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A design workflow for effective solar shading of pedestrian paths

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ABSTRACT

Shading pedestrian paths is strategically important to ensure accessibility and comfort for pedestrians in cities. Limited applicability in practice of previous research about the effectiveness of natural and artificial shading devices was found. This paper proposes a workflow to design effective installations of shading devices on sidewalks; it relies on a design tool developed prioritising compatibility with other software/processes for its application to urban design. The methodology was tested on the city of Milan; the performance of 60 % linear path in shade was set as the design goal. Based on solar radiation exposure of urban canyons, a time of the day was associated with each simulated summer scenario. A library of shading devices was compiled allowing designers to test various proposals. The workflow was applied at first to theoretical urban canyons, then to a real case study sidewalk. Results included a catalogue of solutions with installation guidelines, a table to estimate the recommended number of shading devices for each sidewalk location, and the opportunity to iteratively test master planning proposals. Four applications of the workflow were proposed in response to resources availability and increasing outcome suitability. The workflow would support urban designers in implementing solar radiation exposure analysis in their practice.

1. Introduction

The heat exchange between the human body and the surrounding environment is the basis for the physiological approach to thermal comfort, and solar radiation is a key climatic variable in outdoor contexts, as emerged in assessing thermal indexes for outdoor environments [1]. Especially under clear sky conditions, solar radiation has a large impact on the human heat balance [2,3], therefore exposure to solar radiation can lead to outdoor heat stress [4].

Microclimatic conditions of pedestrian paths deserve critical attention because walking is impacted by environmental factors [5]. Outdoor heat stress has been demonstrated to influence pedestrians' behaviour due to increase in the perceived travel time [6] and altering of walking speed [7,8]; additionally, the presence of shade was reported to affect route choice [6].

Shading the walking paths is one of the most effective strategies to improve pedestrians' comfort in summer sunny conditions [9–12]. Metrics such as the Shade Index [13] are useful to evaluate the presence of shade, and consequently prioritise mitigating solutions. The calculation of shade has been performed considering the entire urban canyon horizontal surface [14], only the sidewalk surface [15–17], or the linear path length [18].

To foster better urban environmental quality, local authorities have established performance targets and turned them into recommendations for urban designers. For implementing and monitoring urban forest and greening, the 3-30-300 rule was recently introduced by Konijnendijk [19]; three trees visible from every home, 30 % tree canopy cover in every neighbourhood, and 300 m from the nearest green space. In addition to urban greening, the World Economic Forum has indicated shade standards as a critical solution to cope with extreme heat [20]. Shading coverage targets on walkaways have been recommended for various cities; e.g., Abu Dhabi (continuous shading from 60 % to 80 %), Tel Aviv (minimum continuous cover of 80 %) and Maricopa County (20 % as minimum, 60 % as excellent, calculated for a 20 min route) [12,21].

1.1. Solutions to shade pedestrian paths

In the absence of shading provided by buildings, natural and artificial shading devices can be strategically installed. Specifically, adopting deciduous trees and temporary artificial solutions allows pedestrian exposure to solar radiation in winter when it is beneficial [22]. Trees

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impact energy balance in two ways, by converting energy into latent heat (evapotranspiration), and by blocking and absorbing direct solar radiation (shading) [23]. Pace et al. [24] collected microclimatic data in Munich (DE) and found a ratio of around 1:10 between the two above effects, demonstrating the critical shading effect of canopies. Nature-based solutions bring crucial benefits to the urban environment and people [25]; specifically, trees are considered a critical strategy to improve thermal comfort [11,26]. In addition to trees, artificial shading devices such as overhead covers [27,28] and stand-alone canopies [29] can be used to screen urban streets from solar radiation [30]. Artificial devices are a successful strategy, for instance, when plants have not yet reached maturity [28] and in existing urban environments [31], where there is no room for plants to grow [26]. Natural and artificial shading devices can also be combined, as demonstrated by Peeters et al. [14] simulating a pergola covered with vegetation.

1.2. Problem statement and approach

Urban design is a process of balancing conflicting interests, comfortable microclimatic conditions being only one of them [32]. Similarly, the installation of trees is subject to various factors: economic, cultural, ecological, and aesthetic [33]. Researchers have already investigated the use of trees to shade pedestrian paths, aiming at quantifying the shade coverage [17,18], assessing the effect of various shade coverage on thermal comfort [14,34,35] and analysing the impact of tree geometry [15,16,36-38]. The shading effect of trees and other shading solutions changes based on a seasonal, daily, and even hourly basis; therefore, shadows fall differently on the ground, and on people underneath. For being beneficial for pedestrians, positioning of the shading solutions must consider the resulting screening effect; thus, urban designers need systematic approaches to position the shading solutions for improving the outdoor shading provision.

Different software tools have been developed to simulate microclimate, such as SOLWEIG [39], Ladybug tools [40], RayMan [3], ENVI-met [41], and TUF-Pedestrian [42]. Keibach and Shayesteh [43] evaluated software tools for climate adaptation planning based on six characteristics: functional suitability, reliability, performance efficiency, usability, compatibility, and information quality. On most occasions, limited compatibility and interoperability of software results in time-consuming operations [44], which might discourage microclimatic analysis at the early stages of the design process. Further, the need for ease of use and high interoperability between software was highlighted in a survey about the solar design of buildings [45]. Therefore, compatibility with other software or processes, and performance efficiency become key in applying the microclimatic analysis to urban design, especially in early design phases, when specialists are seldom consulted [46].

To ensure the relevance of the proposed workflow to urban designers, the current research employed tools predominantly used by architects and urban designers in practice. Grasshopper [47], the visual scripting interface for Rhino [48], was selected. Rhino allows urban designers to either import 3D models from other modelling tools [43], or accurately model urban morphology in 3D, which is a critical feature in shadow studies. Additionally, geometries could be dynamically modified, and design options tested multiple times within the same digital environment. The target audience is urban designers working at the street scale. Therefore, tools developed for the GIS environment were not considered.

This paper presents a design workflow formulated for urban designers to evaluate the effectiveness of installations of natural and artificial shading devices to shade pedestrian paths. The research was carried out in collaboration with academia and industry, and feedback from designers was crucial in fine-tuning the workflow structure, relevance of analysis and communication of results. The workflow is presented and then applied to a case study city. After setting up the boundary conditions of the design area, the design tool allows to systematically compare shading solutions to screen the pedestrian paths in summer. This is done at first theoretically, exploring the effectiveness of shading devices on changing their position; then, shading solutions are applied to a specific case study, adapting general guidelines to real settings. Finally, the innovative features of the proposed workflow are highlighted.

2. Methodology and materials

The interaction between urban morphology (buildings and shading devices) and sun rays impacts the exposure of pedestrian paths to solar radiation. A rigorous workflow was developed for evaluating solar radiation exposure in various scenarios, based on different hour and day combinations, urban canyon geometry, and shading solutions available. The iterative workflow was proposed to enable urban designers to analyse, evaluate and design the shading solutions within the design process rather than the conventional way of performing modelling exercises separately to assess environmental performance. This workflow relies on a design tool developed in Grasshopper to implement shading devices in urban design; the approach by the Digital Design Unit – TU Darmstadt [49] was followed to analyse the shading effect of urban morphology in Grasshopper. The term 'design tool' is a reference to the work by Ratti [50], who proposed 'a simple reactive tool, allowing for comparison of different architectural and urban options' (p.9). To structure the organisation of the information and data for the design tool, an existing protocol, structured in inventory, calculation, and goal setting, was used as a template [51]. The design tool was accordingly divided into three sections: definition of scenarios, simulation, and selection (Fig. 1). In the first one, materials were assembled to define the case study project. In the simulation phase, the solar radiation exposure in modelled scenarios was analysed; finally, the selection tool was used to select the most appropriate design based on the shading performance. In each section, components were collected into groups ('clusters') referring to specific steps in using the design tool: the sequence of steps aims at comparing design proposals to select the most suitable configuration to shade the sidewalks when pedestrians need it most. In Appendix A, the design tool is presented step-by-step.

2.1. Setting the boundary conditions

The first phase of the workflow analyses the solar radiation exposure performance of the case study, representing either the current state of the urban environment or a preliminary design proposal. After defining an analysis period of interest, the street geometry object of analysis is modelled. Finally, solar radiation exposure simulations are critically analysed to assign a worst-case scenario hour to address in the following iterative phase.

2.1.1. Weather data and analysis period

Solar radiation exposure of pedestrian paths changes based on the position of the sun, in terms of azimuth and altitude. To analyse solar radiation exposure during the whole summer season, simulations were performed from 21 June to 23 September. Hours of the day were aggregated into three time periods of 3 h each (9–11 a.m.; 12-2 p.m.; 3–5 p.m.), and calculations were performed for the central hours: 10 a.m., 1 p.m. and 4 p.m., respectively. Since the aim was to investigate pedestrian paths based on people's typical daily activities, hours referred to daylight saving time (DST). Information about the sun position was downloaded from the EnergyPlus website [52] and imported into the design tool via Ladybug (v. 1.5.0).

2.1.2. Street geometry

To define street geometry, a range of urban canyons of different orientations and morphology was modelled. Four orientations were considered: N–S, E-W, NE-SW, and NW-SE. The shading effect of buildings on street surfaces was identified through the aspect ratio,

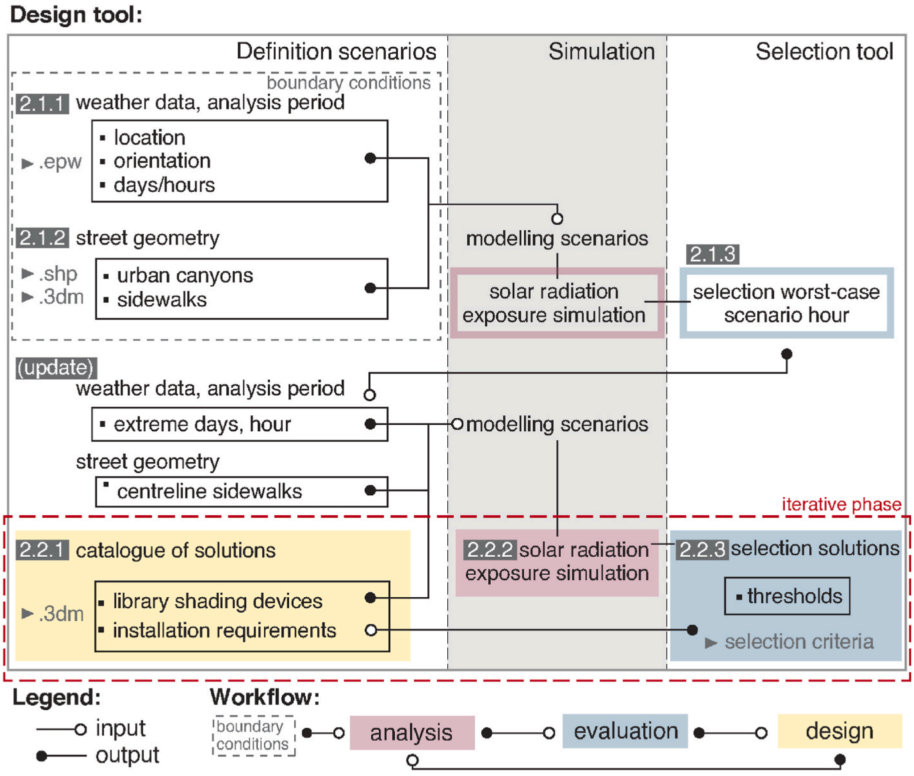

Fig. 1. Scheme illustrating the proposed design workflow for an effective installation of shading devices. The workflow relies on a design tool developed in Grasshopper. Black rectangles correspond to clusters in the Grasshopper code. Grey arrows highlight input data by designers, and dark grey boxes report reference sections in this paper.

referred to as H/W. Three aspect ratio values were selected: 0.5, 1.0 and 2.0, corresponding to shallow, uniform, and deep canyons, respectively [53]. In total, 12 urban canyons were modelled.

Since the aim of this analysis was to assess shading requirements valid for generic urban canyons, no specific sidewalk surface was modelled. The street was divided longitudinally into three parts of equal width (sidewalk – road – sidewalk): the two at the edge were assigned to pedestrians, assuming walking paths would be adjacent to buildings.

2.1.3. *Selection of worst-case scenarios*

Solar radiation exposure was simulated via the 'Direct Sun Hours' component in Ladybug tools; it was simulated on a plane at 1.0 m above the ground, which approximates the centre of gravity of an average standing adult [54], the suggested height for designing for toddlers [55] and the floor-to-shoulder height of a person on a wheelchair [56]. Simulations were performed on the mid-transversal section of the canyon (x-axis), therefore the length (y-axis) was extended to avoid boundary effects due to the edge of the canyon. For each sidewalk, the solar radiation exposure of three virtual sensors was simulated: sensors were positioned on the two edges of the sector, i.e., at the boundary of the sidewalk with the building (b) and road (r), and on the centreline (c) of the sidewalk sector (Fig. 2).

Simulations were performed for every summer day at the three selected hours, for a total of 95 days; the modelling assumed clear sky conditions. The outcome was evaluated to assign one critical hour to each scenario, i.e., urban canyon/orientation model. Among the 3 h simulated, the worst-case scenario was defined as the hour of the day in which the virtual sensors on a sidewalk were exposed to solar radiation

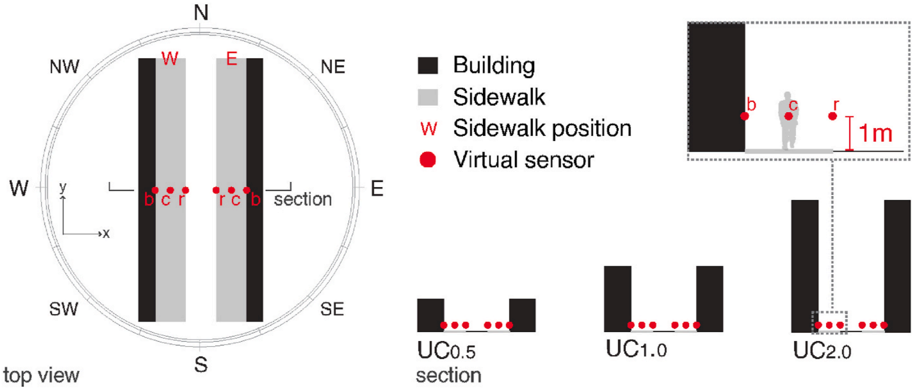

Fig. 2. Scheme of urban canyons analysis. Urban canyons are labelled UC_N, where N=H/W. Red dots indicate the simulated virtual sensors (boundary of the sidewalk with the building, centre of the sidewalk, boundary of the sidewalk with the road). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

on the largest number of summer days. If the results of the three virtual sensors were not conclusive, priority was given to the virtual sensors closer to buildings.

2.2. Iterative workflow to test design proposals

Once the hour to address in the design phase was assigned to each sidewalk position considering street geometry, the phase of setting boundary conditions was completed. In the next phase, an iterative approach is adopted to test the effectiveness of shading solutions to shade pedestrian paths.

2.2.1. Catalogue of shading solutions

For shading pedestrian paths in worst-case scenario conditions, a library of natural (trees) and artificial shading devices was modelled. Since the goal of the workflow was to investigate the effectiveness of shading solutions to screen pedestrian paths, all devices were considered exclusively from a morphological point of view, focusing on the overall dimensions of the devices.

The trees were parametrically described as two components, trunk and canopy. By varying the height of the trunk, the canopy shadow would fall on the sidewalk in different places, making it a critical parameter to detect where the shading effect of the tree would be. The tree canopy was modelled as a solid spheroid blocking sun rays, as the focus was on identifying the exact location of the shading effect. Trees of different sizes were modelled and identified in terms of class sizes provided by local authorities. The modelled artificial devices represented two different typologies of intervention: the punctual installation of stand-alone objects and the extensive coverage through large surfaces.

2.2.1.1. Installation requirements of shading devices. Each shading device has separate requirements and implications for installation in the urban environment. Two parametric distances were defined: the minimum distance between the devices and the sidewalk edge (DS), and between devices positioned in a row (DD_1). For trees, a minimum permeable surface is required around the plant by the local authority; it is identified as a circle at ground level, with the trunk at the centre, of radius determined by tree size. These values were selected as a reference to assign DS distances to trees. Artificial devices had fewer requirements for installation, since restrictions derived mainly from structural features or local authority regulations, with only space required to house the structure. These parametric distances are presented in Fig. 3.

2.2.2. Solar radiation exposure simulation

The design tool allows urban designers to define a design proposal by locating shading devices in an urban canyon of a case study area, and then analysing their performance. Solar radiation exposure is analysed on the centreline of the sidewalk, following the linear approach by Perez [18]: this allows to evaluate the thermal experience of the user along the walk, implementing shading into pedestrian network planning. The shadow-casting analysis is performed in vector mode via the 'Mesh Shadow' component; therefore results are not affected by the model resolution like in the raster calculation methods where calculation of solar radiation exposure takes place at the centre of each piece of surface. The effectiveness of shading devices was analysed at the beginning and end of the summer season, i.e., the summer solstice and autumn equinox days (21 June and 23 September), at the hour assigned in Section 2.1.3. It should be noted that, instead of analysing the whole summer period as done in defining the worst case scenario, the effectiveness of design proposals was tested only on two key days, at the beginning and end of the period of interest. The assumption adopted was that the shading effect on these two days would be valid for the whole summer season, at the selected hour.

2.2.3. Selection of design goal thresholds

The result of the analysis phase was an overview of the shading effect of the solutions installed in the design scenarios, specifically, the percentage of the centreline of the path in the shade during the simulated hour. Then, the design proposal's effectiveness was evaluated, comparing the shading performance to specific targets; performance thresholds were assumed by simulating a decision-making task performed by urban designers and local authorities based on context and urban planning priorities and adjusted to respond to specific design goals.

3. Results

The presented design tool allows urban designers to implement shading solutions in their design proposals with different levels of detail. First, the design tool was applied to theoretical urban canyons, simulating a preliminary stage of the design process; then, a shading proposal was developed specifically for a real case-study sidewalk in Milan.

3.1. Case study city

The city of Milan was selected as a case study. According to the Köppen-Geiger climate classification, its climate is Cfa – humid subtropical with hot, humid summers and cold winters. The morphology of the Po Valley favours low ventilation, with negative effects on air quality and heat stress; historical data analysis shows that heatwaves and tropical nights almost doubled in the period 1991–2017, compared to the previous 30 years [57]. Being the most populated Italian city after the capital (Rome) [58], it is a critical city in the context of solar radiation exposure of pedestrian paths. Further, the Municipality of Milan provides open data [59] and extensive documentation about urban design guidelines and recommendations [60] that were critical in testing the design tool.

In this work, the worst-case scenario hours and the shade coverage targets were associated with the context independently of the application performed. So, this section reports the results of the evaluation phase, which are assumed as valid for all the following design applications.

3.1.1. Selection of worst-case scenarios

To assign one design hour to each scenario, three urban canyons of standard length of 100 m were modelled: the canyon width was constant and representative of urban morphology in Milan (W = 15 m), with resulting heights of 7.5, 15 and 30 m. Sun positions were imported from the weather file of Milano-Linate 160800 (IGDG). The number of summer days for which the virtual sensor under consideration was exposed to solar radiation on each sidewalk for each one of the 3 h is reported in Appendix B: results vary based on H/W ratio and orientation. The worst-case scenarios selected for the design phase are presented in Table 1. If one sidewalk was exposed to solar radiation for multiple periods in summer, the central hour (1 p.m.) was selected to prioritise lunchtime pedestrians; furthermore, shading pedestrian paths at 1 p.m. was assumed to be beneficial in terms of lowering the afternoon surface temperature. Since sidewalk S (south) resulted not exposed to solar radiation at 10 a.m., 1 p.m. and 4 p.m., additional simulations were performed at 9 a.m. and 6 p.m.

3.1.2. Setting the design goal

To test the design tool, a target shaded length along the path was set. Shade values discussed in the Introduction were used as a baseline. Although these cities are located in different climate zones, the lower solar altitude of Milan leads to a higher fraction of solar radiation absorbed by standing pedestrians. Hence, as a tentative target, achieving a 60 % shaded length was evaluated as an excellent goal for improving pedestrians' comfort. This value was assumed for balancing the need for pedestrian shading with planning constraints in existing contexts and

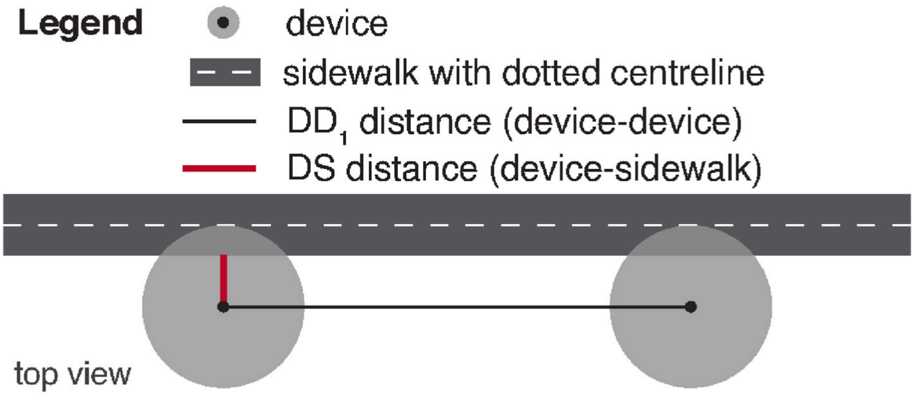

Fig. 3. Scheme of parametric distances defined for installing shading devices to shade sidewalks. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Worst-case scenario hours assigned to urban canyons; detailed results of the analysis are reported in Appendix B.

	$UC_{0.5}$	$UC_{1.0}$	$UC_{2.0}$
N	1 p.m.	1 p.m.	10 a.m.
NE	1 p.m.	1 p.m.	1 p.m.
E	4 p.m.	4 p.m.	1 p.m.
SE	4 p.m.	4 p.m.	4 p.m.
S	6 p.m.	6 p.m.	6 p.m.
SW	10 a.m.	10 a.m.	10 a.m.
W	1 p.m.	1 p.m.	1 p.m.
NW	1 p.m.	1 p.m.	1 p.m.

ensuring comfortable conditions during more than half of the walking route. The 60 % shaded length target was adopted along the pedestrian paths during both the summer solstice and autumn equinox days. In addition, the lowest number of devices possible was selected as a recommendation.

3.2. A catalogue of solutions for diverse combinations of shading device/sidewalk location

The performance of shading devices was analysed based on the urban canyon orientation. The goal of this application was to provide a catalogue of solutions to allow urban designers to select the most suitable shading device for each sidewalk location.

3.2.1. Catalogue of solutions for Milan

Three trees of different sizes were modelled and identified as classes II, III and IV according to the reference material [61]. Specific plants included in the census database [62] were modelled: trees selected belonged to a row of plants along a sidewalk and were of height close to the dimension reached to maturity [60]. Table 2 reports the morphological parameters of the three trees identified, together with the tree ID for reference. A list of species that match the modelled morphologies can be found in the material provided by the local authority [61].

Two artificial devices were modelled. The first one was a stand-alone canopy, specifically a foldable umbrella-shaped structure; an existing shading device was taken as a reference for this application [63]. The second artificial solution was a large textile cover installed above pedestrian paths. The shape of the surface is susceptible to design; the catalogue featured a rectangular canopy 2.2 m high (according to the Municipality's requirements), connected to the ground every 3 m, and as wide as the footway. All five modelled shading devices are reported in Appendix C.

In addition to the minimum permeable area around trees, the local authority reports the preserved portion of ground in which roots could grow, for each class size. These measures are calculated from the edge of the trunk and were reported as useful information to avoid conflicts between the root space and underground facilities. Minimum and adopted DS and DD$_1$ distances are collected in Table 3.

3.2.2. Updating installation requirements based on the effectiveness of shading devices

At first, a recommended DS distance for each device/sidewalk location was defined. The pedestrian path was modelled 1.5 m wide, as the minimum footway clearance [60]. Starting from the minimum installation requirements (Table 3), their suitability to effectively shade the linear path under investigation was assessed. The analysis showed that for some combinations, the adopted buffer zone was not a suitable DS distance to shade the pedestrian path; the proposed design tool was therefore used to update the adopted DS distances.

In some cases, class size III trees were positioned at a larger distance from the sidewalk edge: specifically, 3.3 and 5.8 m, and the additional space could host a bike path and a car lane, respectively. Class size II trees were moved by 4.5, 6.5, 8.0 and 10.0 m on sidewalks of different orientations. These measurements were selected to accommodate additional space for mobility, i.e., combinations of car lanes, parking lanes and bike paths. The parameter evaluated for the large cover was its position against the path: the simulation aimed at identifying the appropriate distance from the path to install the cover for effectively shading pedestrians. Even though the shading effect was constant throughout the summer season, this additional space might be a barrier to implementing this solution on narrow sidewalks. Fig. 4 presents

Table 2
Morphological parameters of the trees included in the library.

Class size	Maturity height[a] [m]	Specie[a]	Canopy shape[a]	Tree ID[b]	Height[b] [m]	Canopy width[b] [m]	Øtrunk[b] [m]	Trunk height[b] [m]
II	15–25	*Celtis australis*	Sphere	13875	22	11	0.79	11
III	8–15	*Acer negundo*[c]	Sphere	134302	13	8	0.39	5
IV	<8	*Prunus cerasifera*	Sphere	37367	6	4	0.20	2

[a] Municipality of Milan & AMAT [60].
[b] Municipality of Milan [62].
[c] Specie object of monitoring and controlling measures.

Table 3
Minimum requirements and suggested distances for positioning shading devices.

Device	Minimum root space radius[a] [m]	Minimum permeable area[a] [m^2]	Minimum DS (squared/circular surface) [m]	Adopted buffer zone [m] (DS distance)	Suggested distance between devices[b] [m]	Adopted minimum distance [m] (DD$_1$ distance)
Tree II	2.50	6.25	1.25/1.42	1.50	7.5–10	7.50
Tree III	2.00	4.00	1.00/1.13	1.30	5–7.5	5.00
Tree IV	1.50	2.25	0.75/0.85	1.00	3–5	3.00
Stand-alone canopy	–	–	–	0.40	–	3.20
Large cover	–	–	–	–	–	–

[a] Municipality of Milan [61].
[b] Municipality of Milan & AMAT [60].

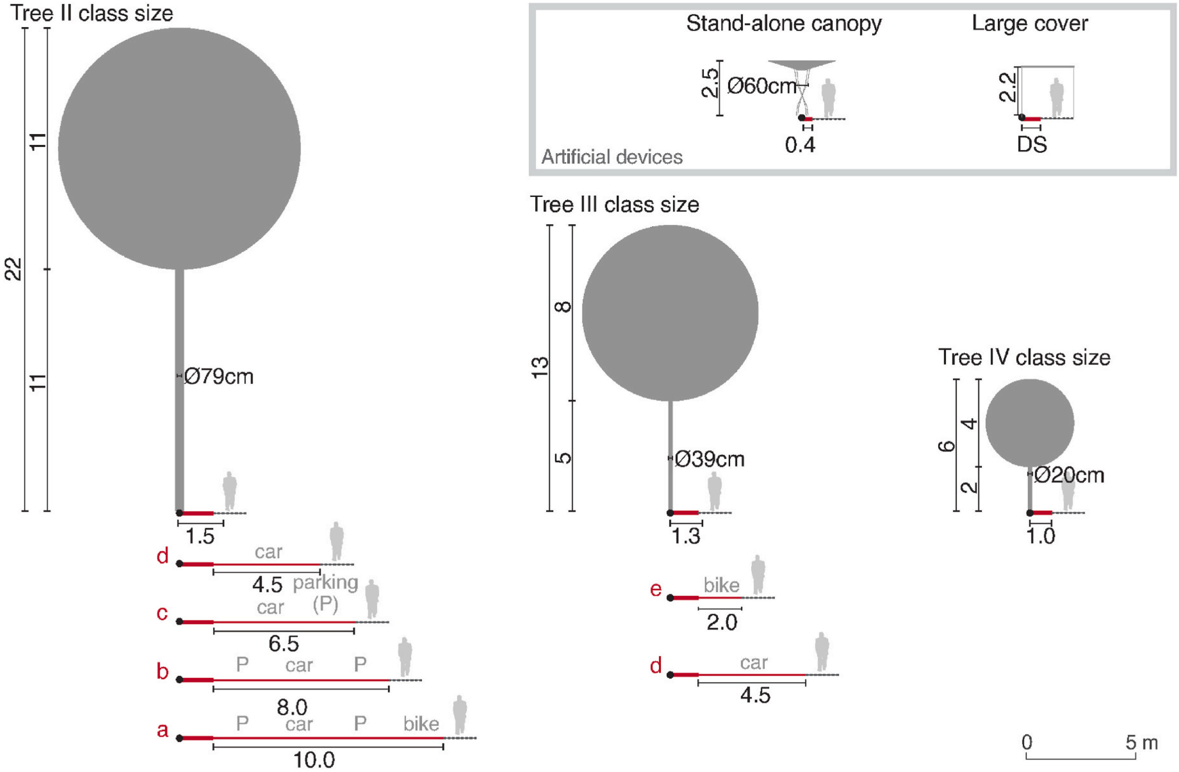

Fig. 4. Catalogue of solutions for Milan with recommended installation guidelines.

guidelines that update the installation recommendations reported in Table 3 by integrating the shading effect.

3.2.3. *Assessing the recommended distances between shading devices*

After assessing the recommended installation guidelines for shading devices, the number of devices necessary to reach the pre-set 60 % shaded length goal based on the sidewalk location was assessed. For the current purposes, the assessment was limited to H/W = 1.0, and the five devices included in the library were positioned in urban canyons of four different orientations. A sidewalk of standard length (100 m) and 1.5 m wide was simulated, therefore the centreline for calculations resulted at 0.75 m from the edge of the sidewalk. A total of eight scenarios were analysed; hours assigned to each orientation were selected according to Section 3.1.1 (Table 1).

Fig. 5 reports the outcome of this application. For each device-sidewalk combination, the maximum DD$_1$ distance to reach the 60 % shaded length goal was reported, as well as the corresponding minimum number of devices per 100 m long streets. Each device-sidewalk combination resulted in a different number of devices being installed on the standard path. Results indicated that sidewalk S was a challenging scenario as all solutions worked only at the beginning of the summer season. Since it resulted in being shaded most of the day (Table 1), this could be considered low priority in terms of shading requirements. On average, simulations lasted 36 ± 21 s.[1] The process could be repeated for other types of urban canyon (H/W = 0.5 and H/W = 2.0).

Fig. 6 illustrates three device-sidewalk combinations of Fig. 5. The devices were positioned at the distance reported in Fig. 5,[2] in a 100m-long urban canyon of H/W = 1.0 (width 15 m). The simulated sidewalk was 1.5 m wide, and 0.5 m from the closest building façade; therefore, the centreline was 1.25 m from the façade. Additional simulations on 21 July and 21 August were performed to visualise the progressive changes in the shading effect, and are reported both in the drawings and in the summary table. In the case of sidewalk N, buildings on the opposite side shaded the centreline of the sidewalk only on the last days of summer (as reported in Appendix B). The shading effect of devices was almost constant throughout the summer season. Sidewalk SW was never shaded by the building, therefore the installation of

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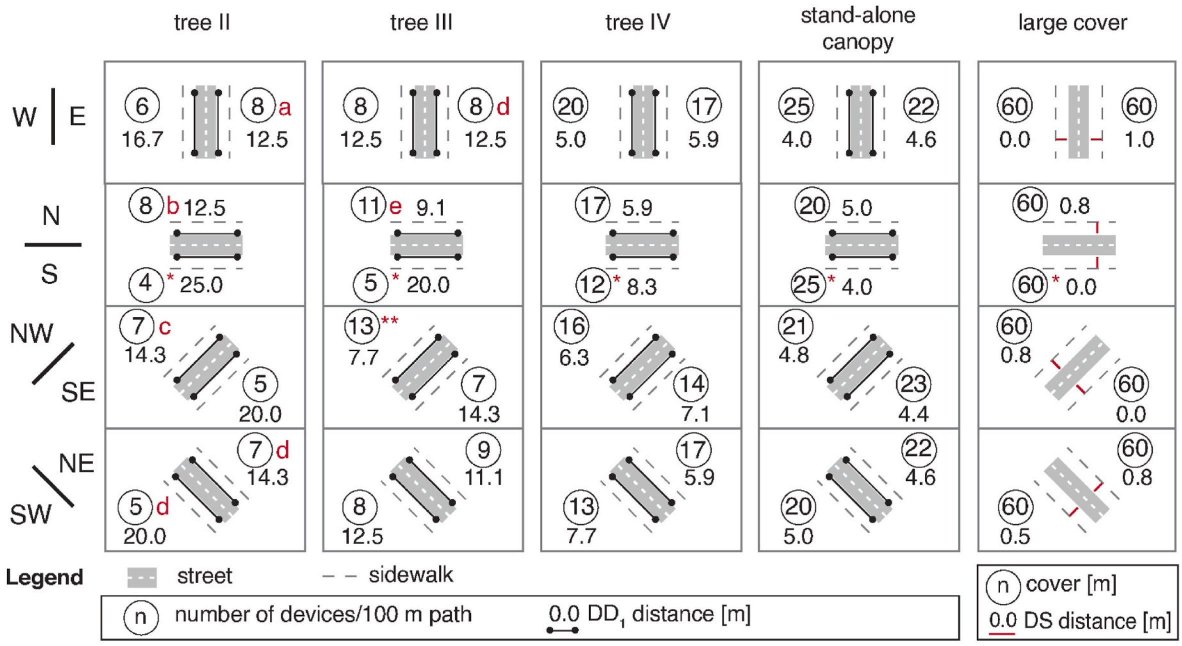
[1] Processing times reported in this section refer to simulations performed on a local computer (i7-7700HQ CPU, 16.0 GB).

[2] To avoid the boundary effect, i.e., to take into account shadows landing outside the considered line, an additional device was added to the number reported in Fig. 5.



modified DS distances: a additional 10 m; b additional 8 m; c additional 6.5 m; d additional 4.5 m; e additional 2 m.

* effective on 21 June, not 23 September. ** if e: ⑧, 12.5

Fig. 5. Suggested number of devices and distances to shade 60 % of the pedestrian path on the respective worst-case scenario hour. Red notes refer to Fig. 4. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

shading devices was critical to improving pedestrians' comfort; during the autumn equinox, the sidewalk resulted in complete shade.

3.3. Positioning shading devices from the library into an urban design proposal

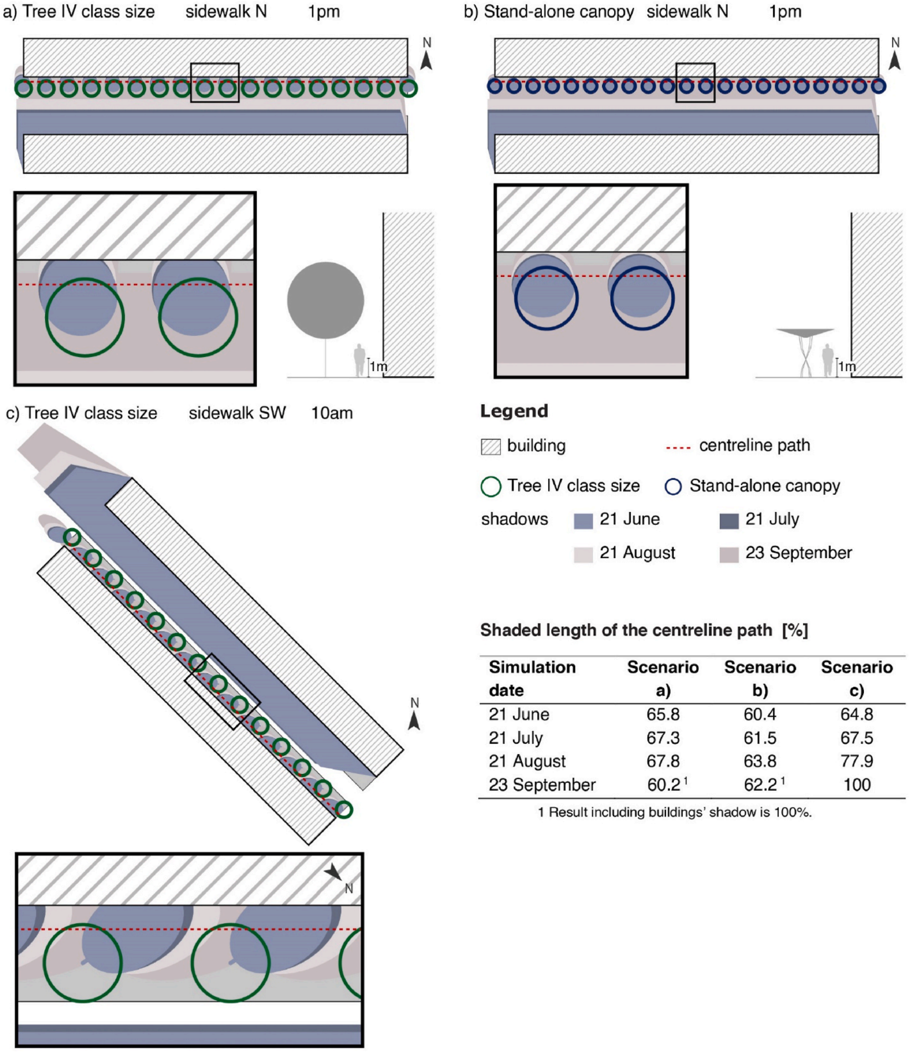
In principle, the assessment of Fig. 5 provides the urban designers with an estimated number of devices required to shade pedestrian paths for the above-said aspect ratio setting (Section 3.2). To apply this to the design process and simulate the outcome, i.e., moving from theoretical urban canyons to real case studies, a master planning proposal for Milan was selected. Based on Table 1, sidewalk N was considered a critical case study to focus on; the corresponding urban canyon orientation E-W has been extensively reported as the worst orientation for thermal comfort conditions during the day [13,64], confirming the relevance of this choice. A representative sidewalk in Milan was modelled: it is situated on the northern side of via Sabotino, in the southern part of the city (Fig. 7). The presence of a bus stop was another critical reason for selecting this part of the pedestrian network. The sidewalk is 165 m long, with the width varying from 2.0 to 6.0 m, in correspondence with the bus stop. The H/W ratio is about 1.0, being the width of the canyon about 17.0 m and the average height of buildings 16.8 ± 7.4 m (data source: [59]). The boundary condition analysis of the sidewalk reported exposure to solar radiation in all summer simulated hours (Table 1), confirming a consistent need for shading.

Critical locations to position shading devices were in proximity of the streetlight, the bus stop, and in front of commercial activities such that pedestrians could access them during the day. Due to limited installation space, class size IV trees were selected as suitable for the case study sidewalk based on installation requirements. Based on Fig. 5, 17 trees distributed along 100 m would have been recommended for shading the sidewalk N, resulting in a total of 28 trees for 165 m length. Nevertheless, for reasons such as preserving access to driveways, preventing obstacles near the crossroad, and keeping access by ramps to the bus stop, it was possible to position only 10 trees; the resulting shaded length was 23 % on 21 June and 33 % on 23 September. Since it was not possible to achieve the 60 % shading threshold exclusively with trees, artificial devices were additionally used for shading part of the sidewalk. Various combinations were iteratively tested; simulations were performed individually and the average simulation time was below 5 s. The final design proposal consisted of 11 stand-alone canopies and 21 m of large cover, together with the 10 class size IV trees (Fig. 8a). In total, 55 % and 64 % of the path resulted in the shade during the summer solstice and autumn equinox, respectively, at 1 p.m. (Fig. 8b). It should be noted that, if the bus stop shelter was modified to shade the pedestrian path behind it, the minimum threshold could be achieved on 21 June as well.

Where possible, the devices were installed within the sidewalk area. Installation of seven trees and three stand-alone canopies required modifying the sidewalk edge: six parking lots were removed to position shading devices, for a final count of 11 parking lots (14 in winter, after removing temporary shading devices). This design choice is one example of the existing conflicts among priorities in public spaces: the pedestrian-centric perspective adopted in this work led to prioritising pedestrians' comfort over parking needs. The opportunity to re-purpose parking lots recently found space in the public debate, especially as an emergency solution during the COVID-19 pandemic [65]; in the analysed sidewalk, two parking lots are already occupied by near commercial activities.

4. Discussion

This paper presented a workflow for evaluating the effectiveness of the installation of shading devices to shade pedestrian paths. The geometry and position of shading devices were defined following a parametric approach; the design parameter for evaluating the shading performance was the resulting shaded length of the centreline of the sidewalk. An iterative workflow relying on the proposed design tool was developed and divided into analysis, evaluation, and design. This research focused on the summer season and the city of Milan; therefore sun position and shading devices were selected accordingly. Two



Shaded length of the centreline path [%]

Simulation date	Scenario a)	Scenario b)	Scenario c)
21 June	65.8	60.4	64.8
21 July	67.3	61.5	67.5
21 August	67.8	63.8	77.9
23 September	60.2[1]	62.2[1]	100

[1] Result including buildings' shadow is 100%.

Fig. 6. Visualisation of three device-sidewalk combinations reported in Fig. 5. The devices are installed in an urban canyon of H/W = 1.0, and additional simulation days illustrate the progressive changes in the shading effect of buildings and devices.

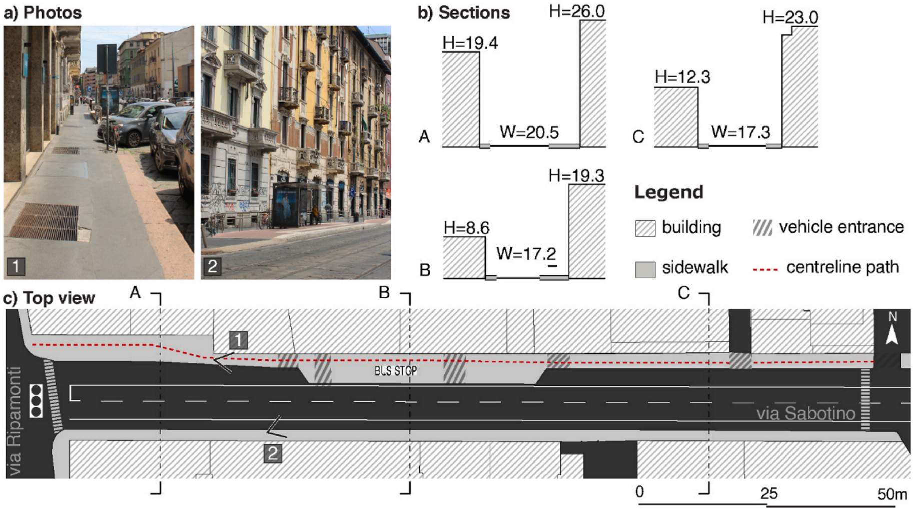


Fig. 7. Presentation of the case study sidewalk in via Sabotino (Milan, IT): a) field photos taken on 29 June at 1 p.m.; b) sections and c) top view of the case study urban canyon (data source: [59]).

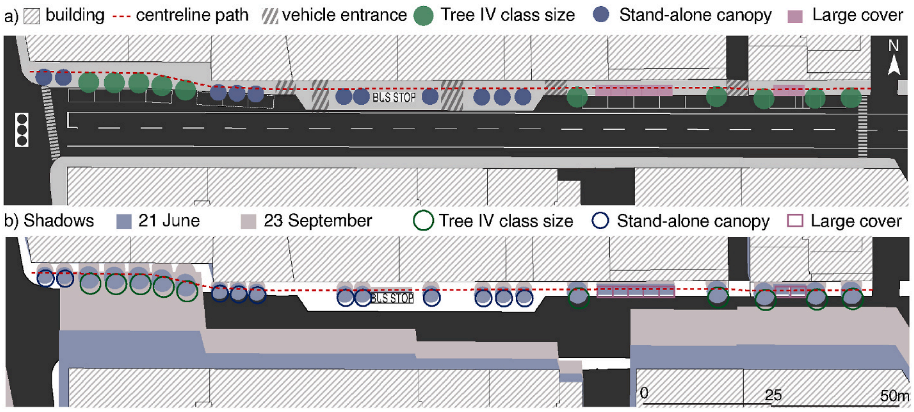


Fig. 8. Final design proposal developed through the design tool: a) location of shading devices; b) shadow analysis on summer solstice and autumn equinox days.

applications of the design tool were presented; a catalogue of shading solutions for standard urban canyons, and a master planning proposal where shading devices were positioned to shade an existing sidewalk. The results were threefold: a library of shading devices complemented with installation requirements and guidelines; the possibility to quickly compare the number of shading devices needed to reach a pre-determined shaded length goal; a systematic approach to select effective shading strategies in urban design practice.

4.1. Key findings of this study

In the process of optimisation of factors concerning outdoor spaces [32], this workflow promotes the integration of solar shading analysis in professional practice. Results obtained with the proposed design tool adhere to installation requirements, making them applicable to real case studies. One key result of this work was to assess potential conflicts between installation requirements and the actual effectiveness of shading devices, as illustrated in Section 3.2.2. The documentation provided by the Municipality could be supplemented with information collected in Figs. 4 and 5; urban planners and stakeholders operating at the city scale would be able to estimate resources needed to reach a desired performance, reducing the barrier represented by the lack of resources for microclimatic analysis in urban design. The application at the administrative level would make space for microclimatic analysis in a field previously dominated by socioeconomic issues [66], and where air quality and noise are more regulated than climate [67]. This past short-sighted approach disregarded that urban planning impacts microclimatic conditions in cities while potentially strengthening the existing socio-economic inequalities [68]. The selection of minimum microclimatic performance thresholds could avoid this scenario, ensuring fair access to comfortable outdoor spaces across the city.

This research addressed the challenges related to the level of detail required to model the realistic impact of shading devices at the street scale. Previous studies reduced shading devices to generic geometries, modelling them as parallelepiped [35]. Since shade depends on geometry, working in Rhino enabled the representation of shading devices as 3D objects with a higher level of resolution. Although the selected trees were characterised by spheric canopies, the proposed methodology allows urban designers to test more complex shapes, while ensuring compatibility of tools.

The proposed library addressed a specific gap. Langenheim et al. [36] first modelled trees of different shapes in Melbourne, Victoria; once the most suitable geometry needed to shade pedestrian paths was defined, they looked for tree species that would match the required dimensions. An inverse perspective was adopted, populating a library of shading devices available for urban designers, and then testing their effectiveness in the urban environment. The presented library featured devices presented by the local authority (trees) and practitioners (artificial canopy). In the future, a collective platform fostering collaboration across design scales could originate from this work. Multiple natural and artificial shading devices, complete with installation requirements, could be added to the library; a broad and rich library would facilitate the use of shading solutions in urban design, potentially creating new professional partnerships and establishing a direct connection between designers at different scales.

4.2. Applications in urban design practice

The design tool was applied through diverse processes, all following the analysis-evaluation-design workflow. In Fig. 9, four potential urban design applications are positioned against two axes: resources deployment and outcome suitability. The first one refers to resources allocated for the project (time, budget, workforce), extended to data availability and expertise of urban designers, all affecting the choice of which applicative process is followed. The horizontal axis refers to the specificity of results, ranging from rule-of-thumb-like information formulated based on standard case studies to ad-hoc proposals tailored to specific projects. The four applications were defined based on the work presented in this paper and are described in Table 4.

4.3. Limitations and future research

A limitation of this work is the binary rule full shade/no shade used in the evaluation phase. The goal was to investigate the footprint of shading devices on pedestrian paths, nevertheless, solutions are rarely identified as solid surfaces, as evident for the density of tree canopies. Research has confirmed that the tree canopies block almost completely solar radiation in dense foliated conditions [33,69,70]; significant shading was therefore assumed in proposing foliated trees as a shading solution. Tree canopy density varies consistently based on seasons, species, and maintenance programmes [71]; this represents a challenge in modelling and in the standardisation of devices included in the library. Future work could include canopy density; the evaluation phase would consider the solar radiation transmitted through canopies.

Additional work on the library could concern material properties of solutions, since research has demonstrated the impact of radiative properties on pedestrians' thermal comfort [31], and vegetation was reported to be more effective in cooling pedestrians than artificial devices [14]. The simulation potential of Ladybug tools was only partially used in this workflow, yet this sets the ground for future developments. Advanced microclimatic simulations up to thermal comfort indexes could be performed via Ladybug tools: Aleksandrowicz and Ozery [15] proposed a Grasshopper-based tool evaluating sidewalks based on the incident radiation. However, the presented workflow was developed to implement shading solutions at the early stages of urban design practice, with detailed material modelling of canopies traded for time efficiency

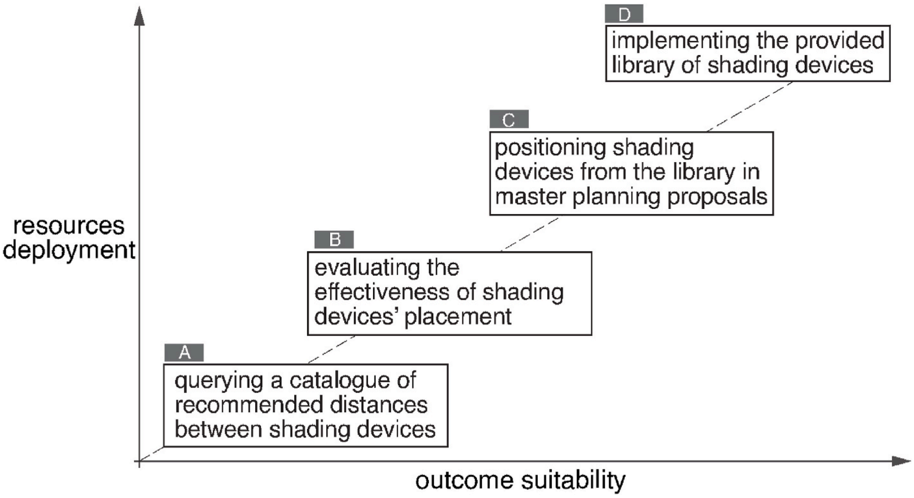


Fig. 9. Position of four workflow applications against increasing resources deployed and narrowing outcome application. Dark grey boxes refer to Table 4.

Table 4
Applicative processes of the workflow referenced in this paper.

	Applicative process	Description	Reference in this paper
A	Querying the catalogue of recommended distances between shading devices.	Urban designers and decision-makers extract rule-of-thumb-like information for positioning shading devices in cities according to the shading performance selected to generate the table.	Reading information collected in Fig. 5.
B	Evaluating the effectiveness of shading devices' placement.	Urban designers assess and consequently update minimum installation requirements based on target performances.	An application is presented in Section 3.2.2.
C	Positioning shading devices from the library in master planning proposals.	Urban designers iteratively evaluate urban morphology modelled in Rhino, position shading devices and simulate solar radiation exposure of pedestrian paths within the design process.	A case study is presented in Section 3.3.
D	Implementing the provided library of shading devices.	The library is expanded with new shading devices: all relevant parameters necessary for evaluating their effectiveness in shading pedestrian paths are provided.	Applying the methodology presented in Section 2.2.1.

and compatibility.

The recommendations proposed in Section 3 are site-specific, as they were elaborated using the Milan library and sun path. Nevertheless, the methodology could be applied to cities at different latitudes, since numerous cities provide recommendations and requirements about tree planting; for example, reference material similar to Milan is already provided by the City of Gothenburg [72]. The library would be adapted to include appropriate tree morphologies for the context, while the lower sun altitudes are expected to lead to different outcomes in terms of performance. In cold climate zones, the design tool could be used with an opposite design goal, i.e., minimising shaded length. The results would detect any possible shadow landing on pedestrian paths when solar radiation exposure is preferable; this application could work also in temperate climates, during the winter season. Finally, the proposed framework could be further upgraded at a strategic decision-making level by assigning additional features to shading solutions (e.g., installation and maintenance costs, economic benefits).

5. Conclusions

This research developed a workflow to assess solar radiation exposure and the potential implementation of shading devices in urban design practice. The proposed design tool addresses the gap of ineffective implementation of outdoor shading in urban design using tools already employed by designers, i.e., the 3D modelling software Rhino and shade-casting algorithms, accessed via Grasshopper. Pedestrians were central in evaluating sidewalks; microclimatic conditions were considered as an infrastructure component of the urban environment, subject to requirements and design guidelines. Recommended positions of natural and artificial devices to shade pedestrian paths were assessed based on location, urban canyon geometry and orientation. The workflow was applied to theoretical urban canyons and a real case study sidewalk, presenting the opportunity to implement solar radiation exposure analyses in urban design with various levels of detail.

Besides minimum installation requirements, the effective installation of shading devices is critical; in summer, ensuring effective shading is as important as plantation space for trees or minimum free footway clearance. Four applications in urban design practice were outlined, demonstrating diverse outcomes achievable through the proposed workflow. Future research will apply this workflow to cities at different latitudes; the selection tool could also include additional design goals.

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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.

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

Screenshots of the code are reported step-by-step in Appendix A.

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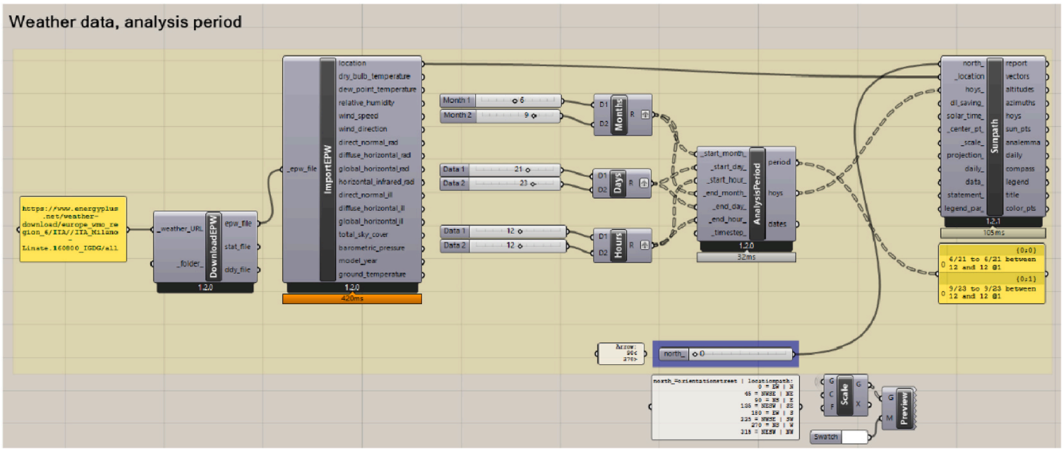
Appendix A

Screenshots of the design tool are presented. The labels [TH] and [MP] refer to workflows to design theoretical sidewalks (Section 3.2) and master planning proposals (Section 3.3), respectively. The Grasshopper code was built following the referenced tutorial [49].



https://www.energyplus.net/weather-download/europe_wmo_region_6/ITA//ITA_Milano-Linate.160800_IGDG/all

Month 1 6
Month 2 9
Data 1 21
Data 2 23
Data 1 12
Data 2 12

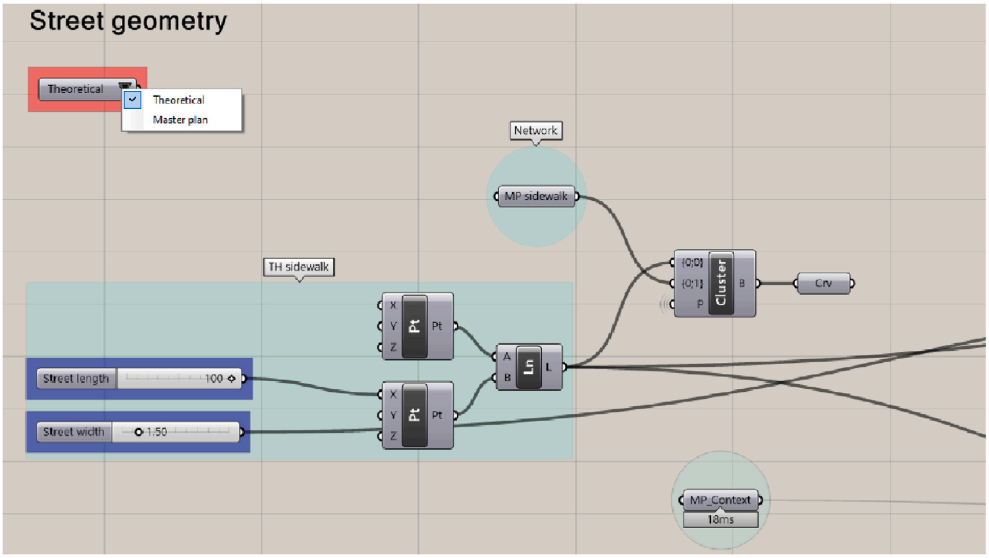
{0;0}
0 6/21 to 6/21 between 12 and 12 @1
{0;1}
0 9/23 to 9/23 between 12 and 12 @1

Arrow:
90<
270>

north_ 0

north_=orientationstreet | locationpath:
0 = EW | N
45 = NWSE | NE
90 = NS | E
135 = NESW | SE
180 = EW | S
225 = NWSE | SW
270 = NS | W
315 = NESW | NW

Fig. A1. Importing the weather file and selection of the simulation period [TH, MP].

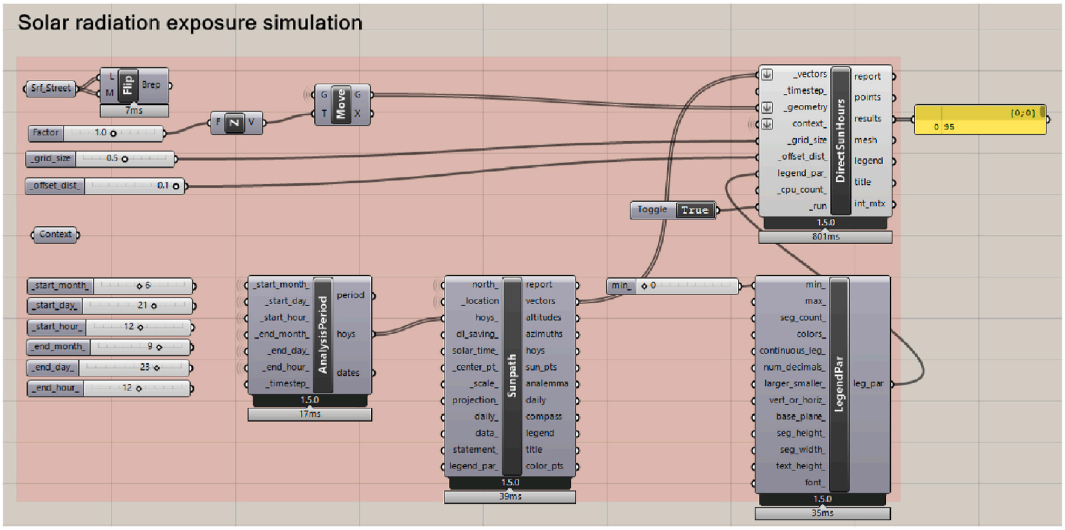


Theoretical

Street length 100

Street width 1.50

Fig. A2. Modelling the street geometry [TH] or importing the centreline of the case study sidewalk, together with context buildings [MP].



```
{0;0}
0 95
```

Fig. A3. Simulation of the solar radiation exposure of the virtual sensor on every day of the simulation period. The panel on the right reports the results [TH, MP].

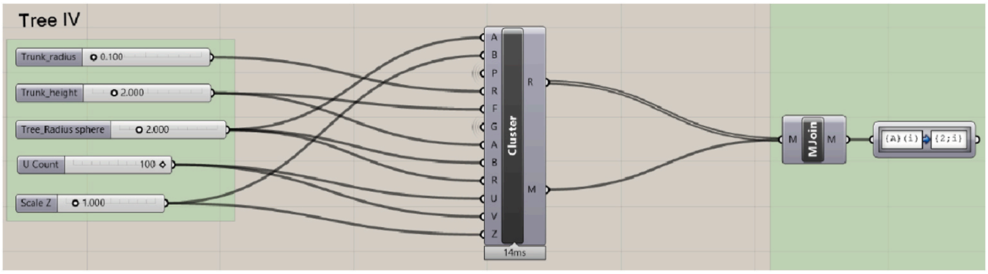


Fig. A4. Parametric model of a shading device [TH, MP]

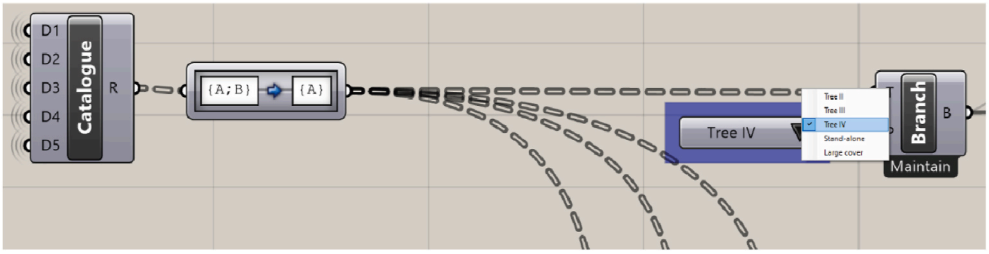
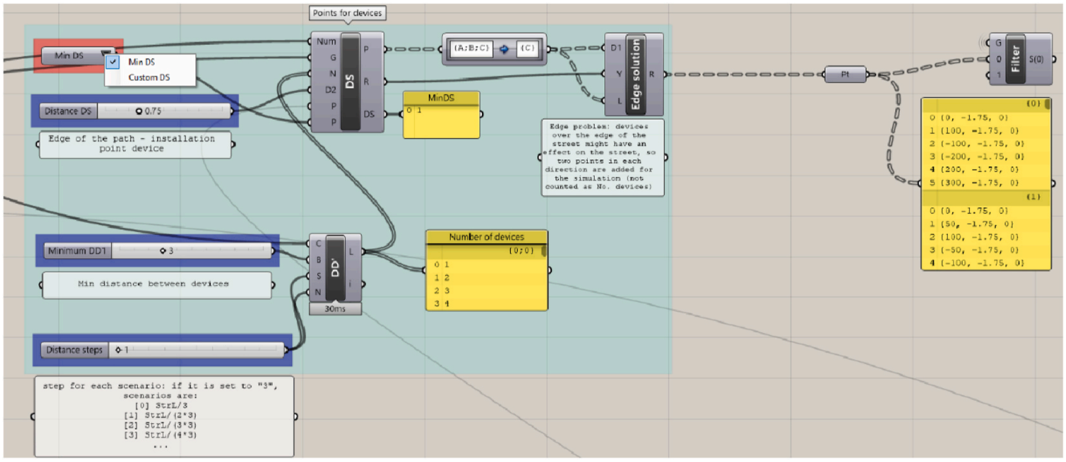


Fig. A5. Selection of one shading device from the catalogue of solutions [TH, MP].



Edge of the path - installation point device

```
MinDS
0 1
```

Edge problem: devices over the edge of the street might have an effect on the street, so two points in each direction are added for the simulation (not counted as No. devices)

```
{0}
0 {0, -1.75, 0}
1 {100, -1.75, 0}
2 {-100, -1.75, 0}
3 {-200, -1.75, 0}
4 {200, -1.75, 0}
5 {300, -1.75, 0}
{1}
0 {0, -1.75, 0}
1 {50, -1.75, 0}
2 {100, -1.75, 0}
3 {-50, -1.75, 0}
4 {-100, -1.75, 0}
```

```
Number of devices
{0;0}
0 1
1 2
2 3
3 4
```

Min distance between devices

step for each scenario: if it is set to "3",
scenarios are:
[0] StrL/3
[1] StrL/(2*3)
[2] StrL/(3*3)
[3] StrL/(4*3)
...

Fig. A6. Parametric setting of the number of design configurations to evaluate. It is possible to set DS and DD_1 distances [TH].

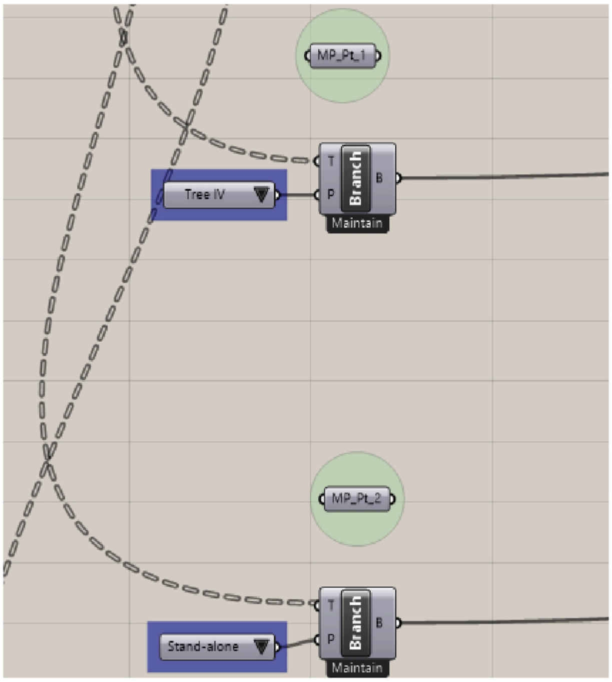


Fig. A7. Assignment of shading devices from the catalogue to the corresponding installation points [MP].

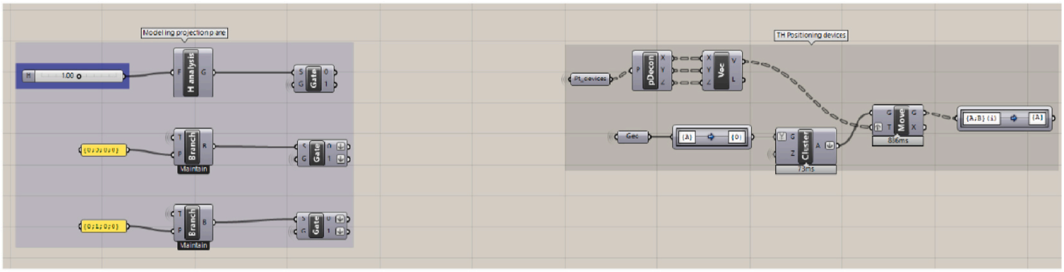
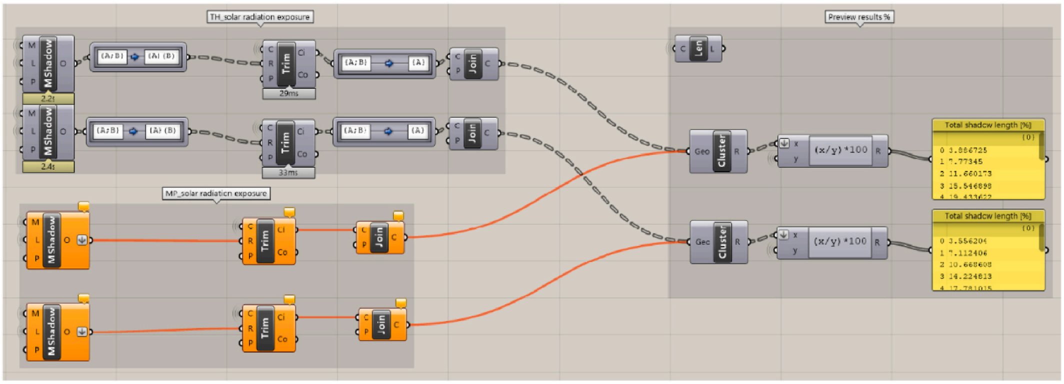


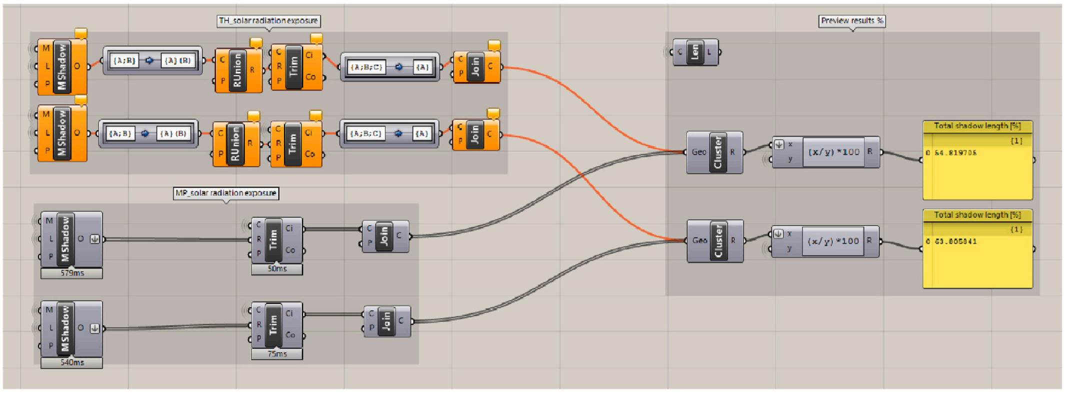
Fig. A8. Selection of the height of the projection plane [TH, MP]. Scenarios are modelled accordingly.



```
Total shadow length [%]
                  {0}
0 3.886725
1 7.77345
2 11.660173
3 15.546898
4 19.433622
```

```
Total shadow length [%]
                  {0}
0 3.556204
1 7.112406
2 10.668608
3 14.224813
4 17.781015
```

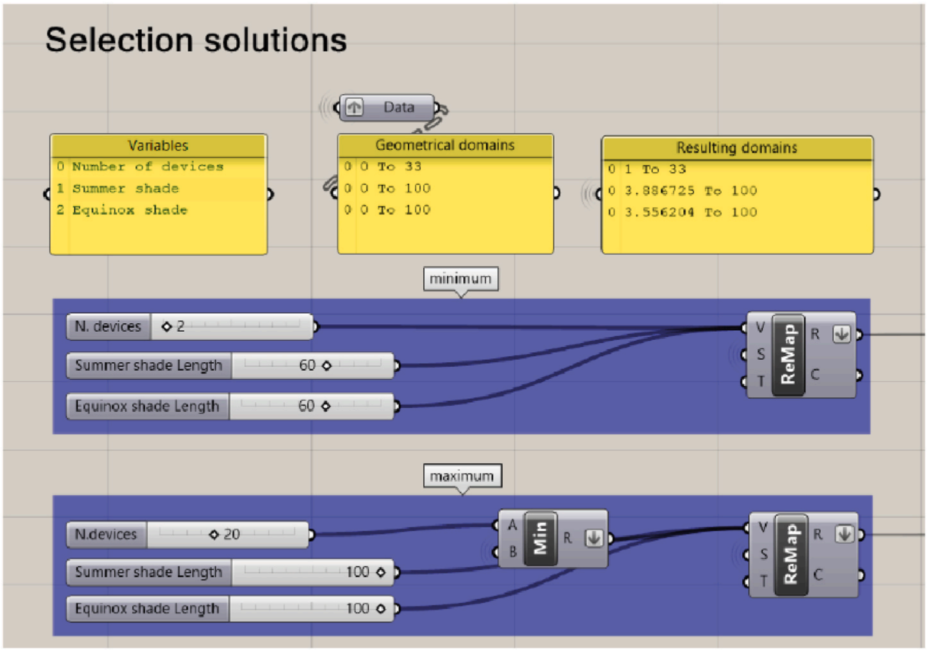
Fig. A9. Simulation of solar radiation exposure of the centreline sidewalk on the two selected days; a preview of results is available in the panels on the right [TH].



Total shadow length [%]
{1}
0 54.819705

Total shadow length [%]
{1}
0 63.805841

Fig. A10. Simulation of solar radiation exposure of the centreline sidewalk on the two selected days; the panels on the right report the resulting shaded length [MP].



Variables
0 Number of devices
1 Summer shade
2 Equinox shade

Geometrical domains
0 0 To 33
0 0 To 100
0 0 To 100

Resulting domains
0 1 To 33
0 3.886725 To 100
0 3.556204 To 100

N. devices 2
Summer shade Length 60
Equinox shade Length 60

N.devices 20
Summer shade Length 100
Equinox shade Length 100

Fig. A11. Definition of selection criteria, such as minimum and maximum number of devices and shading thresholds [TH].

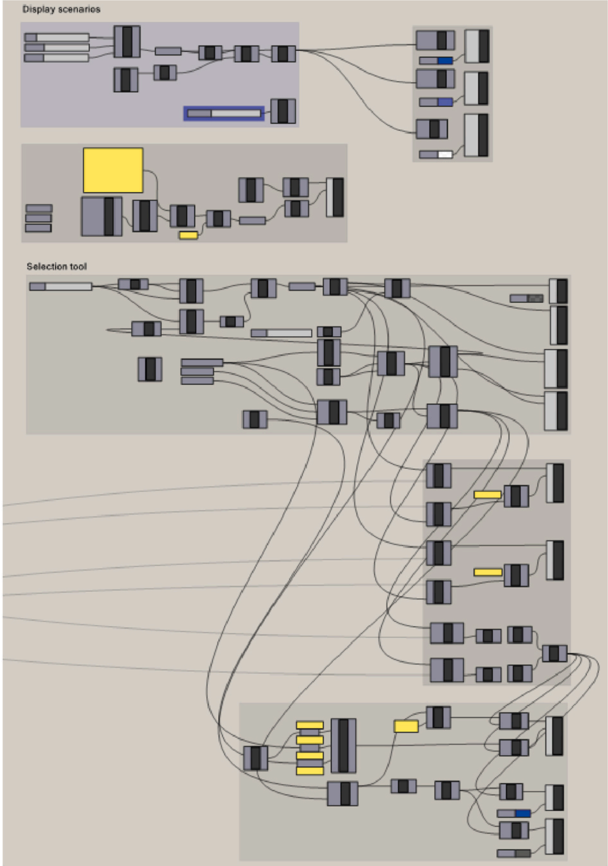


Fig. A12. The design tool includes a graphics part to visualise results in the Rhino workspace. This code reports both the selection tool and the shading device configurations [TH].

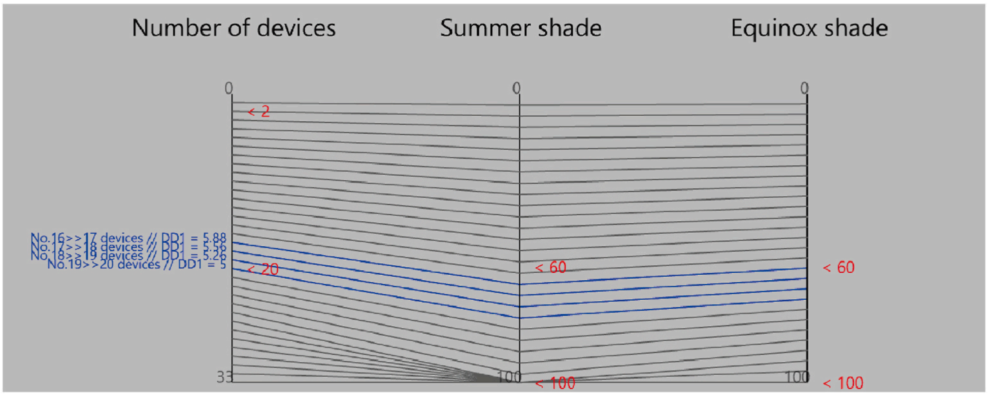


Fig. A13. Visualisation of the selection tool [TH].

Option no. 0
Number of devices 1
DD1 [m] 100
Summer shade [%] 3.89
Equinox shade [%] 3.56

Option no. 11
Number of devices 12
DD1 [m] 8.33
Summer shade [%] 46.64
Equinox shade [%] 42.67

Fig. A14. Visualisation of the shading devices configuration (sample of two configurations). For each scenario, in addition to the devices and the resulting shadows, a brief description of input parameters and resulting DD_1 and shaded length is provided [TH].

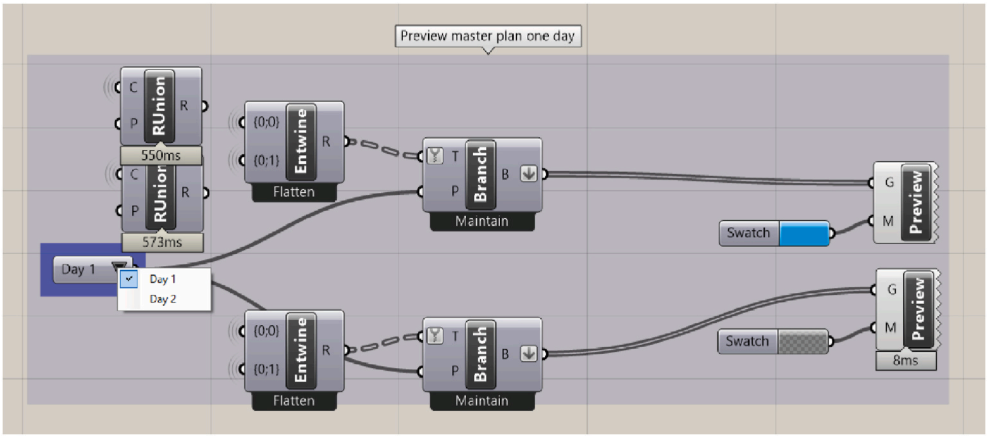


Fig. A15. This cluster imports shadows in the Rhino workspace [MP].

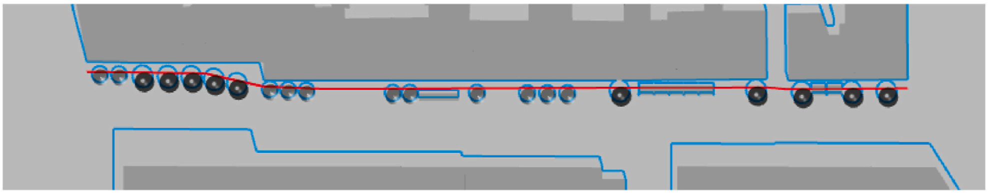
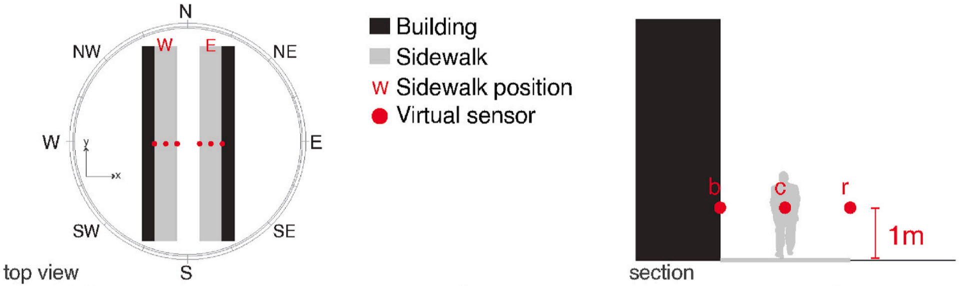


Fig. A16. Visualisation of the resulting shadows in the Rhino workspace [MP].

Appendix B



	10 am									1 pm									4 pm								
	UC 0.5			UC 1.0			UC 2.0			UC 0.5			UC 1.0			UC 2.0			UC 0.5			UC 1.0			UC 2.0		
	r	c	b	r	c	b	r	c	b	r	c	b	r	c	b	r	c	b	r	c	b	r	c	b	r	c	b
N	95	95	95	78	87	95	**45**	**55**	**62**	**95**	**95**	**95**	**68**	**84**	**95**	▨	20	40	95	95	95	74	86	95	25	41	53
NE	95	▨	▨	▨	▨	▨	▨	▨	▨	**95**	**95**	**95**	**95**	**95**	**95**	**57**	**70**	**80**	91	95	95	▨	46	62	▨	▨	▨
E	▨	▨	▨	▨	▨	▨	▨	▨	▨	95	95	▨	95	95	▨	**95**	▨	▨	**95**	**95**	**95**	▨	**61**	**79**	▨	▨	▨
SE	▨	▨	▨	▨	▨	▨	▨	▨	▨	92	25	▨	▨	▨	▨	▨	▨	▨	**95**	**95**	**95**	**95**	**95**	**95**	**95**	**95**	**95**
S[1]	85	68	33	65	51	29	52	42	27	▨	▨	▨	▨	▨	▨	▨	▨	▨	**87**	**71**	**34**	**67**	**53**	**30**	**56**	**43**	**28**
SW	**95**	**95**	**95**	**95**	**95**	**95**	▨	**3**	**14**	95	66	▨	59	▨	▨	▨	▨	▨	26	▨	▨	▨	▨	▨	▨	▨	▨
W	86	95	95	▨	▨	▨	▨	▨	▨	**95**	**95**	**95**	**95**	**95**	**95**	**95**	**95**	**95**	39	▨	▨	▨	▨	▨	▨	▨	▨
NW	78	95	95	▨	10	40	▨	▨	▨	**95**	**95**	**95**	**85**	**95**	**95**	▨	**32**	**52**	95	95	▨	95	15	▨	6	▨	▨

[1] 9 am instead of 10 am; 6 pm instead of 4 pm.

Fig. B1. Selection of worst-case scenarios for urban canyons. Urban canyons are labelled UC_N, where N=H/W. Red dots indicate the simulated virtual sensors (boundary of the sidewalk with the building, centre of the sidewalk, boundary of the sidewalk with the road). In the table, numbers refer to summer days in which each virtual sensor was exposed to the sun at that specific hour. Grey boxes represent urban canyon/hour combinations always in the shade during the summer season; the selected simulation hour for each urban canyon is reported in bold.

Appendix C

A. Tree II class size
B. Tree III class size
C. Tree IV class size*
D. Stand-alone canopy
E. Large cover**

source photos: authors

* The tree included in the catalogue is not specifically the one represented in the picture because of limitations during field visit.

** Various examples of large textile covers are represented in this picture, which serves as an inspiration for designers.

Fig. C1. Photographs of shading devices included in the library.

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