

4.4. Accepted time travel and estimation of the OAI

At the moment, a national or local accessibility goal has not been set that may adapted for the study area. Based on the survey answers, we set an accessibility goal: 90% of all user types to have access within a period of time (*t*) to at least one destination per opportunity type. The time *(t)* is estimated by the respondents' answers in the survey by considering the reverse cumulative frequency that each user accepts to reach a destination. For example, the pedestrians should have access by walking within five minutes to at least one education facility (i.e., if we want to satisfy 90% of the pedestrians, then at least one education facility should be located within five minutes of walking).

Estimated times are the input data for each user type in the GIS to create isochronous curves with the center being each opportunity type. These isochronous curves cover all or a share of the study area and this percentage of the catchment area determines the share of users that may access each opportunity. The OAI takes values between 0 and 100. For example, in the case that all pedestrians within the study area can reach

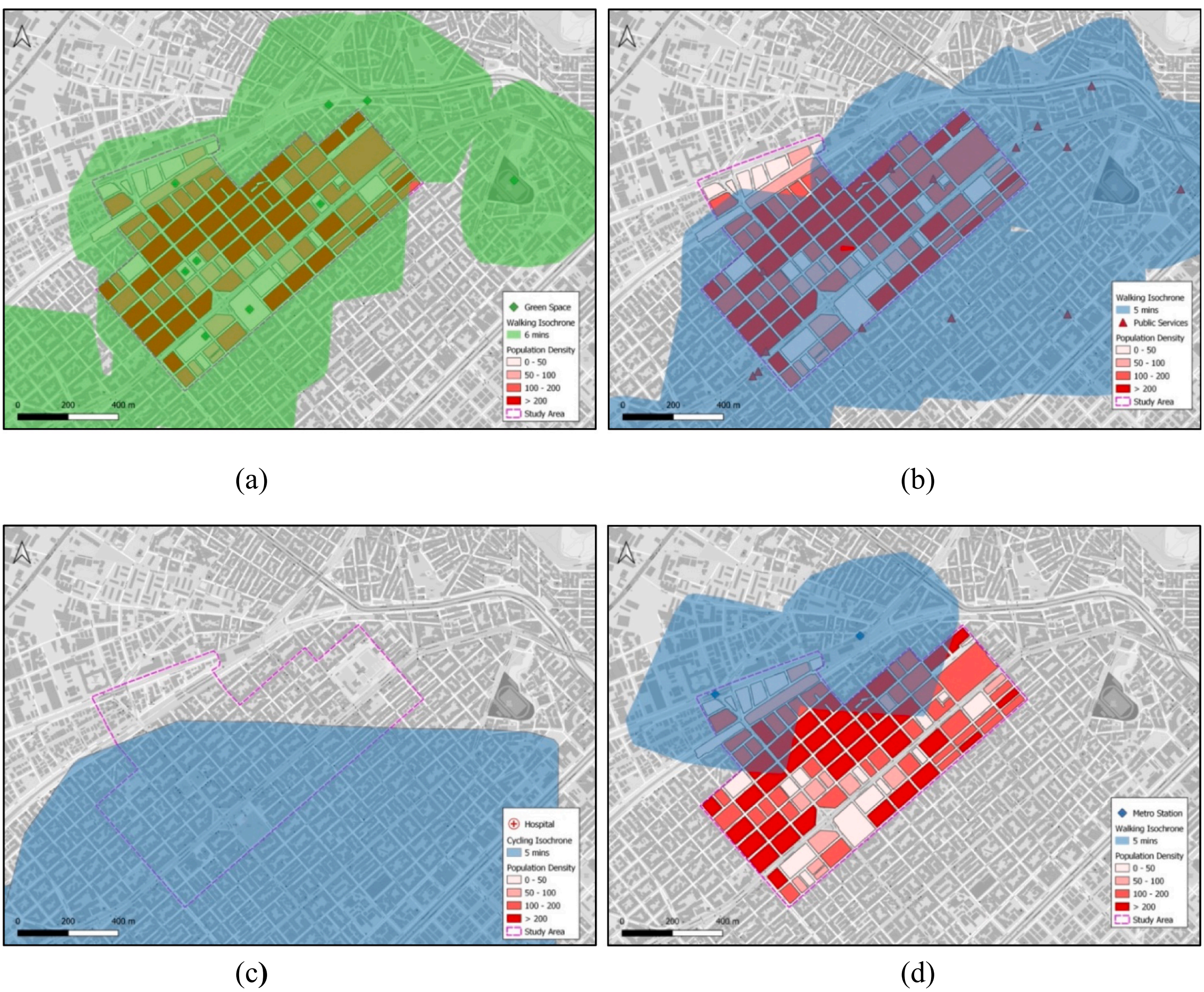

Fig. 4. (a) Isochrone for walking – Green spaces (OAI = 100), (b) Isochrone for walking – public services (OAI = 96.9), (c) Isochrone for biking – Health building (OAI = 70.4), (d) Isochrone for walking – rail-based PT (OAI = 28.1). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

at least one education facility (the facility may be located inside or outside the study area) within 5 min of walking, then the OAI equals 100. It should be noted that the OAI is capable of providing accessibility information beyond the study area, as shown in Fig. 4, with buffer zones extending well beyond the borders of the study area, thus providing a cumulative opportunity measure (considers all destinations reached within a pre-defined travel time threshold, which corresponds to 90% of users). It is assumed that all users are homogeneously distributed across space, due to data sensitivity; however, this assumption may imply a limitation of our analysis.

The average travel time, the time that covers the 90% goal per user type to reach an opportunity, and the OAI are estimated and summarized in Table 5.

Fig. 4 presents a sample of these cases by using the GIS tool and Table 6 summarizes the results of the OAI per user and opportunity.

Two accessibility indices have been developed and implemented in the study area. The aggregated results may be summarized as follows:

- The IAI for each road section is estimated as the weighted average of the four infrastructure types. It should be noted that the estimated IAI for each road section considers only the existing infrastructure to avoid penalization when an infrastructure is not present (e.g., no bike lane along a road section). The total infrastructure accessibility index (IAI) for the study area is calculated as the average for the 64 roads, and its value is 37.5.
- The opportunity accessibility index (OAI) of the study area is estimated as the average of all destinations and users, and its value is 80.3. All opportunities are considered to be equally important.
- The overall accessibility index of the study area is calculated as the average of the IAI and the OAI, since both of them are considered to be equally significant; its value is equal to 51.05.

Table 5
Average travel time (minutes) and accepted travel time (minutes) by 90% of users to reach each opportunity.

	Mean value	Goal of 90%	Opportunity Accessibility Index
	Green spaces		
Pedestrian	12.8	6.0	100
PWD	12.1	5.0	73.3
Bike user	12.9	7.0	100
PT user	16.4	8.0	100
	Recreational spaces		
Pedestrian	13.2	6.0	100
PWD	13.2	9.0	96.5
Bike user	13.3	8.0	100
PT user	19.7	11.0	100
	Education building		
Pedestrian	11.1	5.0	100
PWD	10.9	5.0	72.7
Bike user	11.3	6.0	100
PT user	15.5	8.0	100
	Health building		
Pedestrian	11.5	5.0	0
PWD	12.1	5.0	0
Bike user	12.0	5.0	70.4
PT user	17.3	5.0	100
	Public service building		
Pedestrian	10.6	5.0	96.9
PWD	11.7	5.0	61.4
Bike user	11.7	7.0	100
PT user	15.9	9.0	100
	Commercial uses		
Pedestrian	11.8	6.0	100
PWD	12.3	5.0	100
Bike user	12.2	8.0	100
PT user	17.3	10.0	100
	PT stop		
Pedestrian	9.2	5.0	28.1
PWD	9.4	5.0	5.7
Bike user	9.3	5.0	100
PT user	-*	–	–

(*): The time for PT users to reach a public transport stop is not applicable. The time to reach a PT stop is applicable to all other user types.

Table 6
Opportunity Accessibility Index per user.

	Pedestrian	PWD	Cyclist	PT user	Overall OAI
Green spaces	100	73.3	100	100	93.3
Recreational spaces	100	96.5	100	100	99.1
Education buildings	100	72.7	100	100	93.2
Health buildings	0	0	70.4	100	42.6
Public service building	96.9	61.4	100	100	89.6
Commercial uses	100	100	100	100	100.0
Public transport stop	28.1	5.7	100	–	44.6

5. Discussion

The notion of accessibility is a transformative concept that will shape the form of future urban road (Tsigdinos et al., 2022). Hence, the existing corpus of literature should be further enriched by new studies, revealing "hidden" aspects about accessibility and social inclusion. In this context the multi-level approach employed in this research gives the opportunity to acquire significant findings related to accessibility conditions in the district of Kallithea, and also generalize them into other similar areas. First and foremost, the auditing process, which involves a 4-dimensional mapping of the infrastructure conditions, presents a decisive role in the calculation of the overall accessibility of the area. Through the analysis, it was found that the majority of the road sections, in terms of the IAI, score between 25 and 50, meaning that the existing situation does not provide to vulnerable users the proper conditions for walking and cycling. This can be due to the reduced free width of the sidewalks, which is usually not >1.0–1.5 m. Furthermore, a considerable absence of curb ramps and tactile paving is encountered, as well as numerous deficiencies and issues (e.g., discontinuity of tactile paving, inappropriate design of curbs, etc.). Finally, illegal parking which is a serious problem in Greek cities (Zoika et al., 2021; Spiliopoulou and Antoniou, 2012), is found to be intense in the study area, thus undermining the movement of pedestrians and cyclists.

Moving to crosswalks, it should be mentioned that the vast majority of road sections also presents poor conditions. Particularly, for most road sections the accessibility scores do not exceed the value of 25. Low scores occur mainly due to safety issues, including many obstacles in sidewalks, mostly illegal parked vehicles and bins. Moreover, the coloring of the crosswalks is found to be poorly preserved and, in many cases, vertical signs are absent. Additionally, none of the crosswalks had an appropriate audio warning to guide blind people.

The third infrastructure index that depicts the conditions in terms of cycling shows that existing cycle lanes fulfil the majority of accessibility regulations. However, a bike lane exists only to a few road sections, underlining the hostile conditions for cyclists in the studied area.

Finally, when analyzing public transport stops, the existing conditions do not favor vulnerable road users. More specifically, apart from certain road sections being part of major arterials, all the rest do not meet the standard accessibility standards, such as an accessible platform, real-time information, benches, shelters for shading or rain protection, etc. Existing conditions provide very unfriendly conditions that discourage the use of public transport.

In general, many deficiencies regarding the accessibility conditions of infrastructure are recorded, showing that the study area cannot facilitate vulnerable road users' mobility properly. This is in line with the findings of Paraskevopoulos et al. (2020) who conducted similar research in a neighbor Greek district, highlighting the inadequacy of the area (mainly in terms of sidewalks) to foster vulnerable users' needs. Social inequalities in accessibility are not only a Greek phenomenon, since similar results are found in other places worldwide (Weiss et al., 2018) like Hangzhou, China (Su et al., 2019), Sao Paulo, Brazil (Slovic et al., 2019) and Maputo, Mozambique (Massingue and Oviedo, 2021), manifesting that almost the same accessibility disparities are found in completely different places. Therefore, strategies analyzing and improving accessibility should think globally, but act locally, embracing the concept of sustainable communities (Powell, 2009).

Assessment of opportunities' accessibility enables a non-linear distance-based estimation of accessibility, rather than an approach that assumes that the users' preference to travel, changes in space linearly. Additionally, it disaggregates destinations and concludes that users do perceive time differently according to the transport mode they travel with and their destination. The opportunity accessibility index (OAI) shows that most of the assessed opportunities score between 76 and 100. However, a health center to serve pedestrians and PWD within a walking time of five minutes does not exist in the district. Considering the OAI per opportunity, exposes the necessity to improve accessibility issues to health services, since it has ranked with the lowest OAI value (42.6). The second lowest score is attributed to PT stops (44.6), with only 28.1% and 5.7% of pedestrians and PWD, respectively, in the study area being able to access at least one PT stop within 5 min.

As the widening of the sidewalks in all problematic road sections is impossible, the identification of road cross-sections that allow such interventions should be required. Accessible road networks to and from opportunities should be created to serve all users, including the vulnerable ones. It is important to create a dense network for people with disabilities, since travel duration of 11 min and more, decrease their mobility. Interventions should also focus on the proper identification of hazards on sidewalks and other outdoor areas, and on the construction of sidewalk guides for blinds.

Regular maintenance of the road pavement and crossings is very important. At the same time, the projection on the ground of protruding elements that cannot be detected by people using blind-sticks should also be a main priority. Regarding people with vision problems, light-sound signals should be used to warn them, which will simultaneously emit light and sound signal and should be placed at the crossing points, as well as at temporary or permanent obstacles within the walking zone. Finally, it should be clear that piecemeal interventions at limited sidewalk widths are virtually ineffective as they restrict the continuous mobility of people with disabilities.

The proposed method suggests that national guidelines may be integrated with public perception to assess accessibly conditions. Establishing metrics that are based on public perception versus a normative top-down decision hinder the risk of not being applicable to other study areas with different governance or/and mobility habits. Update of guidelines based on different stakeholders is also envisioned in a recent EU transport project, for which urban logistics measures were assessed and weighted by different stakeholder groups (e.g., Novelog (2021)). The redefinition of standards has also been discussed in other articles as well, displaying almost similar results. For instance, Doğan (2021) tried to explore the success of walkability standards in Turkish cities, demonstrating that there is an urgent need for questioning the existing design standards. Moreover, Edwards and Dulai (2018) proposed that design standards shall adopt specific measures and interventions on certain infrastructure types (e.g., stairs) to promote walkability for all. The proposed accessibility indices may be adjusted to local conditions by capturing the users' priorities through a well-designed survey. Alternately, workshops organized by public organizations and respective municipalities that foster public participation may be used to reach to a consensus regarding local transport issues.

6. Conclusion

This study provides a methodological framework for assessing and monitoring accessibility in urban areas. The aggregated accessibility index is composed of two accessibility indices that are modelled by using different methods to address the needs of pedestrians, people with disabilities, bikers and public transport users. The infrastructure accessibility index assesses existing infrastructure, including sidewalks, crosswalks, bikeways and public transport stops. The opportunity accessibility index is a destination-based measure integrating a spatial interaction model with the propensity to travel to different destinations.

The main issues that were identified in the assessed area include the lack of a continuous accessible walking network, the illegal parking of cars, the absence of off-road parking spaces, the absence safe pedestrian crossings and the lack of infrastructure for people with disabilities. The geographic distribution of opportunities is found to be satisfactory for the majority of the users (i.e., 90% of the users) within the estimated travel times. The overall accessibility index for the district of Kallithea is characterized as "moderate" when considering both the IAI and the OAI, indicating to local authorities that they should implement measures and rehabilitate existing infrastructure features to improve accessibility.

The overall accessibility index is used as a measure of the accessibility level that integrates micro and macroscale features for assessing districts and neighborhoods. The incorporation of weights within the developed method enhances the planning process by prioritizing infrastructure types based on citizens' preferences. The OAI connects infrastructure and space via potential, providing the basis for assessing what areas meet a certain goal or an acceptable requirement level (Larsson and Olsson, 2017). The OAI provides a tool to public authorities to demonstrate their progress towards improving accessibility conditions in their jurisdiction. Both the IAI and the OAI may be used by local authorities to assess the level of accessibility and compare the effectiveness of proposed interventions before actual implementation. The range of interventions (e.g., in a single road or group of roads) the type of interventions (e.g., to improve the crosswalks, pathways or bike lanes) and the location and type of an opportunity development, may assessed by using the proposed accessibility indices.

The assessment results provide recommendations for improving the accessibility of the study area, by considering the national accessibility standards. More questions could have been implemented in the audit to capture additional infrastructure attributes; however, these may not be covered by national accessibility standards, and they may have led to misleading recommendations. Limitations in the method are linked to the data that are collected and used for modeling the two accessibility indices. The audit checklist requires many resources and its application in a larger area increases significantly the work effort. Although, the residents; opinion is considered, the assessment does not consider the public-authorities' priorities. The development of a survey for local-authorities or even different groups that might have conflicting interests in the same area, would allow the inclusion of their preferences in the accessibility assessment. Using careful research design and sampling procedures to avoid bias when conducting the survey are essential, since biased data would likely result to false estimation of infrastructure prioritization. Biased data imply that the distribution of the sample size is not representative of the populations being sampled. Therefore, the estimated weights for prioritizing infrastructure could be affected if some user groups were over- or under- represented in the sample. For example, a survey completed by groups of bicycle users would likely result to prioritize bike lanes over the other infrastructure types. This study tried to overcome this limitation by formulating a representative sample which displays similar characteristics (i.e., age, gender, car ownership) with the population of Kallithea. However, due to COVID-19 restrictions and the use of digital means, the sample is slightly younger than the overall population. Additionally, the opportunities are equally significant in the present study. Data categorization in the survey (i.e., time groups) and accessibility index levels determine the visual representation on the provided maps. In this study we attempted to combine simplicity with detail to the level that the outcome is easily understandable to the reader. More time ranges for accepted travel times or accessibility levels may be used, however, such choices may result to the readers' confusion and failure to capture accessibility differences between roads, road section and infrastructure types. Finally, census data refer to the year 2011, since results for the 2021 national census are not yet published. To this end, new studies that utilize the proposed methodology should use the latest available census data to generate updated outcomes.

The proposed study provides a holistic, yet time-demanding, method for assessing accessibility levels in urban areas. However, the method could be used partially to analyze and assess different levels of accessibility (i.e., IAI or OAI of an area) due to its "modular" profile. For example, the IAI could be implemented to selected or prioritized sidewalks or paths, and the OAI to residential areas or blocks of municipalities. Incorporation of open city data and development of data platforms in the future, may facilitate the assessment of similar large-scale transport/land use policy schemes.

This paper sheds light on the multidimensional issue of accessibility, however this topic cannot be fully discussed in one paper solely. Therefore, future work employing new research questions and utilizing new methods and tools is definitely necessary with the aim to enrich the existing literature. In this context, future research could examine how national goals for accessible infrastructure and opportunities should be integrated into the process of urban mobility planning and bring about policy changes that benefit all types of users. Moreover, further research attempts could adopt combinatorial approaches (e.g., artificial intelligence and Geographic Information systems) in order to extract more concrete and comprehensive results. In addition, different multicriteria analysis methods that will assign weights to the parameters of the indices could be tested (e.g., AHP or REGIME method). What is more, accessibility studies could be strengthened via the use of modeling and simulation tools. More specifically, research could be focused on the evaluation of infrastructure and opportunities, the simulation of infrastructure use, and the willingness to reach the aforementioned opportunities (e.g., agent-based simulation tools).

Finally, this study has the potential be a fair contribution to research efforts dealing with planning issues from a data-driven perspective. To be more precise, the present study could function as a multiscale background, indicating existing accessibility conditions, thus minimizing vagueness in the urban mobility planning schemes that will integrate it.

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CRediT authorship contribution statement

Lambros Mitropoulos: Conceptualization, Methodology, Data curation, Formal analysis, Validation, Writing – original draft. **Christos Karolemeas:** Visualization, Data curation, Software, Formal analysis, Investigation, Validation. **Stefanos Tsigdinos:** Data curation, Writing – original draft, Formal analysis, Visualization, Software. **Avgi Vassi:** Investigation, Writing – review & editing. **Efthimios Bakogiannis:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare no conflict of interest.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jtrangeo.2023.103566.

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