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Dynamic analysis of a pedestrian network: The impact of solar radiation exposure on diverse user experiences

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ABSTRACT

The walking experience is impacted by solar radiation exposure of pedestrian paths; this is a critical consideration for walkability assessment. The presented systematic methodology evaluates the impact of solar radiation on the user experience of pedestrian networks. Simulations were performed modelling the urban morphology in 3D and evaluating the shading provision of sidewalks at key times of the year. Three issues were investigated: the variability in solar radiation exposure of sidewalks, the difference in path length if discomfort resulting from exposure to solar radiation was prioritised over distance, and the access to shading for pedestrians of diverse walking abilities. Four user profiles were characterised by walking speed and ability to climb the stairs; adopting the perspective of diverse users provided critical information to design cities meeting the needs of vulnerable pedestrians. The resulting maps illustrated the dynamic nature of solar radiation exposure of the pedestrian network, with a critical cue on the paths chosen for optimising comfort, and the time that pedestrians would spend in the sun before finding shade. This work is a first step forward in the systematic implementation of microclimatic analysis in the walkability assessment, aimed at supporting designers in proposing solutions for ameliorating thermal stress.

1. Introduction

Walking is beneficial for health (Baobeid et al., 2021; Lee & Buchner, 2008). As reported by Speck (2018), investing in walkability pays off in terms of wealth, health, environmental quality, equity, and community. Analysing walking environments is therefore a critical first step towards improving public health and liveability in cities.

People travel in the street layout following the mental pedestrian paths, which are materialised into a sequence of segments such as sidewalks and crosswalks. A pedestrian network is a collection of pedestrian path segments and their relations; it includes characteristics of topology, geometry, and connectivity (Cooper et al., 2021). Research about pedestrian networks is focused on which routes pedestrians walk (wayfinding and movement patterns) and the context in which they walk (environmental features). Pedestrian movement has been investigated by modelling streets interrelations (Sevtsuk et al., 2021; van Nes & Yamu, 2021), assigning wayfinding tasks to virtual agents (Puusepp & Coates, 2007), and analysing GPS data (Bongiorno et al., 2021). Additionally, since walking can be either facilitated or hindered by physical environmental attributes (Giles-Corti et al., 2005; Stockton et al., 2016), research focused on the analysis of environmental features; the built environment is characterised based on questionnaires, observational audit tools, and digital datasets (Brownson et al., 2009; Dragović et al., 2023).

The purpose of walking can vary and can be considered related to health (exercise and restoration), transport, and pleasure (Forsyth, 2015). Gorrini et al. (2016) divided pedestrians into people driven by time, space, and social motivations, with consequences on path choice. The walking purpose influences the way environmental features (e.g., road quality, aesthetics, and available destinations) impact path choice. Speck (2018) pointed out that people look for useful, safe, comfortable, and interesting walking experiences. The term 'comfortable' comprises various characteristics. In walkability analysis, it was associated with spatial features such as width (Transport for London, 2020) and quality (Alves et al., 2021) of sidewalk surfaces, as well as perception, i.e., thermal, visual and acoustic comfort (Nikolopoulou, 2004). Baobeid

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et al. (2021) stressed that the thermal component is mostly overridden in walkability evaluation, even though it has considerable influence on the decision to walk.

1.1. The impact of microclimate on walking

Microclimate affects activities in public spaces (Gehl, 2013; Nikolopoulou, 2021), including walking (Forsyth, 2015). The relationship between thermal comfort and walking activity has been investigated using measurements that are coupled with surveys (Labdaoui et al., 2021-a; Santucci et al. 2020; Vasilikou & Nikolopoulou, 2020), and simulations (Jia & Wang, 2021; Tsichritzis & Nikolopoulou, 2019). Within the above said research spectrum, of particular interest were the associations of thermal stress with perceived travel time (Melnikov et al., 2022; Rakha, 2015) and walking speed (Bosina & Weidmann, 2017; Mouada et al., 2019). Microclimate can thus be listed among barriers or facilitators for walking (Stockton et al., 2016) and must be included in evaluating pedestrian environments.

Among microclimate variables, solar radiation has a critical role in outdoor thermal comfort (Kenny et al., 2008). Research has evidenced that in case of heat discomfort, shaded places provide relief (Aljawabra & Nikolopoulou, 2018), contribute to thermal acceptability, and increase users' exposure time (Faustini et al., 2020). On the contrary, in the winter season, sunny public spaces record greater attendance (Mi et al., 2020). Focusing on pedestrian activity, shade has been recorded as critical in wayfinding (Melnikov et al., 2022; Tabatabaie et al., 2023). Furthermore, the effect of direct solar radiation on pedestrian user experience is linked to personal characteristics with regard to physiology and mobility. In fact, research has found that heat stress has a larger impact on vulnerable people (Kabisch et al., 2017; Tomasi et al., 2024). Additionally, the diverse walking abilities of users result in different speeds, which can lead to longer time spent under the sun. All these highlight the relevance of shading analysis in walkability studies.

1.2. Evaluation of shading in walkability analysis of pedestrian networks

Dozens of audit tools and indexes have been developed to assess walkability in cities through the analysis of street network variables. The variables considered may differ in data sources (e.g., GIS databases, observations, audits, surveys) and units of analysis (location, segment, area) (Maghelal & Capp, 2011). Most indexes include indicators related to environmental characteristics contributing to achieving a comfortable state, yet not all of them explicitly address the thermal component of comfort. Furthermore, information specifically about shade from trees and buildings is hardly collected, and modelling assumptions disregarding the dynamic and geometrical nature of shading may result in inaccuracies impacting results. Relevant audit tools and indexes that include variables related to sidewalk shade and trees positioned along the sidewalks are listed in Table 1. The table excludes tools considering only the presence of trees and overhangs without further investigation on their position, spacing or shading effect.

Instruments that quantify the amount of shading on sidewalks provide accurate information compared to the simplified assumption that trees installed close to sidewalks would result in shading them. In the case of discomfort, seeking diverse thermal conditions is a means of adaptation (Nikolopoulou, 2021). Pedestrians, however, must be provided with comfortable routes because their need to reach destinations limits their adaptation choices (Yu & de Dear, 2022). The use of walkability indexes could find application in urban design by analysing the comfort of sidewalks and accessibility to attraction points. Cain et al. (2017) highlighted that microscale components of the urban environment could be subjected to short-term modification, unlike macroscale features such as connectivity and land use mix. Shading and street trees are microscale features, therefore analysing pedestrian networks and testing shading solutions is beneficial to improve the quality of sidewalks.

1.3. Research questions

Two layers impacting the pedestrian experience were isolated and analysed, solar radiation exposure and walking ability. Solar radiation exposure was selected because of its critical impact on thermal stress; as a result, it could be considered as a proxy for outdoor thermal comfort. Additionally, due to its geometric nature, urban designers can propose

Table 1
Review of walkability indexes and evaluation tools including trees and/or shade as indicators. Information in brackets refers to results reported in sources.

Reference	Name	Unit of analysis	Data source		Variables of interest	
			Digital	Observation	Trees	Shade
(Pikora et al., 2002)	SPACES	segment		✓	Number and height of trees along the verge	
(Dannenberg et al., 2005)	WAT	segment		✓		Amount of shade at different times of the day
(Boarnet et al., 2006)	I-M	segment, area	✓[1]	✓	Number of trees	Is the sidewalk shaded by trees?
(Clifton et al., 2007)	PEDS	segment	✓	✓	Number of trees shading the walking area	
(Hoehner et al., 2007)	Checklist	segment		✓	Tree shade along the walking area at approximately noon	
(Millstein et al., 2013)	MAPS	segment		✓	Number and spacing of trees	% sidewalk shaded
(Taleai & Taheri Amiri, 2017)	MCE model	segment	✓		NDVI	Shade area/total area, 3D computation [1 September 2015 at 10 am and 5 pm]
(Serra-Coch et al., 2018)	Mapping based on TOD-standard	segment	✓		Specific location points of trees	Shade around location points fixed to the average radius of trees in the area
(Al Shammas & Escobar, 2019)	WI	area	✓	✓[2]		Shade on the sidewalk, 3D computation [11 am and 5 pm in summer, 1 and 5 pm in winter]
(Perez, 2020)	Method for Quantifying Sidewalk Shade	segment	✓	✓[2]	Trees modelled in 3D	3D computation [12, 2.30 pm]
(Aleksandrowicz et al., 2020)	Shade maps	area	✓		Tree Canopy Cover	Shade Index, Tree Shade Efficacy Index
(Labdaoui et al., 2021-b)	SWTCI	segment	✓	✓	Number of trees	PET [26 and 28 August 2017, from 8 am to 8 pm, at 2-h intervals]
(Li et al., 2022)	GSV data-based algorithm	segment	✓		Trees included in GSV panoramas	Sunlight exposure [15 July 2018 at 9 am, 12, 2 and 5 pm]

1 supplementary data 2 only for validation

solutions to tackle excessive exposure to solar radiation. Therefore the analysis was carried out within the premise of a practical urban design approach to address the thermal stress issue. Walking ability was established through walking speed and usability of stairs, i.e., two key variables to describe the time spent under the sun and the accessibility to segments of the pedestrian network, respectively.

The impact of solar radiation exposure on walkability was investigated by addressing the following three research questions.

- How does solar radiation exposure of a pedestrian network change in response to the dynamic nature of shading?
- How does seeking optimal solar radiation exposure impact path length?
- What is the impact of solar radiation exposure on the user experience of pedestrians of diverse walking abilities?

This research analysed microclimatic and spatial features over which urban designers have control. This approach made the proposed methodology relevant in practice, therefore a first step forward in the systematic implementation of microclimatic analysis in walkability assessment.

2. Materials and methodology

This research used computer modelling to simulate shading on pedestrian paths; the selected case study location was a neighbourhood in Milan (Section 3.1). The user experience was evaluated for a range of solar radiation exposure during key times of the year (Section 2.1.3). Four user profiles were delineated assessing walking speed and usability of stairs as a proxy for diverse walking abilities (Section 2.2); different user perspectives were systematically adopted. The analysis phase addressed the above three research questions.

2.1. Modelling process

The pedestrian network and urban morphology were modelled in Rhino, using the visual scripting interface Grasshopper (Grasshopper, n.d.; Rhinoceros, n.d.). This software is used by urban designers at the neighbourhood scale and enables detailed 3D modelling of the urban morphology with short computational times. The variable under investigation was the exposure to direct solar radiation of pedestrian paths. Therefore, first, objects that could cast shadows on the sidewalks were modelled. This was followed by the pedestrian network; then, the time periods for the analysis were selected.

2.1.1. Shading objects

Building volumes and trees, i.e., the urban morphology, were modelled as shading objects. The building layout was imported from *.shp* geometries via the plugin Urbano (Dogan et al., 2020); building volumes were then modelled by extruding the building footprint by the relative height attribute. Trees of different dimensions were modelled and collected in a library. Tree canopies were considered as whole shading devices and thus modelled as solid volumes throughout the year. Each point identified in the case study area was assigned one tree from the library.

2.1.2. Pedestrian network

The pedestrian network was modelled from imported *.shp* geometries describing sidewalk surfaces. Following the approach by Cooper et al. (2021), the pedestrian network was modelled as a system of centre lines of sidewalks and crosswalks. The centre lines of sidewalks were drawn in Rhino, and lines were used to model the slopes of stairs. To account for a diverse range of users, the network was modelled at 1 m height as it approximates the centre of gravity of an average standing adult (Matzarakis et al., 1999), the suggested height for designing for toddlers (Vincelot, 2019) and the floor-to-shoulder height of a person on a wheelchair (Jarosz, 1996).

The analysis was limited to part of the urban pedestrian network. The surface to delimitate the isolated pedestrian paths was defined 'area of interest' (AOI); only urban features within the AOI, or in proximity to its edge, were modelled. The pedestrian network was not cut off at the edge; the continuity of pedestrian paths avoided interruptions that could generate bias in the simulations.

2.1.3. Sun path, days and hours combinations

Ladybug tools (Ladybug, n.d.) were used to import the relevant weather file, extract the position of the sun, and select the key dates to simulate. To analyse the seasonal variability of solar radiation exposure, three days of interest were selected: the two solstices (21 June and 21 December) and one equinox (23 September). Similarly, the variability of solar radiation at different times of the same day was analysed, and three hours were simulated on each selected day; 10 am, 1 pm and 4 pm, corresponding to morning, lunchtime, and afternoon. In summer, the selection took into consideration daylight saving times to prioritise pedestrians' activity. In total, 9 key days and hours combinations of the year were analysed, covering the extreme positions of the sun path in the location under study. As a result, the solar radiation exposure variability throughout the year was captured.

2.2. Definition of user profiles

To cover a variety of sidewalk users, four user profiles were defined: a standard pedestrian, a wheelchair user, a pedestrian using a cane, and ITCs (Infants, Toddlers and Caregivers). As walking speed varies greatly among pedestrians, Bosina & Weidmann (2017) reviewed the literature on walking speed and defined a reference value of 1.34 m/s as the baseline to compare attributes influencing walking speed. This value refers to adults walking outdoors, alone, on a flat walkway separated from car lanes, and was adopted in the current work to delineate a standard pedestrian profile, i.e., a young adult with no mobility impairment.

Investigating mobility impairments, Oxley et al. (2004) and Turner et al. (2006) reported the mean walking speeds of pedestrians with various mobility impairments or using assisting devices. The values of 1.08 and 0.80 m/s were selected for wheelchair users and pedestrians using a cane or a crutch, respectively. During tests performed in controlled environments, a wide range of speeds among wheelchair users was recorded; the critical variables were the level of injury (Beekman et al., 1999) and whether wheelchair users were assisted (Boyce et al., 1999). The value of 1.08 m/s was in accordance with the literature (Kwarciak et al., 2011; Slowik et al., 2015; Tsuchiya et al., 2007). Observations in real-life settings (Arango & Montufar, 2008) and controlled experiments (Boyce et al., 1999) confirmed a walking speed of 0.80 m/s for pedestrians with a cane. The same value is reported as the walking speed of the elderly (Bosina & Weidmann, 2017; Pinna & Murrau, 2018; Zaninotto et al., 2013).

For children under the age of 6, the walking speeds ranged from 0.80 to 1.10 m/s (Cavagna et al., 1983). Bosina & Weidmann (2017) reported a larger range and outlined the fast increase in walking speed following children's growth, which represents a challenge in defining a characteristic walking speed for children. Nevertheless, design guidelines for ITC-friendly neighbourhoods recommended the walking speed of 0.50 m/s for adults holding hands with toddlers and caregivers pushing a stroller (Bernard van Leer Foundation, 2019); this last value was adopted for urban design purposes. The characteristic walking speeds assigned to the respective user profiles are summarised in Table 2.

Walking speed for stairs was also defined: an average value was assumed valid for both directions (climbing and descending). Past research on measuring walking speed on stairs was reviewed (Fujiyama & Tyler, 2004; Kretz et al., 2008); assuming that the steepness of public stairs would be low, only results about staircases of limited inclination were considered. The adopted speed was the average horizontal speed

Table 2
Walking speeds assigned to selected user profiles.

User profile	Walking speed [m/s]	References
Standard pedestrian	1.34	(Bosina & Weidmann, 2017)
Wheelchair user	1.08	(Oxley et al., 2004)
Cane user	0.80	(Oxley et al., 2004)
ITCs	0.50	(Bernard van Leer Foundation, 2019)

among the ones reviewed, i.e., 0.72 m/s; considering that the walking speed of standard pedestrians was defined as 1.34 m/s, the walking speed on stairs resulted in about half the one on flat surfaces, as suggested by Weidmann (1992).

2.3. Network analysis

The user experience was simulated at key times of the year. The analysis of the pedestrian network was performed in three steps, moving from the background solar radiation exposure to a more complex investigation of diverse user experiences.

The AOI was considered as a circle with a 400 m radius, corresponding to a 5-minute walk for standard pedestrians. As a comparison, *The Planning for Walking Toolkit* defined a walkable catchment area with an 800 m radius, specifying though that it would be non-accessible for some pedestrians (Transport for London, 2020). Indeed, 400 m was indicated as an accessible distance for preschoolers (Bernard van Leer Foundation, 2019).

This study adopted the concept of the street-segment graph (Marshall et al., 2018); street segments are the object of analysis, while junctions are assimilated to connections between streets. Accordingly, each pedestrian path segment is analysed initially as a distinct element of the system, then movement simulations are performed connecting segments of the network.

The pedestrian network was segmented at intersections and junctions (Fig. 1a). A manual cleaning procedure was performed to get a continuous network with precise intersections and no stubs, ensuring model usability. To simulate the solar radiation exposure of pedestrian paths, each segment of the network was subdivided at a constant distance, creating smaller segments ('steps') (Fig. 1b). The step length was set to 1.50 m, which is the stride measure for a standard pedestrian, i.e., 'two consecutive heel strikes' of the same foot; this is in agreement with the findings of Buddhadev et al. (2020) and Sekiya et al. (1997), and ancient Romans were already using the stride as a measurement unit (Duncan-Jones, 1980).

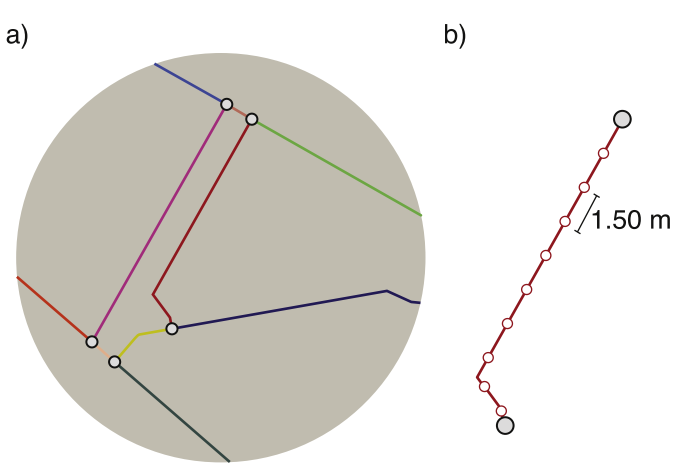

Fig. 1. Segmentation process: a) network segmentation, b) subdivision of segments in steps.

The centre point of each step was then processed in Grasshopper with the 'Occlusion' component, which determines whether a point in space is exposed to the sun or shaded by the context. The result of the occlusion process was aggregated into three analyses in which solar radiation exposure was increasingly related to the user experience of pedestrians.

2.3.1. Solar radiation exposure analysis of pedestrian segments

At first, the solar radiation exposure analysis was performed on the network to isolate the microclimatic component of interest. Each step was analysed to determine whether it was in the sun or shaded by the urban morphology. This analysis showed the distribution of shading, i.e., the number of steps where the shade and sun condition changed along the segment, and the presence of long stretches of one condition. Then, results were grouped into network segments, which were therefore categorised from the most shaded to the most exposed one. According to the season, positive and negative impacts on using the network segments could be hypothesised based on their exposure to solar radiation. The outcome illustrated the exposure of each segment to the range from exposed to solar radiation to shaded, with different levels of variability in between.

2.3.2. Difference in path selection based on distance and solar radiation exposure

Providing good shading in thermal stress conditions was hypothesised as a positive service for pedestrians, and the difference between the shortest and the most comfortable travel paths was evaluated, as performed by Li et al., 2022 in the summer. Different priorities in path choice were assumed, i.e., the optimisation of distance and comfort; the term 'comfort' is here defined as the most shaded path in summer and exposed to solar radiation in winter. All potential trips starting from the centre and ending along the edge of the AOI were analysed. Initially, the shortest path was assigned to each travel, simulating time-driven pedestrians; then, the path which optimised the comfort for pedestrians was simulated. The difference between the shortest and the most comfortable path (ΔDC) was calculated.

2.3.3. Shade and sun accessibility by diverse user profiles

The profiles of four users of diverse walking abilities were adopted to evaluate the level of accessibility to shade and sun provided by the pedestrian network. For the wheelchair and cane users, and ITCs, the network was modified to remove slopes too steep for the users. For each step, the closest point along the network in which the solar radiation exposure changed was defined. The resulting path length was assigned to steps as the minimum distance to walk to change solar radiation exposure in that position. By considering the assigned walking speeds (Section 2.2), distances were measured in terms of travel time, and the resulting shade and sun accessibility map responded to the selected user profile. The maximum time before finding shade was set at two minutes, which was identified as a short exposure time that would cause only slight discomfort in pedestrians, even under high solar radiation exposure (Yu & de Dear, 2022).

3. Results

3.1. Case study area

A neighbourhood in Milan (IT) was used to test the proposed methodology. The sidewalk system around the metro station 'Lodi T.I.B.B.', positioned in the southern part of the city on the NW-SE metro route, was selected. This public transport node is located in the residential neighbourhood of Porta Romana; it is adjacent to a railway yard object of a redevelopment project, the Parco Romana master plan (*Scalo Di Porta Romana*, 2023). This paper presents a preliminary design proposal. However, this proposal could be subjected to changes due to the ongoing authorisation process with the Municipality of Milan.

At the end of the year 2022, the city of Milan recorded about 1.4

million residents, of which 12.8% were over 75 years old and 3.0% were under 4 years old (Municipality of Milan, 2023). Furthermore, 5.0% of the Italian population was recorded with a disability (ISTAT, 2021). In an interview, mobility resulted the most encountered barrier in the life of people with disabilities; it was reported by 66.2% of interviewees in Italy (Eurostat, 2012). These data articulate the need to consider diverse user profiles in urban planning practices for the city.

3.1.1. Modelling the case study area

The AOI was defined by drawing a circle of 400 m radius around the two metro station accesses (Fig. 2a). The geometry of the existing buildings was downloaded from the Municipality web portal (Municipality of Milan, n.d.-a); buildings subject to design were imported from the designers' model and simplified to obtain the main volumes. In the master plan area, two levels can be distinguished; in addition to the ground level, an east-west oriented linear elevated greenway is located above the existing railway. In the eastern part, close to the metro station, the elevated urban forest enlarges into a square surrounded by commercial and office buildings. Access to this upper level is enabled by stairs, ramps and elevators as the project aims to connect the fragmented surroundings through north-south oriented paths. To model the terrain morphology, the existing city level was assumed as flat ($z = 0$), while the elevated space of the master plan was set 7.7 m high (Fig. 2b). The pedestrian network was segmented at intersections, and slopes too steep were classified as not accessible by ITCs, wheelchair and assisting device users. According to the Italian legislation[1], network segments of inclination above 5% are regarded as inaccessible, except for ramps of length 10 m inclined of maximum 8%.

The position of existing trees was downloaded from the Municipality website and supplemented with information from the Municipality database (Municipality of Milan, n.d.-a; n.d.-b). According to the Municipality documentation (Municipality of Milan, 2022), trees were grouped by dimension into three class sizes; plants of dimensions close to maturity were modelled as representative of class sizes, and are reported in Fig. 3. Trees in the master plan area were assimilated to the same class sizes.

3.2. Solar radiation exposure analysis of pedestrian segments

Sun positions were derived from the weather file Milano-Linate 160800 (IGDG) (EnergyPlus, n.d.). The solar radiation exposure analysis resulted in two maps; one showing the solar radiation exposure of each step, and the other where network segments were coloured based on the total exposure. These maps show how the solar radiation exposure of the network changes during the day and in different seasons. More specifically, focusing on 1 pm, it is shown how a path customarily walked every day at the same hour can be impacted by solar radiation in the different seasons. The complete analysis of all simulated days and hours combinations is presented in Appendices A and B.

The distribution analysis aims at visualising how shade is distributed along the network segments. Fig. 4 illustrates the results calculated for the different seasons. On the summer solstice, many long stretches in the sun constitute barriers to walk comfortably; this condition is mitigated at the end of summer, especially in street segments where trees are planted. In terms of distribution, a lot of variety can be observed in the existing park area towards east and on the east-west axis in the master plan. In winter, a few stretches in the sun can be found in open areas and in SW-NE oriented sidewalks.

In Fig. 5, the results of the solar radiation exposure analysis of network steps are aggregated into network segments; blue segments are shaded by buildings and trees, while red segments are exposed to solar radiation. As expected, the two solstice days represent two extremes in terms of total solar radiation exposure; yellow segments are mostly shaded by trees, that allow sunlight to filtrate in the space between canopies.

The combination of maps provides relevant information about how the solar radiation exposure impacts the experience of a pedestrian walking during lunchtime throughout the year. These results have application in urban design to decide on which sidewalks need shading in summer, where temporary shading devices could be installed, and which sidewalks are likely to be more walked in cold weather.

3.3. Difference in path selection based on distance and solar radiation exposure

Since a pedestrian network is a mobility infrastructure, this analysis examined how the public service of sidewalks can be evaluated differently when solar radiation exposure is considered. Trips from the metro stations to the boundaries of the AOI were modelled. Destinations were generated by intersecting the network with the border of the AOI; then, each point was assigned to the closest metro station, which was labelled as the origin. A total of 44 trips were analysed by simulating pedestrians moving from the metro accesses to the edge of the AOI. Fig. 6 reports results on 21 June at different times of the day, with each line representing one trip, and the colour corresponding to the difference between the shortest ('D') and the most shaded ('C') path. It can be observed that in the morning, pedestrians moving from the metro accesses in the west direction would be required to travel almost twice the shortest distance if shading was a priority. Considerable additional distance can be observed towards SW and NE, also during lunchtime. On the contrary, walking towards SE would not be served by many alternative routes; this is valid also in the afternoon.

The same exercise was repeated for all 9 days and hours combinations. Fig. 7a reports the ratio between shaded length and total trip length, in terms of average and range (minimum to maximum value). Results refer to all 44 trips that were aggregated by travel direction, starting from the metro accesses. In summer, longer walks would result in sensible advantages in terms of shading gained, since trips would be shaded for at least 60% in most travel directions; the trade-off is represented by the additional distance, thus time, travelled. In Fig. 7b, the resulting values of ΔDC are divided by trip orientation and days and hours combination. It can be observed that in summer, every travel direction would require a longer path to prioritise shading for at least one hour among the ones analysed. In winter, because of the dense urban morphology, the sun availability is limited, therefore there is a scarcity of alternative comfortable paths.

3.4. Shade and sun accessibility by diverse user profiles

The potential experiences of a pedestrian network by users of diverse walking abilities are presented here. In this section, one representative critical condition in terms of discomfort is discussed, i.e., walking during lunchtime in summer; results for 21 June at 1 pm are thus reported in Fig. 8 (and more combinations are illustrated in Appendices C – E).

In the first instance, the lower the walking speed, the greater the presence of stretches in the sun and shade can be observed. The comparison between maps provides a clear picture of the different experiences users would have along the analysed network; taking certain routes would result in a long exposure to solar radiation for slower users, with no opportunity to find relief in the middle of the walk. On the other hand, 'safe' itineraries could be drawn, selecting routes where the exposure to the sun could be considered acceptable.

An interesting result can be observed in proximity of the park towards east; even though the paths within the green area resulted as exposed to the sun, with no stretches above two minutes even for the slowest pedestrians, most sidewalks surrounding the park would be challenging in terms of solar radiation exposure; shading solutions should thus be installed to preserve the access to the green area. In the combination presented in Fig. 8, the absence of stairs or steep ramps

[1] DM 14 June 1989, no. 236

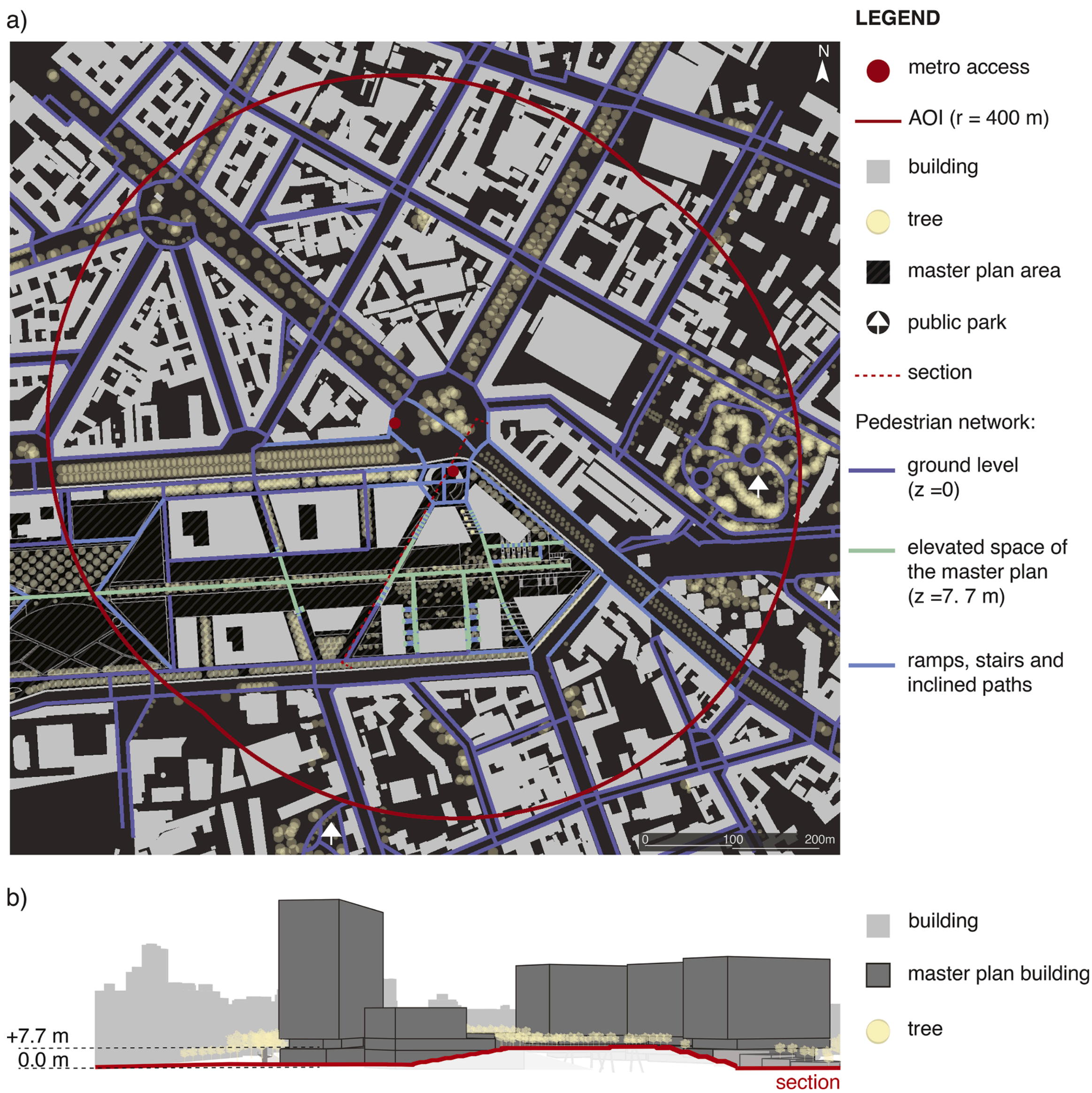

Fig. 2. a) Case study area modelled in Rhino with network segments assigned to different levels; b) Section of the master plan area.

would not impact the shade accessibility by users. Nevertheless, it can be noted that a sequence of ramps in the southern master plan area resulted in the sun; since users would need to walk for more than two minutes to complete this path, the installation of temporary shading devices is recommended.

4. Discussion

This paper analysed the solar radiation exposure of a pedestrian network to investigate its resulting impact on the pedestrian experience. The extensive modelling phase focused on the pedestrian network, the urban morphology screening surfaces from the sun (buildings and trees), and the selection of critical days and hours combinations to analyse. Four user profiles of pedestrians were characterised based on walking speed and ability to climb the stairs. The analysis was divided into three steps, each one focusing on a specific issue resulting from the impact of solar radiation exposure of pedestrian paths. The methodology allows urban designers to evaluate pedestrian paths and subsequently test shading installations to gain meaningful information on how solar radiation exposure affects the walking experience.

4.1. The implementation of solar radiation exposure on pedestrian network analysis

This research argues the relevance of thermal comfort in walkability analysis, progressing beyond the most common trend of prioritising functional or amenity factors over it (Baobeid et al., 2021). Specifically, thermal comfort was simplified as presence or absence of shading. This geometrical approach could be used by urban designers to propose solutions, as solar radiation is of primary consideration in early design phases, when different options are tested.

The solar radiation exposure analysis can be considered as an additional layer of pedestrian network studies, characterised by precise spatial localisation and variability throughout the day, although consistent in time. In Section 3.3, optimal solar radiation exposure was compared to the path of the shortest length (metric distance). In transport modelling, route distances are also defined as topological (fewer turns) and geometric (lowest angular change). The different concepts of distance are the basis for movement modelling techniques aiming at categorising mobility networks based on potential footfall. Pedestrian trip models would benefit from the inclusion of network attributes in the travel cost calculation (Sevtsuk, 2021), with the proposed methodology

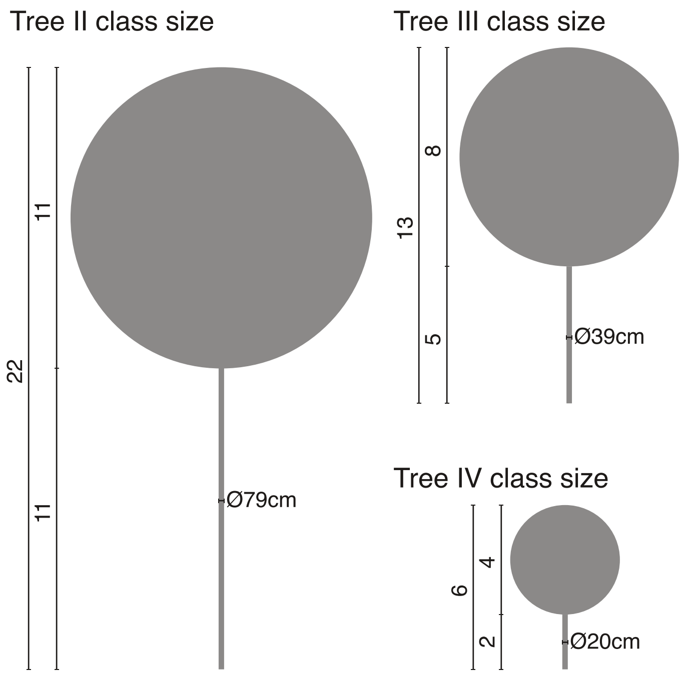

Fig. 3. Trees modelled as representative of class sizes, according to the Municipality documentation.

being a step towards this direction. Because of the dynamic nature of shading, including the solar radiation exposure layer in mobility modelling would add complexity to the performed analysis, describing the human experience of the urban environment. Furthermore, the installation of shading devices could be prioritised based on the overlaying of solar radiation exposure and pedestrian traffic, bridging the analysis of movement patterns and environmental features.

In analysing the solar radiation exposure, the sole presence of shading devices such as trees or horizontal coverage was not considered sufficient to estimate shading on sidewalks; similarly to many tools reviewed in Table 1, the analysis procedure also simulated whether street tree positioning was effective in shading pedestrians at a specific time, ensuring accurate results. The software Rhino facilitates collaboration among professionals working at different scales; for example, decision-makers could assign priority to shading installations in a neighbourhood, and designers at the street scale could iteratively test shading options in the same digital environment. Modelling a larger network is possible, at the cost of higher modelling and computational time. Alternatively, this methodology could be applied at the urban scale in the GIS environment, similar to Aleksandrowicz et al. (2020). This would result in a trade-off, analysing extensive urban areas would result in lower modelling detail, particularly due to the 2.5D modelling technique.

4.2. Toward more inclusive cities

Improving walkability in cities will benefit citizens who are not driving a car (Baobeid et al., 2021), including the elderly and children. This paper fits in a branch of research investigating walkability for the elderly (Alves et al., 2020), women (Gorrini et al., 2021), and children (Gorrini et al., 2023). Its contribution is the inclusion of solar radiation exposure as an urban environmental feature, which impacts differently the experience of pedestrian paths by the users, as well as their physiology (Tomasi et al., 2024). The proposed methodology allows

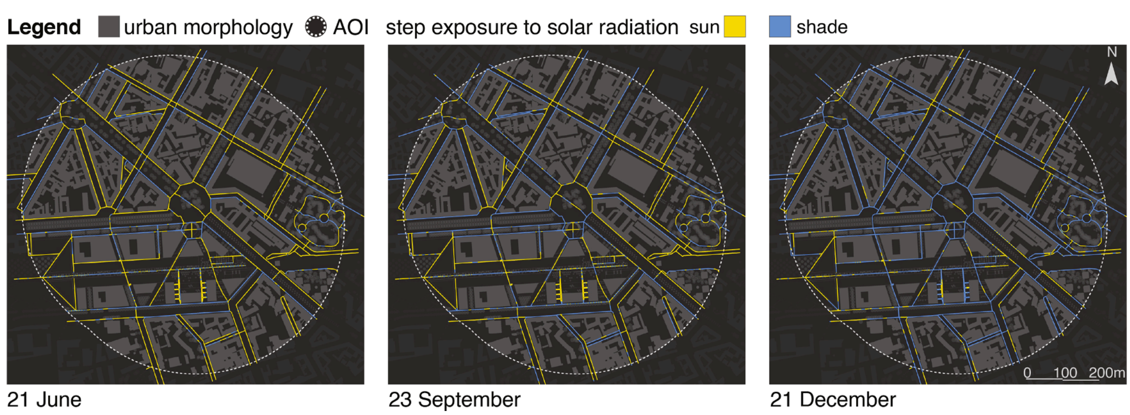

Fig. 4. Distribution analysis of shading on the pedestrian network on all three simulated days at 1 pm.

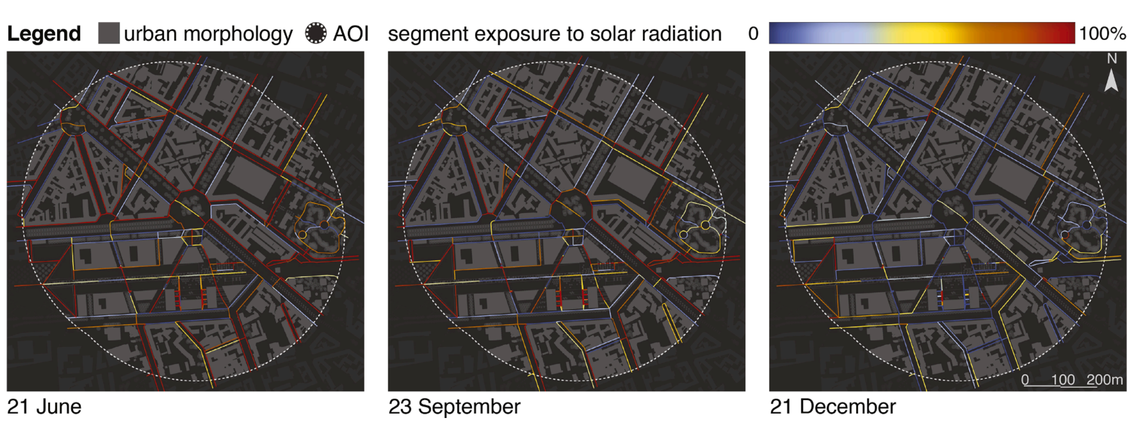

Fig. 5. Solar radiation exposure of the pedestrian network on all three simulated days at 1 pm.

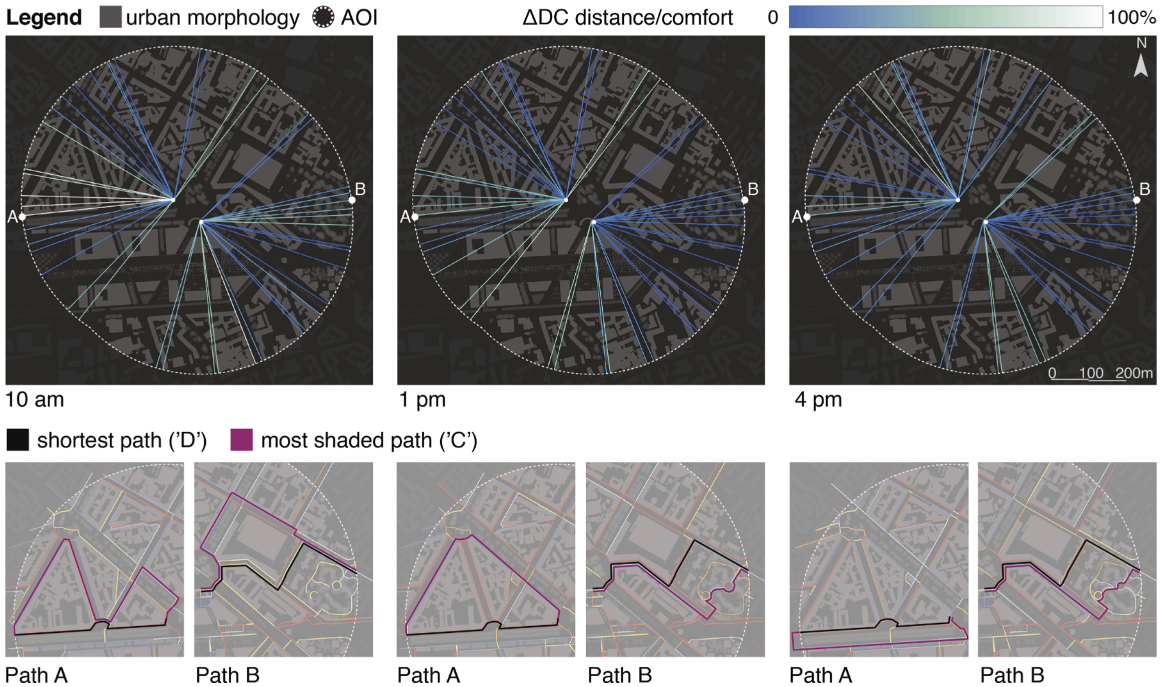

Fig. 6. Difference between the shortest and the most comfortable path (in terms of solar radiation exposure) on 21 June at all three simulated hours. The focus on two specific paths illustrates to what extent the most shaded paths would differ during the summer solstice day.

professionals to adopt diverse user perspectives in evaluating pedestrian paths, as suggested by Alves et al. (2021) in their work about the elderly. Additionally, shading solutions could be proposed according to the results; urban design proposals could be tailored in response to people's needs. For instance, the resulting maps would be critical in planning safe paths for children going to school, accessible services for the elderly, or inclusive sidewalks.

Ensuring favourable microclimate conditions of pedestrian paths would also benefit accessibility to public open spaces (Giles-Corti et al., 2005). Currently, indicators for proximity to urban green spaces have been formulated, defining a minimum walkable distance to access a park (WHO, 2016). Applying the proposed methodology on a pedestrian network selected around a green space, rather than a mobility hub, would supplement accessibility metric requirements with information about the experience of pedestrians walking to that park. Additionally, the definition of user profiles of different walking speeds would contribute to include diverse walking abilities in assessing such accessibility indicators.

4.3. Limitations of this study and future work

The manual process of modelling centre lines of sidewalks was a resource consuming activity that could be a limitation of this work; processes to automatically draw the centre lines could be developed, yet supervision of results is recommended. Shading is strictly localised on sidewalks, therefore granular modelling of pedestrian path segments is required in shading analysis; the pedestrian network could not be simplified, such as in studies that focused on urban layout (Cooper et al., 2021). Similarly, the focus on sidewalks prevented the use of data referring to the centre of the street, like GSV images (Li et al., 2022). The trade-off between model detail and calculation time in relation to the modelling scale is a key point to solve in future work, especially if the proposed analysis would be coupled with movement modelling techniques.

The four users profiled in this paper were defined to cover a wide range of walking abilities. Nevertheless, as reviewed in Section 2.2, walking speed could vary across subjects of similar characteristics. In the case of specific applications, more detailed user profiles should be defined. For example, children of a certain age range could be modelled for assessing comfortable walking paths to encourage them to walk to and from school (White et al. 2017).

Three reasons led to narrow down the microclimate analysis to solar radiation exposure: its critical impact on thermal comfort, therefore path choice (Section 1.1); the possibility to modify sidewalks' exposure through design; and the geometrical approach requiring limited computational time and basic modelling skills. This choice impacted the modelling approach; tree canopies were modelled as solid spheroids even though in winter, the absence of leaves on deciduous trees would allow sun rays to pass between branches. Nevertheless, the model detail/calculation time issue, along with the adoption of the binary rule 'shade or no shade', led to the assumption of tree canopies as solids. However, detailed modelling of the canopy of trees as well as analysis on additional microclimate variables provides scope for future research.

Ladybug tools could be next used to simulate the radiation energy exchange between surfaces; research has demonstrated the different impact of shading devices on thermal metrics, with natural solutions being more effective in reducing thermal stress than artificial canopies (Middel et al., 2021). As regards thermal comfort, a more comprehensive analysis could include the wind speed, which has been analysed for open spaces (Chatzipoulka et al., 2020; Tsichritzis & Nikolopoulou, 2019). In this research, the simulation focused on solar radiation exposure, which can be controlled by designers and largely impacts pedestrians, while a possible further step can also include thermal comfort indexes such as UTCI. Further analysis would require significant expertise in modelling and simulation, specialised technical tools not widely employed by practitioners, and high variability in response to meteorological conditions. Similarly, additional factors influencing walkability and user preferences could be modelled, such as sidewalk width and destinations availability.

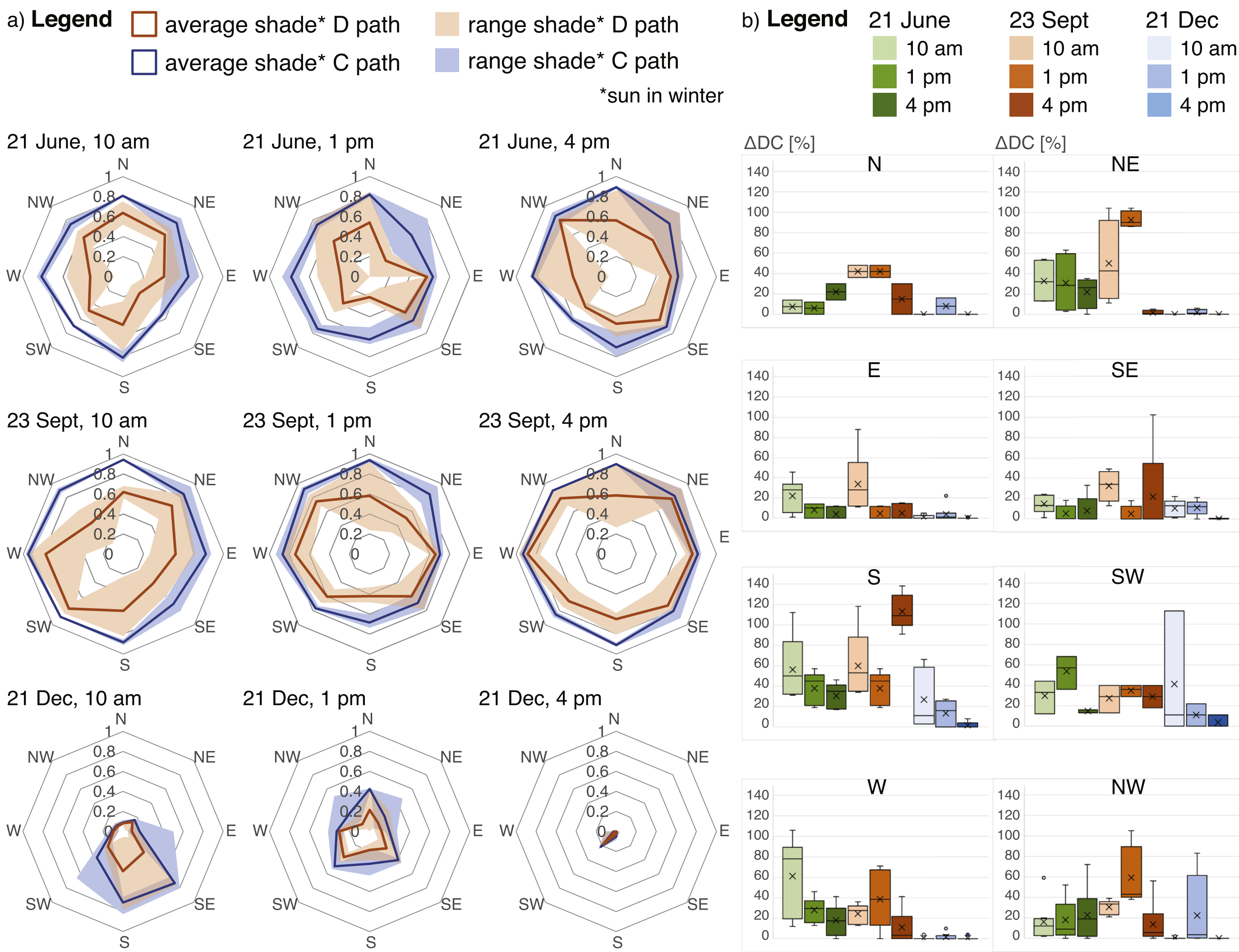

Fig. 7. Synthesis of the ΔDC analysis designed to provide insights based on travel direction and days and hours combination: a) range and average of shaded path ratio for each travel direction; b) ΔDC values divided by trip orientation and days and hours combination.

5. Conclusions

This paper has presented a systematic methodology to evaluate how solar radiation affects the user experience of a pedestrian network. The detailed modelling method was designed to provide accurate results about shading on sidewalks, in order to inform urban designers to propose solutions to improve the accessibility and the comfort of pedestrians. The three-step analysis investigated the variability of solar radiation exposure of sidewalks, the difference in path length if discomfort resulting from exposure to solar radiation was prioritised over distance, along with the accessibility by pedestrians of diverse walking abilities. This latter analysis originated from the user-centred approach adopted in this research; embracing the perspective of diverse users provides critical information to exploit in the design of inclusive cities, where the needs of vulnerable pedestrians are met. The contribution of this research to urban design is the systematic inclusion of solar radiation exposure and walking ability in pedestrian network evaluation. Specifically, shading was modelled in 3D rather than assuming it based on environmental features; pedestrians were included by adapting the pedestrian network to their accessibility characteristics, and then analysing how their walking speed would impact the time spent under the sun.

Cities are spaces where people are impacted by multiple factors and multidisciplinary approaches are key to improving liveability, therefore urban designers need specific instruments to implement them in practice. The adopted practical approach analysed a specific issue that could be addressed through short-term solutions. In fact, design proposals can directly impact solar radiation exposure; on the contrary, larger scale phenomena such as the urban heat island effect require more extensive and less immediate solutions (Aleksandrowicz et al., 2020). This research bridged academic research with professional practice, selecting variables under designers' control and relying on tools familiar to practitioners. The inclusion of multiple variables affecting the pedestrian experience would contribute to a multidisciplinary assessment of walkability in the urban environment, providing benefits in terms of liveability, environmental quality, and health.

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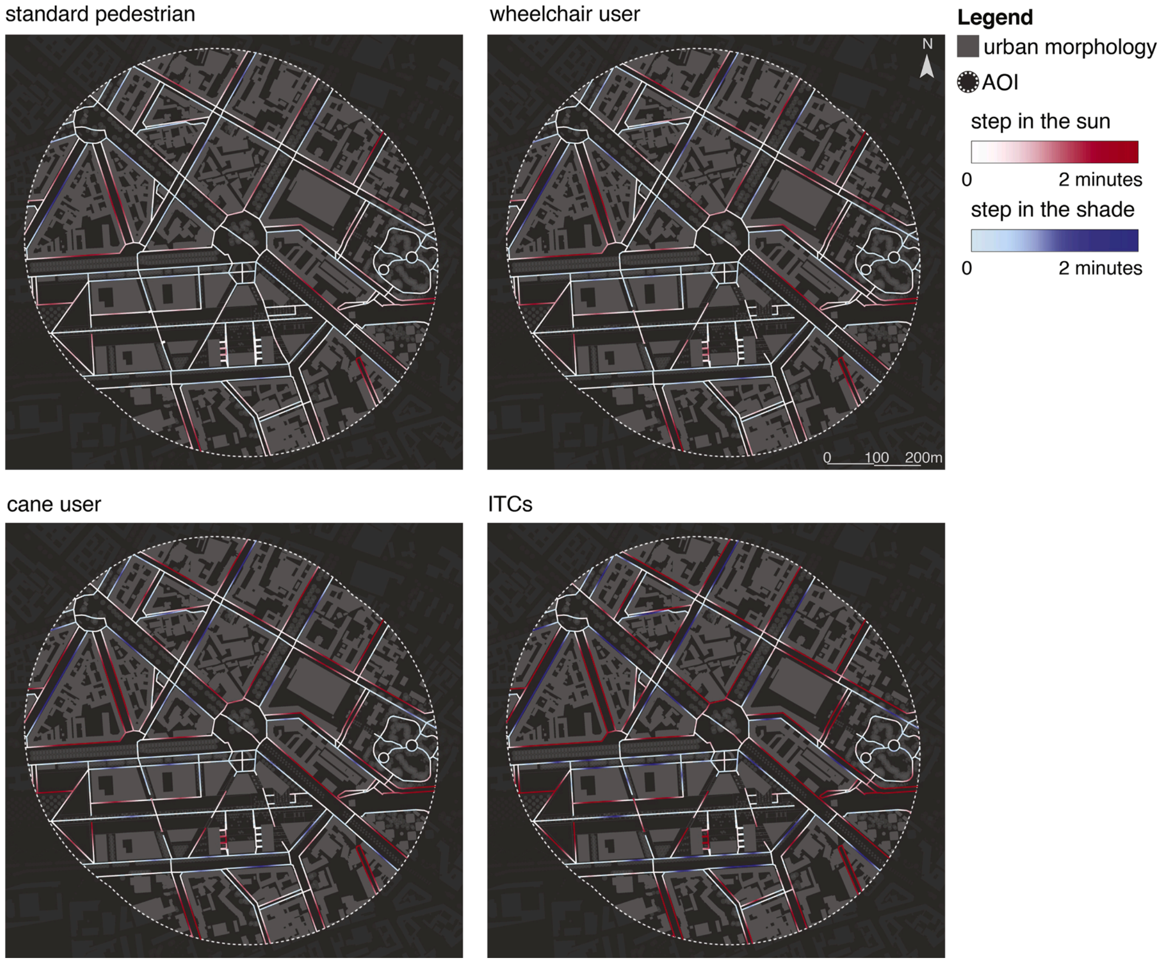

Fig. 8. Shade accessibility analysis on 21 June at 1 pm.

CRediT authorship contribution statement

Marika Tomasi: Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Marialena Nikolopoulou:** Writing – review & editing, Supervision, Conceptualization. **Renganathan Giridharan:** Writing – review & editing, Supervision. **Monika Löve:** Supervision. **Carlo Ratti:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Sources for weather data and existing urban morphology are provided; the data used for the master plan are confidential.

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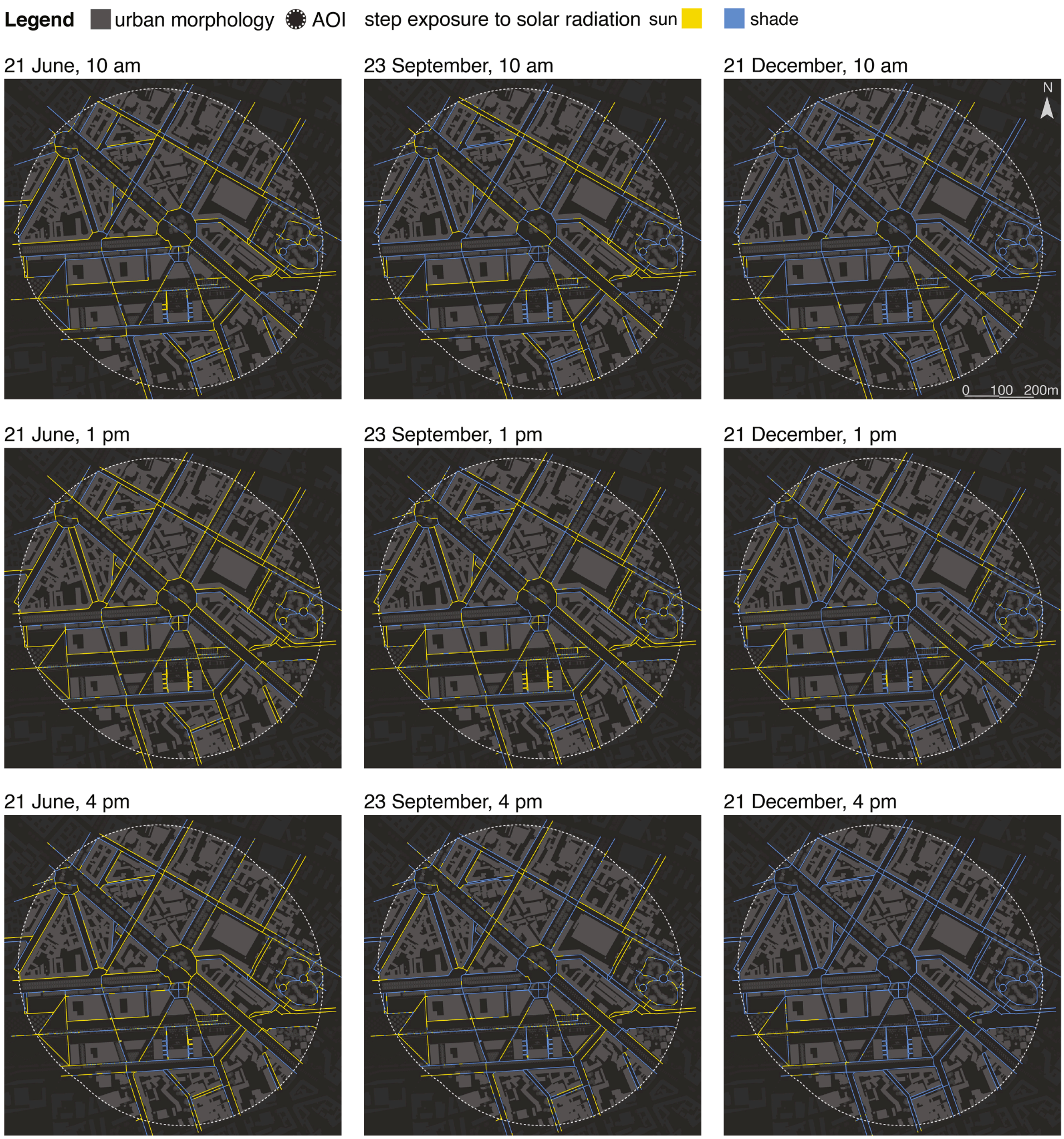
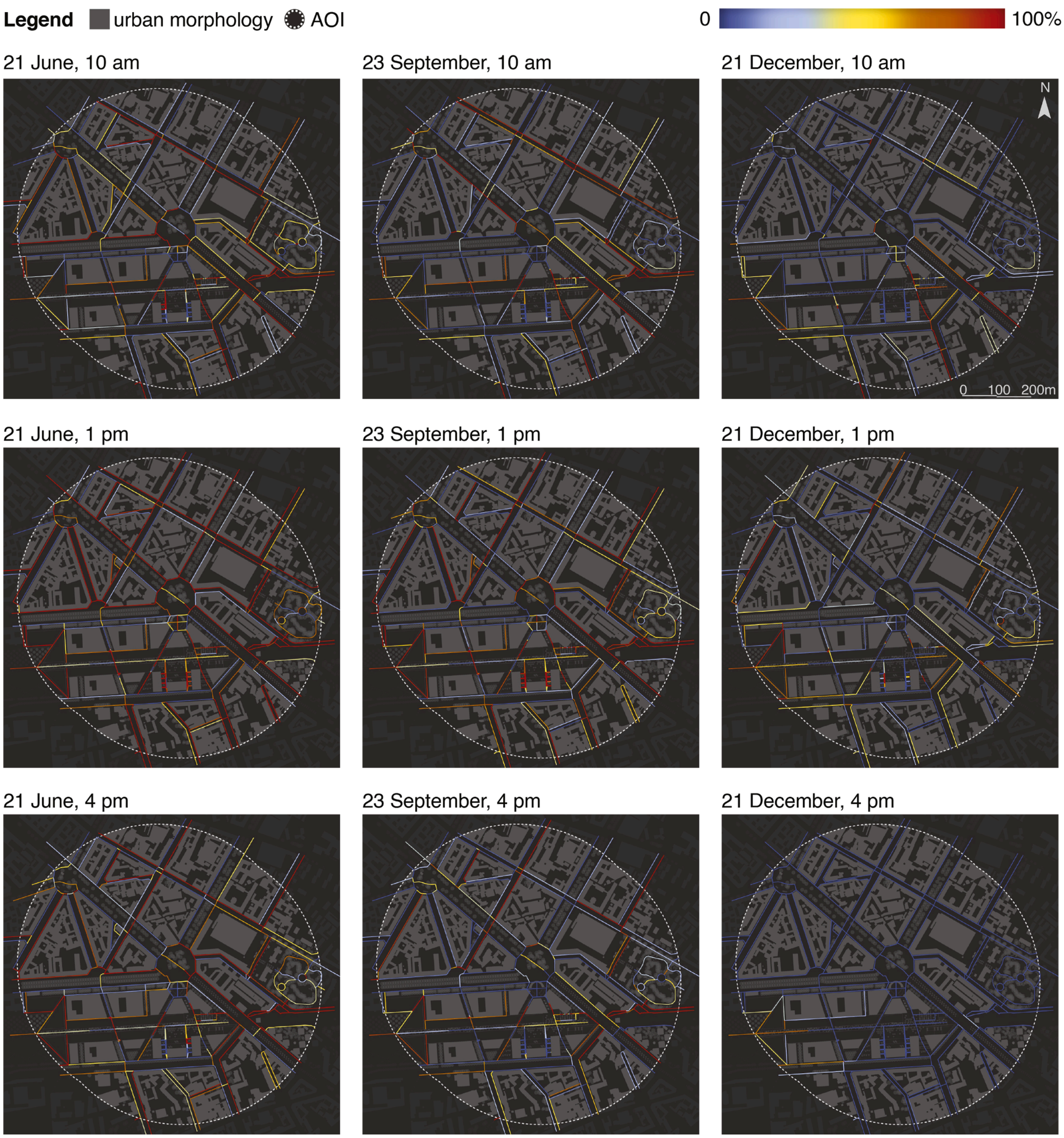
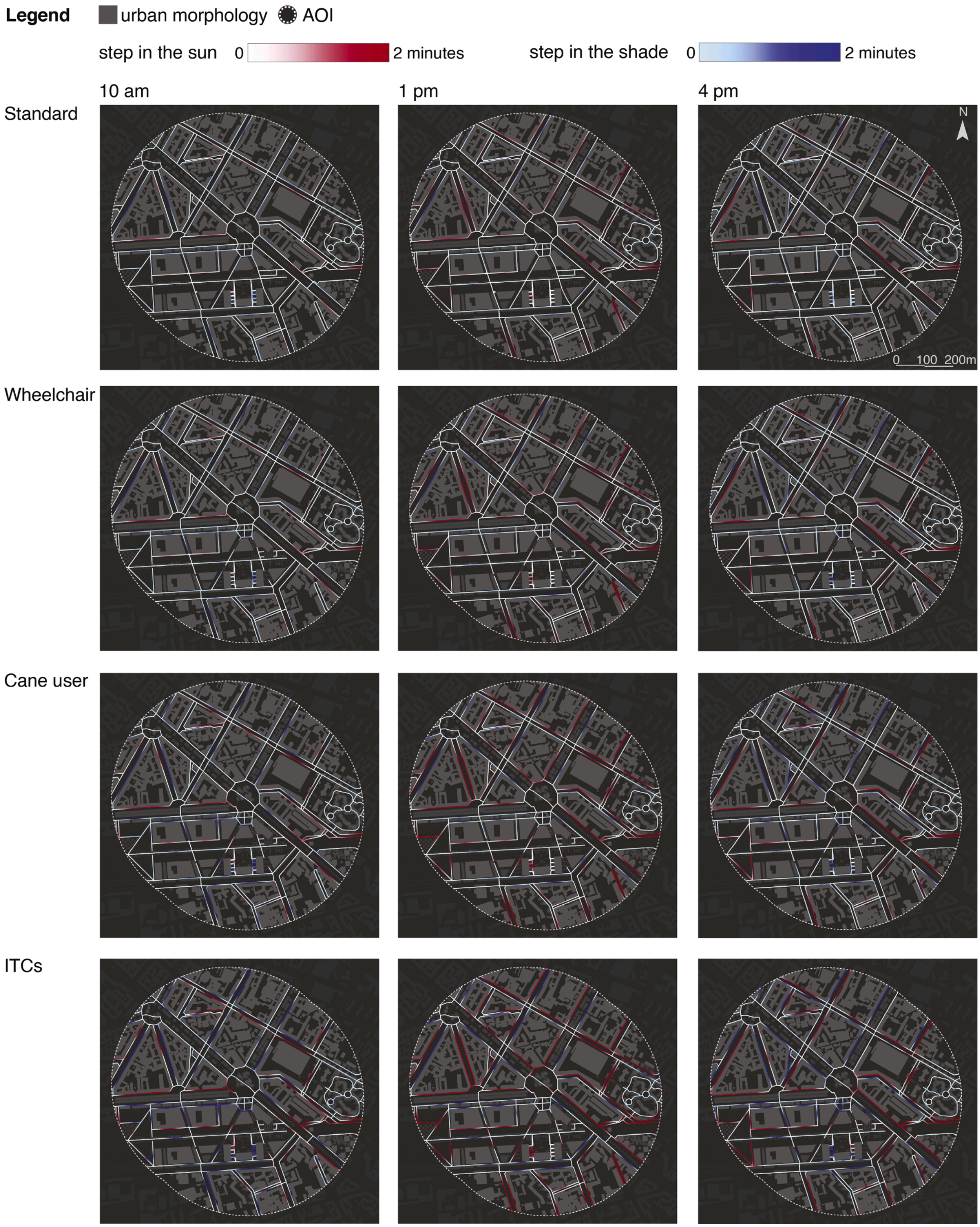
Appendix A. Distribution analysis for all days and hours combinations.



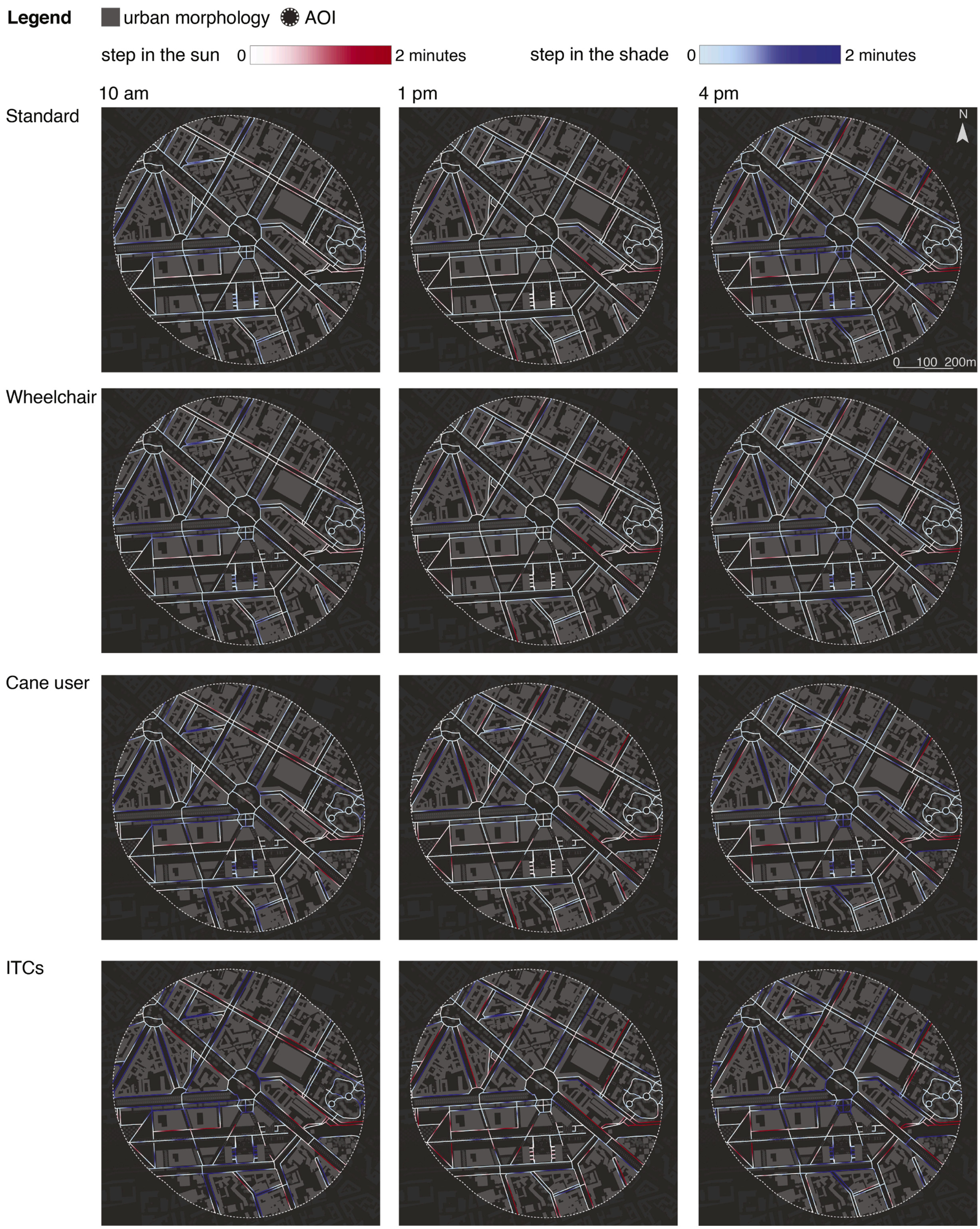
Appendix B. Solar radiation exposure analysis for all days and hours combinations.



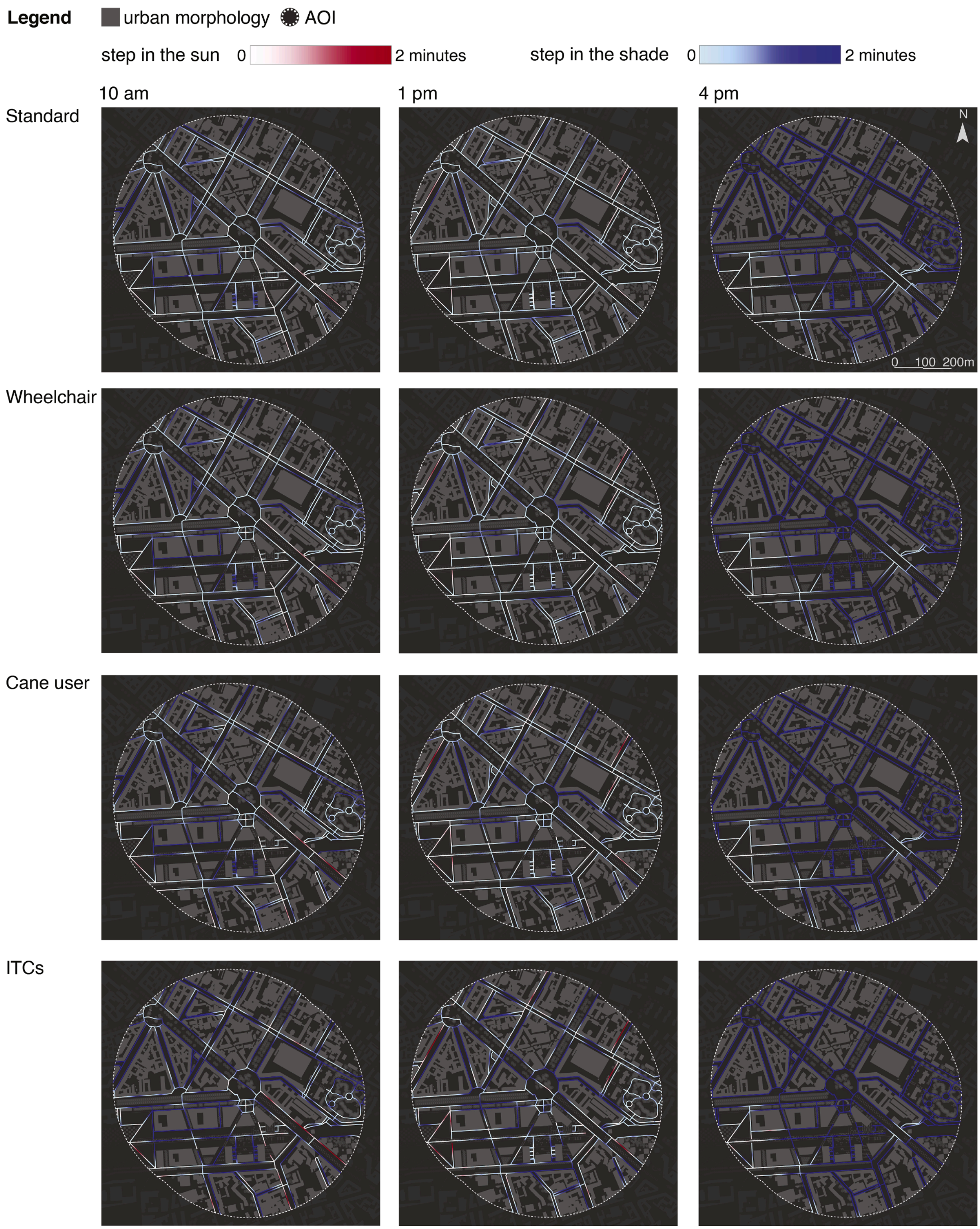
Appendix C. Shade accessibility analysis on 21 June



Appendix D. Shade accessibility analysis on 23 September



Appendix E. Shade accessibility analysis on 21 December



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