Effective shading implementation for pedestrians in master planning

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ABSTRACT

The solar radiation exposure of pedestrian paths impacts the walking experience; this is critical in assessing walkability in cities, particularly within the effort to promote healthy and comfortable urban environments for pedestrians. Practitioners can strategically propose solutions to improve the solar radiation exposure of pedestrian paths, however, the applicability of research about the effective implementation of natural and artificial shading devices is limited by barriers in communication and usability in practice.

This research was developed within the framework of the SOLOCLIM project, a European Industrial Doctorate aimed at elaborating solutions for outdoor climate adaptation between academic and industrial environments. The framework was implementing climate-responsive systems in master planning; it was then narrowed down to analysing the impact of solar radiation on the walking experience of pedestrians and proposing solutions to tackle thermal stress in response to insufficient shading. Specifically, the three objectives of this research were assessing the impact of the solar load on pedestrians, systematically simulating the changes in the user experience in response to solar radiation exposure and proposing a protocol for the effective implementation of shading solutions developed prioritising its accessibility by practitioners.

This research spanned across different areas, urban microclimate, outdoor thermal comfort, and climate-responsive urban design. A specific climate-responsive system was defined, combining solar radiation, shading solutions, and pedestrians. This selection was motivated by the critical impact of the solar load on people and the opportunity to adapt the urban morphology for providing shading; to do so, a systematic methodology and accessible tools are needed by urban designers.

Methods and tools for modelling and simulating microclimate and pedestrian networks were reviewed, and a first methodology was proposed. This was tested through a preliminary study, which provided meaningful insights for upscaling it at the neighbourhood scale; on this occasion, two user profiles of diverse walking abilities were defined, introducing the inclusivity angle to this research. Consequently, three research areas about specific aspects of shading implementation on pedestrian paths were defined. According to the adopted structure of

thesis-by-publication, each research area was developed in a peer-reviewed journal paper; the three papers are included as chapters.

At first, the impact of the solar load on pedestrians was assessed, proposing a methodology to select a maximum threshold of solar radiation exposure before feeling exhausted during the walking activity. The users were characterised based on walking speed and physiology. Then, following an upscaling process from the user to the neighbourhood, the dynamic exposure to solar radiation of sidewalks was investigated at the neighbourhood scale. A pedestrian network was modelled for simulating walking experiences; various analyses were proposed to simulate the pedestrians' experience in response to the sun position, including the comparison between experiences of users characterised by diverse walking abilities. The third paper presents a methodology to design effective installations of shading devices, collected in a catalogue; the applicability of the proposed methodology in practice was a key objective, leading to define different exercises to employ the proposed iterative workflow.

The final outcome of this research is presented in the form of a protocol, formulated by combining the work presented in the three journal papers. The protocol for effective shading implementation follows an iterative workflow, allowing professionals to test and select design proposals; the developed design tool allows urban designers to implement it within their design process. The innovation of this research lies in combining the user-centred approach, the design-oriented analysis of solar radiation exposure of pedestrian paths, and the development of strategic solutions applicable by urban designers.

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LIST OF ABBREVIATIONS

A/C .... Air conditioning

AOI .... Area of Interest

DSR ...... Direct Solar Radiation

DST ...... Daylight Saving Time

GSV ...... Google Street View

H/W ..... Aspect ratio, i.e., 'non-dimensional ratio of the height of the buildings (H) to the street width (W) in an urban canyon' (Oke et al., 2017, p.470)

ITCs ...... Infants, Toddlers and Caregivers (Bernard van Leer Foundation, 2019)

PET .... Physiological Equivalent Temperature

PMV ..... Predicted Mean Vote

SVF .... Sky View Factor, i.e., 'The ratio of the radiation received (or emitted) by a planar surface to the radiation emitted (or received) by the entire sky hemisphere' (Oke et al., 2017, p.480)

T_{mrt} .... Mean Radiant Temperature

UC_N ...... Urban canyon of H/W = N

UHI ...... Urban Heat Island

UTCI ..... Universal Thermal Climate Index

1. INTRODUCTION

1.1. Background

Urban environments are defined by Mills (2015) as 'densely populated areas where the landscape is substantially covered by manufactured materials and dwellers engage primarily in non-agricultural activities' (p.5). This definition features the two components concurring to create a city: urban form and urban functions. The former refers to the geometrical arrangement of elements (e.g., buildings, streets, trees), and the cover materials, while the latter includes activities that shape a city such as land use and economy (Oke et al., 2017). A tight connection is evident between the two urban components; for instance, the residential land use implies not only emissions and resources consumption, but also the physical modification of the environment to fulfil the needs of dwellers. Both urban form and urban functions impact climate in cities, with consequences on the environment and the population's health.

Even though the impacts of the urban environment on climate have been studied since the end of the XIX century, the application of this knowledge to urban planning has been missing for a long time. The past lack of consideration of the climatic information in urban planning was attributed to the perception of people, who considered climate as a 'constant' entity; in addition, the importance of environmental issues was obscured by the pressure of other forces, like socioeconomic needs and wishes (Ng, 2015). The complex nature of cities, where social, cultural, economic, and environmental interests meet, forces urban planners to define priorities, and profitable objectives are often driving urban development proposals (Erell et al., 2010).

In recent years, the consequences of climate change have contributed to creating awareness about the impact of climate on the environment (Lenzholzer et al., 2020), as well as health, economy, and society. At first, climate mitigation strategies were proposed to reduce the anthropogenic impact on the environment; then, climate adaptation measures were also implemented, with the aim of not only limiting the negative impacts but also taking advantage of the potential benefits of climatic conditions. The urban climate mitigation and adaptation efforts, here enunciated together to highlight the possibility of their integration, were internationally recognised and supported via initiatives like Climate-ADAPT (European Commission & EEA, 2012), C40 Cities (C40 Climate

Leadership Group, n.d.), and the Adaptation Knowledge Portal by UNFCCC (NWP, n.d.). An encouraging fact is that in the almost ten years separating the last IPCC report (2023) from the previous one (2014), an increasing number of literature and projects about urban climate adaptation was observed, even though only part of the plans have been applied (Dodman et al., 2022).

The COVID-19 pandemic exacerbated existing global trends, including the high vulnerability of groups of citizens to health-affecting hazards, including environmental and climate-related risks (Dodman et al., 2022). According to the megatrends currently observed, the presence of vulnerable population groups is bound to increase in number, due to population growth and ageing (UN DESA, 2019). Additionally, the urbanisation phenomenon demands the development of healthy cities and the avoidance of an excessive burden on the environment, especially in less developed regions (Mills, 2015). Today, more than half of the world's population lives in urban environments, and this number is growing; in fact, the urban population is projected to increase by 2.5 billion people by 2050, reaching the figure of 68% of the world population (UN DESA, 2019). When urban population growth happens in hot-climate cities, the number of people exposed to extreme heat increases; global warming makes this issue critical for an increasingly large number of countries. Future rises in temperature simulated in Representative Concentration Pathway (RCP) scenarios describe the expansion of areas characterised by extreme climatic conditions; in comparing the current and future Köppen-Geiger classifications (Figure 1.1), Beck et al. (2018) highlighted the expansion of arid areas and the shift to extreme conditions (warm to hot).

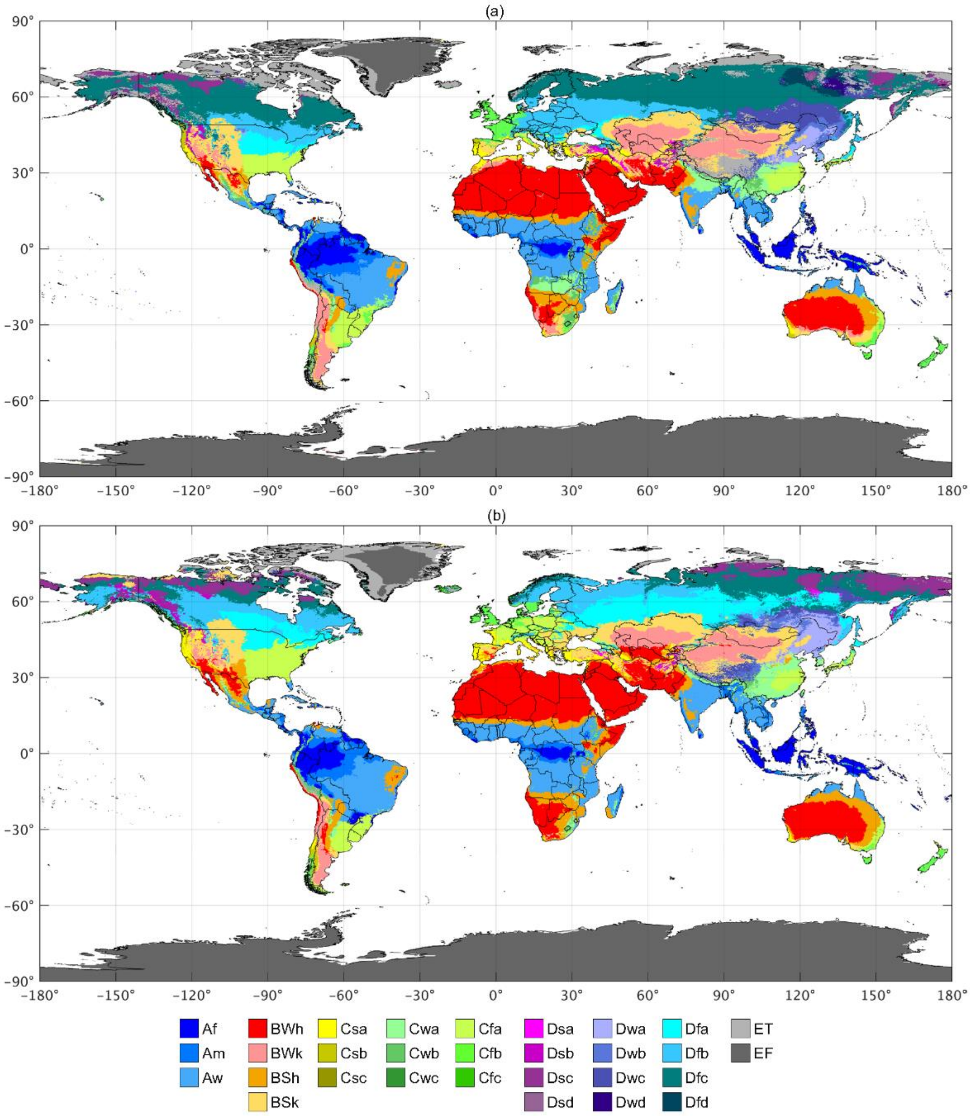

Figure 1.1 New and improved Köppen-Geiger classifications. Part (a) shows the present-day map (1980–2016) and panel (b) the future map (2071–2100) (source: Beck et al., 2020).

Extreme climate zones represent a challenge for climate adaptation; water shortage in arid areas makes the effective design of urban greenery a complex task (Ahmadi Venhari et al., 2019). Similarly, research established that exceptional conditions such as heatwaves may reduce the benefit of street trees, challenging the effectiveness of vegetated solutions as a mitigation strategy (Gao et al., 2024). These results do not hinder the beneficial effect of well-assessed climate-adaptation strategies, especially nature-based solutions; instead, it is evident the need for applied knowledge to optimise the efficacy of mitigation and adaptation measures in cities.

1.2. The SOLOCLIM project

This PhD research is part of the project 'Solutions for Outdoor Climate Adaptation' (SOLOCLIM, 2019), a European Industrial Doctorate (EID) in the programme Innovative Training Networks (ITN). The project is part of the Marie

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1.2.1. Scope of SOLOCLIM

The SOLOCLIM project provided a doctoral training programme allowing Early-Stage Researchers (ESRs) to develop solutions for urban outdoor spaces that bridge the academic and industrial environments. The project aimed to develop climate adaptation solutions for the urban environment, with a focus on the application and implementation in real case study cities. The solutions investigated were urban green infrastructure (UGI), water-based solutions, and flexible systems responding to climate. SOLOCLIM emphasised the integration across scales, framing the design of solutions at the small scale (single devices) and their implementation at the neighbourhood or city scale.

1.2.2. Structure of the research program

The project consortium featured three universities, Wageningen University (NL), University of Kent (UK), and Politecnico di Milano (IT); and four industry companies, Arcadis (NL), CRA – Carlo Ratti Associati (IT), ZinCo (DE), and Foster + Partners (UK). Each of the six Early-Stage Researchers (ESRs) spent at least one year at the assigned university, and two years at the industry facilities, following the scheme 6 months – 2 years – 6 months. The SOLOCLIM research proposal was structured by combining the three typologies of climate adaption solutions and two scales of investigation, i.e., at the street scale, with the development of prototypes, and the neighbourhood scale; the combination of solutions and scales generated six research topics, assigned to the Early-Stage Researchers. The research presented in this PhD thesis was developed at the University of Kent (Canterbury, UK) and CRA – Carlo Ratti Associati (Turin, IT); the developed topic was the implementation of climate-responsive systems at the master planning scale.

SOLOCLIM prioritised the dissemination of results, with the double benefit of providing feedback to ESRs during the research activity and joining the relevant conversations worldwide. To achieve this goal, three international public events were organised at a one-year distance (Table 1.1). On these occasions, ESRs presented the work-in-progress status of their research and discussed it with experts in the relevant fields from the academic and industrial environments. Additionally, each ESR was required to present their research at three international conferences and publish three journal papers within the open access scheme.

Table 1.1 SOLOCLIM events for the public presentation of the research.

Event	Location	Dates
Mid-symposium Outdoor solutions for climate adaptation - from street to city-scale.	Turin, Italy	8-10 September 2021
Prototypes Ready! Symposium	Nürtingen, Germany	19-20 September 2022
COOLING CITIES - Solutions for Urban Climate Adaptation	Milan, Italy	19 June 2023

1.3. Relevance of the research and problem statement

Climate change permeates the international discussion because of its global impacts; therefore every country is called to make an effort towards mitigation for the benefit of all communities. Similarly, mitigation and adaptation strategies must be shared worldwide, as distant countries may face similar challenges related to climate and health. However, the strong link between climatic conditions and context (i.e. land morphology, latitude, and human activities) makes it complicated to find universal methods and solutions. So, a challenge for urban designers is to translate the large-scale assessment of the urban environment into local projects; as Kaltsa (2016) said, 'thinking global and acting local' (p.158). This quote is a key milestone in the implementation of hyper-local scale solutions in master planning to tackle climate-related challenges. A systematic approach for moving from the urban scale to the street scale, and then backwards, is needed to ensure the efficacy of climate mitigation and adaptation solutions. The SOLOCLIM theme about the implementation of climate-responsive systems at the master planning scale falls in this gap.

Having defined the global context in which urban climate strategies are implemented, the process to narrow down the macro-theme of this research started by downscaling the focus to the human scale, adopting the perspective of street users to define relevant issues to address in terms of climate and health.

1.3.1. The primary role of climatic conditions in the use of public spaces

The human factor is often overlooked in urban climate mitigation strategies, even if cities are hubs where daily choices impact people and their environment (Kaltsa, 2016). 'For decades the human dimension has been an overlooked and haphazardly addressed urban planning topic', and dominant planning ideologies 'have specifically put a low priority on public space, pedestrianism and the role of city space as a meeting place for urban dwellers' (Gehl, 2013, p.3). The quality of public spaces is doomed to be more and more critical because of the increasing frequency of extreme climatic events (Dodman et al., 2022), as well as population growth and ageing (UN DESA, 2019). The COVID-19 pandemic has further stressed the importance of public spaces as a crucial asset during a crisis, to improve mental and physical health as well as contribute to maintaining social distances (UN-Habitat, 2020).

The availability of public spaces, and equally important, the accessibility to them, is a first challenge in urban planning; initiatives to ensure equal distribution of relief spots and public outdoor areas must be developed to tackle inequalities, especially in neighbourhoods with low socioeconomic status since urban planning can broaden differences in this matter (Villadiego & Velay-Dabat, 2014). However, this effort towards equal access to public spaces is incomplete without considering the climatic conditions, which are unavoidable outdoors, yet crucial (Santucci, 2020).

1.3.1.1. Solar radiation as a driver for the usability of public spaces

Microclimate affects activities in public spaces; uncomfortable or even extreme environmental conditions are a barrier to spending time outdoors. In highlighting the importance of meteorological conditions to allow people to stay and move through outdoor spaces, Gehl (2013) offered an underlying reference to outdoor climate adaptation; 'weather as good as it gets given the situation, place and season' (p.88). In indoor spaces, people can generally adjust environmental conditions, e.g., by modifying the settings of A/C, opening or closing windows, and moving portable heaters. This condition represents a situation of 'perceived control', in which users are in the active position of adapting the surrounding environment to their preferences, or at least, are aware of the available options to do so. On the contrary, outdoor spaces cannot be adapted via technological solutions, apart from rare exceptional sites. Therefore, in case of uncomfortable climatic conditions, people must rely on available relief spots and solutions (Yu & de Dear, 2022).

The most intuitive option to modify the personal thermal state is moving from places in the sun to the shade, and vice versa. This behaviour has been observed on various occasions (Aljawabra & Nikolopoulou, 2018; Azegami et al., 2023; Klemm et al., 2017) and is possible because the impact of such action is recognised by users, contrary to other environmental factors like humidity (Villadiego & Velay-Dabat, 2014). In fact, the sun is the primary source of heat in outdoor spaces, and exposure to solar radiation can have a warming effect in cold temperatures, as well as worsening heat stress conditions. The possibility to change location is a form of perceived control that is very effective in outdoor spaces (Nikolopoulou & Lykoudis, 2006). This is true notwithstanding the availability of non-homogeneous locations; in fact, research about outdoor thermal comfort has recognised the importance of variable spaces where users can experience environmental stimulation, rather than neutral but static conditions (Nikolopoulou & Steemers, 2003). Two characteristics of solar radiation exposure respond well to this need, i.e., hyper-localisation and variability in time. The first one is due to the geometrical nature of shading that results in variable spaces within a range of metres, contrary to other microclimatic variables such as air temperature. The variability in time refers to the sun's position changing on an hourly, daily, and seasonal basis, creating diverse microclimatic conditions all year round.

1.3.1.2. The importance of comfortable walking environments

The impact of microclimate on activities in public spaces can prevent the success of projects promoting their use. The '15-Minute City' introduces an urban planning model rooted in 'chrono-urbanism', a perspective focused on providing services and activities in proximal relation to residents. If reducing the car-dependency of cities was the initial aim that led to its formulation, additional benefits promoted by the 15-Minute City can be listed, such as increasing social occasions, opportunities for healthy habits such as walking and cycling, and ecological advantages derived from the limited use of cars (Moreno et al., 2021). It is evident that the whole model, of international interest especially after COVID-19, relies on the provision of comfortable and safe walking environments. Similarly, the provision of green parks and public spaces within a city cannot be a successful strategy if not combined with an accessibility assessment of those spots.

High-quality walking infrastructure serves not only as a means of transportation; a neighbourhood where people are moving slowly is more alive, social, and attractive since people are attracted by the presence of other people (Gehl, 2013). In discussing walkability, Forsyth (2015) provided an extensive panorama of the complexity of defining, therefore designing, walkable spaces. The various attributes of pedestrian paths were collected into three themes; dimensions of facilities (traversable, compact, safe, and physically enticing environments); perceived outcomes (lively and sociable, sustainable transportation options, and exercise-inducing); and elements representative for successful design, namely multidimensional themes put together as holistic solutions. The outcome of Forsyth's work is the evidence that diverse walking purposes, needs, and preferences, insist on the same pedestrian space; in this multifaceted framework, microclimatic conditions are a common thread affecting the walking experience of everyone.

1.3.1.3. Including the vulnerability component

The choice of grounding an urban planning principle into a temporal window of 15 minutes might seem an arbitrary choice. Moreno et al. (2021) replied to this comment by highlighting the flexibility of the 'chrono-urbanism' concept, which is valid regardless of the selected time dimension; in fact, they also suggested adapting this threshold to the needs and characteristics of cities. An additional adaptation effort is required by the Goal 11 of the 2030 Agenda for Sustainable Development, calling for inclusive cities with specific attention to women, children, the elderly, and people with disabilities (UN DESA, 2015).

In advocating for prioritising people in the urban design of public spaces, Gehl (2013) provided an interesting parallelism between the size of most squares and the social field of vision, set to approximately 100 m. The narration continues by picturing a pedestrian spotting someone at that distance and then walking for around one minute to meet, at a standard speed of 5 km/h; this image reveals a sensitive open point in urban design about inclusivity. Pedestrians do not walk at the same speed, and disabilities of various natures can create obstacles in moving within the urban environment. This awareness must be implemented in urban design projects by locating diverse users at the centre of the planning activity, not only a standard pedestrian. From an urban design perspective, a call for caution was formulated by Gehl (2013); rather than creating special places for diverse user groups, it is better to create flexible spaces where many needs can be accommodated. In enumerating the 101 rules for a walkable city, Speck (2018) reserves a central position for wheelchair and stroller users, stating that 'when a city works well for people in wheelchairs, it works well for everyone' (rule no.80).

The impact of microclimatic conditions must also be studied for pedestrians with diverse characteristics because research has demonstrated the higher vulnerability of some user groups to heat stress (Dodman et al., 2022; Kabisch et al., 2017). The analysis of mortality data recorded in the 1990s in Europe revealed a strong link between heat and people over 75 years old; above an apparent temperature threshold specific for every city, following a 1°C increase in maximum apparent temperature, an increase in deaths for respiratory diseases of 8.1 and 6.6% was reported in Mediterranean and north-continental regions, respectively (Baccini et al., 2008). Specific knowledge is thus needed to tailor urban design proposals to protect vulnerable people, not only in terms of physical accessibility barriers but also as regards environmental and microclimatic conditions.

1.3.2. The gap between theoretical knowledge and design applications

In 2010, Mills et al. highlighted five types of gaps in climate knowledge and the ability to apply it to urban planning and design. The theoretical and knowledge gaps were mostly assigned to the research community, which was encouraged to systematically implement compatibility across methods and tools, increase the amount of data and focus on less studied climate regions, such as the tropics. In terms of sustainability, the authors called for a more explicit connection between climate impacts and vulnerability across scales. The most interesting gaps for this research concern the communication and application of climate knowledge to planning. The first one refers to barriers in terms of language, accessibility of information, international presence, and communication across fields of expertise. The application gap calls for making climate knowledge accessible by urban planners and policymakers, and systematically implementing it in tools and policies. Although successful experiences in implementing climate principles in regional and urban planning are found (Ng & Ren, 2015; Ren & McGregor, 2021), good applications in practice have been defined as scarce, and their effectiveness questioned (Palme & Salvati, 2021).

Professionals in the urban planning and design field need methods and tools to formulate and implement climate information into urban planning and design projects; the challenge is to translate scientific knowledge into planning languages (Ng & Ren, 2015). To bridge this gap, collaboration between the academic and industrial environments is critical. Schoenefeldt (2018) presented an experience where academic research was followed by the translation of the gathered knowledge as usable for designers and the facilitation of its use in practice. The need for an integrated approach linking theoretical research and practitioners was addressed by Giridharan (2016), who suggested designers and theorists collaborate for developing models and tools to implement climate knowledge in practice. A first step would be training practitioners to understand theoretical principles, such as boundary conditions of simulations. Palme and Salvati (2021) noted how climatologists and designers look at the same urban features from different perspectives, abstracting only components of interest, and thus creating barriers in communication and interdisciplinary knowledge. From a more practical perspective, this collaboration would ensure the parametrisation of variables relevant to urban design, that practitioners could manipulate; in this regard, a theme of critical importance would be defining a suitable operational scale. The specific requirements of tools for the implementation of climate knowledge can be found in a survey administered to architects and engineers (Kanters et al., 2014); compatibility of models with existing workflows; suitable visualisation capacity, in support of the creative tasks and useful for communication; and a user-friendly design interface, which resulted as the most important factor influencing software selection.

1.4. Research aims

This research investigates the impact of the solar radiation load on pedestrians and the critical role of solar radiation exposure of pedestrian networks on their experience. Furthermore, it aims to develop a tool for practitioners to implement the solutions available to reduce users' thermal stress in master planning proposals.

In the context described in Section 1.1, heat stress and exceptional events are reported as a threat to the urban population; nevertheless, working to provide comfortable access to outdoor spaces is a crucial task that must be endured considering also less risky, but more common, microclimate conditions. The solar radiation load on people can provide instant relief or worsen their comfort, or even threaten their health; this research aims to quantify the impact of solar radiation exposure on pedestrians in relation to their thermal comfort during the walking experience. In the field of urban planning, decisions are mostly based on data and indicators spatially referenced; this analysis seeks to fulfil this requirement by providing quantifiable results for informing practitioners and stakeholders. Furthermore, the vulnerability to environmental and climatic conditions varies based on personal and social characteristics, this analysis cannot overlook that people experiencing outdoor spaces might be affected differently, and mitigation and adaptation measures should be tailored to be beneficial for as many people as possible. Therefore, in line with the call for more inclusive cities and accessible public spaces (SDG 2030, Goal 11), this research seeks to characterise pedestrians based on their physical and physiological characteristics, rather than grouping them into the 'users' concept. The adoption of multiple perspectives in simulating the walking experience is directed towards increasing the awareness among practitioners about barriers of vulnerable groups, providing them with useful information to design healthy and comfortable public spaces for a large number of people. Therefore, the first research question is formulated as:

- What is the impact of the solar radiation load on pedestrians?

After analysing the user, the focus is upscaled to the context in which pedestrians move, i.e., the urban environment. Commonly, the concept of comfortable pedestrian paths is associated with accessibility in terms of mobility. However, the presence of the shade or sun along walking paths impacts thermal comfort and can be perceived as a barrier. Because of the directional character of the sun rays, the exposure of urban surfaces to solar radiation changes within the same day, as well as during the year. Based on the context set earlier in this chapter, it is reasonable to affirm that the user experience of a pedestrian network thus changes according to the time of the day, and the day of the year when it happens. The presence of the sun or shade affects not only the path selection, directing pedestrians according to their exposure preferences whenever possible, but also the pedestrians themselves, here considered from the physiological point of view. This research aims to map the diverse solar radiation exposure on a pedestrian network, investigating how it would affect the walking experience of a person. It seeks to demonstrate that exposure to solar radiation is a critical component that must be spatially represented in analysing pedestrian networks and that the experience of users varies according to the time of the day, with impacts on the usability of pedestrian paths. As before, when simulating walking experiences, the perspective of diverse users must be adopted. Therefore, the second research question is:

- How does the user experience on a pedestrian network change based on its solar radiation exposure?

The previous two objectives may be located in an analytical phase. The final outcome of this thesis is the provision of solutions to protect users from heat stress due to solar radiation exposure on pedestrian paths. The challenge from an urban designer perspective is where to locate shading devices for effectively being beneficial for pedestrians. As this research was developed between academia and industry, this is performed by adopting a practice-oriented approach. The implementation of climate-responsive urban design in practice requires making such knowledge accessible to practitioners. The term ‘accessible’ is here used to describe the clear and available communication, together with the possibility of integrating any new tool within the workflow of practitioners. This aim permeates the whole research process since the overall outcome must be accessible to urban planners and designers. Finally, the third research question is:

- How to make the effective implementation of shading solutions accessible for practitioners?

To summarise, this research aims to investigate how solar radiation impacts pedestrians directly, in terms of physiological effect, and indirectly, as regards their walking experience in outdoor spaces. Once assessed these two components of their experience of outdoor pedestrian networks, this research seeks to develop a tool to implement the formulated knowledge in practice, adapting the communication and accessibility of results to the target professionals (urban designers). According to the macro-theme delineated by the SOLOCLIM project, the final output is the implementation of climate-responsive solutions in master planning.

1.5. Research framework

This research was developed at the University of Kent and CRA-Carlo Ratti Associati. The experience was divided as follows. The first six months were dedicated to the analysis of the context aimed at identifying the research gaps in which to fit the macro-theme framed by the SOLOCLIM project. After this period, the research was based at the industry partner premises in Turin for two years. This experience brought several advantages to the research; the discussion with designers helped in shaping the research questions (Section 1.4) and selecting the relevant points for the application of results, discussed in Section 1.3. During the industrial experience, the case study was selected; since it was an ongoing project, multiple phases of the design were analysed. The final time period was spent at the university, where the research was finalised.

This work was developed as a thesis-by-publications. Three articles were published in peer-reviewed journals and are included in the thesis as chapters. The journal papers are a bridge between the academic and the industrial environments and illustrate how climatic information can be applied in practice. The peer-review process was a formal discussion that improved the developed research, providing feedback from experts in the field. All papers were published within the open access scheme, satisfying the dissemination objective set up by the SOLOCLIM project. Table 1.2 reports the details of the journal papers, including the publication process.

Table 1.2 Details and publication process of the journal papers.

Details	Tomasi, M., Nikolopoulou, M., Giridharan, R., Löve, M., and Ratti, C. (2024). Definition of a maximum threshold of direct solar radiation exposure for pedestrians of diverse walking abilities. *International Journal of Biometeorology, 68*(1), 17–31. https://doi-org/10.1007/s00484-023-02567-4	Tomasi, M., Nikolopoulou, M., Giridharan, R., Löve, M., and Ratti, C. (2024). Dynamic analysis of a pedestrian network: The impact of solar radiation exposure on diverse user experiences. *Sustainable Cities and Society, 112,* 105631. https://doi.org/10.1016/j.scs.2024.105631	Tomasi, M., Nikolopoulou, M., Giridharan, R., and Löve, M. (2024). A design workflow for effective solar shading of pedestrian paths. *Building and Environment, 261,* 111718. https://doi.org/10.1016/j.buildenv.2024.111718.
Received	12 April 2023	29 February 2024	8 February 2024
Revised	6 August 2023	23 May 2024	1 May 2024
Accepted	11 October 2023	27 June 2024	3 June 2024
Published	4 November 2023	4 July 2024	6 June 2024
Thesis position	Chapter 4	Chapter 5	Chapter 6

1.5.1. Thesis outline

The thesis is organised in eight chapters (Figure 1.2). Chapter 1 introduced the context of this research, both in terms of contents and structure. At first, the current context in which urban planners and designers operate was introduced, highlighting global challenges manifested as consequences of climate change and megatrends. This background fostered the proposal of the SOLOCLIM project, an industrial doctorate training professionals to develop solutions for urban climate adaptation. The relevance of the research was explained as the opportunity to contribute to issues about walkability and microclimatic conditions in cities; these specific themes are located in a larger framework, supported by international actions such as the 2030 Agenda. The formulation of issues was then translated into the three research questions addressed in this thesis.

Chapter 2 presents a review of urban microclimate, outdoor thermal comfort, and climate-responsive urban design. After providing background information about microclimate in cities and outdoor thermal comfort, it presents case studies about urban planning and devices. The reported case studies differ in scale, climatic variables addressed, and applications; nevertheless, in this multifaceted body of work, common principles and approaches can be found. Finally, the responsive character of shading devices to solar radiation and its relevance to outdoor thermal comfort are presented.

In Chapter 3, the climate-responsive system investigated in this research is defined; it combines solar radiation, urban morphology, and pedestrians. A review of methodological approaches and tools to analyse and model microclimate, urban morphology and mobility networks is presented. A first methodological approach was tested through a feasibility study on a specific open space, with the aim of subsequently adjusting the methodology at the neighbourhood scale. This exercise brought two benefits to this research; it allowed the critical evaluation of the methodological steps, leading to a range of changes in the approach; and it highlighted three research areas that became the central focus of the journal papers, presented in the next chapters.

Chapters 4, 5 and 6 present the three journal papers. At first, the contents' sequence follows an upscaling process (from the user to the neighbourhood); then, the solutions developed to apply the gathered climate knowledge to urban design are illustrated. Specifically, the first paper is about the characterisation of two pedestrians of diverse walking abilities based on their physiology, followed by the definition of a maximum threshold of solar radiation exposure that each user could experience before feeling exhausted. Chapter 5 presents a set of analyses performed on a pedestrian network to investigate the dynamic exposure to solar radiation of sidewalks. In

Chapter 6, a catalogue of shading solutions is presented; the paper simulates different exercises to design effective installation of devices to shade pedestrian paths, focusing on the applicability of the proposed workflow in practice. Each paper is introduced by a section outlining the relevant research area; at the end of the chapters, the contribution of each journal paper to this research is explained. These two sections are critical to combining all insights into a coherent body of research, highlighting the corresponding contributions to its development.

In Chapter 7, the final outcome of this research is presented; a protocol divided into three methodological steps and made available for professionals through a digital design tool developed prioritising usability by urban designers. The protocol systematically collects the knowledge presented in the journal papers, making it accessible to practitioners and allowing them to adapt the methodology based on the professional context (e.g., design phase and objectives).

Chapter 8 provides the overall conclusions of this research. At first, specific results addressing the research questions are summarised. Then, a broader view is adopted to illustrate the contribution of this research to the field of climate-responsive urban design, outlining the opportunities to adapt its outcome to various issues and microclimatic scenarios. Finally, the limitations of this research and potential further steps are presented.

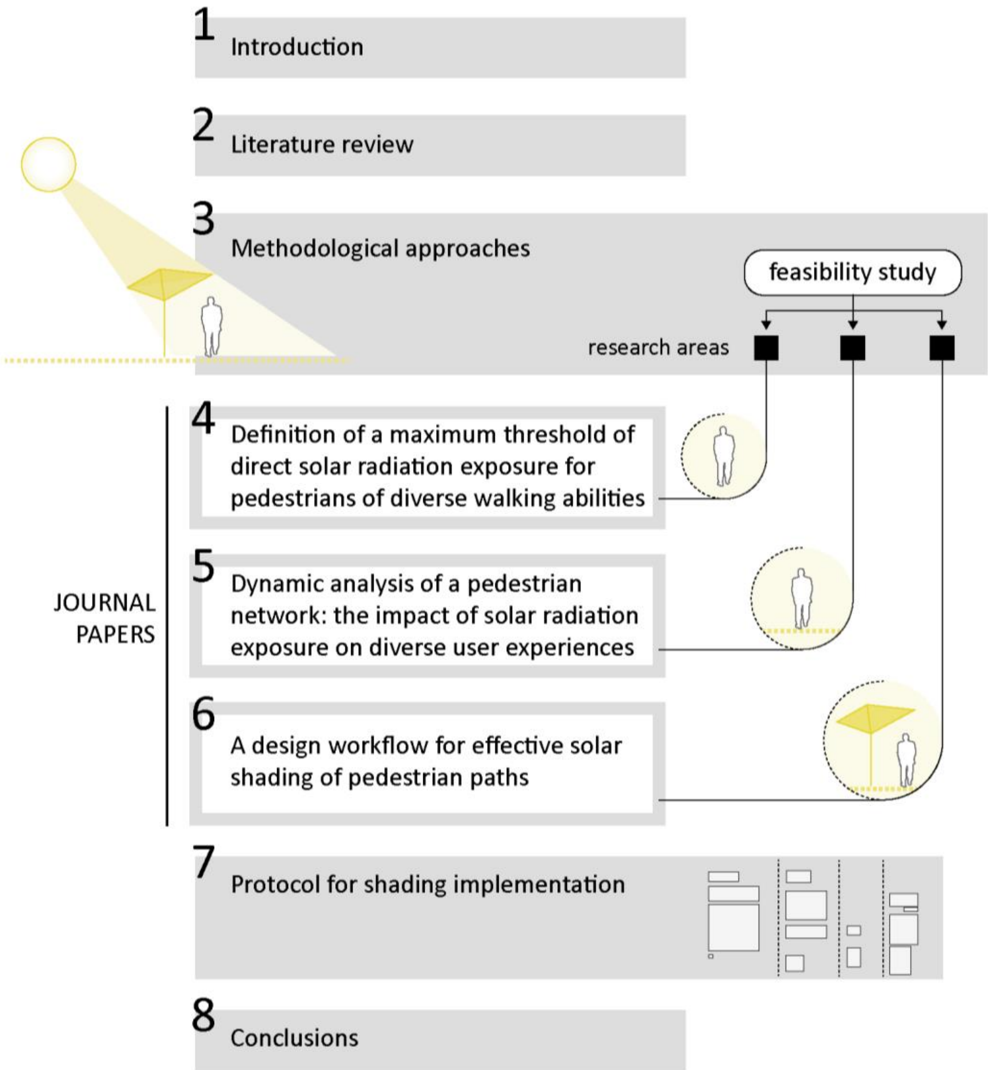


Figure 1.2 Thesis outline.

2. LITERATURE REVIEW

2.1. Introduction

In this chapter, a review of the impact of microclimate on people is provided, demonstrating the importance of climate-responsive urban design. At first, an overview of urban microclimate is presented, with specific attention to climatological parameters with design implications and the different spatial and temporal scales of atmospheric phenomena. Then, outdoor thermal comfort is presented, moving from the physiological approach to the inclusion of subjective factors.

Sections 2.4 and 2.5 present experiences of climate-responsive design following a downscaling process, from the regional/urban to the street scale. Accordingly, recommendations and tests at the urban/neighbourhood scale are followed by specific climate-responsive devices to materialise climate-responsive planning proposals. Finally, the climate-responsive character of shading is analysed, isolating the impact of solar radiation exposure on people in terms of thermal comfort and behaviour; this section is closed by a review of shading solutions to tackle excessive heat stress.

2.2. Microclimate in cities

The complex interactions between atmospheric and landscape features range from the atmospheric scale to the near-ground level, yet fundamental principles and definitions are valid across scales. Following a downscaling process, an overview of the Earth-Atmosphere system is presented, including the definition of terms and variables; then, the specific properties of urban microclimate are described, focusing on the characteristics of the urban morphology influencing microclimate at the street level.

2.2.1. Introduction to the energy and water balance

The Earth's surface and the Atmosphere form a system where interactions are described through energy and water balances. In this section, an introduction to fundamental knowledge of energy and water balance of the Earth-Atmosphere system is provided, compiling information from Mills et al. (2021), Oke (1987), and Oke et al. (2017).

The only source of energy of the Earth-Atmosphere system is the sun, which emits radiant energy towards the Earth. The energy balance outlines energy exchanges, which are categorised by mode of exchange as radiation, conduction, and convection. The sun emits radiant energy as shortwave radiation, which can be directly incident on surfaces or diffused by the atmosphere (clouds). All materials (above -273.2°C) emit energy as longwave radiation (Figure 2.1a). When radiation is incident on a surface, it is transmitted, reflected, or absorbed, based on the characteristics of the receiving material (Figure 2.1b). Other processes of energy exchange are conduction, mainly referred to solids, and convection (liquids and gases). Exchanges of energy are also categorised based on the type of energy exchanged as radiation, indicating energy transferred as waves; sensible heat, when the body temperature changes; and latent heat, involving no difference in temperature. The water balance outlines the amount of water present in the Earth-Atmosphere system in any of the three states; the mechanism of moving state (e.g., from liquid to vapour) requires energy in the latent heat form.

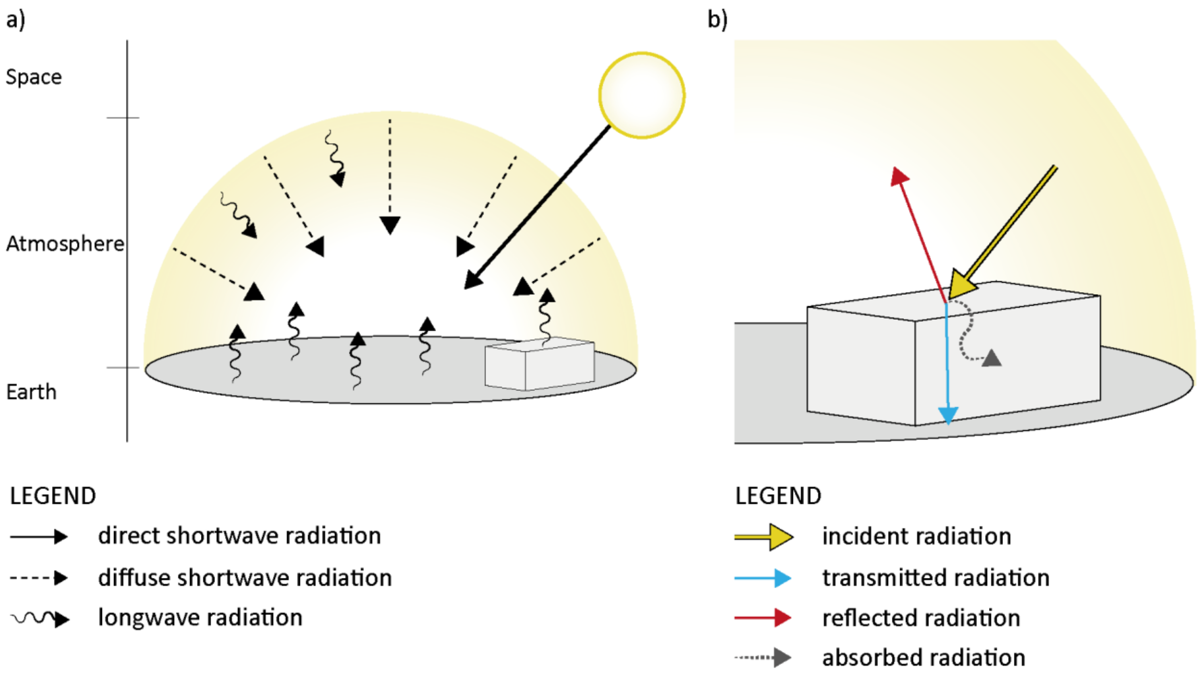


Figure 2.1 Schematic representation of radiation energy exchanges; a) short- and longwave radiation exchanges in the Earth-Atmosphere system; b) subdivision of incident radiation into transmitted, reflected and absorbed radiation.

To describe the status of the atmosphere, i.e., the energy and water balance, climatological parameters (temperature, wind speed, humidity) are introduced as measurable indicators. Temperature measures the sensible heat content of air, soil, and landscape elements. Differences in temperature result in energy exchanges, aimed at re-establishing a balanced energy state. The horizontal difference between air and surface temperatures generates horizontal pressure differences, leading in turn to air circulation, i.e., wind. The roughness of the surface, as a result of the presence of vertical objects (trees and buildings), modifies the wind patterns at various scales (from regional to local scale, to ground-level air flows). Humidity is representative of the amount of latent heat content in the air and it is measured as vapour density. Solar geometry parameters are used to describe the relation between the Earth's surface at a specific location (latitude and longitude) and the solar rays. The vertical angle between the position of the sun and the local horizon is defined as 'solar altitude' (γ, also found as β and Z); the higher the altitude, the higher the direct component incident on a horizontal surface (Figure 2.2a). The angle between the projection of the sun on a horizontal plane and a reference direction (conventionally, the North) is defined as 'solar azimuth' (Ω) (Figure 2.2b). Additional parameters that control energy exchanges refer to the landscape morphology and surface materials (e.g., emissivity and albedo[1]), and atmospheric properties (e.g., cloudiness).

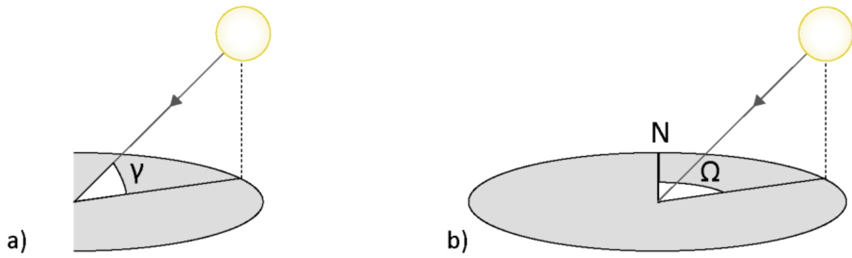


Figure 2.2 Solar geometry parameters; a) solar altitude, b) solar azimuth.

2.2.2. The impact of the built environment on urban climate

Built-up areas (urban form) and human activities (urban functions) modify the natural energy and water balance; as a result, the climate self-regulation and adaptation properties found in the biosphere are hindered by anthropic-induced modifications (Butera & Palme, 2021). Usually, urban climate modifications are unplanned consequences of urbanisation and lead to negative effects on the environment and living beings. The urban form is characterised by surface cover, construction materials, and three-dimensional morphology (Mills et al., 2021). When surfaces are paved, evapotranspiration is reduced, therefore radiation is converted into sensible heat rather than latent heat; this leads to increasing air and surface temperatures. Additionally, impermeable surfaces reduce the amount of infiltrated water, increasing runoff and thus the risk of flooding. Artificial materials usually have high thermal conductivity and heat capacity; emissivity is typically high, while reflectivity depends on the

[1] Emissivity (ε) is the 'ratio of the total radiant energy emitted per unit time per unit area of a surface at a specified wavelength and temperature to that of a blackbody under the same conditions'; albedo (α) is 'the ratio of the shortwave radiation reflected by a surface (reflectance) to the shortwave radiation reaching that surface (irradiance)' (Oke et al., 2017, pp. 469 and 472).

albedo. The morphology of urban areas, characterised by vertical elements of various orientations and geometries (buildings and trees), modifies radiative exchanges, thermal fluxes, and wind patterns (Oke et al., 2017). Urban functions such as fuel combustion and electricity are a source of heat, whose magnitude follows people's activities pattern (Mills et al., 2021).

The Urban Heat Island (UHI) is a well-known consequence of urban climatic modifications, specifically as regards the energy balance. It describes the difference in temperature between urban and rural areas, and it was measured for the first time by Luke Howard in the XIX century (Stewart, 2019). The UHI is classified based on the scale and processes investigated (Oke et al., 2017). For local studies, two UHI are of particular interest; the canopy layer UHI (CUHI), measured in the layer of air surrounding urban surfaces, and the surface UHI (SUHI), measured at the solid-air interface (Mills et al., 2021). The difference in scales and magnitude of the two effects mirror the properties of the two temperatures compared, i.e., air and surface temperature, respectively. The temperature of a volume or layer of air varies based on the time of the day and year, and the presence of wind and clouds. The surface temperature depends on the properties of landscape elements; therefore it varies based on materials and the position of objects toward the sun. As a consequence, the SUHI effect can be detected with a higher spatial resolution, and the temperature difference is usually of a higher magnitude than the CUHI (Oke et al., 2017). The UHI effect brings implications for people, such as leading to larger cooling energy consumption in summer (Mavrogianni et al., 2011; Santamouris, 2016) and worsening the detrimental impact of heat waves (Li & Bou-Zeid, 2013).

Urbanised areas impact climate by generating effects at different scales. The subdivision of the atmosphere into layers allows one to study and describe phenomena with similar spatial and temporal distribution; accordingly, associating environmental features to anthropic-induced phenomena at the right scale is the first step for finding mitigating solutions in case of negative effects. For example, reducing the UHI effect requires mitigating solutions extended to large urban areas, e.g., increasing green parks and reducing impermeable surfaces; instead, unpleasant wind draughts around tall buildings are detected at a smaller scale, therefore the solutions concern one block at most.

2.2.3. Definition of urban microclimate

Microclimate corresponds to the specific conditions caused by atmospheric processes and landscape properties at the microscale. Horizontally, this scale extends from millimetres to one kilometre; temporally, processes last from minutes to hours (Oke et al., 2017). Among microclimatic phenomena at the microscale, shadow casting and wind flow patterns can be listed; both are impacted by the urban morphology, intended as the three-dimensional layout of buildings and other urban elements. Specifically, the positioning and height of buildings create unique urban canyons, characterised by the height of the two vertical surfaces and the width of the street underneath, i.e., the aspect ratio (H/W). The orientation of the urban canyon is key in assessing solar radiation access and in relation to prevailing wind directions (Chatzipoulka et al., 2020; Jamei et al., 2016). Furthermore, the properties of materials (albedo, emissivity) strongly impact the resulting radiative environment, modifying energy exchanges between surfaces (Kotopouleas et al., 2021; Salvati et al., 2022). The morphology of urban canyons facilitates multiple energy reflections; longwave radiation emitted from surfaces varies during the day in relation to surface temperatures (Oke et al., 2017). The combination of the building arrangement and surface materials results in specific urban microclimatic conditions (Jamei et al., 2016); architects and urban designers can thus be considered professional figures whose decisions have effects on the microclimate (Erell et al., 2010).

2.3. The impact of microclimate on people

The combination of climate phenomena at different scales, e.g., climate change and UHI, increases the vulnerability of people in cities, especially during severe events such as the 2003 heat wave in Western Europe. Besides extreme events, microclimate impacts the experience of people outdoors in ordinary conditions and on a daily basis; therefore, studying the effect of environmental features on thermal sensation is critical.

2.3.1. The physiological approach to thermal comfort

The human body transforms food into energy that is used for internal functions and physical activity. The energy exchanges within a body (i.e., from core to skin) result in ‘metabolic heat’ that must be dissipated to the surrounding environment and regulated to maintain normal body temperatures. Heat exchanges with the external context are performed via thermoregulatory processes such as shivering and sweating, together with behaviours like modifying the environment. The heat exchanges of a body with the surrounding environment occur through respiration and at the skin level. The energy balance governing external thermal flows is written as follows (ASHRAE, 2005):

$$M - W = q_{sk} + q_{res} + S$$
$$= (C + R + E_{sk}) + (C_{res} + E_{res}) + (S_{sk} + S_{cr}) \quad \text{(Eq. 2.1)}$$

where M = rate of metabolic heat production (W/m^2)

W = rate of mechanical work accomplished (W/m^2)

q_{sk} = total rate of heat loss from skin (W/m^2)

q_{res} = total rate of heat loss through respiration (W/m^2)

S = total rate of heat storage (W/m^2)

C+R = sensible heat loss from skin (via convection + radiation) (W/m^2)

E_{sk} = total rate of evaporative heat loss from skin (W/m^2)

C_{res} = total rate of convective heat loss from respiration (W/m^2)

E_{res} = total rate of evaporative heat loss from respiration (W/m^2)

S_{sk} = rate of heat storage in skin compartment (W/m^2)

S_{cr} = rate of heat storage in core compartment (W/m^2)

For calculating terms in Equation 2.1, personal and microclimatic variables are required (Figure 2.3). Individuals are characterised by the activity performed and the properties of the surfaces at the interface between the body and the atmosphere (i.e., clothing). Microclimatic variables depend on meteorological conditions, time of the day and landscape features. In addition to air temperature, wind speed, and humidity, presented in Section 2.2.1, the mean radiant temperature is introduced. It summarises the external radiative environment in which a person is positioned, and it is key in thermal calculations because it is strictly dependent on surrounding surfaces and solar radiation.

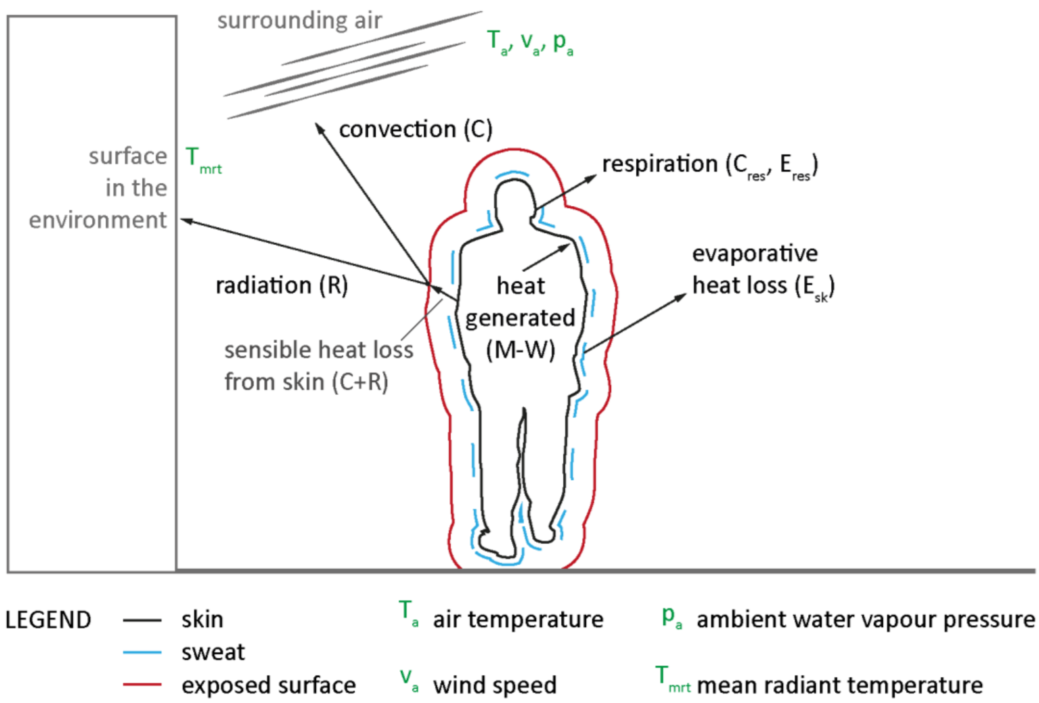


Figure 2.3 Heat flows between a body and the surrounding environment (adapted from ASHRAE, 2005).

If the environmental conditions challenge the thermal equilibrium of a person, the human body experiences thermal stress and makes a physiological effort to reinstate normal conditions; this activity is defined as 'thermal strain' (Oke et al., 2017). Oke et al. (2017) defined thermal comfort as the 'environmental conditions where an individual feels no thermal stress and exhibits no sign of thermal strain. In these circumstances, the net heat gain/loss of the body will be close to zero' (p.482). This definition emphasises the impact of the context on the energy balance of people. It can therefore be associated with the physiological approach to thermal comfort, which has produced numerous indices to evaluate the thermal load on people (Nikolopoulou, 2011). When it comes to software computation and communication with professionals of diverse fields, three indicators stand out: Physiological Equivalent Temperature (PET) (Höppe, 1999), Universal Thermal Climate Index (UTCI) (Jendritzky et al., 2007), and Predicted Mean Vote (PMV) (International Organization for Standardization, 2005). The indices PET and UTCI were developed for outdoor studies and are expressed in °C. On the contrary, PMV was formulated for indoor environments, therefore it shouldn't be used in dynamic environmental conditions of outdoor contexts; the thermal perception is described from very cold (-3) to very hot (+3).

The PET and UTCI are conceptually similar: both thermal indices are formulated to return the equivalent air temperature that, at specific reference conditions, would produce the same physiological response as the analysed microclimate. However, the environmental reference conditions are slightly different[2]; furthermore, the two indices are derived from different models of the human energy balance (MEMI and UTCI-Fiala, respectively). In the Munich Energy-Balance Model for Individuals (MEMI), the energy balance, together with internal (core to skin) and external (through clothes) heat fluxes, is calculated for the whole human body. The clothing properties and personal characteristics can be customised, but the steady-state approach of the model presents limitations in outdoor simulations. The reference conditions defined for UTCI include the walking speed of the person (1.1m/s), making it suitable for the evaluation of dynamic states; this was set as a goal from the beginning of the process that led to its definition (Höppe, 2002). In the Fiala model, the heat fluxes are differentiated for 12 body parts, considering asymmetric thermal exchanges; the calculation of UTCI is independent of clothing and personal characteristics. Because of the different models adopted, the same equivalent temperature obtained through the two indices corresponds to different thermal responses (Table 2.1).

Table 2.1 Original assessment scales of the UTCI and PET (after Pantavou et al., 2018), and PMV (after Matzarakis et al., 1999).

Thermal Stress	**Thermal Sensitivity**	**UTCI Range (°C)**	**PET Range (°C)**	**PMV**
Extreme cold stress	Very cold	< - 40	< 4	< - 3.5
Very strong cold stress		- 40 to - 27		
Strong cold stress	Cold	- 27 to - 13	4 to 8	- 3.5 to - 2.5
Moderate cold stress	Cool	- 13 to 0	8 to 13	- 2.5 to - 1.5
Slight cold stress	Slightly cool	0 to 9	13 to 18	- 1.5 to - 0.5
No thermal stress	Neutral	9 to 26	18 to 23	- 0.5 to 0.5
Slight heat stress	Slightly warm		23 to 29	0.5 to 1.5
Moderate heat stress	Warm	26 to 32	29 to 35	1.5 to 2.5
Strong heat stress	Hot	32 to 38	35 to 41	2.5 to 3.5
Very strong heat stress		38 to 46		
Extreme heat stress	Very hot	> 46	> 41	> 3.5

2.3.2. Subjective factors influencing outdoor thermal comfort

The thermal energy balance is at the basis of thermoregulatory models, but the dynamic environmental conditions of outdoor spaces hinder the achievement of a balanced state. Therefore, such models present limitations in capturing outdoor thermal comfort (Nikolopoulou, 2021). According to ASHRAE (2005), thermal comfort is ‘that condition of mind that expresses satisfaction with the thermal environment and is assessed by

[2] PET: $T_a = T_{mrt}$, wind speed = 0.1m/s, humidity = 50% at 20°C. UTCI: $T_a = T_{mrt}$, wind speed = 0.5m/s, humidity = 50%.

subjective evaluation' (p. 9.1). This definition is more vague than the one by Oke et al. (2017); this can be traced to the complexity of the matter (Nikolopoulou, 2021). Subjective factors contribute to outdoor thermal comfort in addition to physiology and can be of priority, as research established (Nikolopoulou et al., 2001).

Combining environmental analysis with subjective factors, such as people's perception and activity, provides meaningful information for researchers and planners (Chen & Ng, 2012). Models merging the physiological and psychological aspects of outdoor thermal perception have been delineated in theory (Lenzholzer & de Vries, 2020); however, until now, studies have drawn conclusions by simply comparing objective measures with subjective responses (e.g., Villadiego & Velay-Dabat, 2014). Reviews about outdoor thermal comfort studies reached similar conclusions (Aghamolaei et al., 2023; Johansson et al., 2014; Kumar & Sharma, 2020). First, published articles about outdoor thermal comfort present an increasing trend in terms of number and spatial distribution across climate zones. The primary motivation for pursuing outdoor thermal comfort studies is improving knowledge, followed by testing mitigation strategies. The complexity of outdoor thermal comfort is mirrored by the differences in methods employed in thermal comfort surveys. As regards environmental factors, the number of models and tools formulated results in different thermal indices employed; even when microclimatic factors used in thermal indices are the same, the use of different instruments to measure such variables contributes to differentiating survey methodologies. The largest variability can be found in questionnaires, designed to capture human perception. Differences concern the number of interviews, personal characteristics recorded, and the number of questions; additionally, the adopted thermal evaluation scales are not standardised in terms of wording or answer options.

Despite the lack of standardisation, questionnaires contribute to understanding how subjective factors influence thermal sensation. Of particular interest are questionnaires comparing responses recorded in different cities or by user groups in the same context, like locals and tourists. Based on the answers, a significant influence on thermal comfort of two subjective factors can be identified: long-term experience and expectations. Long-term experience refers to the impact of thermal history on the degree of tolerance towards extreme microclimatic conditions. For example, locals in Greece reported higher tolerance to heat than British people, but less tolerance to cold weather (Pantavou et al., 2018); similar results were obtained interviewing locals and tourists in Taiwan (Lin & Matzarakis, 2008) and locals in European cities at different latitudes (Nikolopoulou & Lykoudis, 2006). Additionally, cultural differences in clothing, drinking cool beverages, and usage of A/C systems, result in different thermal stress thresholds, as demonstrated by comparing interviews between Phoenix and Marrakech (Aljawabra & Nikolopoulou, 2018). This knowledge is useful when thermal comfort tools are designed for people of diverse cultural backgrounds, such as in proposing thermal comfort calendars for tourists (Ma et al., 2019). The other subjective factor listed is past experience in terms of thermal comfort, which impacts current sensation by creating specific expectations (Nikolopoulou, 2011). When weather conditions are in line with such expectations, people are more tolerant of thermal stress (Höppe, 2002) and spend more time outdoors (Aljawabra & Nikolopoulou, 2018). Finally, cooling spots along a walk under the sun were found to contribute to reducing fatigue sensation (Ali Smail et al., 2024); this is related to the concept of 'thermal *alliesthesia*', i.e., a positive or negative perception following a thermal stimulus (de Dear, 2011; Vellei et al., 2021).

2.3.3. Adaptation to outdoor thermal comfort

In Section 2.3.2 the complexity of assessing outdoor thermal comfort was highlighted through research comparing objective data with subjective responses. Once assessed which factors influence outdoor thermal comfort, this section reviews how people reduce thermal stress, unconsciously or through specific behaviours. Nikolopoulou and Steemers (2003) defined 'thermal adaptation' as the actions taken by individuals to improve their thermal sensation, achieved by adjusting factors contributing negatively to it.

Adaptation options concern both approaches adopted to define thermal comfort and can be divided into physical, physiological, and psychological adaptation (Nikolopoulou & Steemers, 2003). Physical adaptation is the active modification of the heat flows between the human body and the environment; it includes changing clothes, drinking, and seeking shade. Physiological adaptation refers to the acclimatisation process, i.e., a gradual adjustment to environmental conditions for reducing thermal stress, which is unconscious and requires a long time. Psychological adaptation combines the multifaceted, and often unconscious, subjective factors influencing thermal sensation. It can be associated with the perception of the environment, i.e., the degree of naturalness and environmental stimulation due to variable rather than static contexts. Personal attributes such as expectations and experience, as reviewed in the previous section, contribute to increasing, or reducing thermal stress. They also contribute to shifting the thermal neutrality zone established in comfort indices, which describes the conditions in which people feel neither warm nor cold (Nikolopoulou & Lykoudis, 2006). Finally, factors related to the specific event affect thermal comfort, such as the time spent outdoors, the motivation for being outside and the perceived control of the surrounding environmental features.

Architects and urban designers can mitigate uncomfortable thermal conditions by modifying the spatial layout. Especially under extreme microclimatic conditions, the urge to create homogeneously comfortable spaces could manifest; an example might be the provision of uniform shade under a sunny day. However, research has demonstrated how spaces of diverse microclimatic conditions are a more effective solution; this recommendation moves towards thermal diversity, which is important to allow people to choose the preferred environmental conditions spatially and temporally (Chatzipoulka et al., 2020; Nikolopoulou & Steemers, 2003).

2.4. Climate-responsive urban design: case studies and lessons learnt

Microclimate analysis informs designers and planners about how landscape features and urban morphology affect microclimatic conditions, therefore outdoor thermal comfort. The next step is deploying this knowledge in practice according to climate-responsive urban design, i.e., the proposal of strategies to benefit from opportunities and address barriers posed by the urban environment (Nikolopoulou, 2004; Tamminga et al., 2020). The term ‘responsive’ focuses on the active approach of modifying the environmental context in response to microclimate, rather than just ‘sensing’ microclimatic features. Climate-responsive urban design can address both climate mitigation and adaptation goals (Daniel et al., 2023) and must ensure overall integration between single projects to be beneficial (Brandsma et al., 2024). Applications range from proposing recommendations at the regional to neighbourhood scale to testing specific proposals (via digital simulation or practical installations).

2.4.1. Recommendation maps and design guidelines

The urban climatic map (UCMap) system is an information and evaluation tool to implement urban climatic information into planning considerations (Ng & Ren, 2015). The basis of the UCMap system is the classification of the landscape into *climatopes*, i.e., ‘areas of characteristic combinations of climatic factors and of similar relative significance for their surroundings, operating on a spatial scale of several tenths to hundredths of meters’ (Scherer et al., 1999). Climatopes describe homogeneous geographic areas where microclimatic conditions are similar; their definition is grounded in data, mainly referring to land use and morphology (Baumüller, 2015). The UCMap system is structured in two components: the analysis and the recommendation maps. The analysis map visually displays climatopes, therefore it is a synthesis of climatic and morphological information. The recommendation map critically evaluates the climate knowledge assessed in the analytical phase, bringing out issues and climate-sensitive areas that require strategic interventions. It is the outcome of multidisciplinary collaboration among professionals and addresses the specific context of interest. A successful example of this methodology can be found in the city of Stuttgart, where planning recommendations to improve ventilation and greenery were included in the Climate atlas (Baumüller & Reuter, 2015); numerous examples of UCMap applications were collected by Ng and Ren (2015).

Mapping microclimatic conditions allows professionals to overlay additional information, uncovering valuable insights about the urban environment as a context for people to live in. Smith et al. (2015) developed recommendation maps to tackle heat waves and flooding hazards through the systematic combination of climatic and physical elements with socio-spatial indexes. As a result, in the UCMap for Greater Manchester, climate adaptation interventions were prioritised based on the population's vulnerability to heat and floods. Moving to a smaller scale, Hendel et al. (2020) developed a digital tool for emergency urban cooling, overlaying vulnerability to microclimatic maps. Data such as population age, household income and pedestrian traffic were added to indicators of heat stress; as a result, outdoor public spaces were classified based on the heat-related health risk, prioritising the use of pavement watering as a heat mitigation measure.

The recommendation maps have a key role from the urban planners' perspective to prioritise interventions and select vulnerable areas within a city; however, this information must be complemented with design guidelines at the street scale to tackle thermal stress conditions. The EU-funded research project 'RUROS: Rediscovering the Urban Realm and Outdoor Spaces', a pioneer study about outdoor thermal comfort in Europe, collected design principles and applications to implement the newly gained knowledge in practice (Nikolopoulou, 2004). Following this experience, guidelines about climate-responsive urban design were developed to support professionals in designing urban green infrastructures (Andreucci, 2017; Klemm, 2018) and contributing to climate change mitigation and adaptation (Dessì et al., 2017). The project 'Really cooling water bodies in cities' (REALCOOL) not only provided guidelines for designing effective water body installations but also reflected on the communication of urban design guidelines to professionals (Cortesão et al., 2019; Cortesão et al., 2020).

2.4.2. Testing design proposals

A further step towards climate-responsive urban design is moving from availing of design guidelines to test solutions, evaluating the impact of the developed proposals on the urban microclimate. Kotopouleas et al. (2021) used a 1:10 physical model of an urban canyon to monitor the variations of radiative exchanges based on various materials applied on horizontal and vertical surfaces. The physical model was also used to validate digital simulations, transitioning from a confined physical model to a digital one suitable for testing a larger number of design options (Salvati et al., 2022). This experience mirrors the digitalisation trend of testing design configurations in virtual environments, enabled by simulation tools available for professionals.

The availability of a range of simulation software has generated a massive body of case study projects; the following examples were selected as representative of the principles and purposes driving the testing activity. At the mesoscale, the impact of changes in materials and vegetation was tested in Austria, simulating future RCP scenarios defined by IPCC (Oswald et al., 2020). Similarly, Tomasi et al. (2021) simulated the effectiveness of vegetated ventilation corridors and green roofs on air temperature and wind speed, moving from the neighbourhood assessment to design proposals at the street scale. As regards urban design, the firm White Arkitekter proposed a new layout for a square in Kiruna (Sweden); parametric studies about surface materials and trees' arrangements led to defining a design proposal based on the simulated outdoor thermal comfort performance (Diéguez et al., 2017). Palomo Amores et al. (2023) used digital models to simulate the evolution in time of trees' plantation, proposing temporary installations to maintain outdoor mitigation effects while plants were growing. At a later stage of the design process, the evaluation of the competition submissions for the main square in Leskovac (Serbia) was performed through microclimatic software, investigating to what extent the proposals would meet the call requirements (Djukic et al., 2016).

Digital simulations represent an abstraction of the urban environment; however, the consistent body of research and validation exercises has made them well-assessed among practitioners in the field. A research branch about digital urban design currently under development is represented by digital tools for generating climate-responsive urban layouts and building forms. In these tools, the generated outcome fulfils parametric requirements inserted upstream; rather than testing specific solutions, they are meant to support urban designers in the conceptual phase (El Dallal & Visser, 2017). ÇalıŞKan (2017) highlights the emerging approach of parametric modelling in urban design, outlining a new planning practice trend based on design codes rather than blueprints ('planning without plan'). Without entering the debate around creativity versus artificial intelligence, the positive contribution of this trend to climate-responsive urban design is the focus on performance-driven solutions, which can be at the centre of more 'conservative' parametric urban design approaches.

2.5. Climate-responsive solutions: case studies and lessons learnt

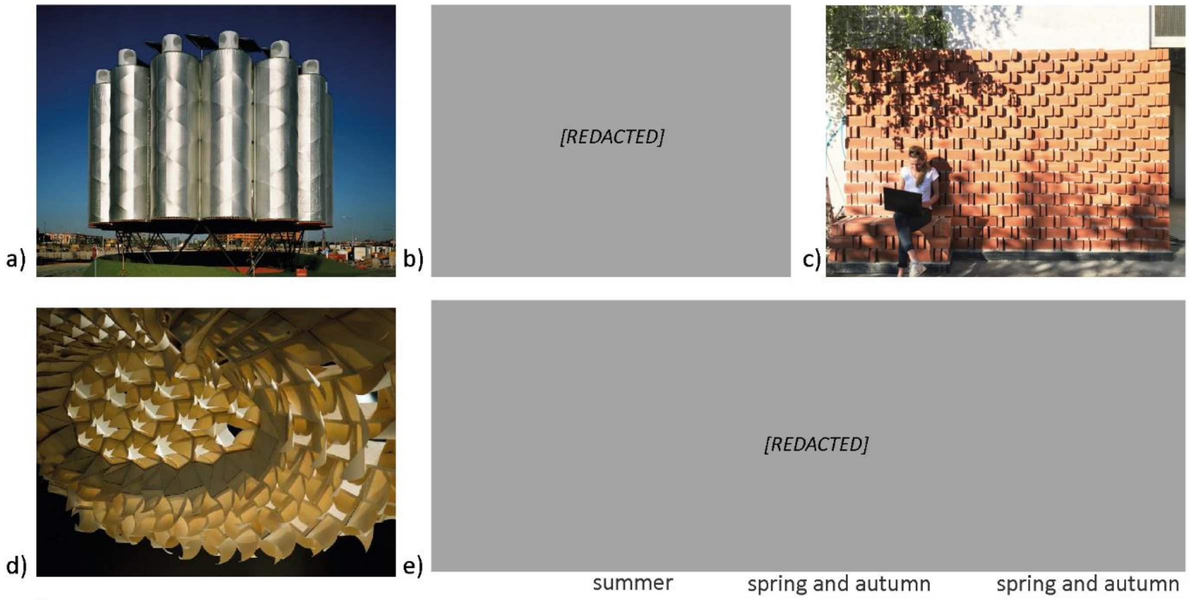
As reviewed in Section 2.2, microclimatic conditions vary based on context, i.e., latitude, morphology, and human activities; this is a barrier to finding universal solutions to ameliorate outdoor thermal comfort, especially because of its complexity (Section 2.3). Furthermore, opposite to indoor spaces, where technology might be a solution to tackle thermal stress and discomfort, the outdoor urban environment is a challenge as regards thermal comfort. People spending time outdoors have limited control over the environmental conditions, therefore solutions are needed to respond to the microclimate in a beneficial way for the users. Strategies such as the implementation of nature-based solutions and climate-sensitive urban layout configurations are well-assessed among practitioners; additionally, localised, dynamic and short-term solutions have the potential to adapt outdoor spaces in response to microclimatic conditions. According to the definition of climate-responsive urban design reported in Section 2.4, a range of solutions[3] exploiting microclimatic and environmental properties to ameliorate outdoor thermal comfort is presented.

Exhibitions are great opportunities to experiment with climate-responsive design because solutions are built at a limited scale, visited by many people, and have a temporary character that makes it possible to learn lessons to test in future projects. The Expo'92 in Seville was pioneering in implementing microclimatic solutions to ameliorate heat stress in common areas; the design combined water surfaces and micronisers, shading canopies, and vegetated pergolas (Chadwick, 1992; Expo92.es, n.d.). Following this successful experience, these solutions were adopted in later events. The Austrian pavilion built for EXPO 2015, in Milan, aimed to showcase design strategies for ameliorating outdoor thermal comfort. In addition to the use of vegetation, it featured active cooling measures such as forced ventilation, evaporative cooling and mist production strategies (Transsolar, 2015). In Madrid, an installation of three devices includes an Air Tree equipped with sixteen wind towers and an evaporative system of a mechanical fan and water micronisers to reduce air temperature and increase humidity; a regulation controller activates the system when ambient conditions exceed preset thresholds (Soutullo et al., 2011) (Figure 2.4a). Applying technology to microclimate might produce fascinating results, as demonstrated at the Architecture Biennale in Venice, where visitors could walk through a cloud artificially created indoors through air layers of different temperatures (Transsolar & Tetsuo Kondo, 2010) (Figure 2.4b). The walls of the Digital Water Pavilion at the EXPO 2008 in Saragoza were made entirely of water droplets, which were digitally controlled to create a dynamic building, in addition to being beneficial to tackle heat stress (CRA - Carlo Ratti Associati, 2008). A less spectacular yet effective strategy to cool the air is forcing it underground through a system of electric fans and pipes. Known as 'EAHE' ('Earth-to-air heat exchanger'), this technology exploits the high thermal inertia of

[3] In this research, the term 'solution' refers to the strategical implementation of elements or devices in response to an issue.

soil to cool down the air, while fans increase the airflow speed; once above the surface, the air can mitigate heat stress in the surrounding outdoor areas (Zoras & Dimoudi, 2016).

Most of the presented case studies relied on mechanical or electronic devices, e.g., for activating water nozzles or A/C systems, albeit limited in their use; on the contrary, passive solutions are here defined as the installation of devices responding to environmental inputs by shape and materials. The project Climate Active Bricks adopts both strategies, positioning bricks to create a self-shading wall; additionally, watering selected elements improves the cooling effect of the prototype (Studiomolter, 2021) (Figure 2.4c). The Hygroscope project leverages the hygroscopic and anisotropic properties of wood; the device generated through computational design modifies its shape in response to the surrounding level of relative humidity (Menges, 2012) (Figure 2.4d). The content of water in the soil, rather than air, was exploited in proposing wind screening poles forced off the ground during intermediate seasons and let sink underground in dry conditions (Lenzholzer & Brown, 2013) (Figure 2.4e). Another relevant branch of research about passive climate-responsive solutions focused on changing the optical and thermal properties of materials: thermochromic materials respond to temperature fluctuations by moving to darken or lighten colours, thus modifying solar properties (Synnefa & Santamouris, 2016). This is key for outdoor thermal comfort because it can change the amount of radiation transmitted, absorbed, and reflected by materials surrounding people, impacting their energy balance.



Sources:
a) Air Tree (Ecosistema Urbano, 2007)
b) Cloudscapes (Transsolar & Tetsuo Kondo, 2010)
c) Climate Active Bricks (Studiomolter, 2021; photograph: Philipp Lionel Molter)
d) Hygroscope (Menges, 2012; photograph: ©ICD University of Stuttgart)
e) Screening poles (Lenzholzer & Brown, 2013)

Figure 2.4 Set of climate-responsive solutions responding to various microclimate variables.

2.6. The thermal comfort potential of shading solutions

Solar radiation is the only energy source of the Earth-Atmosphere system; its interaction with the built environment leads to changes in temperature and wind patterns, as well as influencing the water cycle (Oke, 1987). At the street level, radiation is transmitted, absorbed, and reflected, creating specific radiant environments where people live; therefore, based on the review in Section 2.3, it can be affirmed that solar radiation impacts the energy balance of humans, influencing their outdoor thermal comfort. Finally, the directional character of sun rays makes the design and positioning of shading devices a climate-responsive urban design task, replicating the principles guiding the case studies listed in Sections 2.4 and 2.5. This summary introduces the final section of this literature review, aimed at presenting the impact of solar radiation on people and their activities.

2.6.1. Direct impacts of solar radiation on people

2.6.1.1. Health risks for users due to solar radiation exposure

The World Health Organization considers overexposure to ultraviolet (UV) radiation, either from the sun or other artificial sources, a public health concern (WHO, 2003). The risk of sunburn and skin damage is related to the Global Solar UV Index (UVI), which is used to describe the level of solar UV radiation at the Earth's surface; the minimum value is zero, and it increases along with the potential damage risk (WHO, 2002). A simple rule for people to determine the solar UV intensity is observing the shadow length, directly linked to solar altitude – the higher the sun, the shorter the shadow, and the higher the UV index. The skin type of people is also a personal relevant factor when sunburn and other skin damage are considered (Diffey, 2018); contrary to popular belief, melano-protected skin types (V and VI) are also vulnerable, even though more adaptable to UV exposure than people of sensitive skin types (WHO, 2002).

When solar radiation is under consideration, the time of exposure is key. Diffey (2018) reported that unacclimatised white skin would need protective measures after around one hour if exposed to UVI of 3-4. Sánchez-Pérez et al. (2019) presented the relationship between exposure time for the appearance of first-degree sunburn and UVI for different skin types; according to the results, a type II (melano-compromised) would suffer from first-degree sunburn after 42 minutes in case of UVI equal to 4, 22 minutes if UVI increases to 8. As a reference, the mean UVI value calculated for London in July is 4, while in Southern Italy it reaches the value of 8 (Vitt et al., 2020). On the other hand, exposure to solar radiation is key to producing vitamin D, therefore a minimum of 10 to 15 minutes per day is recommended (WHO, 2003).

2.6.1.2. Solar radiation and outdoor thermal comfort

Excessive exposure to solar radiation, or lack of it, compromises not only health but also thermal comfort. The resulting effects are generally dangerous for people, yet they are even more critical in extreme microclimatic events such as heat waves. In sunny conditions, the solar radiation amount absorbed by a body has a critical impact on outdoor thermal stress (Kenny et al., 2008). In thermal comfort analysis, this can be formulated as an increase in mean radiant temperature (T_{mrt}); research demonstrated that this variable has a prominent role in describing thermal comfort and was recognised as being more detailed in describing thermal stress at the street scale than air temperature (Aleksandrowicz & Pearlmutter, 2023). Bröde et al. (2012) isolated the critical impact of the surrounding radiant environment on outdoor thermal comfort by proposing a regression equation to calculate the UTCI based on the difference between T_a and T_{mrt} (v_a and p_a at reference conditions):

$$UTCI = 0.995 \cdot T_a + 0.27 \cdot (T_{mrt} - T_a) \quad \text{(Eq.2.2)}$$

This equation was calculated based on data with air temperature included in the range 20°C ≤ T_a ≤ 50°C. Per the regression function, a 10K increment in T_{mrt} corresponds to a 3K increment in UTCI; this rule-of-thumb highlights the direct relationship between the radiant environment and heat stress.

Nikolopoulou (2011) noted that thermal satisfaction might come from thermal stimuli, even though not in agreement with the concept of thermal neutrality. Being exposed to direct solar radiation is an immediate and substantial stimulus for people, therefore it can consistently change the thermal comfort conditions, both in heat and cold microclimates. In heat stress conditions, relief can be found even with a limited number of cool spots breaking down the walking experience with shade (Ali Smail et al., 2024). For this reason, analysing the variable presence of sunny and shaded spots is critical for inferring the usability of outdoor spaces. Furthermore, the presence of both conditions in the same space has been reported as valued by users (Faustini et al., 2020). On clear sky days, an observational study in the Netherlands reported a ratio of 40%, 20% and 40% of park users spending time in the sun, in partial shade, and in shade, respectively (Klemm et al., 2017). This reinforces the importance of thermal variability, which is critical to meeting the requirements and expectations of different users (Lin et al., 2010; Steane & Steemers, 2004).

2.6.2. The behavioural influence of solar radiation exposure

People spend time outside for many purposes such as for pleasure, travelling, working, well-being, and health. Outdoor users can be divided into two groups, based on whether they are staying in one place or travelling through the space to reach a destination. As regards solar radiation exposure, the two groups exhibit different levels of vulnerability and needs. From an urban planning perspective, the 'static' user group requires comfortable spots within reasonable travel distance; this could be defined as an issue about the density of relief spots, which is evaluated by mapping beneficial locations. Planners can categorise neighbourhoods and urban areas to ensure fair access to comfortable spaces across the city, and possibly propose additional relief spots. Once suitable availability of comfortable spaces is ensured, the issue of accessibility to relief spots takes over.

A survey performed among 69 people in Denver (US) recorded shade as the most important factor affecting route choice while walking (Tabatabaie et al., 2023). The same result was obtained through an experiment conducted in Tokyo (Japan), where the presence of shade was the most reported reason for choosing specific routes (28.2%); avoiding tiredness and sunburn were among the reasons for escaping the sun (Azegami et al., 2023). An observational study carried out in an artificially partially shaded alley in Hong Kong reported pedestrians seeking shade, especially the elderly and women (Lee et al., 2020). Melnikov et al. (2022) performed a behavioural experiment in Singapore to analyse the potential influence of solar radiation exposure on path choice; participants of the experiment were required to choose between two proposed paths of different length, linking different spots within the campus. Results confirmed that pedestrians were actively seeking shade while walking, even though the chosen path did not minimise the walked distance; furthermore, walking in the sun was perceived as 16% longer than walking in the shade.

As regards the impact of thermal stress on walking speed, the literature is not in agreement. Obuchi et al. (2021) performed an extensive monitoring campaign in Japan and found a seasonal pattern in walking speed, step length and cadence. Specifically, walking speed was higher in cold months compared to summer; although the difference was very low (0.03m/s), there is agreement in literature that people would walk faster in winter as a warming strategy, while fast movement in summer would be exhausting (Bosina & Weidmann, 2017). Conversely, questionnaires collected in Sidi Okba (Algeria) reported a consistent trend among pedestrians of increasing walking speed when exposed to solar radiation (Mouada et al., 2019); this result highlights the subjective responses of users to heat stress and might be linked to the extremely hot climatic conditions in Algeria, which lead pedestrians to escape heat. Nevertheless, it is clear that solar radiation exposure affects the usability of outdoor spaces, creating opportunities for climate-responsive urban design.

2.6.3. Opportunities of climate-responsive design through shading devices

The directional character of solar radiation enables designers to investigate its interaction with shading devices, from the local to the urban scale: this facilitates the implementation of relevant shading solutions in response to the sun's position. In fact, digital modelling tools allow for accurate shading analysis at multiple times of the year, with limited computational power. Shading is an intuitive concept even for people of limited or no expertise in the field of outdoor thermal comfort; this could contribute to recognising the benefit of installations responsive to solar radiation, increasing support by communities and stakeholders.

Buildings are a relevant source of shading in the built environment, and their shading effect is strictly related to the orientation of the urban canyons, with E-W oriented streets being usually exposed to solar radiation for longer periods than N-S oriented streets (Jamei et al., 2016; Mouada et al., 2019; Nasrollahi et al., 2020). Additionally, a clear relationship between the H/W ratio of urban canyons and shading at ground level has been found, with streets of higher aspect ratios being more shaded, therefore comfortable in warmer conditions (Jamei et al., 2016; Nasrollahi et al., 2020; Nouri et al., 2017). In fact, deep canyons are considered an effective urban configuration for ameliorating outdoor thermal comfort (Lee et al., 2018; Ma et al., 2019), both in hot and dry (Ahmadi Venhari et al., 2019; Mouada et al., 2019) and humid climates (Zheng et al., 2018). In cold and temperate climates, the downside of high aspect ratios lies in the limited solar radiation exposure of ground surfaces in winter, with negative consequences on outdoor thermal comfort (Jamei et al., 2016; Nasrollahi et al., 2020). The combination of orientation and aspect ratio of urban canyons is critical in analysing shading at the street level. For instance, high aspect ratios have been considered not enough to ameliorate thermal comfort in E-W oriented streets, and the plantation of additional trees has been recommended (Ahmari Venhari et al., 2019; Zheng et al., 2018).

Monitoring field campaigns showed that the shade from buildings is the most effective in cooling people underneath (Lee et al., 2018; Middel et al., 2021). However, in existing urban contexts, opportunities to propose climate-responsive urban layouts are limited, therefore, temporary and stand-alone solutions must be studied. The adaptability of outdoor areas through spatial configurations changing on a seasonal or even daily basis can create diverse spaces, potentially responsive to temporary issues such as events, or the recent redefinition of social distances due to COVID-19. Shading solutions installed in existing contexts, as well as new ones, can be categorised as natural and artificial.

2.6.3.1. Natural shading devices

The most popular shading device is represented by trees due to the numerous additional benefits of these nature-based solutions linked to biodiversity, comfort, psychology, and economy (Andreucci, 2017). Besides protecting objects and people underneath from direct solar radiation, trees convert this energy into latent heat through the mechanism of evapotranspiration, cooling the surrounding air (Rahman et al., 2020; Shashua-Bar et al., 2011). However, the beneficial effect of trees for outdoor thermal comfort is mainly attributable to shading rather than evapotranspiration (Pace et al., 2021). Starting from previous research, Gao et al. (2024) hypothesised that in extreme conditions, the transpiration ability of trees would diminish compared to what is predicted by existing models. The comparison of simulation models' results with field data demonstrated such behaviour, leading to the reassessment of climate models and the call for more attention in advertising the mitigating effect of trees during heat waves.

From a psychological point of view, urban greenness was appreciated from an aesthetic perspective (Klemm et al., 2015), and naturalness was identified as influencing psychological adaptation factors such as time of exposure and expectations (Nikolopoulou & Steemers, 2003). Klemm et al. (2015) performed semi-structured interviews in Utrecht (Netherlands), alongside field measurements to quantify the benefits of urban greening on thermal comfort. As expected, the reduction of T_{mrt} was found related to tree coverage of street canyons, linked to the reduced exposure to solar radiation. The consequent decrease in heat stress was also perceived by respondents, who appreciated more vegetated streets compared to urban canyons with no greenery. However, it was not possible to link the thermal perception with greenery, and it was inferred that people were not consciously aware of the role of street green on their thermal comfort state. Even though the effect of trees on thermal comfort may not be fully recognised by non-experts, field measurements have provided proof of this, assessing the benefits of trees in reducing T_{mrt}. A field study carried out in Campinas (Brazil) compared the effect of trees on thermal comfort (de Abreu-Harbich et al., 2015). Weather data including solar radiation exposure were measured below trees (located as isolated or in clusters), both in the summer and winter seasons; tree species were deciduous, semi-deciduous and evergreen, and differed by geometry, canopy permeability, and shape of leaves. Canopy permeability, calculated as PAI (Plant Area Index), had a major role in the cooling effect, with dense canopies blocking sun rays. Interestingly, it was suggested that canopies of moderate density were beneficial for thermal comfort because the wind could pass through; however, the shading effect was considered critical, with a reduction of up to 89% in summer for individual trees. The effectiveness of dense canopies in blocking solar radiation was also measured in Melbourne (Australia), and results showed that trees of diverse geometry but with the same PAI had an equal cooling effect (Sanusi et al., 2017). Konarska et al. (2014) focused only on the shading effect of tree canopies, recording almost zero transmission of incident solar radiation under the shade of densely foliated trees in Göteborg (Sweden).

2.6.3.2. Artificial shading devices

Having assessed the major role of shading in the cooling effect of trees, shading devices are proposed as artificial alternatives to trees. Shashua-Bar et al. (2011) compared the shading benefit of trees and an artificial mesh, positioned in a courtyard in Ben-Gurion (Israel). Results showed that the cooling effect of the artificial solution was only slightly lower than that of trees; furthermore, the substitution of bare soil with grass underneath further reduced thermal stress, highlighting also the synergy between the vertical and horizontal solutions.

Even though missing the additional benefits of trees, man-made shading can be a successful strategy in numerous situations. Palomo Amores et al. (2023) designed a shading system to be installed in a square while new-planted trees were growing; the geometry of the device was engineered in response to the position of the sun during the summer season, modelling a system of slats of inclination and distribution suitable to block direct solar radiation underneath. In existing environments, awnings might be a solution. The field monitoring campaign by Rossi et al. (2020) confirmed the effectiveness of textile awnings in reducing thermal stress, setting an additional challenge in the selection of materials; in fact, installing surfaces of high reflectivity upwards and low infrared emissivity downwards was recommended to cool down people underneath. The studio Kugel Architekten designed convertible fabric membranes to cover large surfaces, such as courtyards (2012) and alleys (2014) (Figure 2.5a). The term 'convertible' refers to the mechanism that allows users to pack the canopy when not needed and open it in case of events on clear sunny days. The convertible concept was adopted in designing the shading device 'Parelio', an umbrella-shaped element with foldable photovoltaic panels on top (CRA - Carlo Ratti Associati, 2021b) (Figure 2.5b). In the prototype 'Sun and Shade' (CRA - Carlo Ratti Associati, 2017), the use of mirrors rather than textiles was tested to reflect solar radiation; the elements of the system move in response to the sun's position and the user's input, allowing people to interact with the shading device (Figure 2.5c).

Sources:
a) Retractable Roof Metzgergasse Buchs (Kugel Architekten, 2014; photograph: Nikolai Kugel)
b) Parelio for Sammontana (CRA - Carlo Ratti Associati, 2021b)
c) Sun and Shade (CRA - Carlo Ratti Associati, 2017)

Figure 2.5 Set of artificial shading devices.

2.7. Conclusions

This chapter introduced the topic of climate-responsive urban design, highlighting the complexity represented by the interaction between climate, urban morphology and people. At first, the influence of building arrangements and surface properties on energy exchanges was presented, with consequences for the radiative environment of urban canyons. The development of sophisticated digital tools and the increasing knowledge about the diverse aspects of outdoor thermal comfort might drive towards the perception of a complicated and extensive subject, a challenge that could discourage professionals from implementing this theme in their practice. The provided overview suggests the need to select specific features to address through the design.

After reviewing the field of climate-responsive urban design, moving from the theoretical assessment to case studies, this chapter focused on the specific theme of solar radiation exposure. This downscaling process aims to isolate a theme among the complexity of outdoor thermal comfort and develop specific solutions to address its challenges and leverage its benefits. The geometric nature of shading, the highly localised effect of solutions and its crucial effect on outdoor thermal comfort drove the selection of solar radiation exposure as the microclimatic component to respond to through urban design.

3. METHODOLOGICAL APPROACHES

3.1. Introduction

Urban designers can contribute to the adaptation of outdoor spaces to climate. Microclimatic conditions are the result of many variables, which differ in terms of spatial and temporal scale. Sophisticated and powerful tools allow urban designers and researchers to grasp a wide overview of many factors contributing to microclimate; however, this comprehensive approach risks remaining theoretical because of the many challenges generated by such various contexts, and lack of knowledge about how to effectively modify microclimate.

This thesis presents digital modelling-based research, in which each component of the selected climate-responsive system is modelled through a suitable methodology. In this chapter, modelling techniques and tools are reviewed, and their features are compared. A case study area was used to test and illustrate the approach. Finally, the industrial experience in CRA – Carlo Ratti Associati, combined with the literature review about applications in professional practice, informal and non-structured discussions with experts in the field, and first-hand tests of the proposed methodology led to selecting the suitable tools for implementing the developed knowledge into practice, applying climate-responsive strategies in a digital urban environment.

3.2. Description of the selected climate-responsive system

In Section 2.5, a collection of climate-responsive solutions was presented. Each solution can be considered as part of a system formed of three elements: climate, device, and effect. The implementation of climate-responsive solutions in the urban environment is commonly driven by design goals, established *a priori* based on urban planning evaluations. This research adopted a user-centred urban design approach; therefore the climate-responsive solutions are developed to pursue benefit for users in outdoor spaces. Specifically, the selected climate-responsive system is formed of solar radiation as the climate component, and the intended effect is the beneficial exposure of users to solar radiation, including protection through shading when exposure would be dangerous. Because of the influence of solar radiation exposure on the walking experience and accessibility of spaces (Section 2.6.2), this research investigated this climate-responsive system in relation to the benefit of a specific group of outdoor users, i.e., pedestrians. Solar radiation exposure analysis was therefore applied on pedestrian paths. Figure 3.1 is the graphical representation of the selected climate-responsive system; the shading effect of the design is evaluated based on the benefit achievable by the pedestrians.

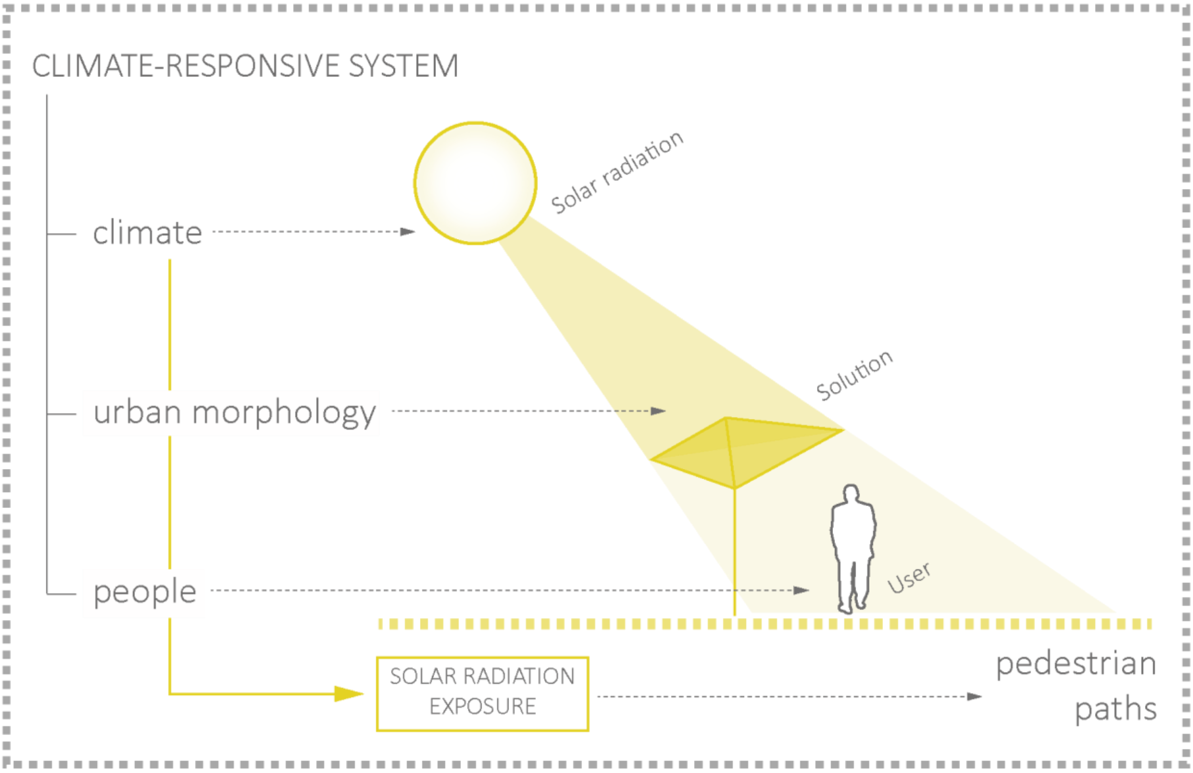


Figure 3.1 Climate-responsive system addressed in this research.

The choice of focusing on the solar radiation exposure of pedestrian paths can be summarised in three points:

- solar radiation exposure has a critical impact on the thermal stress of people;
- designing shading proposals to adapt the urban morphology in response to the sun's position is a solution to ameliorate thermal stress;
- a systematic methodology and accessible tools are needed to support urban designers in addressing this issue.

In the following sections, methodologies to model microclimate, urban morphology and pedestrian networks are reviewed. The objective is to select a suitable method for urban designers to model the selected climate-responsive system and implement the design of solutions within their design workflow.

3.3. Review of microclimate analysis and modelling techniques

In this section, tools for the analysis and modelling of microclimate are reviewed. At first, an overview of data collection techniques is provided, mirroring the first step in a climate-responsive urban design process. Methodologies to analyse how the land and urban morphology impact microclimatic conditions are reviewed, focusing specifically on how microclimatic information is communicated to designers. Finally, specific tools for modelling microclimate are reviewed.

3.3.1. Methods to analyse climatic components

Urban morphology and functions impact microclimate, therefore professionals must be supported in analysing spaces and identifying how spatial features impact energy use, environmental quality, and thermal comfort. In this section, methods and instruments to collect data, analyse it and synthesise results in an informative manner are presented.

3.3.1.1. Collecting data

To analyse the interaction of urban morphology and climatic conditions, data must not only be available but also at a suitable scale. For example, satellite remote sensing provides spatial data free from anthropic boundaries, thus allowing the comparison between different locations (Seto & Christensen, 2013). Over the years, a consistent body of information has been built, enabling the detection of modifications in the environment. However, the low-resolution raster format makes satellite-sensed data suitable for analysis at regional or urban scales, while it is a barrier in urban design, which requires a detailed urban form. When remotely sensed data are converted into editable vector formats (e.g., shapefile), they are suitable to be imported into the geographic information system (GIS) environments; this allows urban planners and designers to manipulate them. Since the value of sharing spatial data is recognised worldwide, governments and public authorities are increasingly processing and sharing data on web portals and open-access databases. However, some limitations can be found in such datasets, such as the lack of updating procedures and being usually confined within administrative boundaries (Mills et al., 2010).

In addition to spatial datasets provided by private and public institutions, research has proposed numerous methods to collect high-resolution data at ground level. Weather stations strategically positioned within, and around built-up areas allow experts to compare how land use and morphology affect microclimate. When stations are stationary, they represent only local conditions, but the results build consistent historical series of meteorological data. To cover large areas, mobile sensors could be positioned on vehicles moving in the city; in addition to Google Street View images, used to detect specific elements along urban streets (Li et al., 2015), research has tested data collection via bus and taxis (Li, 2015) and garbage trucks (Anjomshoaa et al., 2018). Similarly, climate walks are designed for people to carry the sensors during the walking experience, with the additional opportunity to record physiological and psychological feedback (Santucci et al., 2020; Vasilikou & Nikolopoulou, 2020).

3.3.1.2. Synthesis of morphology and climate data

Conveying collected data into climatic maps is fundamental for informing urban planners and designers. In Section 2.4.1, the method of classifying homogeneous landscape areas into climatopes was introduced, followed by relevant case study applications. Stewart and Oke (2015; 2012) questioned the lack of standardization of climatopes in the development criteria since class names and definitions vary widely based on place, experts' knowledge, and data availability. For this reason, they proposed the Local Climate Zones classification, which aimed to detect regions of uniform surface cover, structure, material, and human activity, at a scale from 10^2 to 10^4 meters. The proposed types (10 built, 7 land covers) are based on generalized and simplified knowledge of building form and land cover. Additionally, data about various physical properties are associated with each class.

Overlaying empirical meteorological data with urban morphology contributes to understanding the impact of urban features on microclimate. The urban morphology can be characterised by 'descriptors', which can be natural (i.e. climatic and geographical parameters) or artificial, classified as form-fabric, land-use, and density descriptors (Giridharan, 2016). This method was applied to investigate the impact of urban morphology on UHI (Giridharan et al., 2007; Wong et al., 2016) and outdoor thermal comfort (Yang & Chen, 2016). The use of specific descriptors benefits practitioners' understanding of the impact of design choices on environmental conditions, and isolates control factors that could be manipulated in the design process (Giridharan et al., 2007). However, since not all descriptors are critical in every location, statistical models are developed for specific contexts, which limits their applicability to different sites.

The use of 3D modelling techniques allowed researchers to analyse the impact of urban morphology on microclimate. Chatzipoulka and Nikolopoulou (2018) extracted from digital elevation models (DEM) 18 geometrical variables and analysed their relationship with the sky view factor (SVF), an environmental performance indicator in terms of ground insolation. Then, the same technique was used to analyse the impact of urban geometry on two microclimatic variables of interest, i.e., solar radiation exposure and ventilation. Outdoor spaces were classified as shaded-windy, shaded-lee, sunny-windy, and sunny-lee (Chatzipoulka et al., 2020); this classification method could be considered as simplistic, however, such streamlined information is beneficial to select the specific features to analyse.

3.3.2. Software tools for microclimate modelling

Professionals in academic research and practice can count on various software to apply the different methodologies reviewed in the previous section. Microclimate analysis tools are differentiated on modelling scale, data input, usability, and accuracy, all impacting the selection of the most suitable tool for the specific needs.

The most accurate and comprehensive software in terms of urban climate simulation and environmental analysis is ENVI-met (ENVI-met GmbH, n.d.). Access is via licence, which is tailored to multiple professional groups, and a free trial with restrictions is available. This CFD model simulates surface-plant-air interactions, therefore fluid dynamics parameters are combined with thermodynamic processes (Bruse & Fleer, 1998). The downside of highly complex calculations is the long analysis time (Georgatou & Kolokotsa, 2016; Keibach & Shayesteh, 2022), making it a research-oriented software rather than an option suitable for practitioners (Aleksandrowicz et al., 2020; Graham et al., 2020). Furthermore, because of the gridded environment, all elements are reduced to clusters of cuboids (Georgatou & Kolokotsa, 2016); this is a barrier in the case of complex 3D configurations of buildings and street elements.

CitySim simulates buildings' energy fluxes from the neighbourhood to the urban scale (Robinson et al., 2009). Among its advantages, importing and modelling 3D scenes, and the accuracy in simulating radiation exchanges are listed (Naboni et al., 2017). Similarly to ENVI-met, calculation times were considered too high for practitioners, but the possibility of importing existing DXF models drastically reduced modelling time (Keibach & Shayesteh, 2022).

Integrating tools in modelling environments used by practitioners benefits their usability within the design process. SOLWEIG is an add-on to the open-source Quantum Geographic Information System (QGIS), integrated into the urban analysis platform Urban Multi-scale Environmental Predictor (UMEP). This allows urban designers to modify the urban morphology and simulate radiation exchanges without leaving the GIS environment (Aleksandrowicz et al., 2020). In SOLWEIG, building morphology is modelled based on 2.5 dimensional DEM and digital surface models (DSM), therefore large domains can be calculated (Lindberg et al., 2008). The simplified calculation process prioritises computational times over the accuracy and reliability of results (Aleksandrowicz et al., 2020).

Rayman is an open-source tool for evaluating outdoor thermal comfort. The building morphology is modelled 'free hand' in 2.5 dimensions by associating to relevant points of solids, e.g., corners, values of the z-coordinate (Matzarakis et al., 2007). Results depend on the SVF parameter (Naboni et al., 2017), therefore it can be used to simulate microclimate modifications in response to urban environment configurations with high precision (Georgatou & Kolokotsa, 2016). Computational times are limited, but a downside of the communication of results is that no graphical output is provided since calculations are performed at only one point at a time (Matzarakis et al., 2007).

A data visualisation strategy suitable for practitioners was a key goal in developing Ladybug tools (Roudsari & Pak, 2013), an environmental plug-in for Grasshopper[4], the visual scripting interface of Rhino[5]. Ladybug tools is a collection of open-source applications for environmental design; it relies on validated simulation engines such as EnergyPlus and Radiance, therefore it can simulate various climate and thermal comfort analysis tasks. Practitioners can benefit from convenient computational times and the integration within the 3D modelling software that avoids the remodelling task, yet visual scripting knowledge is required to set up simulations (Keibach & Shayesteh, 2022). Parametric tools such as Ladybug tools and Grasshopper assist practitioners early in the conceptual design process when several alternative solutions can be explored (El Dallal & Visser, 2017).

3.4. Review of pedestrian network analysis techniques

People moving through the city as slow travellers such as cyclists and pedestrians require comfortable sidewalks and routes; in fact, uncomfortable spatial networks could prevent them from moving toward the places of

[4] Created by Scott Davidson, it is a graphical algorithm editor for generating forms with no need for programming knowledge.
[5] Developed by McNeel and Associates, it is a 3D free-form modelling tool that allows designers to manipulate geometrical entities, as well as creating visual renders and animations.

interest, which could hinder the effort to ensure the availability of relief spots. Implementing climate-responsive solutions to ameliorate solar radiation exposure of pedestrian paths benefits diverse users:

- People who would walk for pleasure or health but avoid it because of uncomfortable thermal conditions;
- People who must walk as a means of transport and therefore are bound to be exposed to uncomfortable conditions during their trip.

There is an assessed tradition of spatial network analysis, which must be reviewed to understand how to implement climate-responsiveness in designing comfortable paths. In the following section, different approaches are presented, with the aim of highlighting the most suitable way to systematically add solar radiation exposure to pedestrian path analysis.

3.4.1. Methodologies for spatial network modelling and analysis

In their review of traditions for the physical form of cities, van Nes and Yamu (2021) reported three approaches; the analysis of morphological features, the description of a place based on the phenomenological theory, and the study of the urban network. The three approaches focus on different aspects of the urban environment; however, each tradition adds complementary information to describe the movement within a city. In particular, the first two approaches describe intrinsic spatial properties, i.e., form and meaning of a space, respectively. On the contrary, the urban network approach analyses the extrinsic properties of spaces; the morphology and character of a space are not of interest, and routes are abstracted as lines whose intersection creates a network.

3.4.1.1. The Space Syntax methodology

Space Syntax is a method for analysing spatial structures based on their extrinsic properties (van Nes & Yamu, 2021). Streets and spaces are abstracted as axial lines, i.e., linear elements describing the movement along a direction[6]. An axial map can be translated into a justified graph, which is an abstract representation of a network; in this specific case, streets are represented as nodes and intersections are connections between nodes. The justified graph is critical to explain the mathematical approach adopted by Space Syntax in calculating the relations between streets, specifically, integration and choice[7]. Integration represents the ease of access of each

[6] Complementary of the linear movement is the concept of visual sightline, i.e., a hypothetical line from the eyes to what is seen.
[7] Terms adopted in Space Syntax correspond to mathematical definitions. Integration measures the 'to-movement potential', also called 'closeness'; choice measures the 'through-movement potential', also called 'betweenness'.

street, calculated based on the number of direction changes ('turns') required to reach the destination; choice adds how likely a specific street segment would be selected by a user, according to the theory that people choose paths with minimal angle deviation to preserve linearity (Hillier & Iida, 2005). The distance between any pair of spatial elements is defined 'depth': it can be topological (number of turns), angular or metric (Euclidean).

The Space Syntax method can be applied via the software depthMapX, which can be used as a stand-alone platform or a plug-in for QGIS (UCL Space Syntax, n.d.). A similar approach was used to develop sDNA, a tool for 3D network analysis available both via its Python API (application programming interface) and as a plug-in for the GIS environment and AutoCAD (Cooper & Chiaradia, 2020). By adapting network analysis measures to include three-dimensional turns, vertical connections can be included in capturing pedestrian fluxes; an application was presented for a multilevel indoor and outdoor pedestrian network in Hong Kong (Zhang & Chiaradia, 2022).

3.4.1.2. The inclusion of features driving path choice

Building on the work about urban network analysis, Sevtsuk (2021a) adapted the measure of betweenness to pedestrian studies by implementing new parameters. Origins were weighted based on the number of users potentially travelling from them; similarly, destinations were weighted based on the attractiveness and distance from the origin, which were used also to distribute travellers among competing destinations. Trips were distinguished based on the purpose, e.g., from residential to office buildings. Additionally, the definition of search radii and a detour coefficient simulated observed behaviours like avoiding walking to excessively distant destinations and choosing paths only slightly longer than the shortest one, respectively. The modified betweenness index was tested in Cambridge (Sevtsuk, 2021a) and Melbourne (Sevtsuk et al., 2021) and it is accessible within the Urban Network Analysis (UNA) toolbox (Sevtsuk, 2021b).

A key contribution of the UNA toolbox is the inclusion of human behaviour's components in simulating path choice. Research has investigated drivers affecting pedestrians' behaviour for fine-tuning simulation tools and implementing the human component into navigation. Bongiorno et al. (2021) analysed a large dataset of GPS traces and suggested that not only the deviation from the shortest path increases with longer trips, but more interestingly, that swapping origin and destination leads to different route choices. Basu and Sevtsuk (2022) used GPS data to systematically quantify how diverse variables impacted the willingness to walk; the number of turns was estimated as reducing it, while positive effects were associated with the presence of amenities and vegetation. Understanding such distinctive features of human behaviour can inform computational models for simulating subjects navigating the space; Stieler et al. (2022) categorised the existing literature of modelling subjects into parametric, rule-based and generative, with the latter including agent-based modelling and simulation.

3.4.1.3. Urban morphology analysis

The study of pedestrian networks based on the surrounding morphological features has been extensively performed. Walkscore® is one of the most applied indexes built on this concept, even though this is available only for a few countries. It accounts for destination proximity, block length, and intersection density; studies demonstrated the loose connection of the index with walkability, reframing it as a measure of the 'walking potential' of an area (Hall & Ram, 2018). Walkability was the goal of the index developed by Stockton et al. (2016); in this research, residential density, street connectivity and land use mix were considered.

In the early 2000s, various audit tools were developed to rate and classify walking paths during fieldwork (Dragović et al., 2023). The definition of 'environmental audit instrument' is 'a tool used to inventory and assess physical environmental conditions associated with walking and bicycling' (Moudon & Lee, 2003). Auditors were asked to rate specific features for each path segment, based on the scoring system specifically developed; extensive information and accurate scoring rules were provided as a countermeasure to the subjectivity of auditors. Their observations were collected into a checklist, that was later processed to score walkability on each segment. Items observed were usually grouped into categories and assigned priorities to emphasise selected features.

3.4.2. Shading analysis of pedestrian paths

Among the variables listed in the audit tools, the presence of trees and shading elements is of interest to this research. In some tools, the presence of trees was inserted in the aesthetics category (Evenson et al., 2009; Pikora et al., 2002); Dixon (1996) had already recognised the critical role of shading trees for a positive performance of sidewalks, labelling it as 'amenities', yet the assigned weight was lower than the pedestrian facility features such as width and continuity. Other audit tools explicitly addressed comfort, checking that trees would shade the pedestrian path (Boarnet et al., 2006; Clifton et al., 2007; Dannenberg et al., 2005; Millstein et al., 2013). However, audit tools capture environmental conditions at a specific instant; this is a limit for analysing shading because it does not record its high variability in time unless the analysis is repeated at various times. Dannenberg et al. (2005) recommended accounting for different times of the day in the shading assessment, nevertheless, a more systematic indication is missing in the revised audit tools.

More recent research used advances in technology to fine-tune the shading analysis. Taleai and Taheri Amiri (2017) implemented the vegetation criteria by mapping the Normalized Difference Vegetation Index (NDVI). Additionally, a 3D modelling technique was adopted to perform an accurate shading analysis on the selected pathway, a technique later used also by Perez (2020). The trade-off of three-dimensional modelling and analysis is the limited scale at which this approach can be applied, or the extensive resources needed to model and run the analysis at the urban scale. Several authors used algorithms that were implemented into the GIS environment; data about buildings (Al Shammas & Escobar, 2019) and trees (Serra-Coch et al., 2018) were downloaded from databases of public authorities. The GIS environment allows the elevating of the horizontal footprint of features based on their height attribute, producing a 2.5D map; this technique is less accurate than the three-dimensional modelling of the urban morphology but allows the analysis of a whole city with suitable resolution. Furthermore, a digital model enables the simulation of numerous scenarios, in contrast with specific time frames analysis with audit tools. In the absence of digital data about urban morphology, Google Street View panoramas can be used to model street canyons, as performed by Li et al. (2022) with the sun's position estimated based on location and time of day.

3.5. First methodological considerations about implementing solar radiation exposure into pedestrian path analysis

The extrinsic approach to urban network analysis provides information about the potential footfall of pedestrian paths based on the structural layout of the network; on the other hand, the intrinsic approach is focused on the properties of the space, inferring a potential footfall based on the positive and negative aspects of the paths. Solar radiation exposure can be described as a morphological feature; the presence of shade or sun exposure shapes spatial patterns, even though variable in time, and microclimatic conditions affect the physiology and the psychological perception of a space. Therefore, the microclimate component of interest is here described as an intrinsic property, similar to urban form and attraction points.

A link between the two approaches was tested by Aleksandrowicz et al. (2020), who superimposed their shade index and the integration analysis of Space Syntax to prioritise shading installations; their use of spatial network analysis was directed towards rating the space based on the expected footfall, but path selection as a consequence of shading was not simulated. The UNA toolbox also expands the network analysis with additional layers of information impacting path choice or pedestrians' experience; however, no morphological features were considered in simulating pedestrian fluxes. On the other hand, digital and observational audit tools classify path segments based on people's preferences, but the complex boundary conditions affecting pedestrians' experience might hinder a hypothesised relationship between the scoring system and recorded presence. In fact, investigating how microclimatic conditions of a pedestrian network impact path choice is a research branch of great potential, yet the competition between thermal comfort and other interests driving path selection (e.g., destination availability or safety) would require extensive observational work, and it is not in agreement with the scope of this research.

In fact, this research is oriented towards its applicability in urban design; accordingly, pedestrian paths are considered as an infrastructure at the service of people, and their suitability for walking should be a priority regardless of the footfall expected or recorded. Even though realistically, it is not possible to achieve such a comfortable condition always and everywhere, a great effort should be made to optimise the usability of pedestrian paths, even in thermal stress conditions. For this reason, the adopted approach focuses on proposing solutions in addition to performing analysis; the goal of implementing microclimate analysis is the assessment of thermal comfort on walking paths, followed by the proposal of suitable design solutions to improve their usability.

3.5.1. Modelling tools selected to apply the methodology

In this research, microclimate was modelled using Ladybug tools, which were considered suitable for importing meteorological data and simulating their spatial distribution at the neighbourhood scale. The availability of weather data from web portals (e.g., EnergyPlus) and the use of a standard format to share data (*.epw*) was an advantage in terms of applying the methodology to different contexts. Limited simulation times were accounted for in selecting Ladybug tools over ENVI-met and other tools.

Based on the review in Section 3.3 and 3.4, an accurate 3D modelling tool was considered a priority to obtain detailed and reliable results, focusing on urban elements that could be modified by designers. Therefore, Rhino was selected to model the urban morphology over 2.5D and grid-based modelling tools; the numerous open-source plugins and the interoperability with software used by urban designers (e.g., CAD and GIS tools) contributed to this choice. Furthermore, parametric modelling was explored through Grasshopper, investigating the opportunity to automatise modelling processes to perform multiple simulations.

As regards the pedestrian network, the goal was to ensure detailed modelling of areas where pedestrians would walk. The choice of using Rhino enabled modelling walkable surfaces in 3D, with significant advantages in solar radiation simulations. In fact, because of the strictly directional nature of sun rays, an accurate tracing of pedestrian paths was critical; accordingly, segments of the pedestrian network were precisely drawn simulating where people would potentially walk.

3.6. Evaluating the methodological approach through a feasibility study

A first prototype of the methodology was developed based on the methodological considerations drawn in Section 3.5. The term 'prototype' is used in relation to an iterative process, where a proposal is fine-tuned through multiple applications and subsequent evaluations. The goal was to perform a first experiment on a limited area and then critically evaluate potential issues in applying it to a larger scale. This preliminary application was presented at the PLEA – Passive and Low Energy Architecture conference (Santiago de Chile, 22-25 November 2022).

The presentation was titled 'Walkability and solar radiation exposure for diverse users: climate-responsive urban design to enhance accessibility to outdoor spaces' (Tomasi et al., 2022). It simulated the experience of two pedestrians crossing a master plan area; the users were walking to the same destination but through different routes. In this section, part of the corresponding conference paper is presented.

3.6.1. Case study area

The case study area selected for applying the methodology was the Parco Romana master plan (*Scalo di Porta Romana*, 2021) in Milan (Italy), a project involving the industry partner CRA—Carlo Ratti Associati (2021a). The presented design proposal was a preliminary submission for the Municipality of Milan; changes were possible because of the ongoing authorisation process. The case study master plan is part of a railway yard's redevelopment (Figure 3.2). The area under consideration is the eastern part of the master plan and it will mainly host offices. Buildings are located around an elevated square, above the railway line; access to the square is by stairs, elevators and ramps. Various trees are located in the central part of the square, as part of an urban forest in the east-west direction (the so-called 'Suspended Forest'). In the north, a restaurant faces the square; the southern part gives access to office buildings. Even though the buildings' function would call for a defined typology of user - office workers, the presence of a metro station to the north and buildings of broad interest to the south (e.g.: Fondazione Prada) led to the inclusion of a more varied catchment. In particular, the designers proposed to create new connections in the north-south direction. Analysis of the solar exposure of the user paths would thus provide valuable information to implement in the design phase.

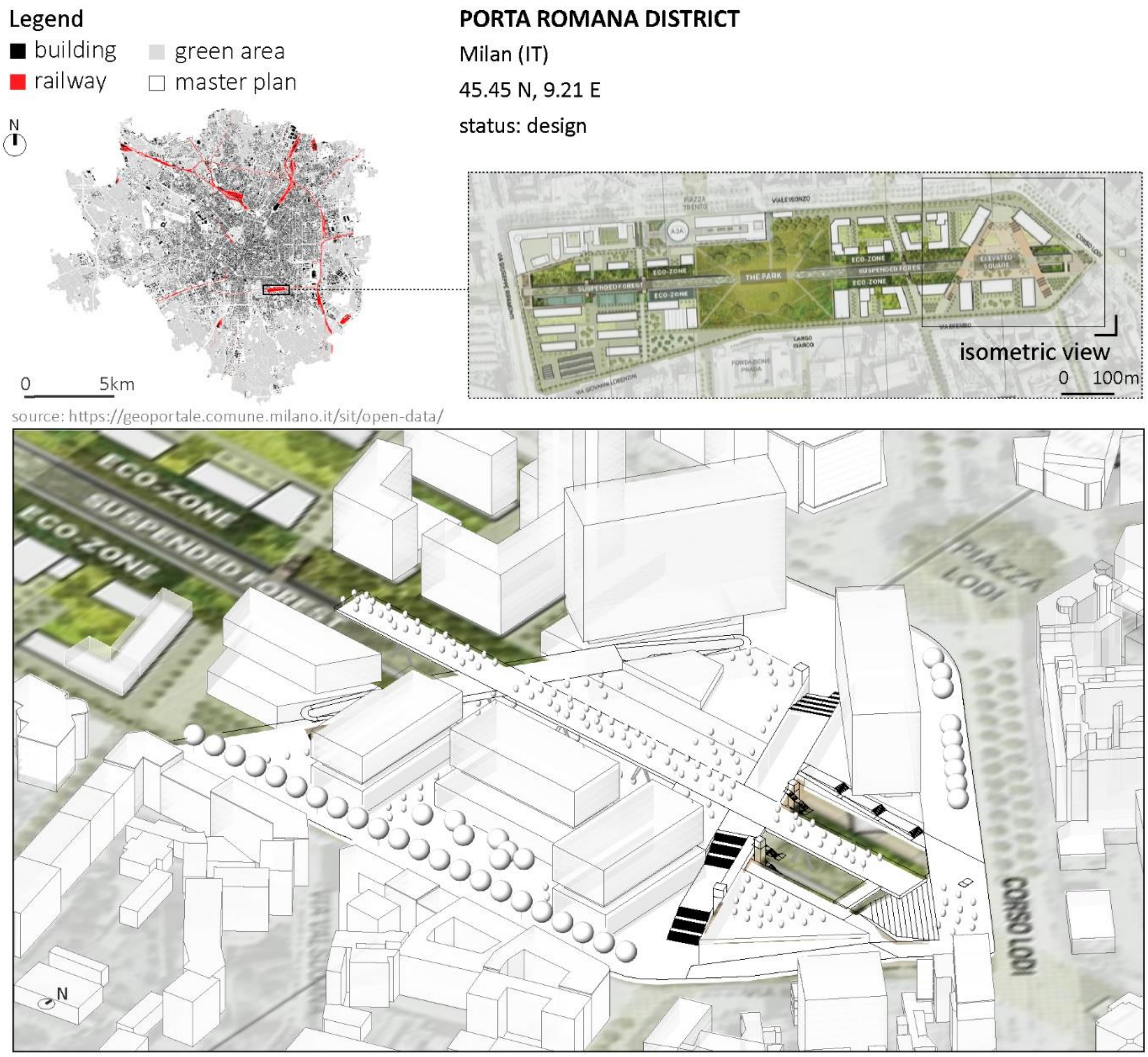


Figure 3.2 Introduction to the case study master plan.

3.6.2. Methodology

3.6.2.1. Modelling the case study

The selected case study was modelled using Rhino. This software allowed the testing of design options without the need to import the model into a different simulation software, and to simulate solar radiation with relatively short computational time compared with other tools. User paths drawn in Rhino corresponded to the main connections around and crossing the area and secondary paths to reach hot spots. The hot spots were defined as attraction points for pedestrians: shops, restaurants, public transport stops, and other places equipped for sitting and gathering.

The incident radiation component in Ladybug is the sum of diffuse and direct radiation reaching the surfaces. The summer and winter solstice days were simulated to represent the extreme conditions in terms of shading. Three time periods were simulated throughout the day: 11:01 am - 12:00 pm, 2:01-3:00 pm and 5:01-6:00 pm (hereinafter referred to as 11 am, 2 pm and 5 pm). To prioritize people's activities at specific times, the summer times were determined by taking into account daylight saving hours. The geometry on which solar radiation exposure was simulated corresponded to the public outdoor space, including ramps and stairs. The surrounding buildings and shading elements such as trees and artificial devices were defined as elements sheltering the space from solar radiation.

The first phase of the analysis included a collection of maps in which solar radiation exposure of user paths was indicated. The linear paths were divided into points drawn every two metres, i.e. the same grid size of solar radiation maps. The value of solar radiation for each point corresponded to the one assigned to the closest pixel of the map. In this way, solar radiation exposure of user paths in different hours was obtained.

3.6.2.2. Measuring space with time

In the second phase, the user experience was further developed to include the concept of time into the design. It proceeded to evaluate how much time a pedestrian spends under the sun when taking these paths. First, walking speeds needed to be defined. In order to make the design more inclusive, pedestrians with different physical abilities of varying walking speeds were considered. These included standard pedestrians and pedestrians using assisting devices (such as cane, crutch, or walker) and walking speeds were determined from literature. Bosina and Weidmann (2017) conducted an exhaustive review of pedestrian speeds, while Oxley et al. (2004) focused on pedestrians with different levels of physical ability, distinguished among assisting devices. The walking speeds employed in this work are shown in Table 3.1. For stairs, horizontal walking speeds were adapted from Fujiyama and Tyler (2010), from graphs relating horizontal walking speeds to stair gradients, for young and elderly users. The average value was selected for ascending and descending movements.

Table 3.1 Walking speeds for users of different physical abilities

User	Speed (m/s)	Speed (m/minute)	Adapted from
standard	1.34	80	(Bosina & Weidmann, 2017)
assisting device	0.70	42	(Oxley et al., 2004)

By measuring space not metrically, but through the time needed by a pedestrian to cover a defined distance, it was possible to further analyse and modify the design proposal. User paths were measured according to the walking speeds: the amount of time a pedestrian spends in uncomfortable, or even harmful, microclimatic conditions was identified. Based on this analysis, areas where further intervention was needed to improve the microclimate were highlighted and provided the focal point of the final phase.

3.6.2.3. Climate-responsive solutions

The microclimatic evaluation of user paths was followed by the design phase, in which the arrangement of shading devices was defined to improve the user experience. Four shading solutions were modelled: two trees and two artificial devices (Figure 3.3). Trees were modelled according to the report "Public space - Design guidelines", attached to the Air and Climate Plan developed by the Municipality of Milan (Municipality of Milan & Agenzia Mobilità Ambiente e Territorio (AMAT), 2021). Two sizes of trees were selected (III and IV, according to Municipality of Milan and AMAT (2021)) to represent deciduous species planted in the surroundings that suit the master plan. Tree canopies were modelled as meshes; the script was based on an example provided by Roudsari (2016). The canopy density was differentiated according to the season, based on images analysis (winter 33%, summer 100%). The artificial shading devices were the stand-alone canopy 'Parelio' (CRA - Carlo Ratti Associati, 2021b) and a large textile cover. The large cover was divided into a grid and its density was set up to 80% to simulate partial transparency of the textile material. Simulating the screening effect of devices in the master plan enabled the proposal to be adjusted accordingly. This climate-responsive methodology addressed issues highlighted by implementing the microclimatic analysis in the master planning process. Moreover, the use of removable devices created dynamic outdoor spaces that could provide outdoor comfort in different seasons.

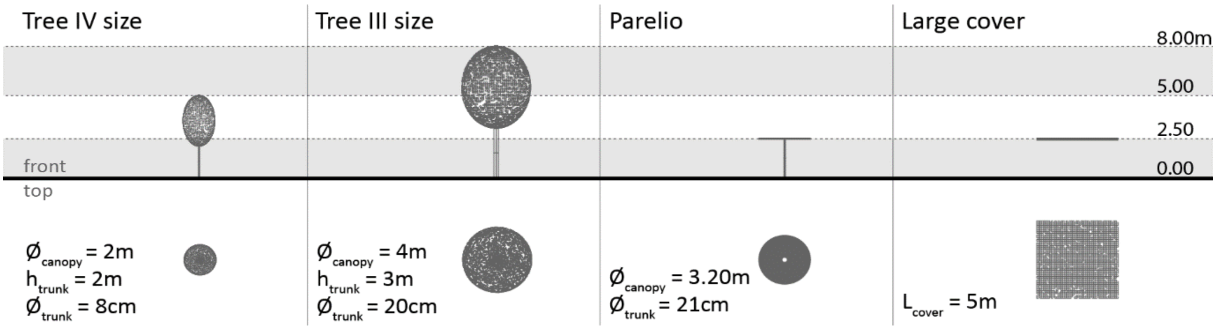


Figure 3.3 Description of shading devices implemented into the master plan design.

3.6.3. Results

3.6.3.1. Solar exposure of the master plan

First, the master plan was analysed to identify user paths. Specific hot spots were highlighted, such as the restaurant and the metro station, while gathering points also emerged. Access points to the elevated square were identified (Figure 3.4).

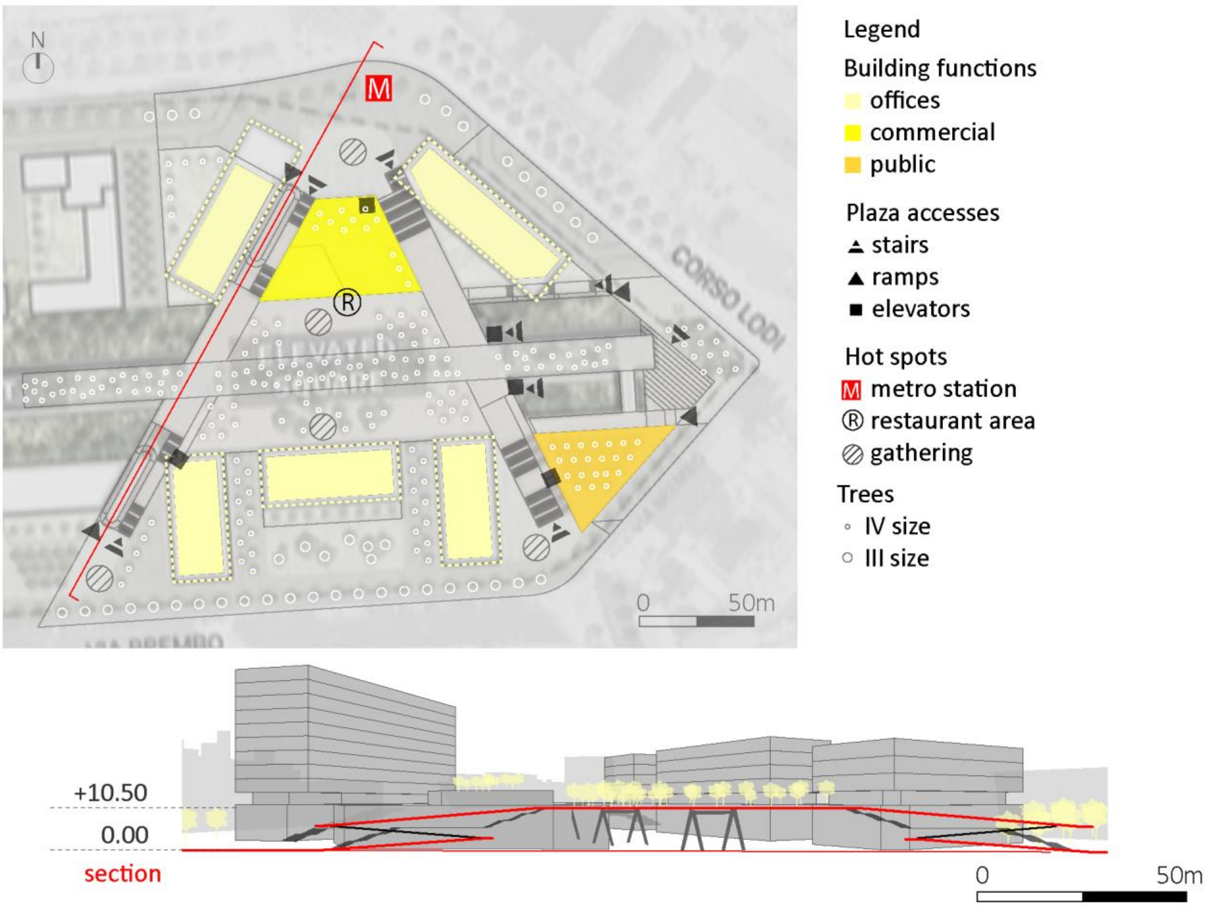


Figure 3.4 Functional analysis of the master plan.

Input weather data to simulate solar radiation were downloaded from the EnergyPlus (n.d.) website – station: Milano-Linate 160800 (IGDG)[8]. Direct and diffuse solar radiation from the input weather file are displayed in Figure 3.5 for both solstice days[9].

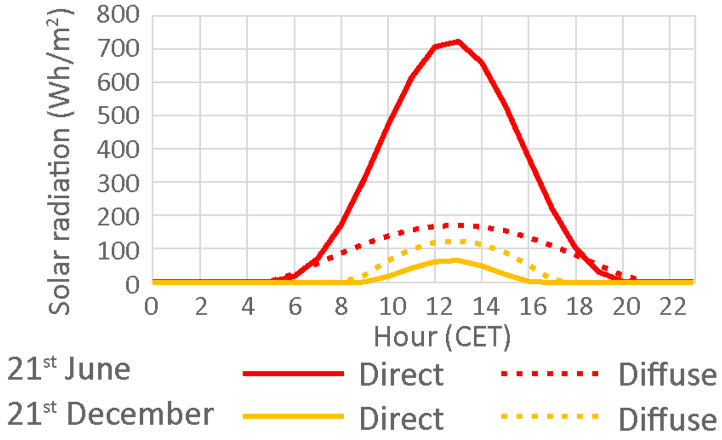


Figure 3.5 Direct and diffuse components of solar radiation on horizontal surface on summer and winter solstice days.

Figure 3.6 reports solar radiation exposure maps simulated during the two selected days. In winter, the simulation of the 5 pm time period is not displayed as the results were not meaningful. The most immediate information provided by the maps was the screening effect of buildings on the ground. Since the solstice days were selected, the displayed shapes corresponded to the maximum and minimum extent that shadows can reach. Trees were also shading the ground; nevertheless, since their reduced height (from 5 to 8 m, due to design constraints such as the reduced soil depth in the elevated square), their impact was limited. The rooftop of the restaurant and the northern plaza had a large potential as gathering spots since they were largely sunny in winter. Installing temporary devices to provide shade in the summer could make them valuable spots during the hottest days, adapting the space in response to seasonal changes. Overall, gathering spots were evaluated as consistent in terms of thermal diversity and solar radiation exposure. On the other hand, walking paths needed further investigation.

[8] The weather data show a typical year.

[9] It should be noted that *.epw* files report radiation data as energy (measured in Wh/m^2), not power. Since radiation is reported as cumulative over an hour, the provided values can be reasonable considered as irradiance (W/m^2): as such, this conversion will be used in the following calculations. As per Ladybug components formulation, during computation processes, variables in a specific hour are associated with solar radiation collected during the 60 minutes after the selected time.

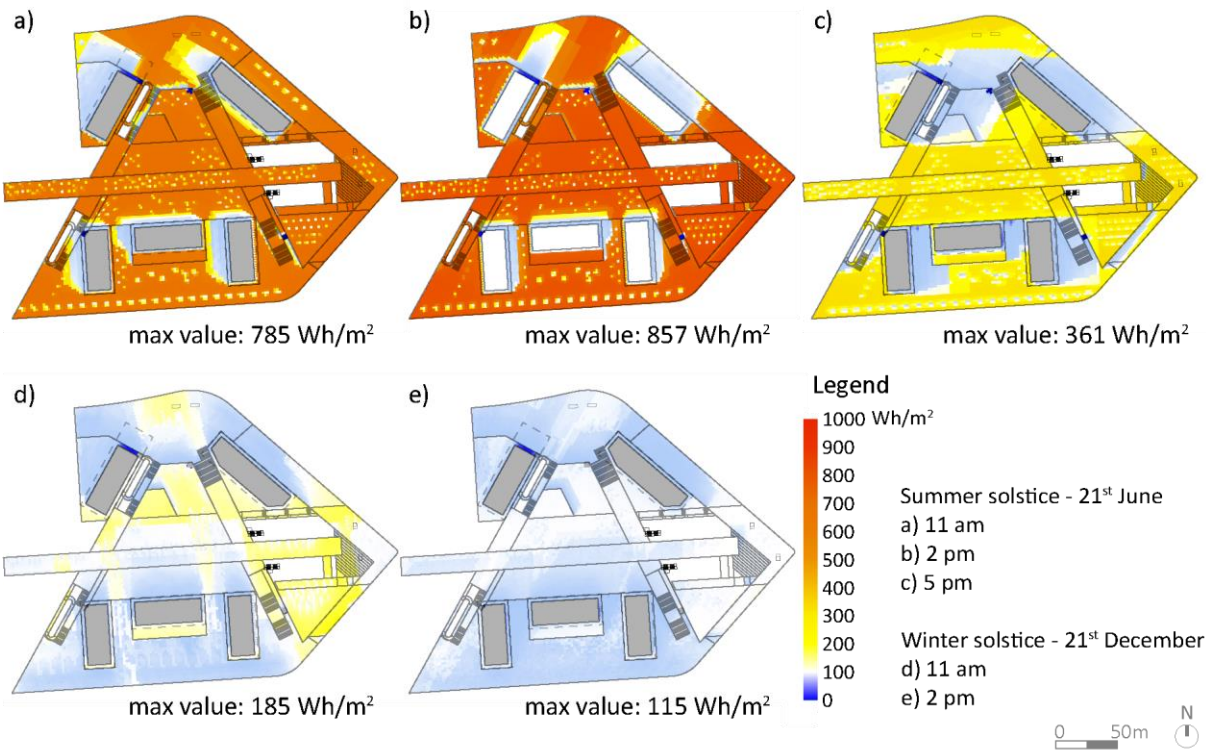


Figure 3.6 Simulation of total solar radiation on outdoor surfaces at different times of the day on the two solstice days.

3.6.3.2. User experience

Focusing on the walking areas, these were mostly exposed to the sun in the summer. Considering the physiological thermal load from the solar exposure combined with the higher metabolic rate from walking, it was important to address this. Figure 3.7 presents this issue for two paths. The map refers to 11 am CEST on 21st June, focusing on the walking paths. Two different walking speeds were assessed, for a standard pedestrian and one with an assisting device. The simulated paths corresponded to origin-destination travels in the south-north direction through different access points (stairs and ramps). Horizontal walking speeds were calculated for the inclination of the stairs (26.6°), with the results presented in Table 3.2.

Figure 3.7 Solar radiation exposure of paths (experiences) taken by two diverse users.

Table 3.2 Horizontal walking speeds on stairs – stair gradient: 26.6°.

Movement	Speed (m/s)	Speed (m/minute)	Adapted from
ascending	0.57	34	(Fujiyama & Tyler, 2010)
descending	0.65	39	(Fujiyama & Tyler, 2010)

In the case of a pedestrian with an assisting device, it was clear that users could access the elevated square through elevators. Nevertheless, the aim was to explore the experience provided by the space if users preferred to spend time outdoors.

The user experience was further analysed using a chart (Figure 3.8). Such analysis has the advantage to represent in a meaningful way the experience provided in the proposed space by relating the numerical results with the paths.

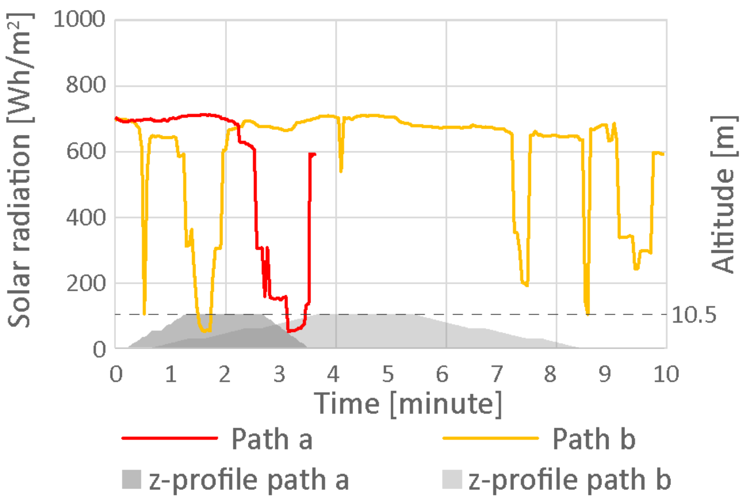


Figure 3.8 Solar radiation exposure of two user experiences in time.

As reported in Table 3.3, the first path was estimated to take 3’34” for a standard pedestrian. Except for the final stairs, the journey resulted in exposure to the sun. The second path was estimated to take 10 minutes for a pedestrian with an assisting device. The graph showed more variety in solar radiation exposure than the previous one; a few spots in the shade on the ramp were provided by the ramp on the upper level. Furthermore, five minutes were spent under the sun without any relief (from minutes 2 to 7).

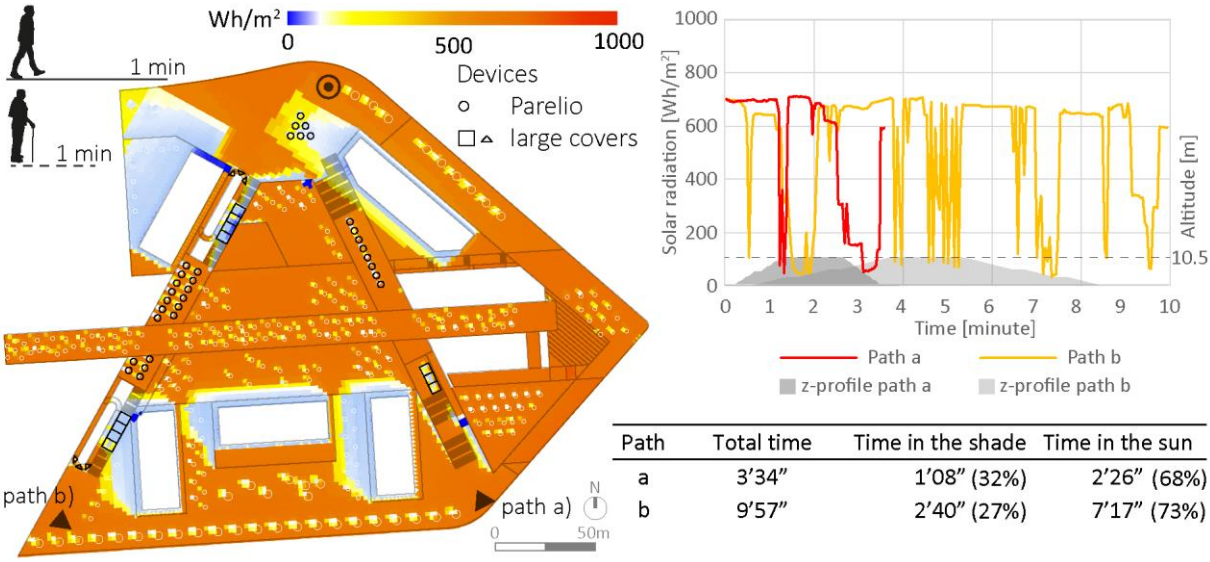
Table 3.3 Time spent in sun/shade.

Path	Total time	Time in the shade	Time in the sun
a	3’34”	58” (27%)	2’36” (73%)
b	9’57”	1’43” (17%)	8’14” (83%)

3.6.3.3. Design proposal

The main aim of the design proposal was to provide users with shaded spots along walking paths in the summertime. In winter, the exposure of walking paths to solar radiation was considered sufficient; this characteristic needed to be maintained. For that, a non-permanent strategy was adopted, installing Parelio devices and large covers along the paths, ensuring they provided shade on pedestrians most of the time. Using large covers could shade landing areas on the elevated square and along the ramps, to enable people to rest from the physical effort. Due to the absence of soil outside the planted areas, they could provide additional shade in spots where trees could not be planted; furthermore, their complete removal in winter would maintain solar radiation exposure. Artificial devices could also become a dynamic component of the space, maintaining sufficient distance from planted areas (such as the Suspended Forest, a signature space of the project), but creating dialogue with nature. Walking paths across the elevated square were screened using Parelio devices. Their location could not become an obstacle for pedestrians: several simulations were performed to optimize the results.

Figure 3.9 presents the final proposal in summertime, with the additional devices shown in black. The graph shows additional shaded spots along walking paths. The table reports the updated time periods: in both cases, time spent in the shade increased. Path (a) shows a shaded landing after climbing the stairs. Even though the time in the shade did not increase much (10”), the graph shows a relief spot in between climbing the stairs and crossing the elevated square. Path (b) presents more thermal variety than before, due to the installation of triangular-shaped covers along the ramps and Parelio devices across the square. Time spent in the shade increased by +55%, and most importantly, shaded spots were distributed along the journey.



Path	Total time	Time in the shade	Time in the sun
a	3’34”	1’08” (32%)	2’26” (68%)
b	9’57”	2’40” (27%)	7’17” (73%)

Figure 3.9 Design proposal to improve solar radiation protection to user paths in summertime.

3.7. Contribution of the feasibility study in developing the methodology

The preliminary research work presented at the PLEA 2022 conference combined all elements of the climate-responsive system illustrated in Figure 3.1 (solar radiation, shading devices, users, and pedestrian paths). This application on a selected outdoor space was the opportunity to adjust the first considerations presented in Section 3.5 and develop the final methodology at the neighbourhood scale.

3.7.1. Assessment of the proposed methodology

The microclimatic analysis confirmed the focus on solar radiation because of the variability of exposure in outdoor spaces (Figure 3.6), and the opportunity by designers to address excessive exposure through the design and test of shading devices (Figure 3.9). However, the simulation of solar radiation exposure on walking paths highlighted the predominant role of the direct over the diffuse component on 21 June; this is particularly valid in clear sky summer days when shading is most needed. Therefore, a binary rule of shading or no shading was introduced, simplifying the microclimatic analysis by focusing on the predominant component of interest. The sun position was retrieved via Ladybug, and the exposure of urban surfaces was calculated with the available raytracing method.

The introduction of a new approach to model solar radiation exposure led to modifying the urban morphology modelling technique accordingly. The diversified density of trees and artificial canopies clashed with the selected binary rule because it introduced fractions of sun exposure as opposed to integer results. Furthermore, the results of the available raytracing method to model sun rays would be biased by volumes not full; for instance, if a sun ray passed through one of the few holes in a high-density surface, the results would return the surface underneath as totally exposed. Therefore, shading devices were assimilated to whole shapes, removing the parameter 'density' from the Grasshopper code. This assumption impacts results in winter since tree canopies make sun rays partially pass through; nonetheless, since the design goal in winter is maximising sun exposure, this assumption would underestimate a positive contribution, and the output would not be impacted negatively.

The modelling approach for urban morphology was confirmed as effective, and the capabilities of Rhino and Grasshopper to model in 3D the buildings and the ground were considered a solid advantage for urban designers. Similarly, the use of Ladybug tools was positively evaluated because of the integration with Rhino, the limited calculation time, and the elevated quality of the graphic output. In the results developed within the framework of the journal papers, the simulation hours were shifted one hour earlier to better represent times when people would be outside (e.g., instead of 2 pm, 1 pm was simulated as it is commonly lunchtime in Italy).

The simulation of solar radiation on large surfaces was not considered effective in analysing pedestrian paths; instead, the representation of paths as lines coloured based on the exposure to solar radiation was deemed useful to evaluate the experience of the users. Therefore, the final methodology modelled pedestrian paths as linear segments, tracing accurately where the pedestrians would pass. Furthermore, the pilot study of two user experiences was extended to potential paths that could be traced in a neighbourhood, including in this way also turns and connections between path segments. A complete network was thus systematically built, and solar radiation exposure was simulated only along the modelled pedestrian paths.

The definition of walking speeds was considered a useful supporting element to apply in practice the conceptual shift of analysing a space based on the user experience. Measuring space not metrically but through the time needed to cover a certain distance, provided useful information in line with the aim of considering the user as a starting point, focusing on the smaller scale. The difference between ascending and descending speeds on stairs was deemed as limited, therefore a median value from the literature review was adopted in the final methodology; this new speed had the additional advantage of avoiding the association with a specific stair gradient.

As regards users, previous literature was reviewed to characterise user profiles of interest. This approach employs a considerable amount of survey-based and monitoring research performed by experts in physiology and medicine. Besides fitting best into the scope of this research, modelling based on specialised literature simulates a typical activity of professionals who are interested in combining different disciplines, demonstrating the critical advantages of adopting a cross-discipline approach. The focus on users of different physical abilities was a first step to model and simulate diverse user experiences; this feasibility study led to pushing forward this purpose. Even though the walking speed provides interesting information about the different experiences of the two users, the juxtaposition of the solar radiation exposure curves in Figures 3.8 and 3.9 triggered a research question about the different impacts of solar radiation on the two pedestrians. This led to further study of specialised literature, replicating the method used to identify walking speeds. Finally, the pedestrians were characterised not only based on walking speed but also on their physiology.

3.7.2. Definition of research areas for journal papers

In addition to representing an opportunity to preliminary test the proposed methodology, the feasibility study contributed to this research by identifying three research areas to expand on in the journal papers, presented in the following chapters.

The first research area is the characterisation of the pedestrians. Walking speed is a specific characteristic that affects the user experience of a pedestrian, yet the impact of solar radiation on people of diverse physiological characteristics can increase the experienced difference. Chapter 4 presents a methodology to quantify the effect of solar radiation exposure on diverse users, associating the thermal stress from being in the sun with performing physical activity. This analogy is used to define a maximum threshold of sun exposure before feeling exhausted, expressed as a percentage of a walking trip, and based on the user’s physiology and the climatic conditions.

The second research area of interest concerns an upscaling process, moving from the pedestrians to the context in which they travel. Modelling a variety of elements requires specific approaches; at the same time, the final models must mutually communicate to ensure a productive integration of disciplines. Chapter 5 presents the adopted methodology to model a pedestrian network and its exposure to solar radiation; this fills the gap in the feasibility study in systematically modelling the pedestrian paths as a network. The digital model is then used to simulate diverse user experiences, transforming the theoretical amount of exposure defined in Chapter 4 into a contextualised travelling activity in an urban environment.

The last research area embodies the solution-oriented approach of the SOLOCLIM project. In Chapter 6, starting from the shading devices modelled for the feasibility study, a range of solutions is proposed. Furthermore, a digital design tool to position these devices for effectively shading pedestrian paths is developed. The experience at CRA – Carlo Ratti Associati, combined with the feedback collected during public events and informal one-to-one meetings, led to defining a range of applicative processes to adapt the implementation of the proposed workflow to the resources available for professionals and the level of detail required at the design stage.

Chapters 4, 5 and 6 feature the three papers published in peer-reviewed journals. Each paper covers one of the illustrated research areas. Some key points are the common thread linking the three publications:

- the proposed methodological steps were tested in the case study city of Milan, where the industry partner CRA – Carlo Ratti Associati was developing the Parco Romana master plan project (Section 3.6.1) during the time spent at their facilities;
- the selection of hours, dates and user profiles was constant to ensure consistency of results;
- the proposed methodological steps were applied through Rhino and the relevant plugins.

3.8. Conclusions

Having reviewed the vast theme of urban microclimate, and its impact on people, this research focused on one specific issue that can be tackled by practitioners. The addressed climate-responsive system comprises solar radiation, urban morphology, and users. Solar radiation exposure was selected because of its critical impact on outdoor thermal stress. The interaction of sun rays with urban morphology allows urban designers to modify solar radiation exposure of people and surfaces, making their design effort significant. The division of outdoor users into people staying in one place and walking (Section 2.6.2) directed the research towards addressing pedestrian paths. In fact, comfortable pedestrian networks bring several benefits such as preserving the healthy activity of walking, protecting travellers, and ensuring pleasant access to relief spots.

To propose effective installations of shading devices, professionals need tools developed prioritising usability, in terms of computational time, modelling process, and communication of results. The tools and methods available to analyse and model microclimate and pedestrian paths were reviewed, and suitable approaches were selected. The methodology developed is based on modelling, which is adapted to the component of the climate-responsive system to analyse. Solar radiation exposure, initially modelled as incident radiation (direct and diffuse components), is distinguished in two cases, i.e., ‘shade’ and ‘no shade’, and simulated through a raytracing method. Urban morphology is modelled in 3D to ensure accurate simulation of shade, particularly under shading devices. Pedestrian paths are modelled as curves and combined to form a network, which can be used to simulate walking trips from origin to destination. Finally, users are modelled based on information retrieved from specialised literature, ascribing suitable values to the relevant user profiles.

A preliminary test of the methodology was performed as a feasibility study, which was presented at an international conference. According to the ‘thesis-by-publication’ approach, the next three chapters present three distinct papers published in peer-reviewed journals. Each journal paper investigates one research area that was highlighted following the preliminary study. To ensure consistency and facilitate the cross-comparison between papers, some elements are maintained, e.g., tools and case study area.

4. DEFINITION OF A MAXIMUM THRESHOLD OF DIRECT SOLAR RADIATION EXPOSURE FOR PEDESTRIANS OF DIVERSE WALKING ABILITIES

4.1. Research area outline

The fact that people of diverse characteristics experience differently the same environmental context is intuitive. This has critical implications in urban design practice and therefore professionals must adopt an inclusive approach. In the feasibility study (Section 3.6), a first step to foster inclusivity in designing walking paths was performed by assigning different walking speeds to pedestrians. In the application phase, in addition to a standard pedestrian, a user with an assisting device was simulated crossing the master plan area. The graphic approach adopted to illustrate the time spent under the sun by the users during their journey revealed issues in the exposure of sidewalks to the sun. These could be addressed through design, e.g., by modifying the proposed arrangements of the sidewalks or installing shading devices. On the other hand, a key information that cannot be modified by changing the environmental context is the intensity of irradiation, which impacts people differently based on their physiology. It should be noted that the two pedestrians simulated in the feasibility study would likely differ not only in terms of walking speed but also physiological characteristics due to the different ages and physical conditions. Comparing how these two human bodies would cope with the increasing heat absorbed should therefore be addressed.

This paper investigates the impact of solar radiation on people from a physiological point of view. The approach adopted to formulate the methodology presented was prompted by the need to transfer theoretical knowledge into practice. This resulted in adopting some assumptions to streamline the process, as well as selecting tools based on their usability and integration with the urban designers' workflow. After characterising the two users of diverse walking abilities from the physical and physiological point of view, the collected knowledge was used to define a maximum threshold of direct solar radiation exposure for pedestrians, after which they would feel exhausted. Based on this, the maximum time a pedestrian would be recommended to spend in the sun was calculated for clear sky hours in summer in the city of Milan. Additionally, the impact of shading pedestrian paths was directly linked to the reduction of fatigue in pedestrians, connecting shading solutions with quantifiable results.

4.2. Introduction

Solar radiation is a critical variable in outdoor thermal comfort because it affects the heat balance of the body (Blazejczyk et al., 1993; Hodder & Parsons, 2007; Kenny et al., 2008): this is relevant when promoting outdoor activities, especially in the warm season. The 15-minute city concept argues for comfortable and safe walking environments (Abdelfattah et al., 2022); because of world population growth and urbanisation trends (UN DESA, 2019), the number of people that would benefit from comfortable urban pedestrian paths is increasing. Santucci et al. (2020) defined walkability as the combination of health, safety, and vitality; the walking activity is strictly dependent on the quality of the public realm. In their review of definitions of walkable spaces, Forsyth (2015) cited climate as a factor influencing walking activity. Labdaoui et al. (2021a) proposed a comfort walkability index as the combination of a questionnaire survey about pedestrian facilities and thermal comfort calculations. Climate walks have coupled the collection of microclimatic data at street level with surveys about the subjective perception of people, highlighting the impact of variations in dense urban morphology on thermal pleasantness (Santucci et al., 2020; Vasilikou & Nikolopoulou, 2020). Literature has also presented associations of thermal stress with increasing perceived travel time (Rakha, 2015) and walking speed (Bosina & Weidmann, 2017; Mouada et al., 2019).

Population ageing has been considered a world demographic megatrend (UN DESA, 2019). Elderly people are considered among the most vulnerable users in cities, especially during hot summer days (Dodman et al., 2022). In developing their Walkability Index for Elderly Health, Alves et al. (2020) reported that an elderly person should perform moderately intense physical activity, such as walking, for about 30 minutes per day. Physical activity indirectly reduces health risks due to heat stress since it improves cardiovascular capacity (Dodman et al., 2022). The main physical activity for the elderly is walking. However, mobility declines with age as well: this can be a barrier in case of uncomfortable microclimatic conditions because it would impede moving in search of restoration (Kabisch et al., 2017). Furthermore, lower walking speeds reduce the number of accessible facilities within the beforementioned 15-minute radius.

Shading pedestrian paths based on their orientation and sky exposure is beneficial for pedestrians during hot clear sky conditions. Exposure to solar radiation can be addressed by modifying the urban morphology, through temporary or permanent solutions. Therefore, professionals involved in urban design and planning need to integrate the evaluation of direct solar radiation into their decision-making process.

This paper focuses on a framework to effectively evaluate the impact of direct solar radiation (DSR) on pedestrians of diverse walking abilities. It hypothesises that a maximum threshold of exposure to DSR could be related to activity, user profile and environmental conditions. Initially, the impact of incoming direct short-wave radiation on heat balance is isolated and the net thermal contribution is compared with the metabolic activity of two users, a young adult and an elderly person with mobility impairment. This proposed theoretical framework is applied to a case study in Milan, with the results presented on a DSR exposure graph, which is a simplified way to evaluate shading needs in different applications.

4.3. Theoretical framework and methodology

The rate of DSR absorbed by the human body and its contribution to thermal stress are outlined. By comparing simulated thermal stress conditions to the definition of neutral state, the required adaptation budget is defined. Finally, this is compared to the exhaustion threshold of each pedestrian, exclusive of the energy consumed to walk at the appropriate speed.

4.3.1. Direct solar radiation contribution to thermal comfort

The thermal interaction of the human body with the surrounding environment is described in the following equation (ASHRAE, 2005):

$$M - W = q_{sk} + q_{res} + S \qquad \text{(Eq. 4.1)}$$

where M = rate of metabolic heat production (W/m^2)

W = rate of mechanical work accomplished (W/m^2)

q_{sk} = total rate of heat loss from skin (W/m^2)

q_{res} = total rate of heat loss through respiration (W/m^2)

S = total rate of heat storage (W/m^2)

On the left side of Equation 4.1, M is the total metabolic rate within the body (sum of M_{act} and M_{Shiv} for activity and shivering respectively) while W is the energy that might be expended as external work. Since this paper is focused on warm/hot microclimatic conditions, M_{shiv} will be considered null. The external work will also be ignored because the ratio W/M is usually less than 0.10, and null in case of walking on a flat surface (ASHRAE, 2005; Jendritzky, 1990). The right side of the equation describes how the net heat production (M-W) is transferred to the environment through the skin surface and respiration. S is any surplus or deficit of energy stored, which causes the body's temperature rising or decreasing; nevertheless, it will be ignored because of the limited thermal storage capacity of the body (Alahmer et al., 2012). Therefore, for the purpose of this research, the metabolic rate derived from muscular activity is defined as the sum of the heat transferred through the skin and respiratory tract via convection, radiation, and evaporation.

Exposure to DSR impacts the energy balance of a pedestrian; its contribution can be isolated and will be hereinafter referred to as R^*. When exposed to DSR, a body absorbs a fraction of it, which is equal to:

$$R^* = I \cdot a_k \cdot f_p \qquad \text{(Eq. 4.2)}$$

where I = DSR on a surface perpendicular to the sun's rays (W/m^2)

a_k = absorption coefficient of the irradiated body surface area for short-wave radiation

f_p = surface projection factor

The standard value adopted for a_k is 0.7 (ASHRAE, 2005). The surface projection factor refers to the area effectively exposed to solar radiation[10] and can be calculated as a function of solar altitude (γ) as reported by Jendritzky (1990):

$$f_p = 0.308 \cdot \cos\left(\gamma(0.998 - \gamma^2/50000)\right) \qquad \text{(Eq. 4.3)}$$

In warm conditions, mean radiant temperature (T_{mrt}) is the parameter with the largest effect on human thermal comfort (Matzarakis et al., 2010). It corresponds to 'the uniform temperature of an imaginary enclosure in which radiant heat transfer from the human body equals the radiant heat transfer in the actual nonuniform enclosure' (ASHRAE, 2005). Both long- and short-wave radiations are included in its calculation. The critical impact of DSR on T_{mrt} during daytime has been reported by previous research, in particular in urban canyons (D E V S et al., 2019). Additionally, short-wave radiation largely varies under clear skies, and in summer, is normally higher (Ji et al., 2022). Because of the moving position of the sun, and the blocking effect of urban morphology, short-wave radiation collected by surfaces can substantially change. Consequently, changes in T_{mrt} can be recorded within a

[10] It should be noted that f_p decreases as γ increases: in fact, when the sun is high in the sky, the surface of a person exposed to DSR is reduced.

few meters radius; for this reason, Naboni et al. (2017) defined it as a 'spatial metric', which makes it relevant for urban design. Jendritzky (1990) isolated the contribution of DSR on T_{mrt}:

$$T^*_{mrt} = \left[T^4_{mrt} + \frac{f_p \cdot a_k \cdot I^*}{(\varepsilon_p \cdot \sigma)}\right]^{0.25} \quad \text{(Eq. 4.4)}$$

where T^*_{mrt} = mean radiant temperature in case of DSR exposure[11]

T_{mrt} = mean radiant temperature with no DSR exposure[12]

ε_p = emission coefficient (standard value = 0.95 (ASHRAE, 2005))

σ = Stefan-Boltzmann constant ($5.67 \cdot 10^{-8}$ W/($m^2 \cdot K^4$))

Numerous models have been proposed to describe thermal comfort as a function of meteorological variables. The Universal Thermal Climate Index (UTCI) was developed specifically to describe the thermal state of a human body in a non-steady state, which suits the description of a pedestrian walking outdoors (COST Action 730, n.d.; Nikolopoulou, 2011). Equation 4.5 defines UTCI as the sum of air temperature and an additional contribution that depends on four meteorological variables (Bröde et al., 2012):

$$UTCI(T_a, T_{mrt}, v_a, p_a) = T_a + offset(T_a, T_{mrt}, v_a, p_a) \quad \text{(Eq. 4.5)}$$

where T_a = air temperature

v_a = wind speed

p_a = humidity (expressed as water vapour pressure)

T_{mrt} = mean radiant temperature

Bröde et al. (2012) proposed a regression function to calculate UTCI through the difference between T_a and T_{mrt} (for given v_a and p_a values, i.e., 'reference conditions'); they found that a 10 K increment in T_{mrt} corresponded to a 3 K increment in UTCI, which highlights the influential contribution of DSR on outdoor thermal stress.

4.3.2. Building the DSR exposure graph

This section presents a model to isolate the contribution of DSR to thermal stress. This contribution is shaped as a DSR exposure graph delivered to urban designers to evaluate the user experience provided by outdoor spaces

[11] Mean radiant temperature calculated including DSR as an additional source of energy.

[12] Mean radiant temperature calculated as the sum of the fluxes received from surrounding surfaces (i.e., for a given surface i, emitted thermal radiation, E_i, and diffusely reflected solar radiation, D_i) plus the diffuse solar radiation from the sky.

and exposure to DSR, with particular attention to pedestrian paths. The core assumption is that in absence of thermal stress, the metabolic heat produced during the performed activity is balanced by the heat exchanged with the surrounding environment. Once the surrounding environment presents uncomfortable conditions, the body attempts to reinstate the neutral conditions (no thermal stress) by releasing the additional heat, mainly via evaporation and convection.

To evaluate the impact of DSR exposure on pedestrians, two scenarios were simulated, users in full shade and under the sun. At first, UTCI was calculated for a pedestrian in shaded conditions, defined as scenario [0]; then, the term R^* in Equation 4.2 was calculated for isolating the DSR contribution to heat balance, as proposed in the previous section. The contribution of DSR to T_{mrt} was determined via Equation 4.4, and UTCI was simulated (Figure 4.1a); these values referred to scenario [1], in which the user was directly exposed to the sun. UTCI values for scenarios [0] and [1], indicated as $UTCI_0$ and $UTCI_1$, were subsequently assigned to three different cases, as graphically illustrated in Figure 4.1b:

- case (a): the user is in no thermal stress conditions in both scenarios;
- case (b): the user is entering in heat stress conditions after being exposed to direct solar radiation;
- case (c): the user is in heat stress conditions already in the fully shaded scenario.

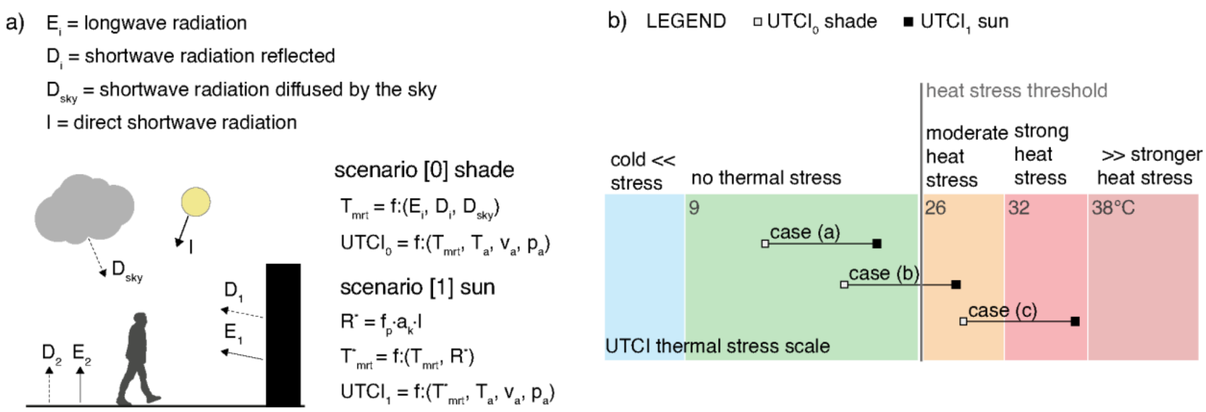


Figure 4.1 a) Radiation fluxes considered to calculate Tmrt and UTCI in shade, scenario [0], and under the sun, scenario [1] (adapted from Naboni et al., 2019); b) Position on the UTCI scale of the three defined cases before and after DSR exposure: in case (a), the UTCI value does not cross the heat stress threshold after the DSR exposure, therefore the person is not in heat stress even under the sun; in case (b), the UTCI value crosses the heat stress threshold; in case (c), the person is already in heat stress even in shaded conditions.

Based on the presented model, the increase in thermal stress value ($\Delta UTCI$) is due to R^*. In order to evaluate the effect of DSR exposure on pedestrians, at first the shaded conditions must be assessed in terms of thermal stress. For each set of microclimatic conditions (T_a, v_a, p_a, T_{mrt}), the amount of absorbed heat necessary to reach the heat stress threshold (UTCI=26°C) when in shade was calculated; this speculative variable was defined as R_0. To calculate R_0, a linear relationship was assumed between R^* and $\Delta UTCI$. Although this relationship is not perfectly linear, the linear regression analysis performed on the available dataset validated this approximation for values close to the heat stress threshold (Appendix A – Section 4.8.1[13]). Therefore, for each hour, $UTCI_0$ was associated with the correspondent R_0 value using Equation 4.6:

$$R_0 = \frac{(UTCI_0 - 26) \cdot R^*}{\Delta UTCI} \qquad \text{(Eq. 4.6)}$$

where R_0 = equivalent absorbed solar radiation in shaded conditions

$UTCI_0$ = thermal stress value in shaded conditions

$\Delta UTCI = (UTCI_1 - UTCI_0)$ = increase in thermal stress value due to solar radiation exposure

In this way, for each hour, an equivalent heat load was associated with the gap between $UTCI_0$ and the threshold value indicating thermal stress, i.e., 26°C, in both directions. The outcome of Equation 4.6 was either a positive or a negative value (Figure 4.2a). In cases (a) and (b), R_0 was the equivalent amount of energy needed to exit the no thermal stress zone; it was therefore a negative number corresponding to the energy budget that could be absorbed by the body while remaining in comfortable conditions. On the contrary, in case (c), R_0 was a positive number and represented an 'equivalent' solar radiation energy as if the pedestrian was accumulating heat even though not being exposed to DSR. In this way, the heat stress condition was represented in the graph. Effective solar radiation (R_{eff}) was consequently defined as the amount of energy that would affect the human body at given conditions, moving it away from the no thermal stress zone, and corresponded to:

$$R_{eff} = R^* + R_0 \qquad \text{(Eq. 4.7)}$$

During a trip in the urban environment, it is rare to walk only under the sun or in shade; instead, it is most common being exposed to DSR for a certain time. To consider the impact of the sun in relation to various percentages of DSR exposure, for each set of microclimatic conditions, an R-line was defined using Equation 4.8.

[13] To facilitate their accessibility, the contents published as Appendices in the journal papers are inserted in this thesis as Sections.

The contribution of R* was weighted based on the percentage of exposure to DSR: 0% corresponded to a trip performed in total shade and 100% totally under the sun.

$$R_{eff} = \frac{R^*}{100} expo + R_0 \quad \text{(Eq. 4.8)}$$

where expo = percentage of exposure to DSR (from 0 to 100%)

A DSR exposure graph was built as a collection of R-lines: it illustrates the effective impact of DSR added to the heat energy balance of a person as a result of an increase in T_{mrt}, considering the remaining meteorological variables included in the UTCI calculation (T_a, v_a, p_a) as constant. Figure 4.2b provides the graphical representation of the DSR exposure graph.

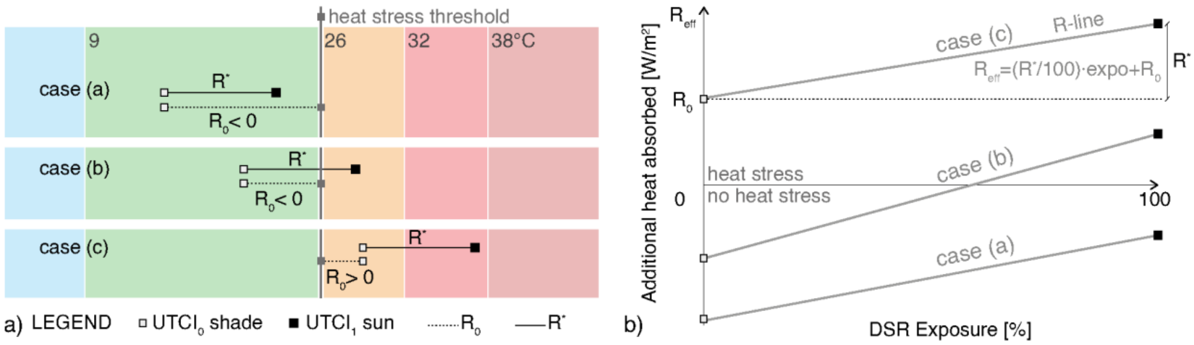


Figure 4.2 a) Graphical definition of R_0: at given microclimatic conditions, it is the equivalent absorbed DSR that represents the gap between the UTCI value in shaded conditions and the heat stress threshold (UTCI = 26°C); b) DSR graph weighting R based on the percentage of DSR exposure and adding R_0 to consider the effective heat load on the human body in fully shaded conditions.*

4.3.3. Profiling users of diverse walking abilities

This section aims to delineate the differences in metabolic heat production among diverse pedestrians. Two user profiles are defined, a young adult and an elderly person with mobility impairment.

To maintain body temperature within a normal range, the heat produced by metabolic activities must be dissipated, transferring it to the surrounding environment. This mechanism mostly happens at the skin level, so it is often convenient to express the metabolic activity in heat production per unit area of skin (ASHRAE, 2005). The body surface area was defined as function of body mass and height of the individual by DuBois and DuBois in 1916 (ASHRAE, 2005). A resting person produces about 100 W; the DuBois area of an average European man is 1.8 m² (height = 1.73 m, body mass = 70 kg). Based on these specifics, the standard metabolic rate of a resting person, sitting quietly, is defined as 58.1 W/m^2 and is called 1 met. Elderly people have a lower resting metabolic rate, which based on previous research was set to 0.75 met (Hall et al., 2013, 2014).

4.3.3.1. Energy consumption in walking

Focusing on pedestrians' activity, the typical walking speed for each user group was defined. Then, each walking speed was associated with the appropriate energy cost for the corresponding user profile, assessed from literature. The term 'energy cost' describes the physiological work in performing one activity; it is derived from the rate of oxygen consumption and, once adjusted based on activity and individuals, it allows comparative analysis (VanSwearingen & Studenski, 2014).

Based on the review by Bosina and Weidmann (2017), a walking speed of 1.34 m/s was adopted for young adult pedestrians. The corresponding metabolic heat production was obtained by values proposed by ASHRAE (2005) through linear interpolation, 2.9 met. Oxley et al. (2004) reported walking speeds of pedestrians with different assisting devices and levels of physical ability. The average walking speed was 0.79 m/s, which is consistent with literature about the effect of age on pedestrian speed (Pinna & Murrau, 2018). VanSwearingen and Studenski (2014) presented three curves of the energy cost of walking based on the walking speed of older adults with impaired motor skills; a value of 0.225 ml O_2/kg/m was extracted from the curve describing the moderately slow pedestrians, as it was associated with the walking speed of 0.79 m/s. After converting the selected value in the appropriate unit[14], the equivalent metabolic heat production by an elderly user for walking was set at 3 met, as 1 met is equal to 3.5 ml O_2/kg/minute (Jetté et al., 1990). Even though consistent with previous studies (Hall et al., 2013), this value is higher than the results obtained by Martin et al. (1992), which reported values around 2.7 met for comparable walking speeds; this may be due to the different physical conditions of participants since the latter study selected older pedestrians with no physical impairment.

Table 4.1 summarises the values presented above. The energy cost of walking for young adults and elderly pedestrians is similar: that is because it is calculated for the appropriate walking speed of each group, while the energy cost for the elderly is higher than younger pedestrians when calculated for the same walking speed (Martin et al., 1992).

[14] Conversion process: 0.225 ml O_2/kg/m * 0.79 m/s = 0.17775 ml O_2/kg/s * 60 s = 10.665 ml O_2/kg/minute / 3.5 ml O_2/kg/minute = 3.0 met.

Table 4.1 Energy cost of resting and walking for two selected users.

User group	Energy cost of resting [met]	Walking speed [m/s]	Gross energy cost of walking [met]
Young adults	1.00[1]	1.34[2]	2.9[1]
Elderly	0.75[3]	0.79[4]	3.0[5]

1. ASHRAE (2005), 2. Bosina & Weidmann (2017), 3. Hall et al. (2013, 2014), 4. Oxley et al. (2004), 5. VanSwearingen & Studenski (2014)

4.3.3.2. Maximum energy capacity threshold

As discussed before, the underlying assumption is that the additional thermal energy R_{eff} is dissipated by the body through skin and respiration. To define a threshold that would indicate walking as an exhausting activity for pedestrians, the value R_{eff} was compared to the physical effort that would induce the body to dissipate the same amount of additional heat. This comparison allowed us to introduce the concept of maximum energy capacity in our methodology.

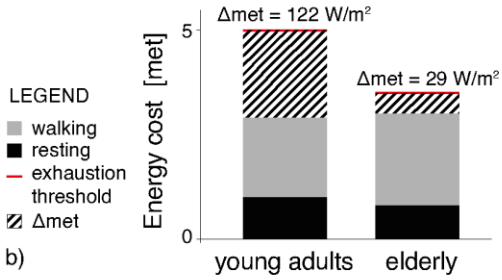
ASHRAE (2005) reports that the maximal capacity to use oxygen ('maximum energy capacity') depends on various factors such as gender, age, physical condition. For this research, the adopted values of maximum energy capacity were 10 met for young adults and 7 met for the elderly. These values refer to a 35-year-old who does not exercise and a 70-year-old man, respectively (ASHRAE, 2005, pp 8.6-7). A person can continuously perform physical activity as long as 50% of their maximum energy capacity is not reached (ASHRAE, 2005). Therefore, the difference between 50% of maximum energy capacity, hereinafter defined 'exhaustion threshold', and the walking energy cost for each pedestrian (refer Table 4.1) was defined as Δmet (Figure 4.3). Within the proposed framework, Δmet was defined as the energy budget ('adaptation threshold') available for the user to cope with outdoor thermal stress before feeling exhausted because of the environmental conditions. Therefore, Δmet for walking was set to 2.1 and 0.5 met for young adults and the elderly respectively. However, if young adults and the elderly were at rest, the adaptation thresholds were 4.0 and 2.8 met respectively[15].

[15] These values correspond to the difference between the exhaustion threshold (Figure 4.3a) and the energy cost of resting sitting (Table 4.1).

User group	Maximum energy capacity [met]	Exhaustion threshold [met]	Δmet for walking [met] (W/m^2)
Young adults	10[1]	5.0[1]	2.1 (122)
Elderly	7[1]	3.5[1]	0.5 (29)

Reference: 1. ASHRAE (2005).

a)



b)

Figure 4.3 a) Definition of walking adaptation thresholds for two selected users as the difference between the exhaustion metabolic threshold and energy cost of walking; b) Energy cost of activities for two user profiles with relative energy budget available to cope with additional heat load ('walking adaptation threshold').

Walking in the urban environment, users regularly cross different DSR exposure levels. The weighted average metabolic rate was thus introduced, in line with the analogy of metabolic activity and additional thermal load. According to ASHRAE (2005), if activities are alternated frequently over time, the weighted average metabolic rate is 'generally satisfactory' (p. 8.7). For application purposes, the investigation of each hypothetical trip during the selected hour was therefore weighted based on how much time a pedestrian would be exposed to or screened from DSR. This simplified model was created to evaluate thermal conditions in the shade and under the sun at a specific moment in time. Therefore, the weighting operation did not consider transitioning from shade to sun (and vice versa), the two conditions were assumed as an instantaneous variation in the heat exchange with the surrounding environment. For the purpose of this research, the term 'walkable' was used to define thermal conditions allowing the considered pedestrian to walk under a percentage of DSR exposure without feeling exhausted. Using the DSR exposure graph, the R_{eff} value corresponding to the percentage of time spent under the sun was compared with Δmet for the selected user, and three outcomes were possible. At the given microclimatic conditions, based on the DSR exposure and metabolism of the pedestrian, a trip could be categorised as always walkable (i.e., always below the exhaustion threshold) as long as R_{eff} was lower than Δmet even under the sun; never walkable, in case Δmet was reached already in the shade (meaning exhausting heat load even if totally screened from DSR); and walkable if partially shaded, where the resulting percentage of DSR exposure corresponded to the value on x-axis (expo) where the R-line (Figure 4.2b) intercepted Δmet. Figure 4.4 summarises the presented methodology and possible categorisation outcomes.

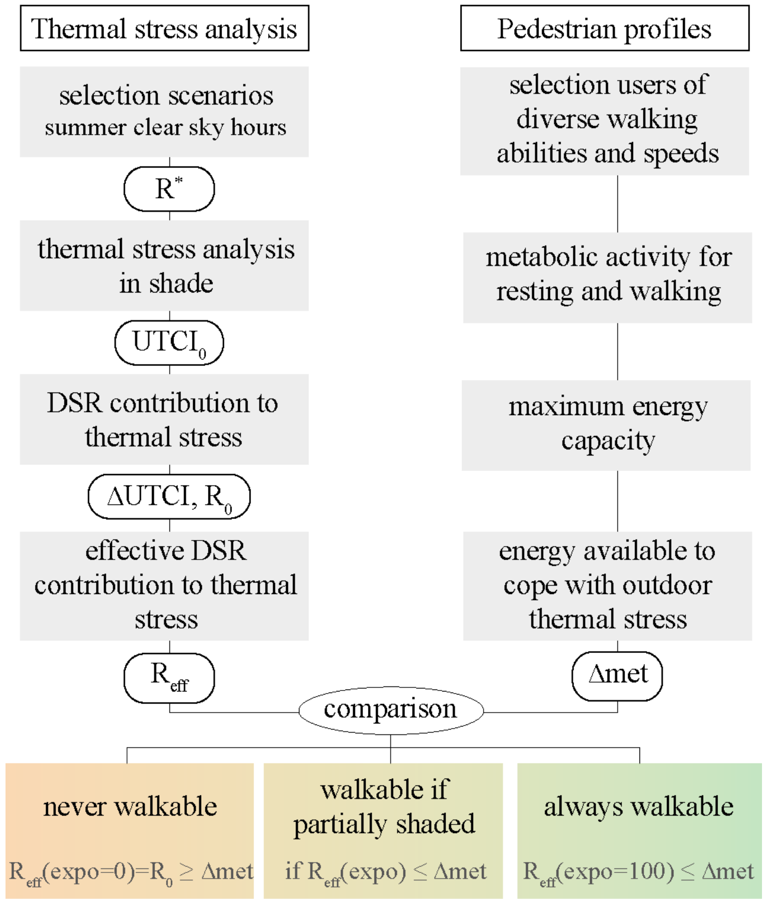


Figure 4.4 Methodological scheme illustrating the comparison between DSR and metabolic activity of pedestrian profiles. The outcome of each step is presented below the relevant description; at the end, the classification of analysed hours in three categories is presented. The term 'walkable' refers to a thermal condition in which the DSR exposure would not make the considered pedestrian feel exhausted.

4.4. Applying the methodology to a case study

The methodology was tested using an open area in the city of Milan (Italy) as a case study. Being in the Po valley, its climate is classified as Cfa - humid subtropical climate, with hot and humid summers. Input weather data were downloaded from the EnergyPlus website (EnergyPlus, n.d). The selected station was Milano-Linate 160800 (IGDG) – location: N 45° 25', E 9° 16'. At the end of year 2021, out of the about 1.4 million residents, 12.9% were over 75 years old (Municipality of Milan, 2022b), which highlights the necessity to delineate diverse user profiles in urban planning practices for this city.

Calculations were performed on an hourly basis because meteorological variables in the dataset were reported every hour, and pedestrians were assumed to walk short distances within the urban environment. DSR exposure in Milan was analysed for hours considered suitable to simulate the contribution of DSR to the human energy balance; the selection process is here reported. All summer days were considered, from June 21st to September

22nd. This selection included the summer solstice day, as well as the hottest and typical weeks based on *.epw* statistics (6-12/7 and 13-19/7, respectively). The hours selected range from 8 am to 5 pm, namely 9 am to 6 pm DST (daylight saving time, UTC+2); hours that registered null DSR were removed. Only clear sky days were considered: the dataset available reported total sky cover in tenths and values from 0 to 2 were selected, as correspondent to the equivalent lowest category of cloudiness in oktas (World Meteorological Organisation, n.d). In the end, 274 hours were analysed; all combinations hour of the day/month were covered.

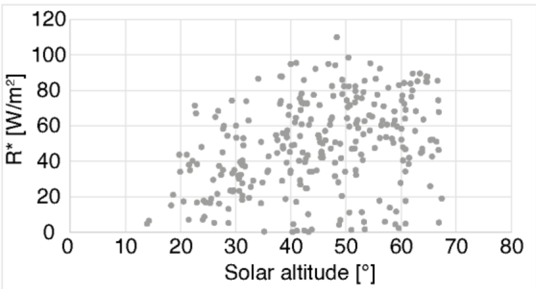
As a proof of concept, the methodology was tested on an open area. This allowed assuming surface temperature as equal to air temperature, avoiding additional complexity from the surrounding surfaces. Simulations were performed using Ladybug tools (v1.5.0) in Grasshopper, the visual scripting interface for Rhino software (*Grasshopper*, n.d.; *Ladybug*, n.d.; *Rhinoceros*, n.d.). R^* was calculated for all selected hours using Equation 4.2. DSR was obtained from the variable 'direct normal radiation' in .epw file, which corresponds to the amount of solar radiation received from a surface perpendicular to the sun's rays in the 60 minutes before the associated time (U.S. Department of Energy, 2022)[16]. Solar altitudes were derived from the *Sunpath* component and were used to calculate f_p. T_{mrt} in shaded scenarios was calculated using the *OutdoorSolarMRT* component, by setting to zero the body fraction exposed to direct sunlight. This component uses the SolarCal model to calculate T_{mrt} considering shortwave solar radiation and estimating longwave radiant exchange with the sky. Then, the additional contribution of DSR to T_{mrt} was calculated using Equation 4.4. It should be noted that f_p is formulated to be independent of the user's orientation to the sun; therefore, results obtained with this method could be used for pedestrians walking in any direction. The two T_{mrt} values were inserted into the *UTCI* component, together with the other meteorological variables required, derived from the .epw file. For each calculated hour, the resulting ΔUTCI was compared against R^*; then, R_0 was calculated to determine the equivalent solar radiation value in fully shaded conditions and the DSR exposure graph was compiled for young adults and elderly. Finally, applications of results were presented.

[16] It should be noted that *.epw* files report DSR as energy (measured in Wh/m^2), not power. Since radiation is reported as cumulative over an hour, the provided values can be reasonable considered as irradiance (W/m^2): as such, this conversion will be used in the following calculations. As per Ladybug components formulation, during computation processes, variables in a specific hour are associated with solar radiation collected during the 60 minutes after the selected time.

4.5. Results

4.5.1. Solar radiation absorbed by pedestrians

Figure 4.5 reports relevant statistics about the outcome of the calculation of R^*. As expected, no increasing trend in the DSR absorbed by a pedestrian at higher solar altitudes could be observed (Figure 4.5a). This is due to opposite trends of I and f_p, both included in the calculation of R^*: while high values of I are generally recorded in the central part of the day (when γ is high), f_p decreases with higher solar altitudes. Therefore, high variability in R^* was found. The average value of R^* was 48.4 W/m^2 and increased to 51.4 W/m^2 if values < 58.1 W/m^2 (0.1 met) were not considered (17 in total, 6% of analysed hours). The maximum value of R^* was 109.95 W/m^2 and corresponded to 2nd September at 12 pm DST.



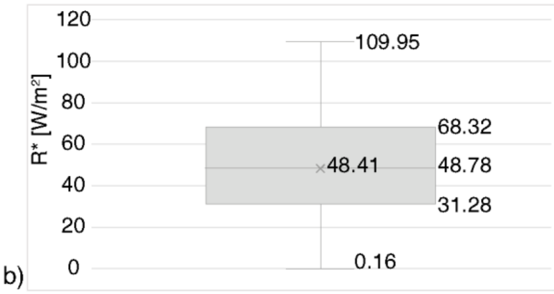


Figure 4.5 a) DSR absorbed by the body (R) compared against solar altitudes; b) Box plot showing the distribution of DSR absorbed by the body (R*).*

4.5.1.1. Thermal comfort analysis via Ladybug

T_{mrt} was calculated in shaded conditions and under the sun, and the corresponding UTCI values were obtained. Since wind speed was reported as null for 126 hours, the minimum value allowed by the UTCI formulation, which is 0.5 m/s, was used in those cases. In total, 44 hours always resulted in the UTCI no thermal stress zone, even if completely exposed to solar radiation (case a). Among these, in two cases, UTCI was less than 9°C under the sun (i.e. slight cold threshold): they corresponded to 3-4 pm DST of August 21st, which reports direct normal radiation values <10 Wh/m^2, T_a<16°C and high wind speed (9.6 to 10.9 m/s). Conversely, 210 hours resulted in heat stress already in shaded conditions, at various levels: 135 moderate, 73 strong, and 2 very stronger heat stress (case c).

4.5.2. DSR exposure graph for an open area in Milan

Results of the linear regression analysis between ΔUTCI and R^* were in good agreement with the hypothesis of approximating the impact of DSR on outdoor thermal stress via linear equation, as reported in Appendix A (Section 4.8.1). Therefore, R_0 and R_{eff} were calculated with Eqs. (4.6) and (4.7), respectively. Figure 4.6 reports the resulting DSR exposure graph (references for its interpretation are presented in Figure 4.2). Every R-line represents one analysed hour; R-lines corresponding to hours always below the heat stress threshold were removed from the graph. For every hour that resulted R_{eff} below the adaptation threshold while walking was represented with a dark line; if it intercepted the walking adaptation threshold, it was coloured only for the length below the relevant limit.

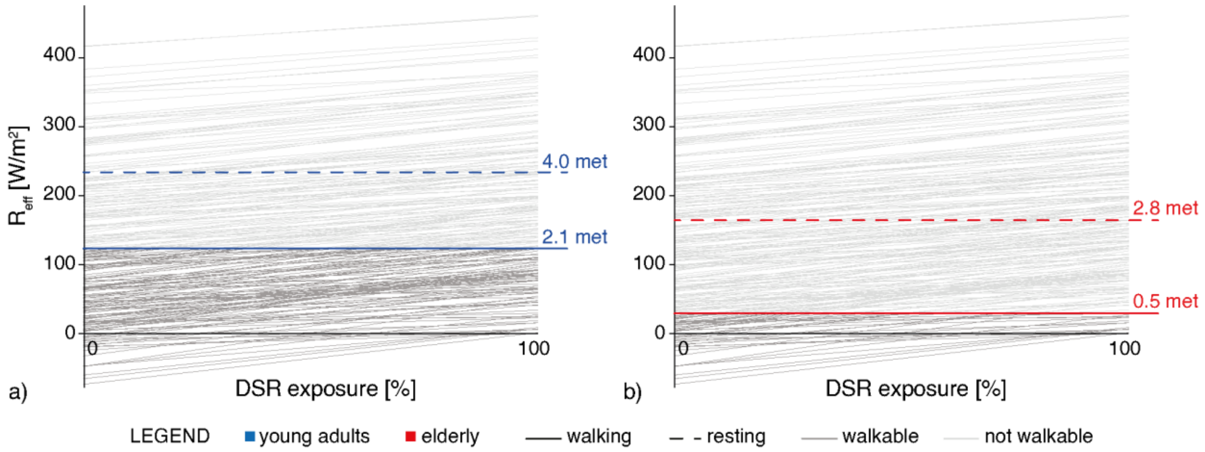
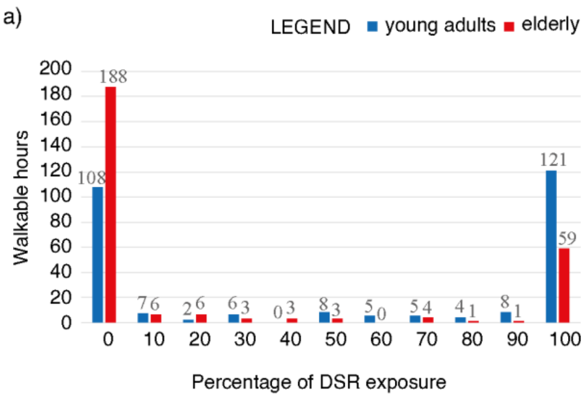
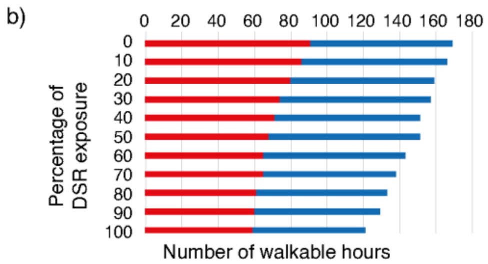


Figure 4.6 Impact of DSR exposure on young adults (a) and elderly (b) in an open area in Milan; Δmet is represented as solid and dotted lines for pedestrians walking and resting respectively. Each R-line represents one analysed hour; hours below the walking adaptation thresholds are represented as dark lines.

Results obtained from the DSR exposure graph are synthesised in Figure 4.7. Hours were allocated into 10% bins representing the recommended DSR exposure percentage for each user profile in that specific combination of microclimatic and environmental conditions. The bin named '50' collected expo values in the range of 50 ≤ expo < 60%. The aggregated evaluation of 274 sets of microclimatic conditions led to drawing some conclusions about environmental conditions through the summer season. For young adult pedestrians, open areas in Milan resulted in being always walkable for 121 hours. On the other hand, 105 hours were too much challenging for their metabolic system, also in shaded conditions. This is a critical result because based on our calculations, walking outdoors would not be recommended for 38% of the analysed hours under clear skies in summer. The remaining 48 hours were distributed almost homogeneously among different percentages of DSR exposure. For elderly pedestrians, the situation was more critical, as expected: walking under the sun would have been possible only for 59 hours (21%), and additional 32 hours would require different percentages of shade.





c)

User profile	Never walkable	Walkable if partially shaded	Always walkable
Young adults	105 (38%)	48 (18%)	121 (44%)
Elderly	183 (67%)	32 (12%)	59 (21%)

Figure 4.7 Synthesis of results of the DSR exposure graph reported in Figure 4.6; a) subdivision of analysed hours in bins (bin N refers to N≤ expo <N+1); b) staked bars to highlight trend in walkability to the change of DSR exposure; c) summary of results based on the three proposed categories.

In addition to statistics presented in Figure 4.7, the DSR exposure graph can be used to evaluate specific user experiences: two cases are highlighted on the same graph and reported in Figure 4.8. Additionally, the step-by-step calculation process for both cases is reported in Appendix B (Section 4.8.2). Line ‘m’ refers to 10 am DST on July 6th. $UTCI_0$ value (in the shade) results as 24.6°C; with ΔUTCI = 3.8K, in sunny conditions, the user comes out of the ‘no thermal stress zone’ and enters the ‘moderate heat stress’ state. Based on R_{eff} values, if exposed to DSR in the analysed microclimatic conditions, elderly pedestrians can walk for up to 71% of the time under the sun without feeling exhausted. Therefore, if a trip of ten minutes is hypothesised, this means that they would need at least three minutes in the shade; instead, young adults could complete the trip without the need to find shade. Line ‘n’ refers to a more extreme case. Microclimatic conditions refer to August 27th at 12 pm DST, and UTCI values range from 29.1 to 31.9°C. In these conditions, the young adult pedestrian also needs to have a break after walking in the sun; 55% is the maximum amount of time to walk exposed to solar radiation without feeling exhausted. Elderly pedestrians would not be recommended to walk outdoors in these conditions, since the adaptation threshold is already exceeded in the totally shaded scenario.

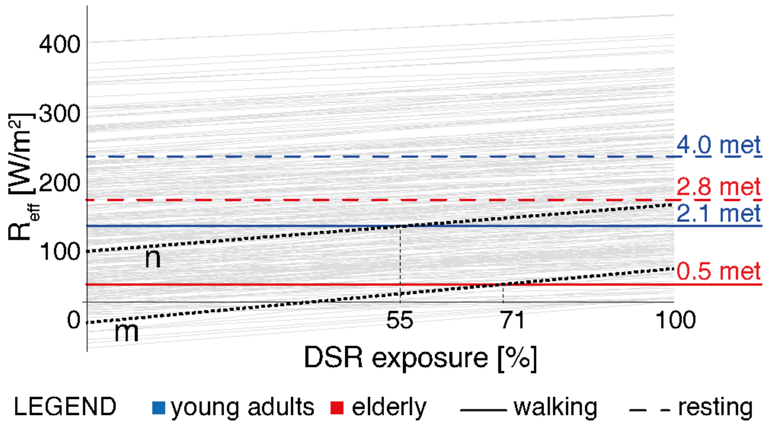
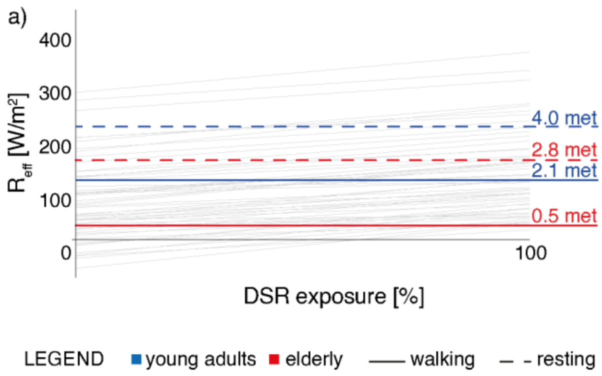
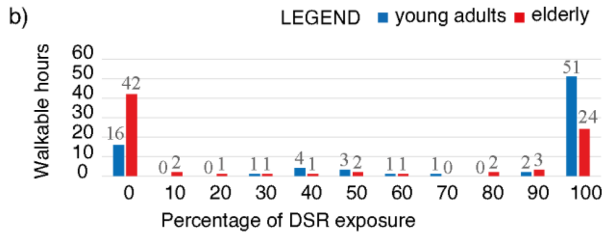


Figure 4.8 Two case study hours are isolated to illustrate the effect of DSR exposure on the two users in selected conditions.

4.5.3. Application to urban design practice

The proposed methodology was developed considering an open area to avoid the additional complexity from modelling surrounding surfaces. The same procedure could be applied in an urban setting by modifying urban morphology descriptors. In this section, an application of the DSR exposure graph in urban design practice is presented. Different aspect ratios (H/W) affect outdoor thermal comfort, resulting in different sky view factors (SVF) for people walking into the urban canyon (Nouri et al., 2017). An urban canyon 15 m wide and of H/W = 1.0 was modelled; a pedestrian was positioned one meter from the closest building. The SVF from that position was calculated through the *HumanToSky* component in Ladybug and resulted in 0.3 (*sky exposure factor* in Ladybug tools). Ground reflectance was set to 0.12 to simulate paved sidewalks. The surface temperature was calculated via Rayman (Matzarakis et al., 2010) and imported in Ladybug. To simulate the design goal of investigating walkability during a specific time of the day, morning hours were selected, specifically from 9 to 11 am. A total of 79 hours were analysed, and the results are presented in Figure 4.9.





c)

User profile	Never walkable	Walkable if partially shaded	Always walkable
Young adults	15 (19%)	13 (16%)	51 (65%)
Elderly	41 (52%)	14 (18%)	24 (30%)

Figure 4.9 DSR exposure impact on young adults and elderly in an urban canyon of H/W = 1.0 in Milan. a) DSR exposure graph, where Δmet is represented as solid and dotted lines for pedestrians walking and resting respectively. Each R-line represents one analysed hour; b) subdivision of analysed hours in bins (bin N refers to N≤ expo <N+1); c) summary of results based on the three proposed categories.

Analysing morning hours is important for walkability in cities since microclimatic conditions are generally more comfortable than the rest of the day. Results obtained through the proposed methodology show that 30% of the hours are categorised as always walkable for elderly pedestrians. A valuable result for urban designers is that, if 70% of pedestrian paths would be shaded during morning hours, walkability for elderly pedestrians would increase by 42%, reaching 43% of walkable morning hours from the dataset (34 hours). This emphasises how paths not completely shaded would have anyway an impact on improving walkability.

4.6. Discussion

This paper has presented a methodology to evaluate the impact of DSR exposure on pedestrians of diverse walking abilities on hot clear summer days. A key finding was the focus on thermal stress and physical effort, because recommended DSR exposure times had been proposed based on health risks due to overexposure to ultraviolet (UV) radiation, such as skin damage (Diffey, 2018; WHO, 2003). The application of this methodology to urban design workflows makes it valuable to evaluate user experiences in design proposals, and accordingly, address emerging issues. The DSR exposure graph could inform urban designers of relevant percentages of shade to achieve in design proposals; allow a multi-perspective analysis of a specific urban morphology (e.g., an urban canyon) by changing input settings; and compare user experiences in different locations evaluating thermal stress through DSR exposure. The application of DSR exposure thresholds obtained through the presented workflow is not limited to urban design practice. Expanding the scale of analysis, they can be included in urban planning requirements, for both existing and new development areas. Comfortable public outdoor spaces must be equally distributed in the city because of their key role in citizens' well-being: public areas are a refuge during extremely hot days, especially for lower-income residents, that cannot afford A/C systems (Aljawabra and Nikolopoulou, 2018). Other applications include public communication at the city level of recommended maximum exposure time to DSR; the definition of minimum distances between relief spots, to allow vulnerable users to have a break decreasing the average energy cost of a trip; measuring the effectiveness of design proposals from the users' perspective. The proposed workflow aims to support urban designers in making decisions, yet they must select the final threshold to be considered in their design, as explained by Hendel et al. (2020).

Ladybug tools were selected because the computational time required for microclimatic analysis is shorter compared to other simulation tools, a key consideration in architectural practice. The downside of fast calculation lies in the assumptions made at the beginning of the process. Especially when the workflow was applied to an urban canyon (Figure 4.9), T_{mrt} in shaded conditions did not take into consideration short-wave radiation reflected by surrounding vertical surfaces, which could have an effect on T_{mrt} (Salvati et al., 2022). Furthermore, the surface temperature was calculated through a different software (Rayman). The potential usability by urban designers and the possibility to perform extensive analysis with acceptable computational time overruled the need for more accurate results. It is worth highlighting that the methodology is independent of the tool used to simulate microclimatic variables; if more detailed analysis was required, software with higher accuracy in results could be used, focusing on a limited number of simulation scenarios, to avoid computational times increasing excessively.

Drawing attention to more inclusive cities is a major objective of this paper. As reviewed in the theoretical framework, standards and comfort scales have been developed considering the physiology of male adults. Nevertheless, cities are required to adapt to a diversified society, especially considering vulnerable people. In this paper, young adults and elderly pedestrians with impaired mobility were analysed, however, considering further user groups is essential. Females, on average, have 30% less maximum energy capacity than men (ASHRAE, 2005), but with a lower metabolism (Ferraro et al., 1992), Δmet would not be expected to vary substantially, although further studies will be required. An additional user group that could be considered in the future is children and toddlers, who have higher resting metabolic rates than adults but lower walking speeds (DeJaeger et al., 2001).

A limitation of this work is that the UTCI scale was not adapted to metabolic activity and walking speed, even though boundary conditions differed from reference conditions[17]. Bröde et al. (2016) adapted the UTCI scale

[17] Reference conditions: walking speed of 1.1 m/s, metabolic activity of 2.3 met (135 W/m^2), exposure time of 2 hours.

based on different metabolic activity levels and duration of exposure. This paper focused on trips walked in the urban environment, that can reasonably be assumed shorter than one hour; for such limited exposure times, the difference between results of the cited work and our parameters was small, therefore we did not adopt adjusted UTCI values as heat stress threshold. Nevertheless, for specific cases, such as people performing intense physical activity or continuous exposure to DSR for several hours, adapting the heat stress threshold would be recommended.

The presented methodology would be valid to define minimum requirements of DSR exposure in winter, to compensate for cold stress. By coupling summer and winter scenarios, design solutions to make pedestrian paths responsive to seasonal changes could thus be proposed. During the cold season, DSR is much reduced compared to summertime; at the same time, a pleasant warm sensation can have a large impact on thermal comfort even if solar energy is low, while also being crucial for gaining vitamin D. Being based on physiology, this research does not take into consideration the psychological component of thermal comfort, or behavioural adaptation (Nikolopoulou & Steemers, 2003). Since urban designers are the target of the proposed workflow, a different perspective is presented: the goal is to maximise potential comfort outdoors for a variety of users.

4.7. Conclusions

This paper has provided a framework to assess the impact of DSR on pedestrians, by proposing a simplified way to evaluate DSR exposure based on environmental conditions and metabolic activity of users of diverse walking abilities. It has compared the energy intake that a walking person could absorb without feeling exhausted to the equivalent amount of DSR that a pedestrian is exposed to. In this way, the maximum energy capacity concept has been used to identify the maximum value of solar radiation energy intake of the human body before reaching the exhaustion threshold. The workflow has been specifically developed for urban designers and planners in their professional practice, to encourage more inclusivity and focus on users in cities.

Two user profiles have been delineated, a young adult and an elderly person with mobility impairment, characterised by metabolic activity, walking speed and maximum energy capacity. The results highlighted that younger adults have an energy budget to cope with DSR three times higher than elderly people. This threshold was compared to thermal stress simulated during clear-sky summer hours to assess walkability, defined as microclimatic conditions allowing pedestrians to walk without feeling exhausted. The framework has been tested in two different environments in Milan, an open area and an urban canyon with a H/W ratio of 1.0 to demonstrate its applicability.

Limitations of the proposed methodology were mainly linked to the tools used for microclimatic calculations. The accuracy of results could be improved using more sophisticated software and workflows: for example, modelling surface materials through Ladybug tools would improve T_{mrt} calculations, yet the contribution of R^* would keep the DSR exposure graph relevant. The user profile catalogue could be expanded to account for diverse user groups and mobility requirements, which would benefit from collaboration across disciplines. Finally, the proposed methodology could be applied to evaluate the thermal stress of pedestrian paths in existing settings and design proposals in cities of diverse climate zone, adapting relevant thresholds.

4.8. Appendices

4.8.1. Appendix A: Statistical analysis to test the validity of the proposed model

Equation (4.6) is formulated assuming a linear relationship between R^* and ΔUTCI. Figure 4.10 presents a linear regression analysis between the two variables based on the open area exercise.

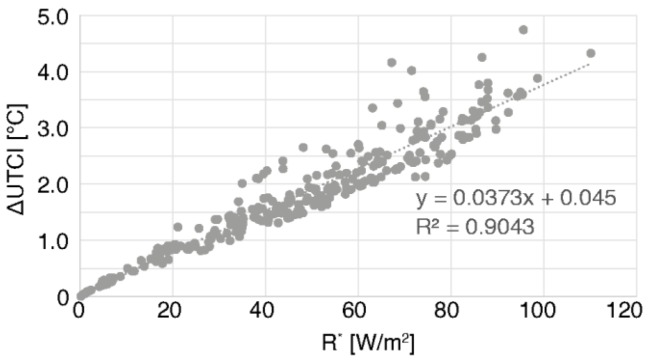


Figure 4.10 Linear regression analysis between R and ΔUTCI. Data refer to the open area exercise.*

To evaluate the accuracy in estimating the variable R_0 via Equation 4.6, an inverse process was applied: in Equation 4.4, R^* was substituted with R_0, and T^*_{mrt} with T_{mrt}. A new T_{mrt} value was calculated ($T_{mrt(26)}$) as the mean radiant temperature that, considering constant the other environmental parameters and simulating a shaded condition, would result in a UTCI value of 26°C:

$$T_{mrt(26)} = \left[T_{mrt}^4 - \frac{R_0}{(\varepsilon_p \cdot \sigma)}\right]^{0.25} \qquad \text{(Eq. 4.9)}$$

Then, $T_{mrt(26)}$ was used to calculate $UTCI_{(26)}$: based on the proposed model, $UTCI_{(26)}$ should be equal to 26°C. The new variable 'u' was defined as the difference between $UTCI_{(26)}$ and 26 °C; Figure 4.11a presents statistical analysis of u, illustrating the distribution of results. A total of 39 outliers were found (14%). Therefore, further investigation about whether this result would affect the outcome of the DSR exposure graph was performed. Figure 4.11b presents the relation between u and $UTCI_0$: all outliers corresponded to hours in which microclimatic conditions in shade were largely distant from the heat stress threshold (26°C). Thus, since all hours labelled as outliers were positioned at the extremes of the DSR exposure graph (Figure 4.12), it was possible to conclude that outliers would not affect the categorisation of microclimatic conditions based on walkability.

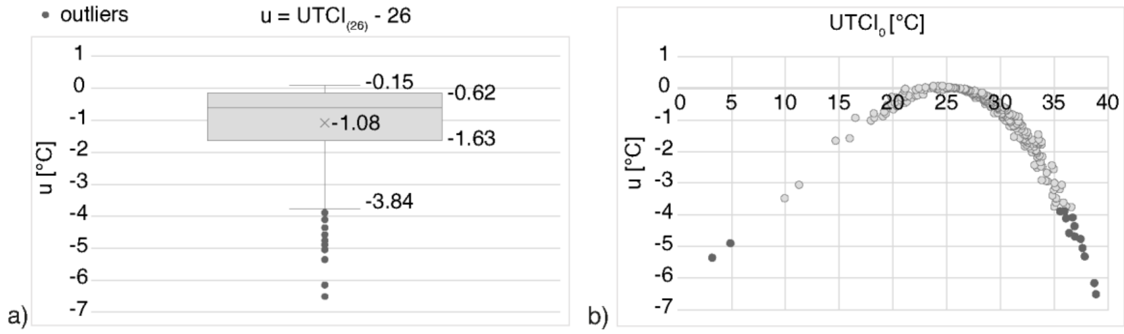


Figure 4.11 a) Box plot presenting the distribution of the variable u, defined as the difference between $UTCI_{(26)}$ (calculated via R_0) and 26 °C; b) relation between $UTCI_0$ and u, showing that outliers are hours in which UTCI value in shade ($UTCI_0$) is far from the threshold value (in this case, 26°C).

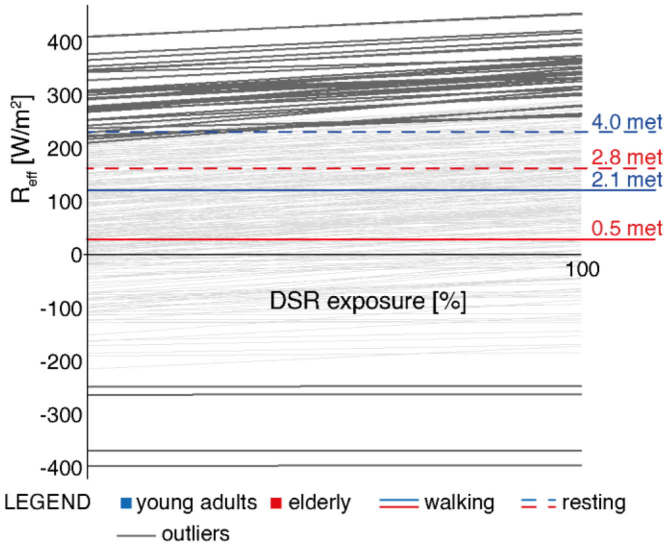


Figure 4.12 Position of hours labelled as outliers in the DSR exposure graph. Since they are located at large distance from the x axis (R_{eff}=0), it is reasonable to conclude that this result does not affect the outcome of the DSR exposure graph categorisation.

Based on this evaluation, the proposed model is a valid tool to evaluate the impact of DSR exposure on pedestrians when microclimatic conditions are not largely different from the selected thermal stress threshold.

4.8.2. Appendix B: Calculation process for two case study hours

The calculation process about the two case study hours isolated in Figure 4.8 is presented. The first set of calculations refers to hour 'm', and the second set refers to hour 'n'.

4.8.2.1. B.1 Hour 'm': 6th July, 10 am DST

Input data from EnergyPlus file:

Dry bulb temperature [°C]	Relative humidity [%]	Wind speed [m/s]	Total sky cover (tenths)
20.9	59	1	0

Direct normal radiation (I) [W/m²]	Diffuse horizontal radiation [W/m²]	Horizontal infrared radiation intensity [W/m²]
526	161	348

LB *Sunpath*: altitude = 42.4°

Eq. (4.3): f_p = 0.233

Eq. (4.2): $R^* = I \cdot a_k \cdot f_p = 526 \cdot 0.7 \cdot 0.233$ = 85.88 W/m²

LB *OutdoorSolarMRT*: T_{mrt} = 33.4 °C

LB *UTCI*: $UTCI_0$ = 24.6 °C

Eq. (4.4): $T^*_{mrt} = \left[T^4_{mrt} + \frac{R^*}{(\varepsilon_p \cdot \sigma)}\right]^{0.25} = \left[(33.4 + 273.15)^4 + \frac{85.88}{(0.95 \cdot \sigma)}\right]^{0.25} - 273.15 = 46.4\ °C$

LB *UTCI*: $UTCI_1$ = 28.4 °C

ΔUTCI = 28.4 - 24.6 = 3.8 °C

Eq. (4.6) $R_0 = \frac{(UTCI_0 - 26) \cdot R^*}{\Delta UTCI} = \frac{(24.6 - 26) \cdot 85.88}{3.8}$ = -31.6 W/m²

Eq. (4.7) $R_{eff} = R^* + R_0$ = 85.88-31.6 = 54.3 W/m²

Eq. (4.8) $R_{eff} = \frac{R^*}{100} \text{expo} + R_0 = \frac{85.88}{100} \text{expo} - 31.6$

Key points on DSR exposure graph:

- Intersection with x-axis (heat stress threshold): $R_{eff} = 0\ W/m^2 = \frac{85.88}{100} \text{expo} - 31.6$ >> expo = 37%
- Walking adaptation threshold for the elderly: $R_{eff} = 29\ W/m^2 = \frac{85.88}{100} \text{expo} - 31.6$ >> expo = 71%

- Walking adaptation threshold for young adults: $R_{eff} = 122\ W/m^2 = \frac{85.88}{100}expo - 31.6$ >> expo = 179%

4.8.2.2. B.2 Hour 'n': 27th August, 12 pm DST

Input data from EnergyPlus file:

Dry bulb temperature [°C]	Relative humidity [%]	Wind speed [m/s]	Total sky cover (tenths)
23.1	62	0	0

Direct normal radiation (I) [W/m²]	Diffuse horizontal radiation [W/m²]	Horizontal infrared radiation intensity [W/m²]
511	232	362

LB *Sunpath*: altitude = 50.2°

Eq. (4.3): f_p = 0.208

Eq. (4.2): $R^* = I \cdot a_k \cdot f_p = 511 \cdot 0.7 \cdot 0.208$ = 74.38 W/m²

LB *OutdoorSolarMRT*: T_{mrt} = 41.9 °C

LB *UTCI*: $UTCI_0$ = 29.1 °C

Eq. (4.4): $T^*_{mrt} = \left[T^4_{mrt} + \frac{R^*}{(\varepsilon_p \cdot \sigma)}\right]^{0.25} = \left[(41.9 + 273.15)^4 + \frac{74.38}{(0.95 \cdot \sigma)}\right]^{0.25} - 273.15 = 52.4\ °C$

LB *UTCI*: $UTCI_1$ = 31.9 °C

ΔUTCI = 31.9 – 29.1 = 2.8 °C

Eq. (4.6) $R_0 = \frac{(UTCI_0 - 26) \cdot R^*}{\Delta UTCI} = \frac{(29.1-26) \cdot 74.38}{2.8}$ = 82.3 W/m²

Eq. (4.7) $R_{eff} = R^* + R_0$ = 74.38+82.3 = 156.7 W/m²

Eq. (4.8) $R_{eff} = \frac{R^*}{100} expo + R_0 = \frac{74.38}{100} expo + 82.3$

Key points on DSR exposure graph:

- Intersection with x-axis (heat stress threshold): $R_{eff} = 0 \frac{W}{m^2} = \frac{74.38}{100} expo + 82.3$ >> expo = -110%
- Walking adaptation threshold for the elderly: $R_{eff} = 29 \frac{W}{m^2} = \frac{74.38}{100} expo + 82.3$ >> expo = -70%
- Walking adaptation threshold for young adults: $R_{eff} = 122 \frac{W}{m^2} = \frac{74.38}{100} expo + 82.3$ >> expo = 55%

4.9. Contribution of this journal paper to this research

This paper proposed a maximum threshold of direct solar radiation exposure for pedestrians based on activity, user profile and environmental conditions, defined as the difference between the energy consumption before feeling exhausted and the energy cost of walking. Two users of diverse walking abilities, a young adult and an elderly person with mobility impairment, were characterised by metabolic activity, walking speed and maximum energy capacity. Based on the theoretical framework, the energy budget of young adults to cope with thermal stress was set as three times higher than for the elderly person. This framework was used to quantify the contribution of direct solar radiation to energy balance and then classify walkability during clear-sky summer hours; the term 'walkable' referred to environmental conditions allowing users to walk without feeling exhausted. The methodology was tested on an open area and an urban canyon in Milan; applicability by urban designers was key in developing a simplified way to evaluate shading needs. This approach could be applied to evaluate solar radiation exposure of pedestrian paths adopting diverse user experiences as an evaluation criterion.

Some assumptions about radiation exchanges were adopted to streamline the simulation process. The focus on direct solar radiation was key in the context of this research, and it was justified by its critical role for outdoor thermal comfort in clear sky conditions. However, surrounding surfaces emit longwave radiation, which impacts pedestrians, contributing to the spatial variation of T_{mrt} at a certain time of the day. In the current work, the surface temperature of the surroundings was hypothesised as one value for the whole urban environment and calculated via Rayman (Section 4.5.3), which is a simplification of radiation exchanges, necessary to isolate the effect of direct solar radiation on human physiology. Furthermore, the time necessary for surfaces to warm up cannot be compared with the instantaneous variation of absorbed radiation experienced when moving from shade to the sun. Radiation exchanges with the sky become more critical during the night, or in overcast conditions, and therefore were given less attention in the simulation process. Reflected solar radiation was not accounted for because of the formulation of Ladybug tools' component. However, it would have a higher impact on T_{mrt} in the case of urban materials characterised by high reflectivity.

As stated in Chapter 3, the approach adopted in this research assigned a central role to users. This chapter demonstrates how designing open spaces must begin by analysing who will use them, and how they would be impacted by the designed environment. The results of this paper are applicable in practice; urban designers, together with stakeholders and planners, could adapt shading goals to diverse users, comparing different magnitudes of physiological impact from being in the sun. The knowledge presented fulfils the need for accessible communication through the comparison of scientific concepts (i.e., energy balance) to conditions experienced by everyone, such as being exhausted from physical effort. Moreover, this knowledge is made accessible via the use of Grasshopper, which allows urban designers to calculate DSR thresholds for various locations. The following step is the calculation of the actual DSR exposure of pedestrian paths, which is addressed in Chapter 5.

5. DYNAMIC ANALYSIS OF A PEDESTRIAN NETWORK: THE IMPACT OF SOLAR RADIATION EXPOSURE ON DIVERSE USER EXPERIENCES

5.1. Research area outline

Results of the user-centred approach presented in Chapter 4 aim to inform urban designers in practice. Once assessed that a maximum threshold of solar radiation exposure can be defined based on diverse users, the next step is to apply this knowledge by investigating the exposure to direct solar radiation of pedestrian paths. The paper presented in this chapter proposed a methodology for modelling a pedestrian network, performing shading analysis, and simulating pedestrians using it. It should be noted that the simulation of users was not performed to classify pedestrian paths based on the foot traffic; instead, the adopted perspective was to analyse how suitable it would be to use a pedestrian network at different times. The network was thus considered as a mobility infrastructure, the use of which was affected by direct solar radiation exposure. An extensive review was conducted to analyse which tools are available to investigate walkability, with a specific focus on how shadows were modelled. In addition to the two user profiles defined in Chapter 4, wheelchair users and individuals collected under the term 'ITCs', i.e., infants, toddlers and caregivers (Bernard van Leer Foundation, 2019) were included.

5.2. 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 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.

5.2.1. 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., 2021a; 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.

5.2.2. 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 5.1. The table excludes tools considering only the presence of trees and overhangs without further investigation on their position, spacing or shading effect.

Table 5.1 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?

Reference	Name	Unit of analysis	Data source		Variables of interest	
			Digital	Observation	Trees	Shade
(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., 2021b)	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

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.

5.2.3. 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 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.

5.3. 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 5.4.1). The user experience was evaluated for a range of solar radiation exposure during key times of the year (Section 5.3.1.3). Four user profiles were delineated assessing walking speed and usability of stairs as a proxy for diverse walking abilities (Section 5.3.2); different user perspectives were systematically adopted. The analysis phase addressed the above three research questions.

5.3.1. 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.

5.3.1.1. 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.

5.3.1.2. 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.

5.3.1.3. 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.

5.3.2. 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 and 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 and 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 5.2.

Table 5.2 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)

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 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).

5.3.3. 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 (Figure 5.1a). 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’) (Figure 5.1b). 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).

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.

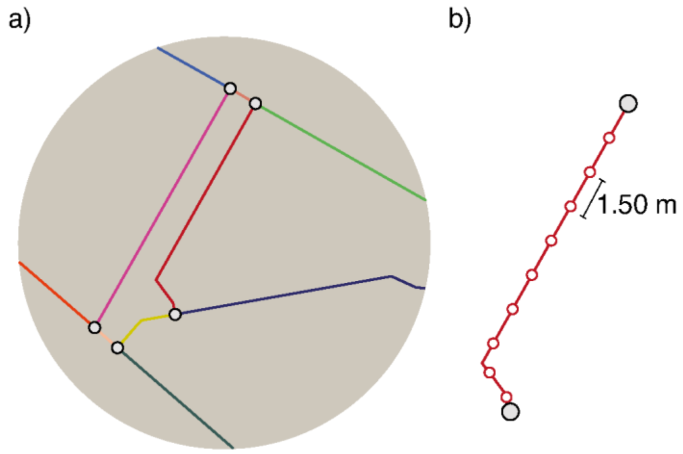


Figure 5.1 Segmentation process: a) network segmentation, b) subdivision of segments in steps.

5.3.3.1. 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.

5.3.3.2. 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.

5.3.3.3. 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 5.3.2), 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).

5.4. Results

5.4.1. 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*, 2021). 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.

5.4.2. Modelling the case study area

The AOI was defined by drawing a circle of 400 m radius around the two metro station accesses (Figure 5.2a). 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 (Figure 5.2b). 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[18], network segments of inclination above 5% are regarded as inaccessible, except for ramps of length 10 m inclined of maximum 8%.

[18] DM 14 June 1989, no. 236

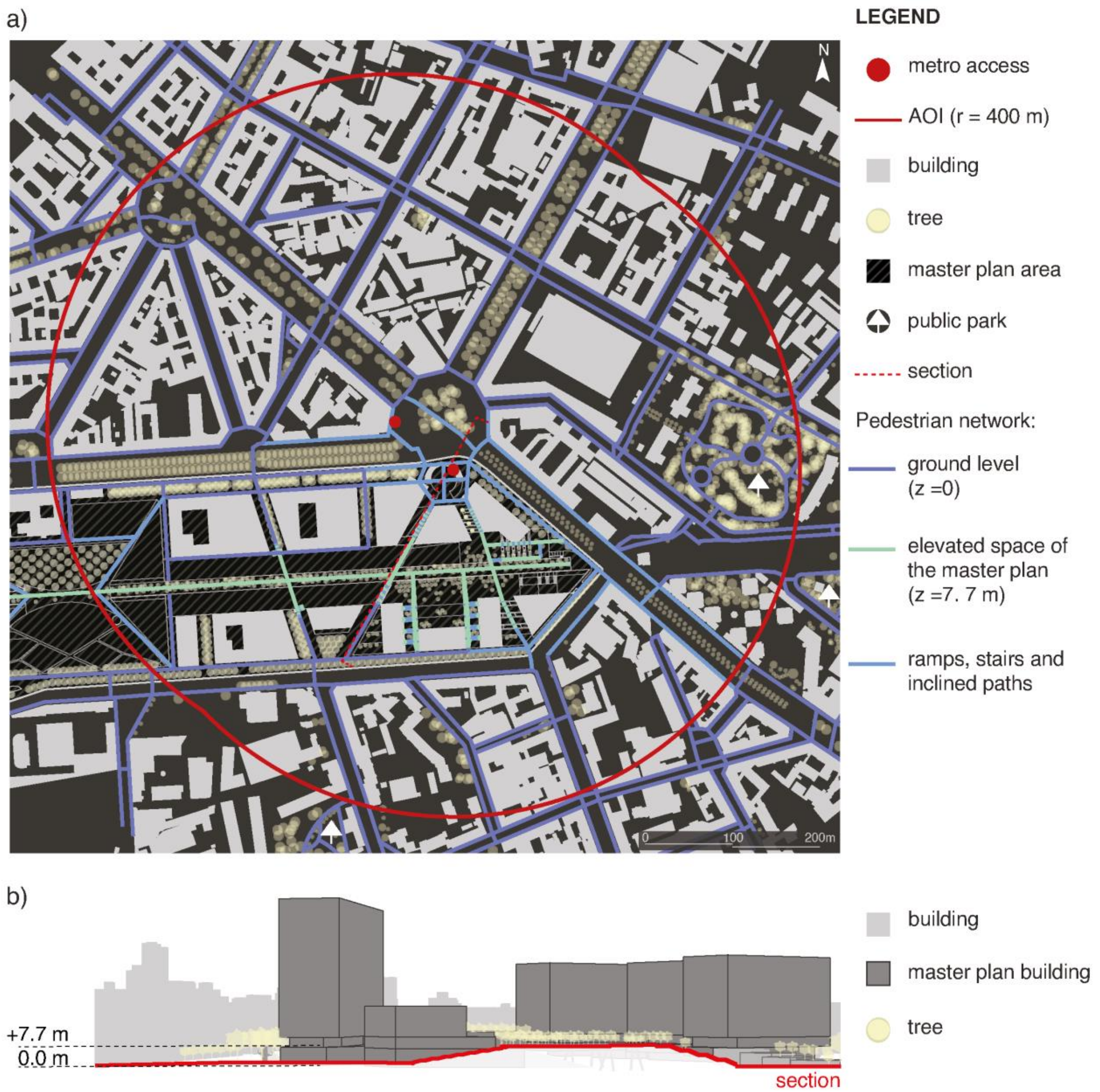


Figure 5.2 a) Case study area modelled in Rhino with network segments assigned to different levels; b) Section of the master plan area.

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, 2022c), 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 Figure 5.3. Trees in the master plan area were assimilated to the same class sizes.

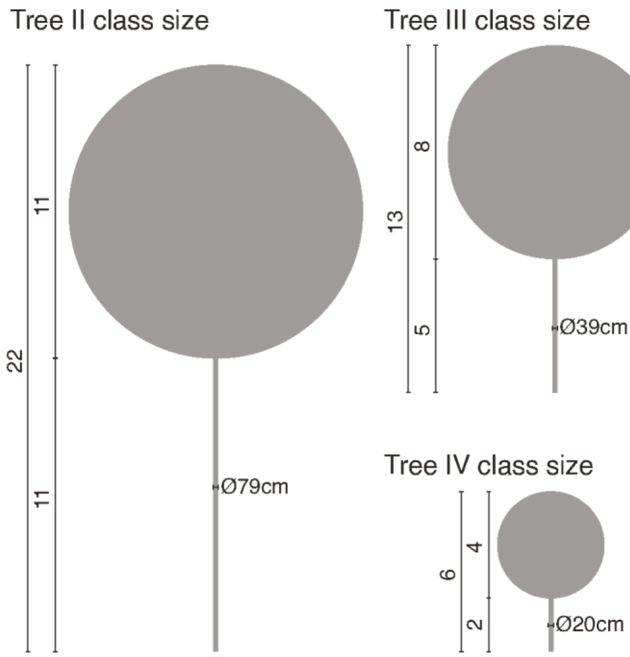


Figure 5.3 Trees modelled as representative of class sizes, according to the Municipality documentation.

5.4.3. 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 (Sections 5.7.1 and 5.7.2, respectively).

The distribution analysis aims at visualising how shade is distributed along the network segments. Figure 5.4 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.

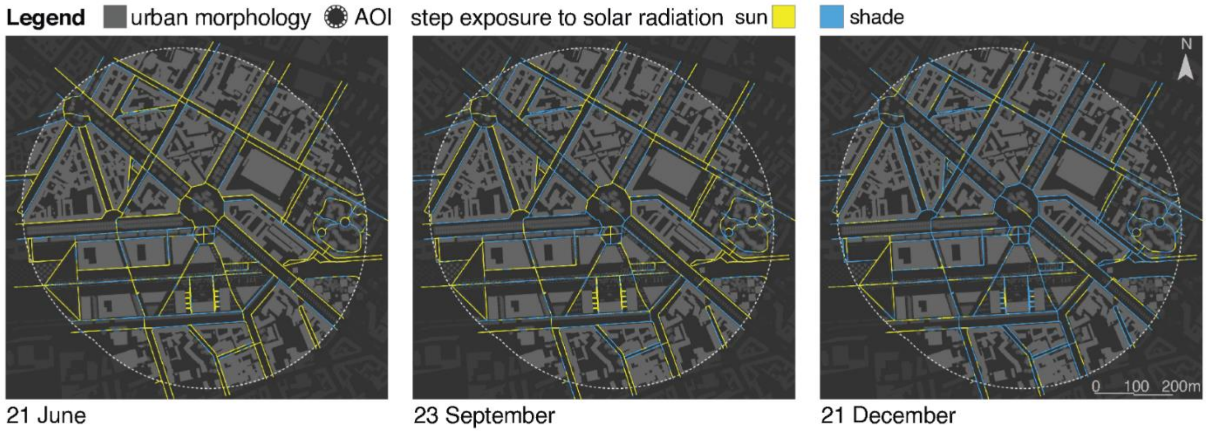


Figure 5.4 Distribution analysis of shading on the pedestrian network on all three simulated days at 1 pm.

In Figure 5.5, 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.

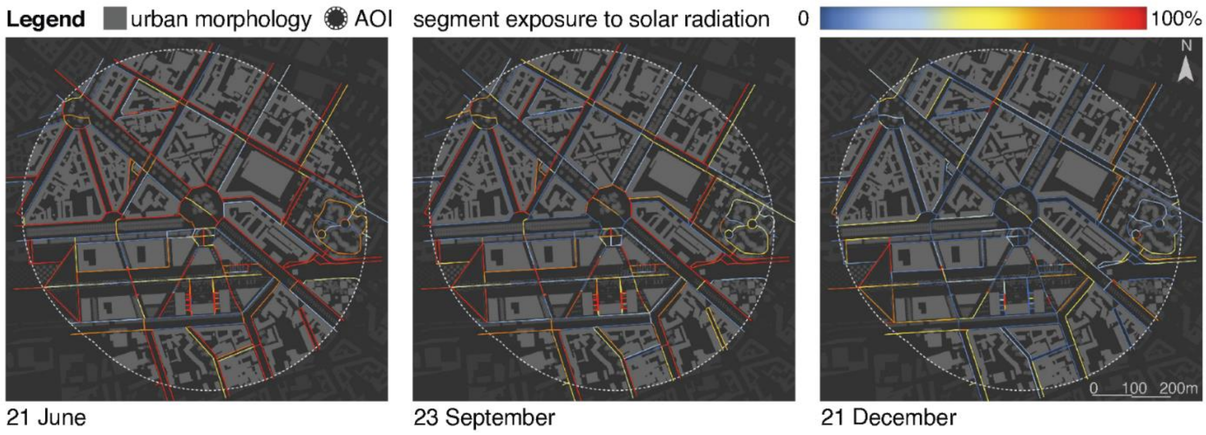


Figure 5.5 Solar radiation exposure of the pedestrian network on all three simulated days at 1 pm.

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.

5.4.4. 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. Figure 5.6 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.

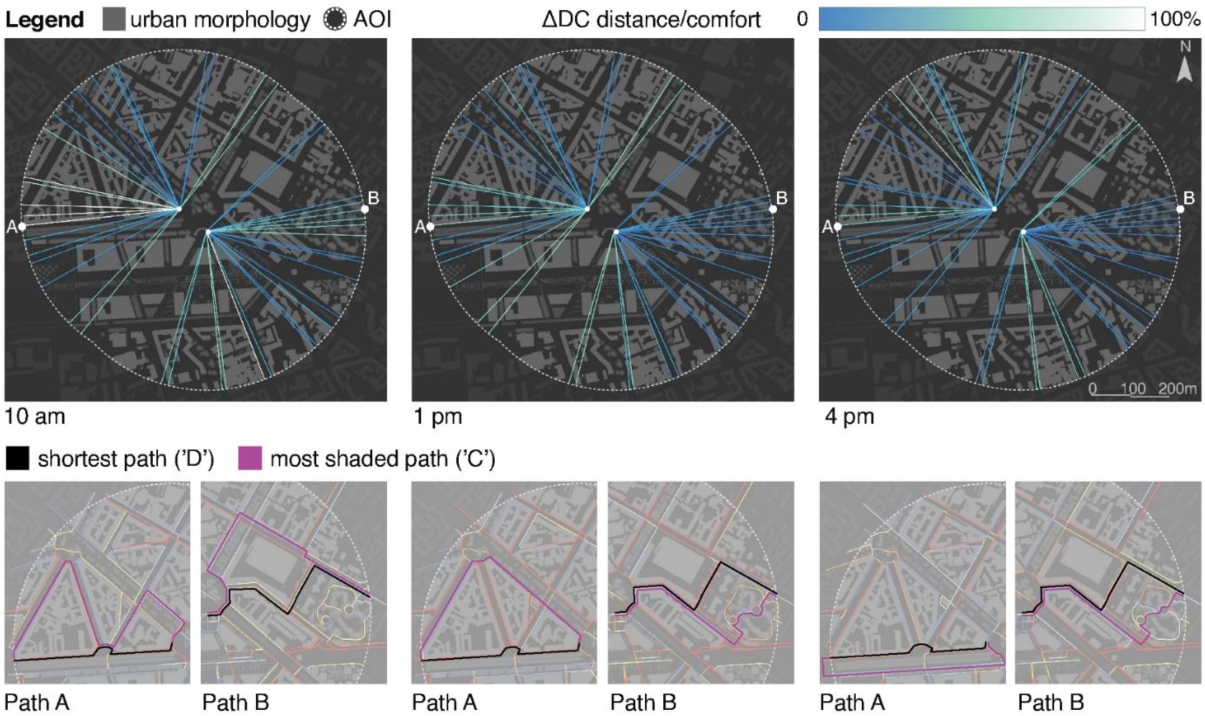


Figure 5.6 Difference between the shortest and the most comfortable path (in terms of solar radiation exposure) on 21 June at all three simulated hours. The focus on two specific paths illustrates to what extent the most shaded paths would differ during the summer solstice day.

The same exercise was repeated for all 9 days and hours combinations. Figure 5.7a 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 Figure 5.7b, 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.

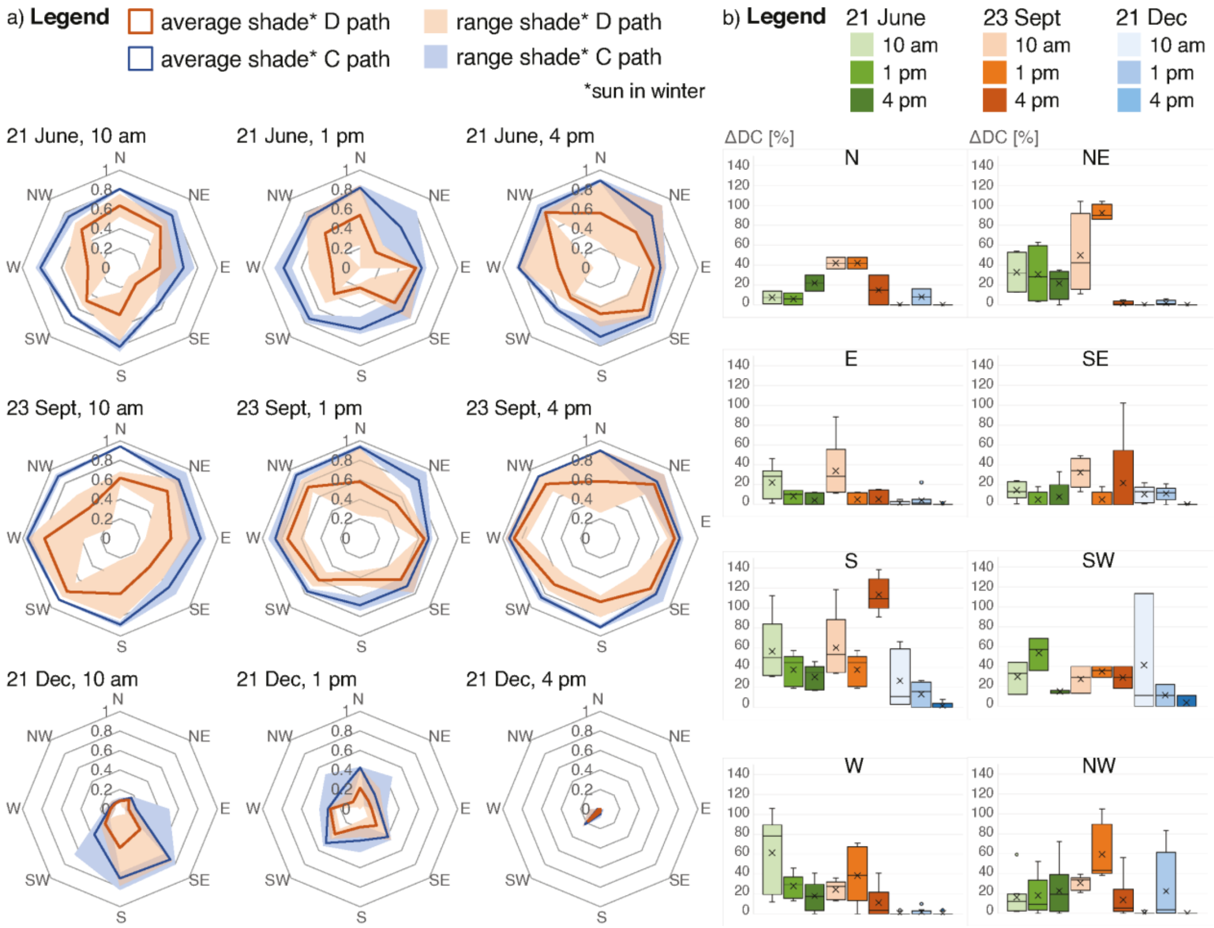


Figure 5.7 Synthesis of the ΔDC analysis designed to provide insights based on travel direction and days and hours combination: a) range and average of shaded path ratio for each travel direction; b) ΔDC values divided by trip orientation and days and hours combination.

5.4.5. 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 Figure 5.8 (and more combinations are illustrated in Appendices C, D and E, positioned in Sections 5.7.3, 5.7.4 and 5.7.5, respectively).

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 Figure 5.8, the absence of stairs or steep ramps 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.

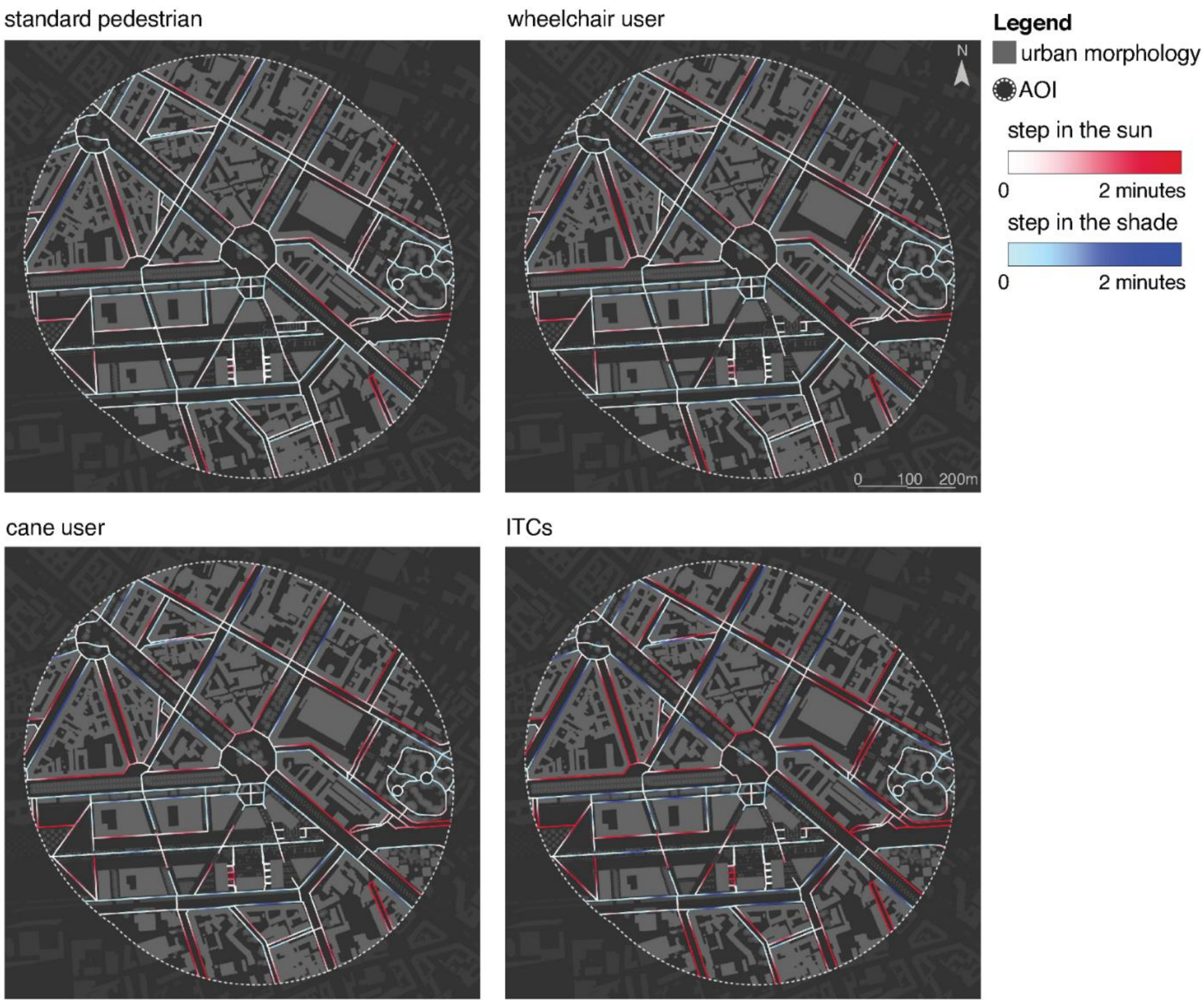


Figure 5.8 Shade accessibility analysis on 21 June at 1 pm.

5.5. 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.

5.5.1. 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 5.4.4, 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, 2021a), with the proposed methodology 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 5.1, 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.

5.5.2. 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 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.

5.5.3. 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 5.3.2, 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 5.2.1); 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.

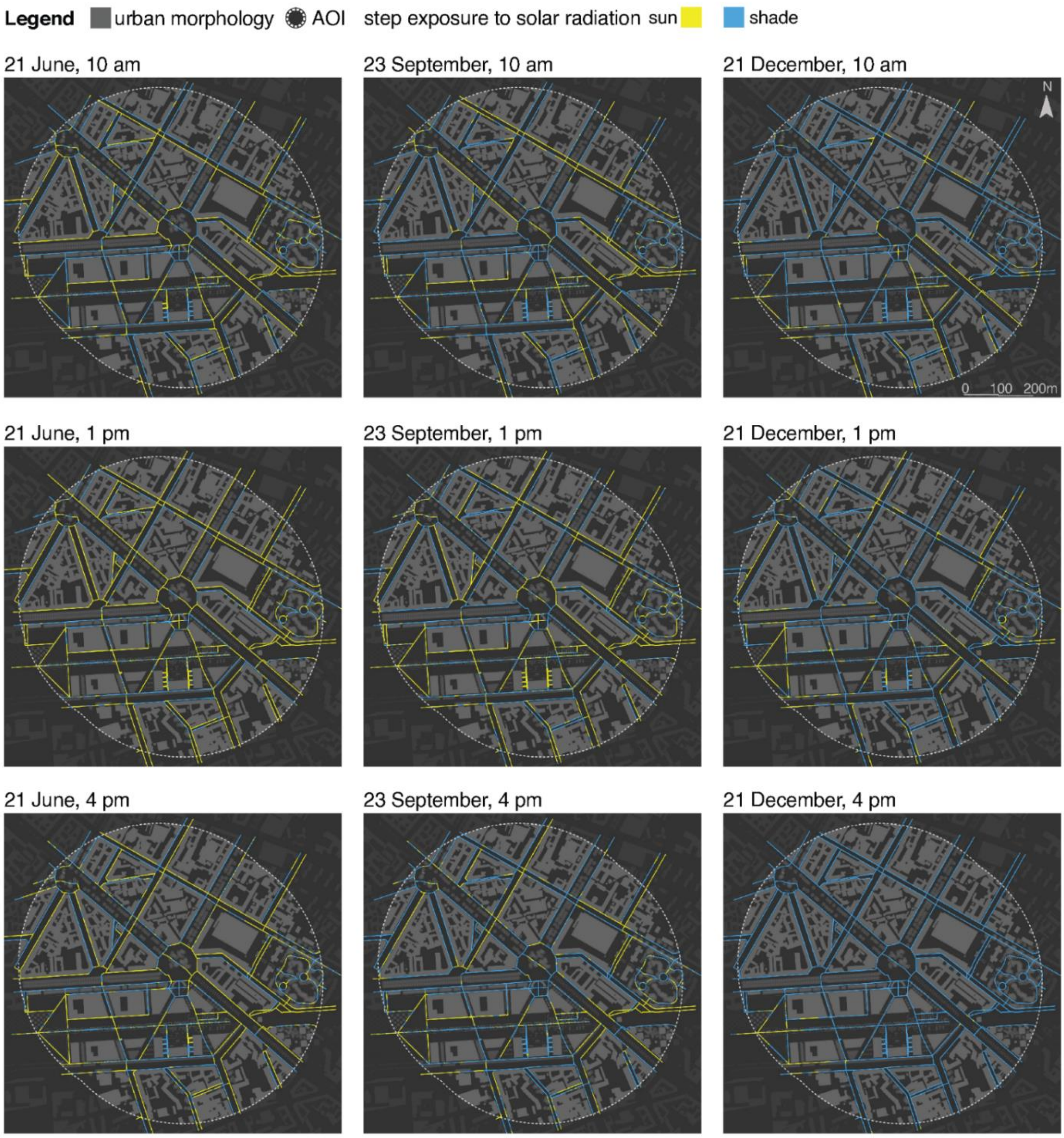
5.6. Conclusions

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.

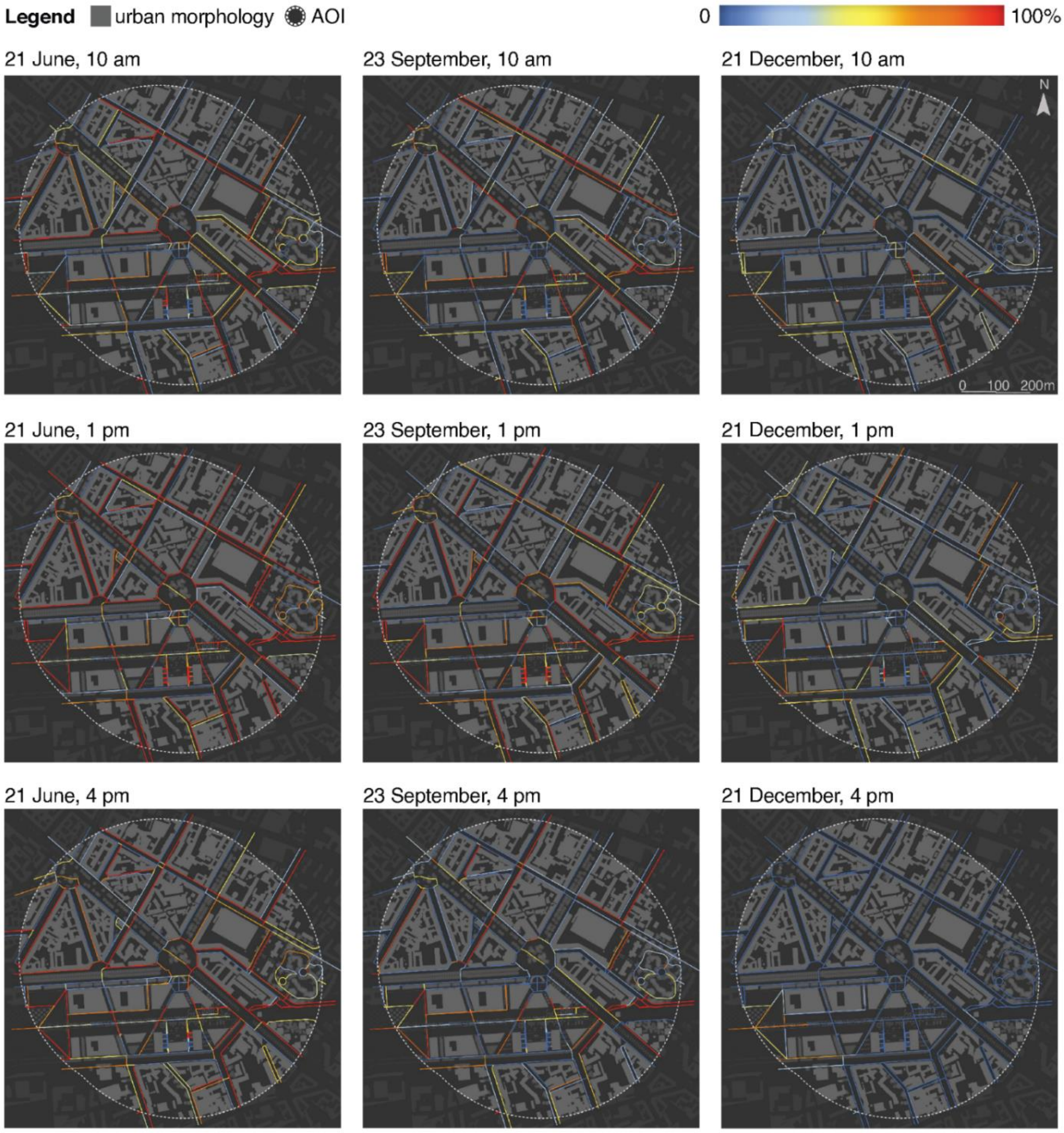
Cities are spaces where people are impacted by multiple factors and multidisciplinary approaches are key to improving liveability, therefore urban designers need specific instruments to implement them in practice. The adopted practical approach analysed a specific issue that could be addressed through 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.

5.7. Appendices

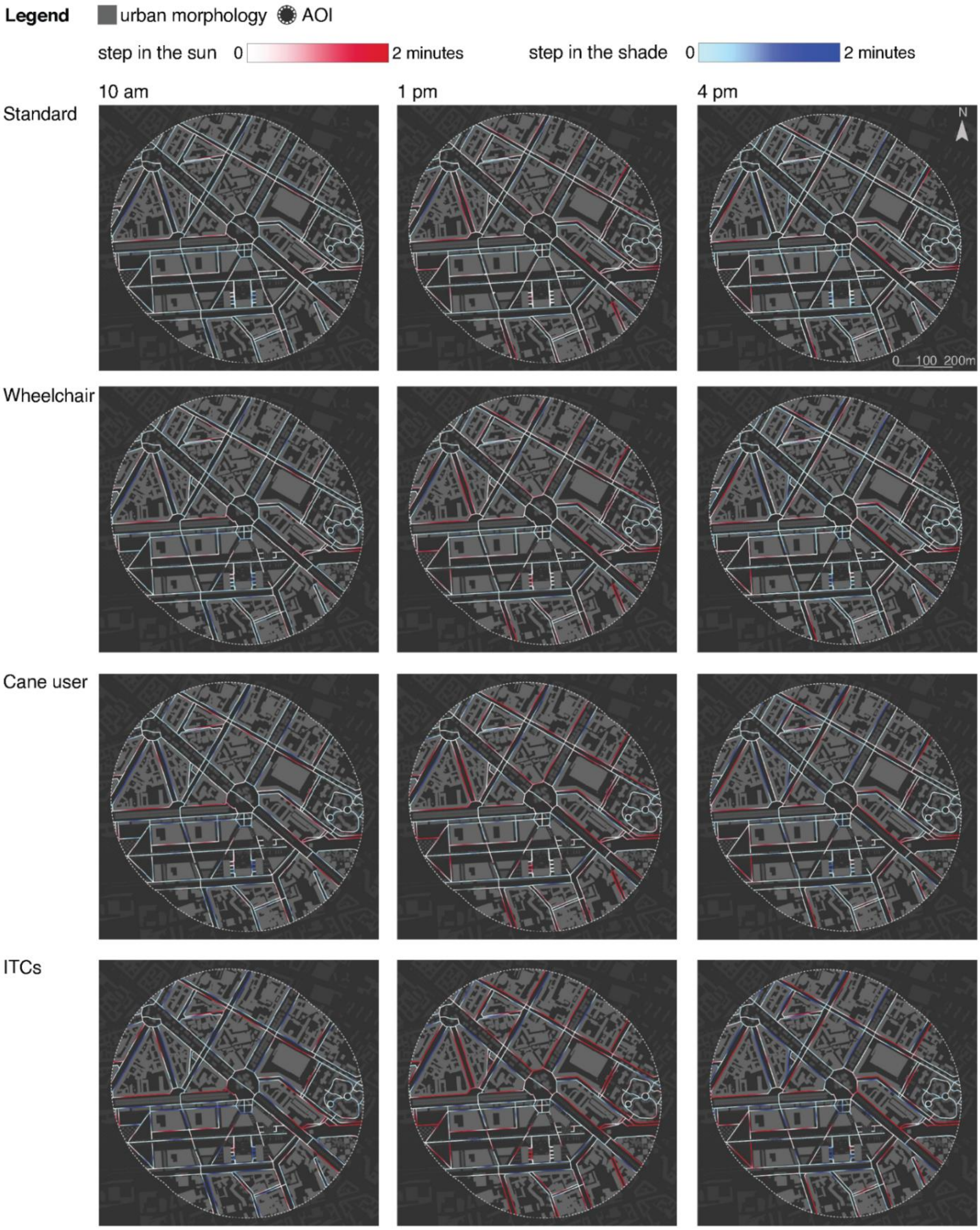
5.7.1. Appendix A: Distribution analysis for all days and hours combinations.



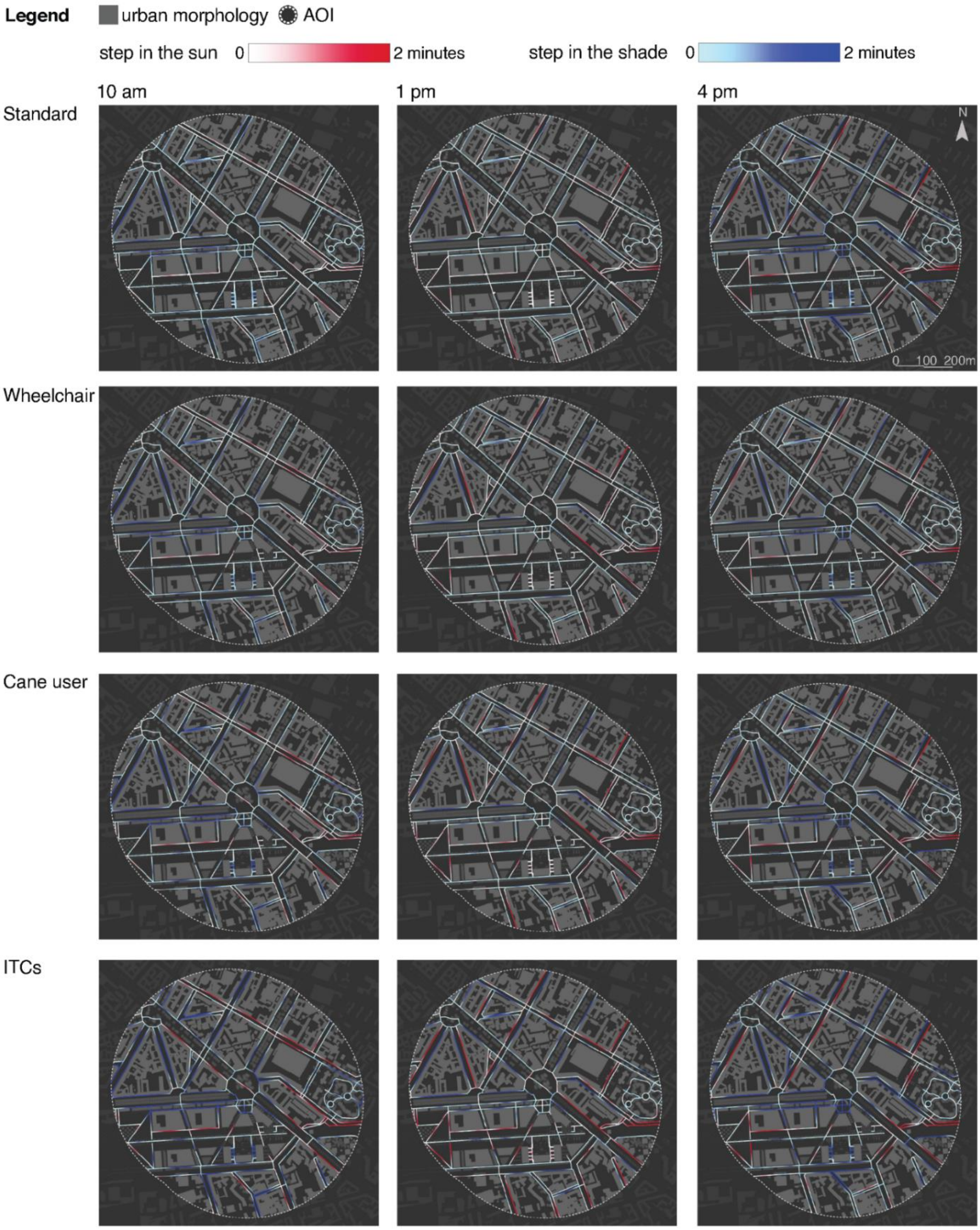
5.7.2. Appendix B: Solar radiation exposure analysis for all days and hours combinations.



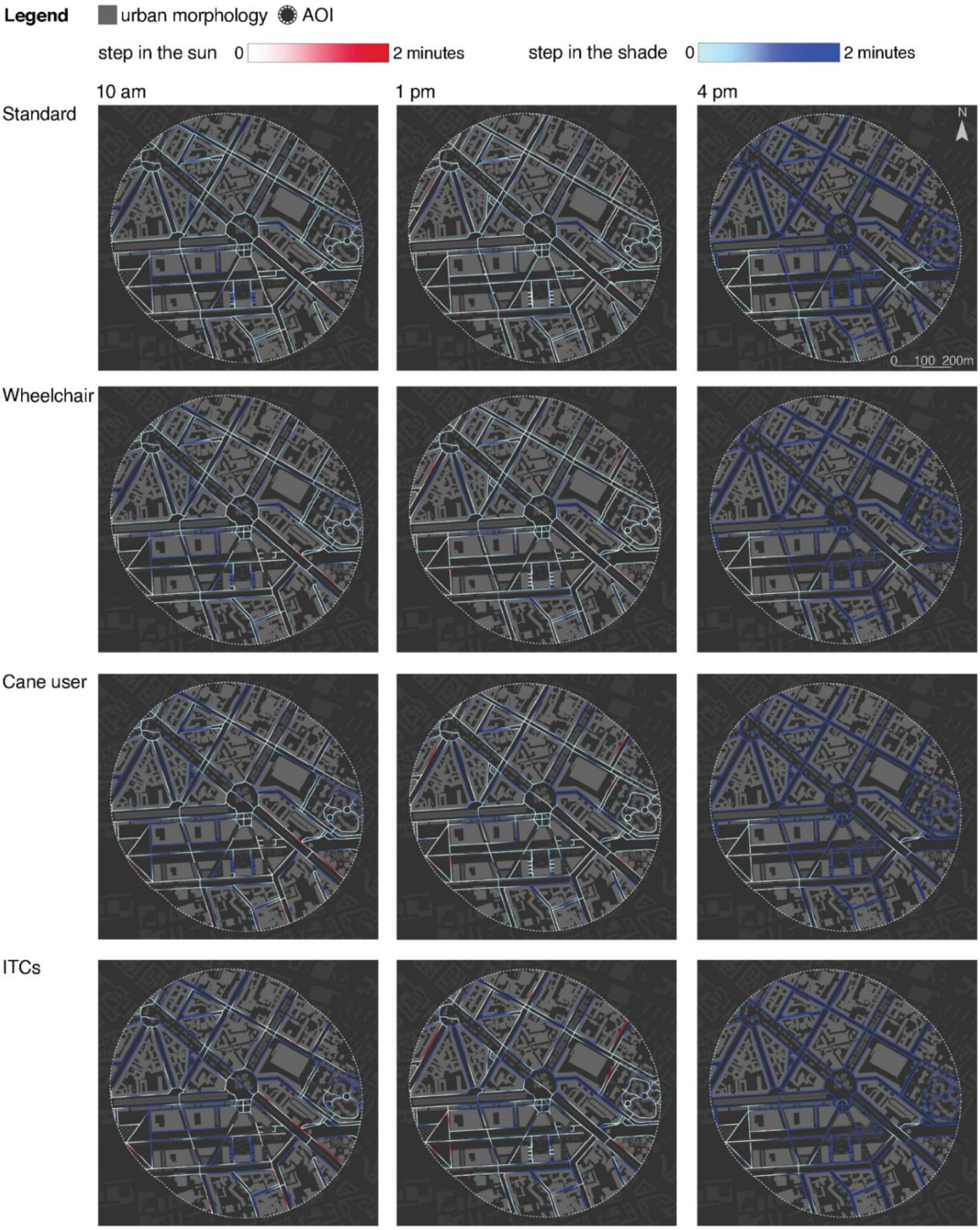
5.7.3. Appendix C: Shade accessibility analysis on 21 June



5.7.4. Appendix D: Shade accessibility analysis on 23 September



5.7.5. Appendix E: Shade accessibility analysis on 21 December



5.8. Contribution of this journal paper to this research

The walking experience is impacted by the solar radiation exposure of pedestrian paths; this is a critical consideration for walkability assessment. The systematic methodology presented 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 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 reducing thermal stress.

The upscaling process performed in this chapter moves from the users to the context in which they travel. The methodology for modelling the network was developed considering simulation times, usability by designers and scale of design. By combining the theoretical knowledge of Chapter 4 and the shading analysis presented in this chapter, it is possible to analyse pedestrian experiences in the same context, which were varied based on the personal characteristics of the users and the dynamic position of the sun. The spatial visualisation of not only DSR exposure but also of potential trips and accessibility issues on the network, represents consistent information for urban designers to propose the installation (or planting) of shading devices. In Chapter 6, a design tool to perform this task is presented.

6. A DESIGN WORKFLOW FOR EFFECTIVE SOLAR SHADING OF PEDESTRIAN PATHS

6.1. Research area outline

This paper contributes to the implementation of microclimate knowledge in urban design practice. After assessing the impact of DSR on diverse users, and analysing how the walking experience on a network is affected by users' and environmental characteristics, the final step is implementing shading strategies beneficial for users. A methodology to integrate shading implementation into the design process was developed. The main goal in elaborating it was to ensure the effectiveness of the design proposals, i.e., the positioning of shading devices. In Section 5.2.2, reviewing the existing walkability analysis tools showed that in some cases, the generalised presence of trees led sidewalks classified as "shaded" and "comfortable". This paper focuses on ensuring that shading devices are installed to provide pedestrians with shade, focusing on specific hours when sidewalks would result in the shade.

For developing this part of the research, discussions with practitioners were critical. Two main insights were considered key. The first one was about the level of detail required by different design phases. It was pointed out that the context in which designers would use the design tool could refer to a preliminary study, in which a rough idea of solutions required would be needed, or an advanced phase of the project, where the specific location of one tree would be necessary. The second point that was addressed in this paper refers to the resources available for a project. It is evident that the implementation of climate-responsive solutions in urban design requires additional resources in the form of time, availability of software, and dedicated practitioners. However, these resources might be limited or not available, yet this should not be a barrier to undertaking the task. This understanding led to adapting the same systematic workflow based on required levels of detail and availability of resources, simulating different professional and project contexts; therefore, different applicative processes were defined to apply the results of this research in practice.

6.2. 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 (Nikolopoulou, 2011). Especially under clear sky conditions, solar radiation has a large impact on the human heat balance (Kenny et al., 2008; Matzarakis et al., 2010), therefore exposure to solar radiation can lead to outdoor heat stress (Aleksandrowicz & Pearlmutter, 2023).

Microclimatic conditions of pedestrian paths deserve critical attention because walking is impacted by environmental factors (Forsyth, 2015). Outdoor heat stress has been demonstrated to influence pedestrians' behaviour due to increase in the perceived travel time (Melnikov et al., 2022) and altering of walking speed (Mouada et al., 2019; Obuchi et al., 2021); additionally, the presence of shade was reported to affect route choice (Melnikov et al., 2022).

Shading the walking paths is one of the most effective strategies to improve pedestrians' comfort in summer sunny conditions (Labdaoui et al., 2021a; Pearlmutter et al., 2007; Sanusi et al., 2017; Turner et al., 2023). Metrics such as the Shade Index (Aleksandrowicz et al., 2020) 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 (Peeters et al., 2020), only the sidewalk surface (Aleksandrowicz & Ozery, 2023; Azcarate et al., 2021; Buo et al., 2023), or the linear path length (Perez, 2020).

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 (2023); 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 (Whiting, 2023). 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 minutes route) (Maricopa Association of Governments, n.d.; Turner et al., 2023).

6.2.1. 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 (Nikolopoulou, 2004). Trees impact energy balance in two ways, by converting energy into latent heat (evapotranspiration), and by blocking and absorbing direct solar radiation (shading) (Rahman et al., 2020). Pace et al. (2021) 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 (Pauleit et al., 2017); specifically, trees are considered a critical strategy to improve thermal comfort (Nasrollahi et al., 2020; Sanusi et al., 2017). In addition to trees, artificial shading devices such as overhead covers (Lee et al., 2020; Shashua-Bar et al., 2011) and stand-alone canopies (Palomo Amores et al., 2023) can be used to screen urban streets from solar radiation (Middel et al., 2021). Artificial devices are a successful strategy, for instance, when plants have not yet reached maturity (Palomo Amores et al., 2023) and in existing urban environments (Rossi et al., 2020), where there is no room for plants to grow (Lee et al., 2020). Natural and artificial shading devices can also be combined, as demonstrated by Peeters et al. (2020) simulating a pergola covered with vegetation.

6.2.2. Problem statement and approach

Urban design is a process of balancing conflicting interests, comfortable microclimatic conditions being only one of them (Erell, 2008). Similarly, the installation of trees is subject to various factors: economic, cultural, ecological, and aesthetic (de Abreu-Harbich et al., 2015). Researchers have already investigated the use of trees to shade pedestrian paths, aiming at quantifying the shade coverage (Buo et al., 2023; Perez, 2020), assessing the effect of various shade coverage on thermal comfort (Lachapelle et al., 2023; Park et al., 2019; Peeters et al., 2020) and analysing the impact of tree geometry (Aleksandrowicz & Ozery, 2023; Azcarate et al., 2021; Langenheim et al., 2020; Morakinyo et al., 2017; Zheng et al., 2018). 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 (Lindberg et al., 2008), Ladybug tools (Roudsari & Pak, 2013), RayMan (Matzarakis et al., 2010), ENVI-met (ENVI-met GmbH, n.d.), and TUF-Pedestrian (Lachapelle et al., 2022). Keibach and Shayesteh (2022) 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 (Diéguez et al., 2017), 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 (Kanters et al., 2014). 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 (Horvat et al., 2011).

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, the visual scripting interface for Rhino, was selected (*Grasshopper*, n.d.; *Rhinoceros*, n.d.). Rhino allows urban designers to either import 3D models from other modelling tools (Keibach & Shayesteh, 2022), 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.

6.3. 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 (2020) was followed to analyse the shading effect of urban morphology in Grasshopper. The term 'design tool' is a reference to the work by Ratti (2002, p.9), who proposed 'a simple reactive tool, allowing for comparison of different architectural and urban options'. 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 (Fong et al., 2021). The design tool was accordingly divided into three sections: definition of scenarios, simulation, and selection (Figure 6.1). 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 (Section 6.7.1), the design tool is presented step-by-step.

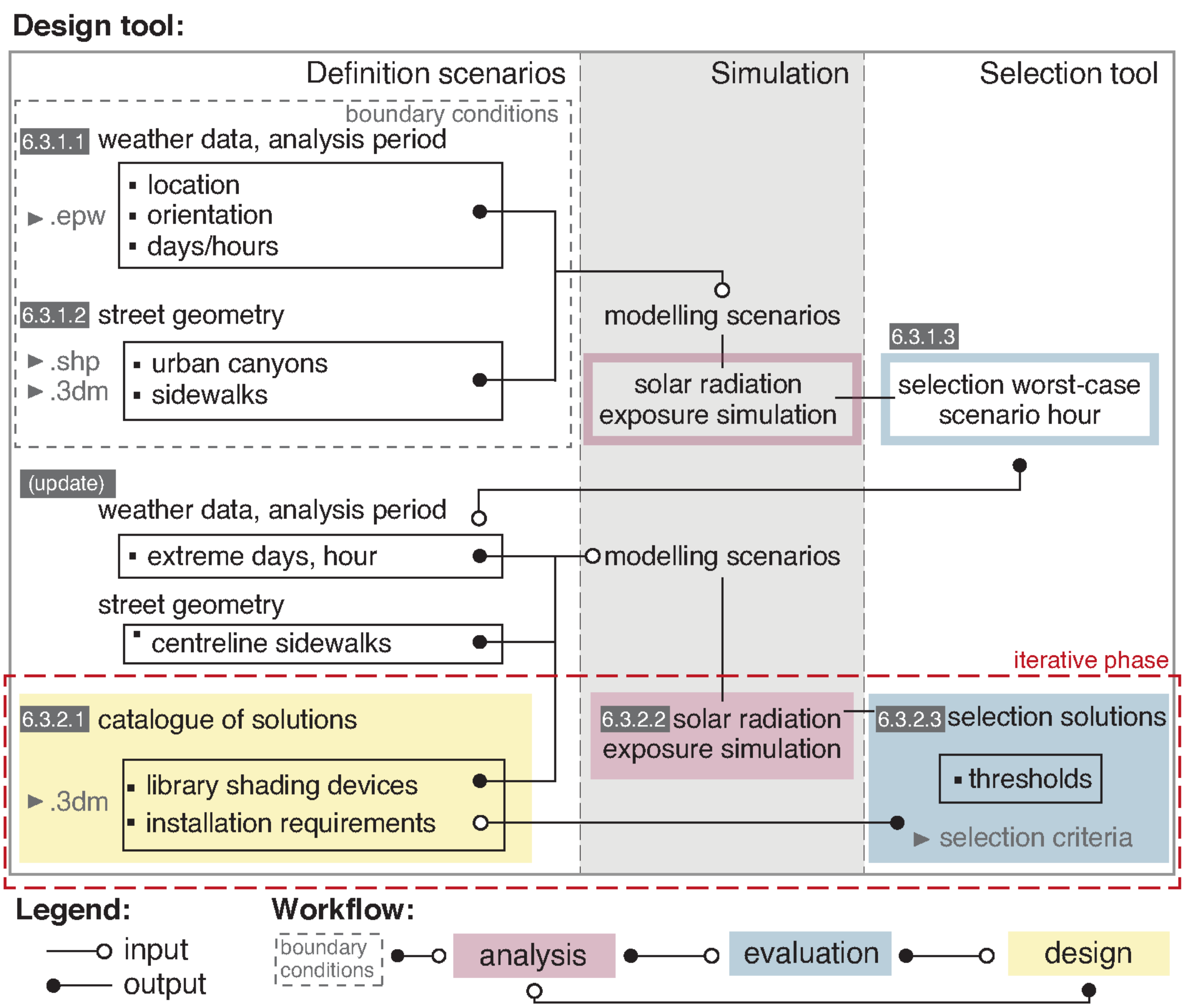


Figure 6.1 Scheme illustrating the proposed design workflow for an effective installation of shading devices. The workflow relies on a design tool developed in Grasshopper. Black rectangles correspond to clusters in the Grasshopper code. Grey arrows highlight input data by designers, and dark grey boxes report reference sections in this thesis.

6.3.1. 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.

6.3.1.1. 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 three hours each (9-11 am; 12-2 pm; 3-5 pm), and calculations were performed for the central hours: 10 am, 1 pm and 4 pm, 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 (*EnergyPlus*, n.d.) and imported into the design tool via Ladybug (v. 1.5.0).

6.3.1.2. 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, 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 (Ahmad et al., 2005). 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.

6.3.1.3. 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 (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). 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 (Figure 6.2).

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 three hours 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 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.

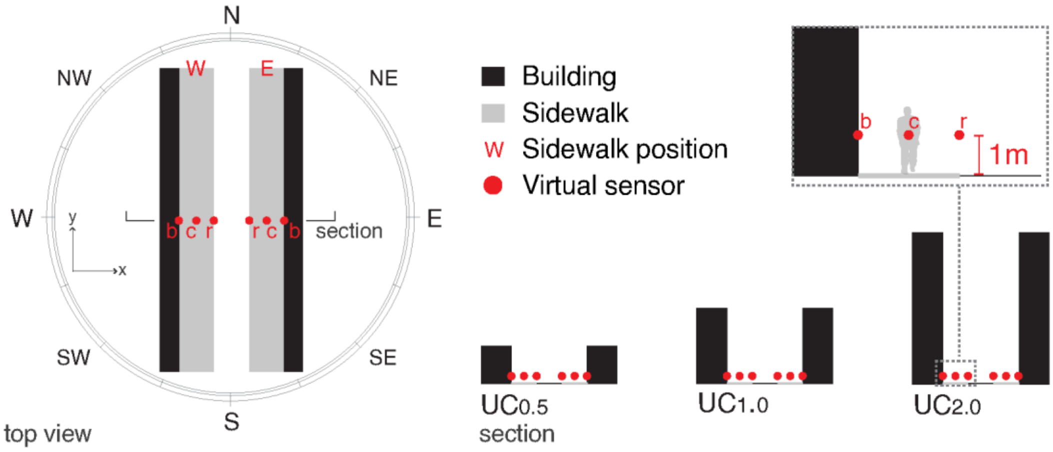


Figure 6.2 Scheme of urban canyons analysis. Urban canyons are labelled UC_N, where N=H/W. Red dots indicate the simulated virtual sensors (boundary of the sidewalk with the building, centre of the sidewalk, boundary of the sidewalk with the road).

6.3.2. 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.

6.3.2.1. 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.

6.3.2.1.1. 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 Figure 6.3.

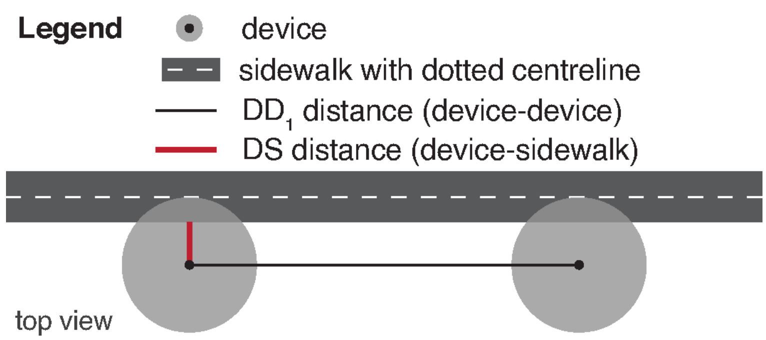


Figure 6.3 Scheme of parametric distances defined for installing shading devices to shade sidewalks.

6.3.2.2. 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 (2020): 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 6.3.1.3. 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.

6.3.2.3. 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.

6.4. 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.

6.4.1. 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 (Municipality of Milan, 2022a). Being the most populated Italian city after the capital (Rome) (ISTAT, 2023), it is a critical city in the context of solar radiation exposure of pedestrian paths. Further, the Municipality of Milan provides open data (Municipality of Milan, n.d.-a) and extensive documentation about urban design guidelines and recommendations (Municipality of Milan & AMAT, 2021) 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.

6.4.1.1. 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 three hours is reported in Appendix B (Section 6.7.2): results vary based on H/W ratio and orientation. The worst-case scenarios selected for the design phase are presented in Table 6.1. If one sidewalk was exposed to solar radiation for multiple periods in summer, the central hour (1 pm) was selected to prioritise lunchtime pedestrians; furthermore, shading pedestrian paths at 1 pm 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 am, 1 pm and 4 pm, additional simulations were performed at 9 am and 6 pm.

Table 6.1 Worst-case scenario hours assigned to urban canyons; detailed results of the analysis are reported in Appendix B (Section 6.7.2).

	$UC_{0.5}$	**$UC_{1.0}$**	**$UC_{2.0}$**
N	1 pm	1 pm	10 am
NE	1 pm	1 pm	1 pm
E	4 pm	4 pm	1 pm
SE	4 pm	4 pm	4 pm
S	6 pm	6 pm	6 pm
SW	10 am	10 am	10 am
W	1 pm	1 pm	1 pm
NW	1 pm	1 pm	1 pm

6.4.1.2. 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 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.

6.4.2. 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.

6.4.2.1. 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 (Municipality of Milan, 2022c). Specific plants included in the census database (Municipality of Milan, n.d.-b) were modelled: trees selected belonged to a row of plants along a sidewalk and were of height close to the dimension reached to maturity (Municipality of Milan & AMAT, 2021). Table 6.2 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 (Municipality of Milan, 2022c).

Table 6.2 Morphological parameters of the trees included in the library.

Class size	Maturity height[1] [m]	Specie[1]	Canopy shape[1]	Tree ID[2]	Height[2] [m]	Canopy width[2] [m]	Øtrunk[2] [m]	Trunk height[2] [m]
II	15-25	*Celtis australis*	Sphere	13875	22	11	0.79	11
III	8-15	*Acer negundo*[3]	Sphere	134302	13	8	0.39	5
IV	<8	*Prunus cerasifera*	Sphere	37367	6	4	0.20	2

[1] (Municipality of Milan & AMAT, 2021); [2] (Municipality of Milan, n.d.-b); [3] specie object of monitoring and controlling measures.

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 (CRA – Carlo Ratti Associati, 2021b). 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 (Section 6.7.3).

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 6.3.

Table 6.3 Minimum requirements and suggested distances for positioning shading devices.

Device	**Minimum root space radius[1] [m]**	**Minimum permeable area[1] [m²]**	**Minimum DS (squared/circular surface) [m]**	**Adopted buffer zone [m] (DS distance)**	**Suggested distance between devices[2] [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	-	-	-	-	-	-

[1](Municipality of Milan, 2022c); [2](Municipality of Milan & AMAT, 2021).

6.4.2.2. 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 (Municipality of Milan & AMAT, 2021). Starting from the minimum installation requirements (Table 6.3), 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. Figure 6.4 presents guidelines that update the installation recommendations reported in Table 6.3 by integrating the shading effect.

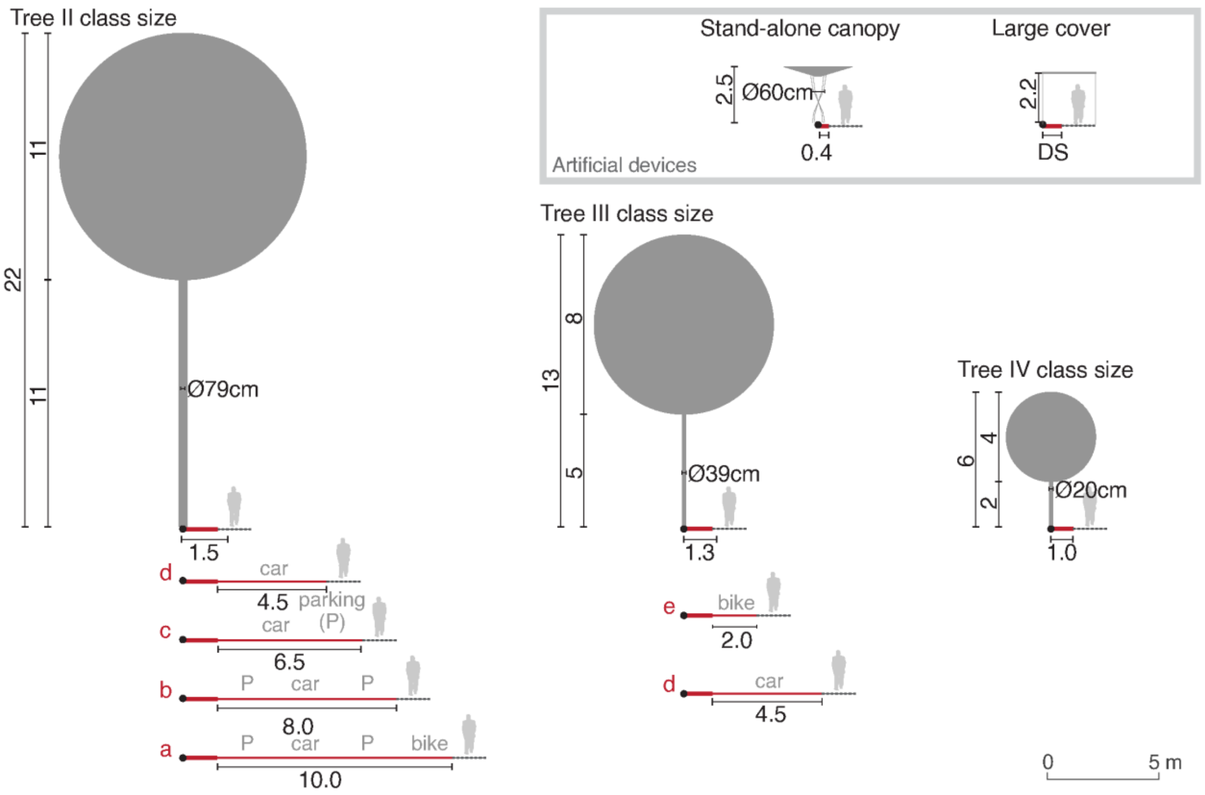


Figure 6.4 Catalogue of solutions for Milan with recommended installation guidelines.

6.4.2.3. 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 6.4.1.1 (Table 6.1).

Figure 6.5 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 6.1), this could be considered low priority in terms of shading requirements. On average, simulations lasted 36 ± 21 s[19]. The process could be repeated for other types of urban canyon (H/W=0.5 and H/W=2.0).

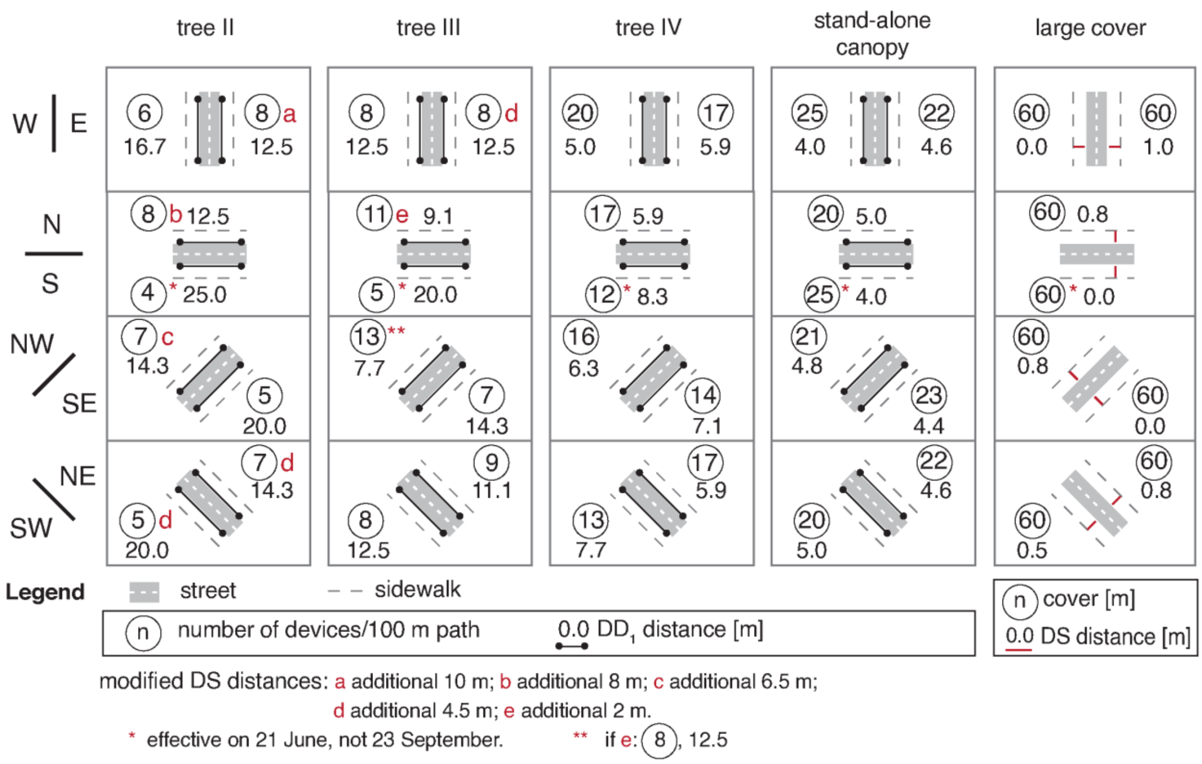
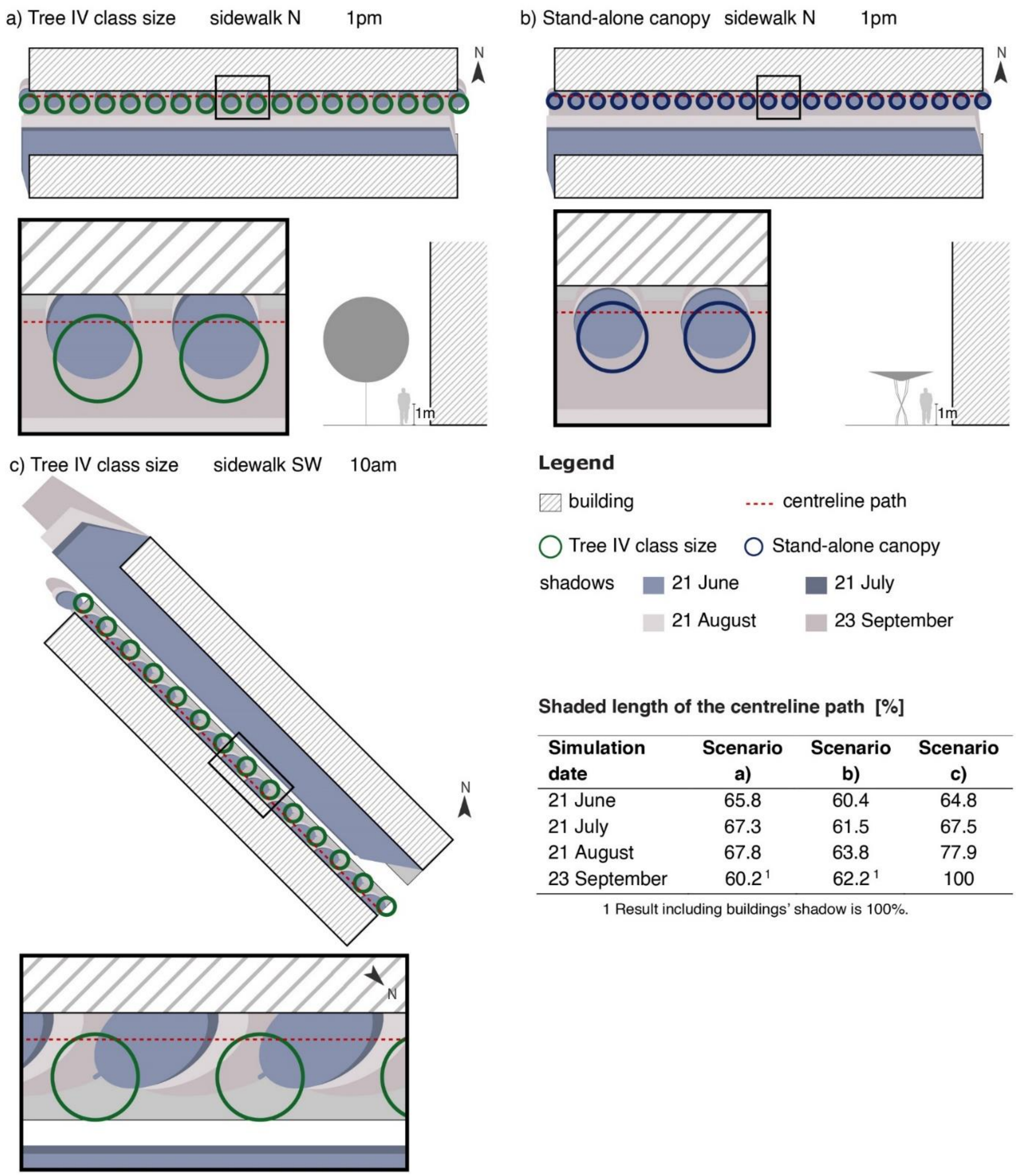


Figure 6.5 Suggested number of devices and distances to shade 60% of the pedestrian path on the respective worst-case scenario hour. Red notes refer to Figure 6.4.

Figure 6.6 illustrates three device-sidewalk combinations of Figure 6.5. The devices were positioned at the distance reported in Figure 6.5[20] 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 – Section 6.7.2). The shading effect of devices was almost constant throughout the summer season. Sidewalk SW was never shaded by the building, therefore the installation of shading devices was critical to improving pedestrians' comfort; during the autumn equinox, the sidewalk resulted in complete shade.

[19] Processing times reported in this section refer to simulations performed on a local computer (i7-7700HQ CPU, 16.0 GB).
[20] 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 Figure 6.5.



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%.

Figure 6.6 Visualisation of three device-sidewalk combinations reported in Figure 6.5. 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.

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

In principle, the assessment of Figure 6.5 provides the urban designers with an estimated number of devices required to shade pedestrian paths for the above-said aspect ratio setting (Section 6.4.2). 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 6.1, 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 (Aleksandrowicz et al., 2020; Jamei et al., 2016), 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 (Figure 6.7). 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: Municipality of Milan n.d.-a). The boundary condition analysis of the sidewalk reported exposure to solar radiation in all summer simulated hours (Table 6.1), confirming a consistent need for shading.

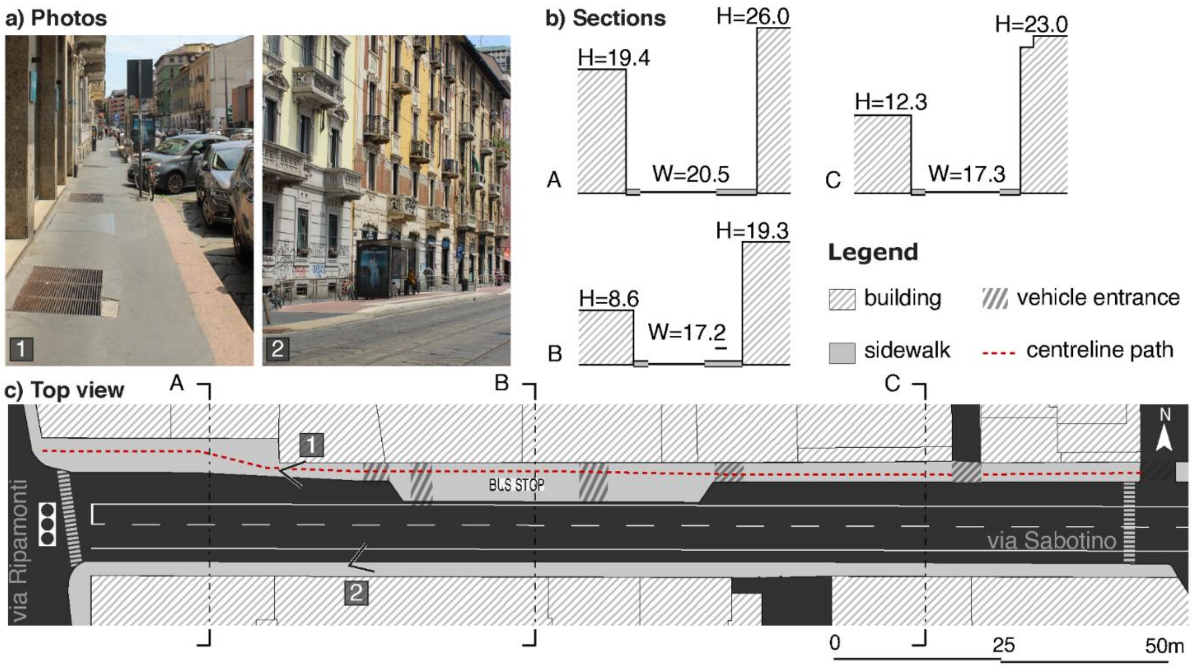


Figure 6.7 Presentation of the case study sidewalk in via Sabotino (Milan, IT): a) field photos taken on 29 June at 1 pm; b) sections and c) top view of the case study urban canyon (data source: Municipality of Milan, n.d.-a).

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 Figure 6.5, 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 seconds. The final design proposal consisted of 11 stand-alone canopies and 21 m of large cover, together with the 10 class size IV trees (Figure 6.8a). In total, 55% and 64% of the path resulted in the shade during the summer solstice and autumn equinox, respectively, at 1 pm (Figure 6.8b). 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 (Municipality of Milan, 2020); in the analysed sidewalk, two parking lots are already occupied by near commercial activities.

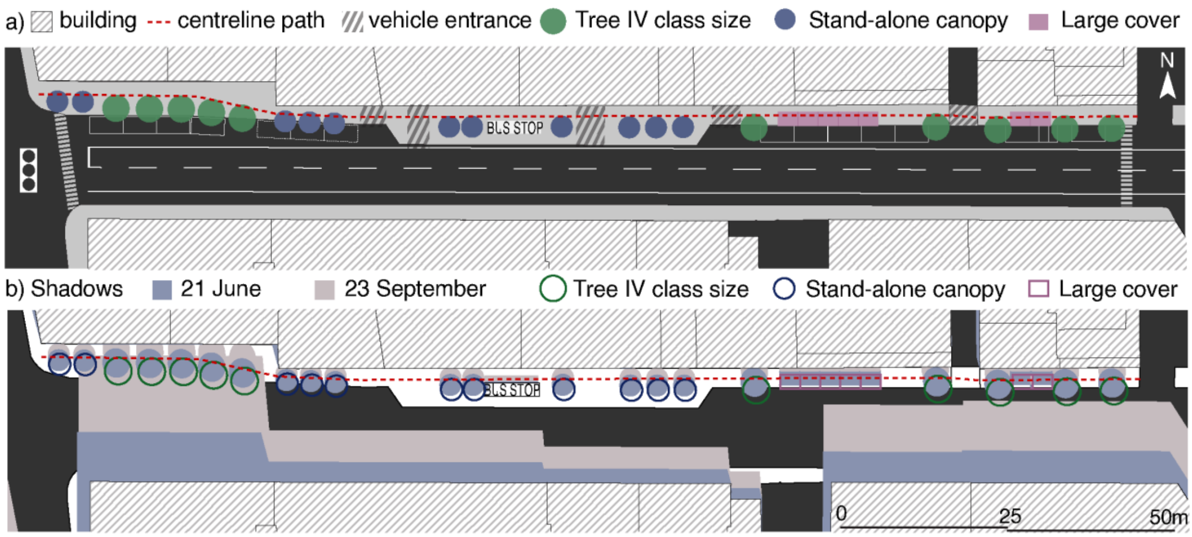


Figure 6.8 Final design proposal developed through the design tool: a) location of shading devices; b) shadow analysis on summer solstice and autumn equinox days.

6.5. 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 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 predetermined shaded length goal; a systematic approach to select effective shading strategies in urban design practice.

6.5.1. Key findings of this study

In the process of optimisation of factors concerning outdoor spaces (Erell, 2008), 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 6.4.2.2. The documentation provided by the Municipality could be supplemented with information collected in Figures 6.4 and 6.5; 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 (Ng, 2015), and where air quality and noise are more regulated than climate (Alcoforado et al., 2015). This past short-sighted approach disregarded that urban planning impacts microclimatic conditions in cities while potentially strengthening the existing socio-economic inequalities (Villadiego & Velay-Dabat, 2014). 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 (Park et al., 2019). 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. (2020) 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.

6.5.2. Applications in urban design practice

The design tool was applied through diverse processes, all following the analysis-evaluation-design workflow. In Figure 6.9, 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 6.4.

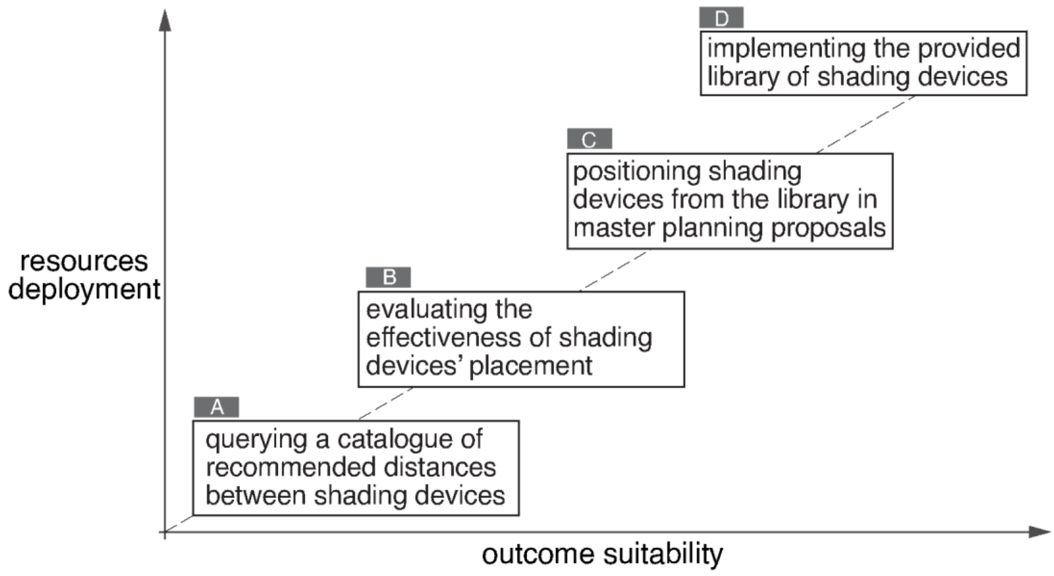


Figure 6.9 Position of four workflow applications against increasing resources deployed and narrowing outcome application. Dark grey boxes refer to Table 6.4.

Table 6.4 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 Figure 6.5.
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 6.4.2.2.
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 6.4.3.
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 6.4.2.1.

6.5.3. 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 (de Abreu-Harbich et al., 2015; Konarska et al., 2014; Robitu et al., 2006); 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 (Bréda, 2003); 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 (Rossi et al., 2020), and vegetation was reported to be more effective in cooling pedestrians than artificial devices (Peeters et al., 2020). 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 (2023) 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 and compatibility.

The recommendations proposed in Section 6.4 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 (2023). 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).

6.6. 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.

6.7. Appendices

6.7.1. Appendix A

Screenshots of the design tool are presented. The labels [TH] and [MP] refer to workflows to design theoretical sidewalks (Section 6.4.2) and master planning proposals (Section 6.4.3), respectively. The Grasshopper code was built following the referenced tutorial (Digital Design Unit – TU Darmstadt, 2020).

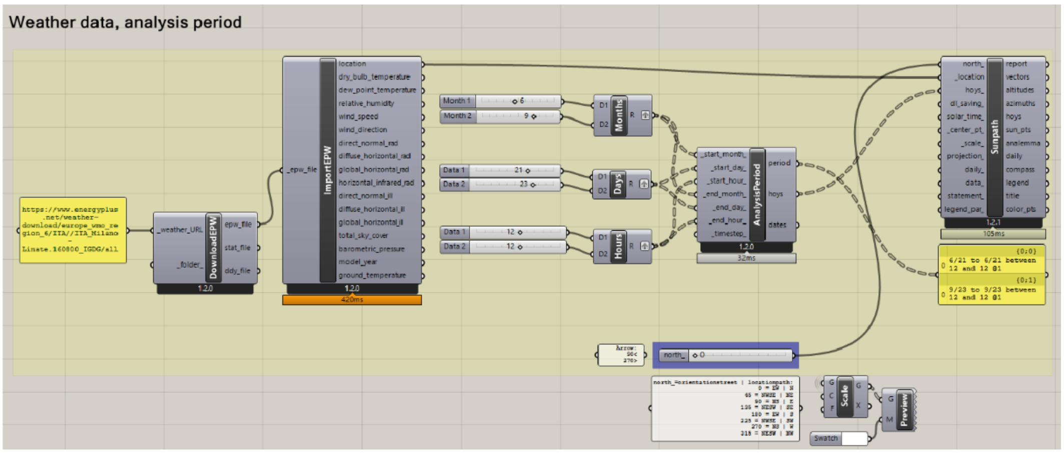


Figure 6.10 Importing the weather file and selection of the simulation period [TH, MP].

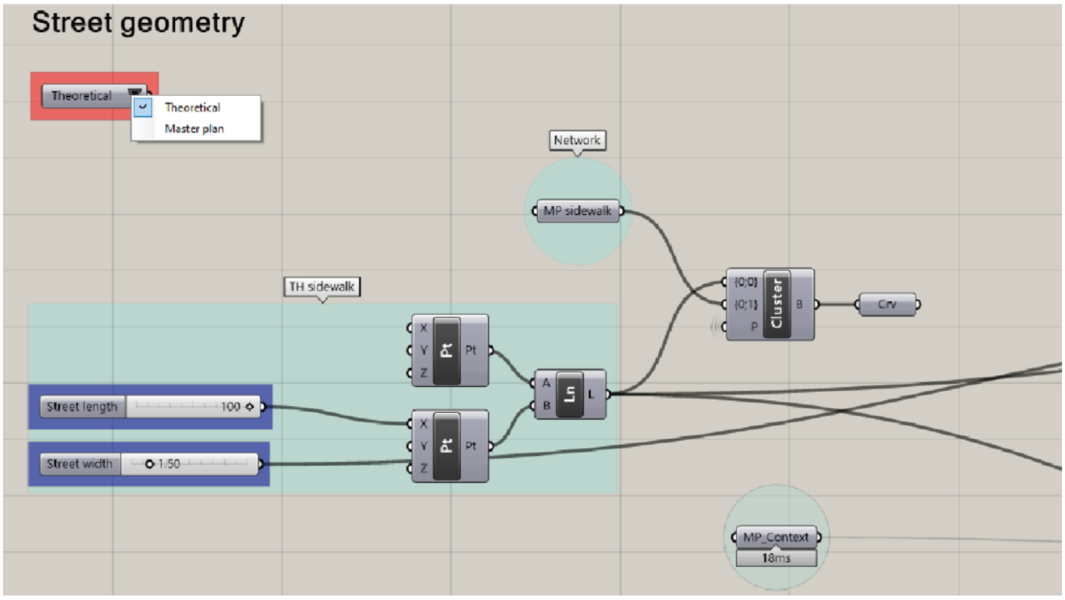


Figure 6.11 Modelling the street geometry [TH] or importing the centreline of the case study sidewalk, together with context buildings [MP].

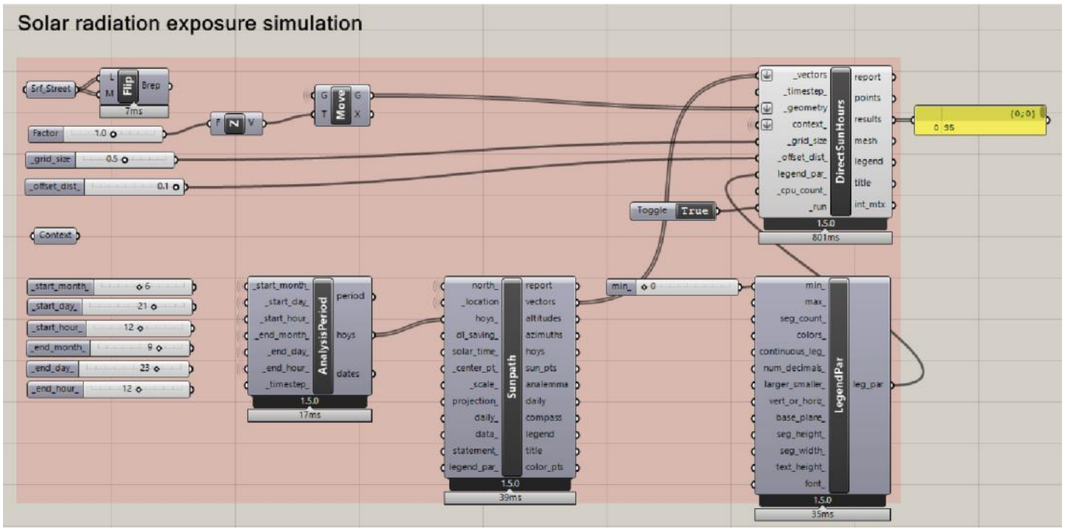


Figure 6.12 Simulation of the solar radiation exposure of the virtual sensor on every day of the simulation period. The panel on the right reports the results [TH, MP].

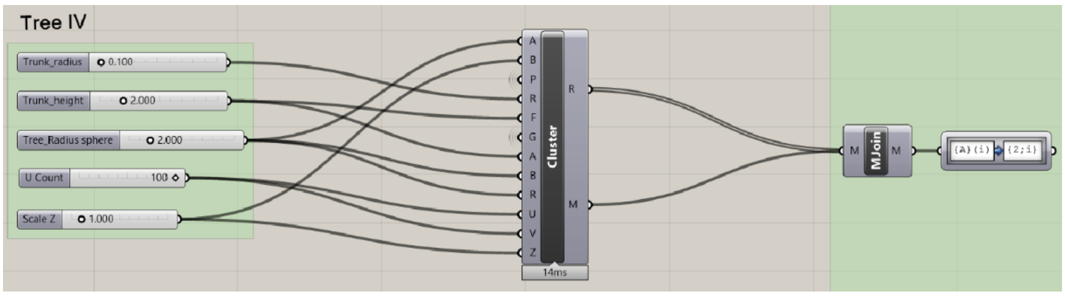


Figure 6.13 Parametric model of a shading device [TH, MP]

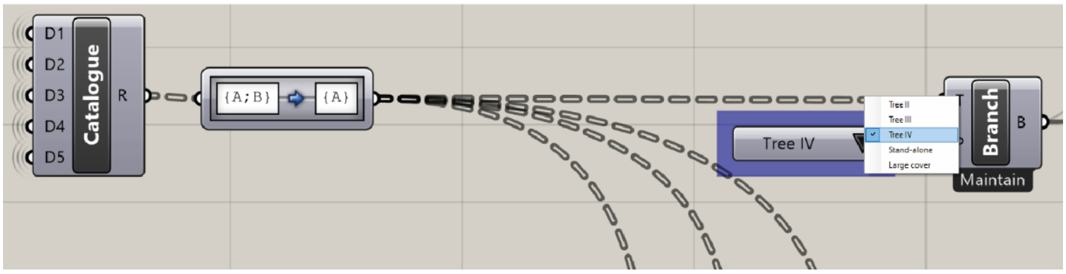


Figure 6.14 Selection of one shading device from the catalogue of solutions [TH, MP].

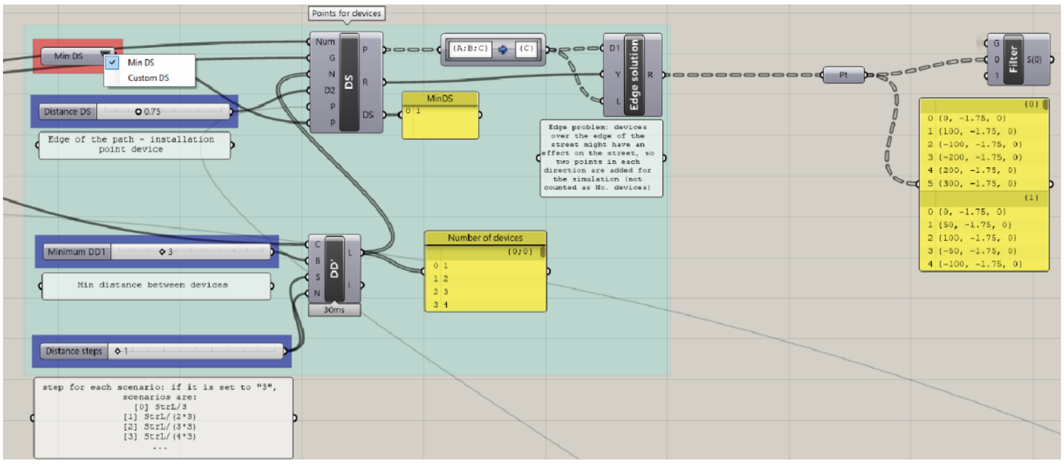


Figure 6.15 Parametric setting of the number of design configurations to evaluate. It is possible to set DS and DD_1 distances [TH].

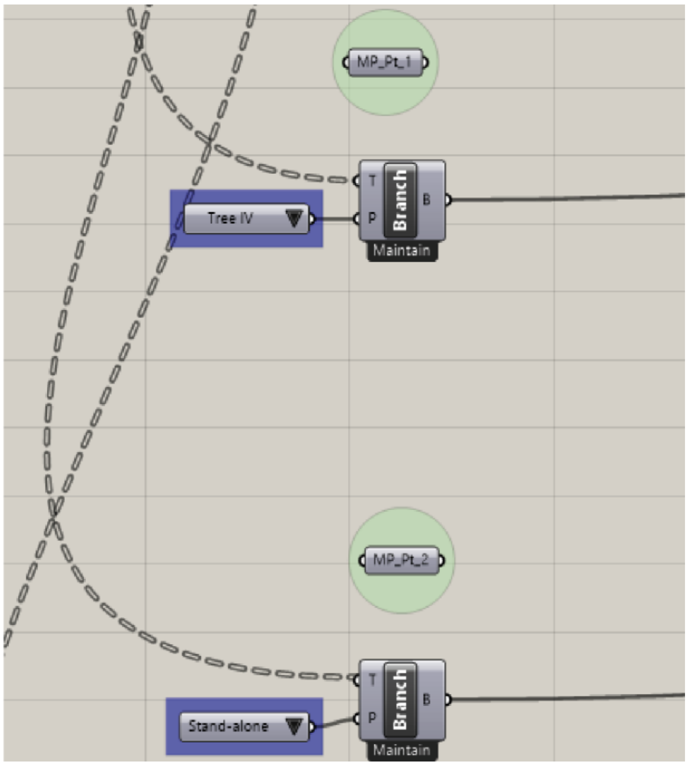


Figure 6.16 Assignment of shading devices from the catalogue to the corresponding installation points [MP].

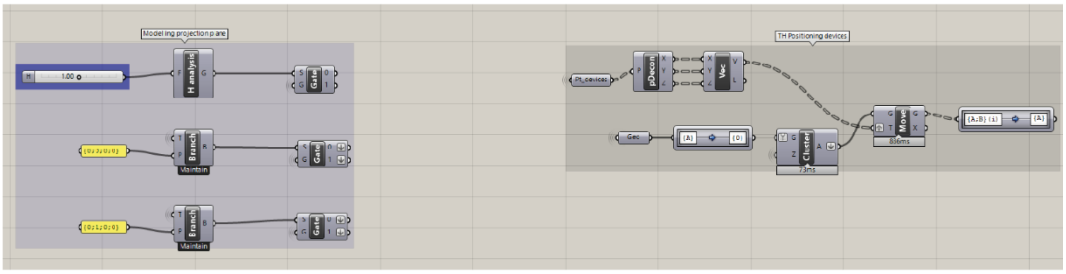


Figure 6.17 Selection of the height of the projection plane [TH, MP]. Scenarios are modelled accordingly.

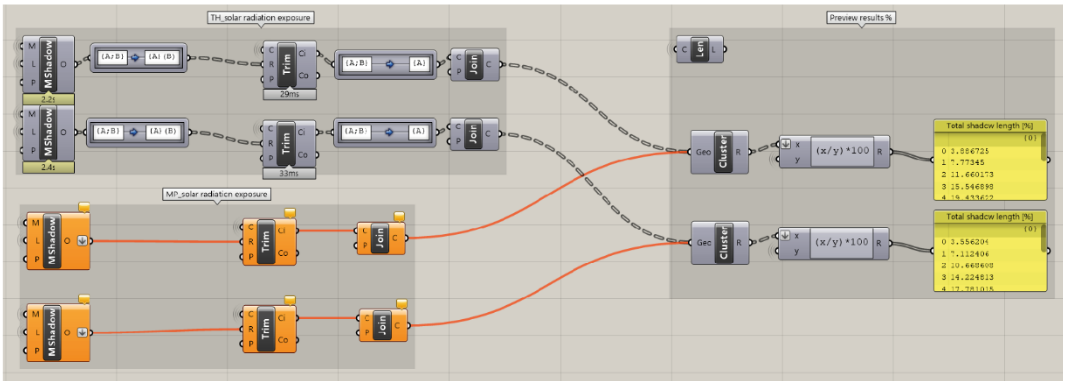


Figure 6.18 Simulation of solar radiation exposure of the centreline sidewalk on the two selected days; a preview of results is available in the panels on the right [TH].

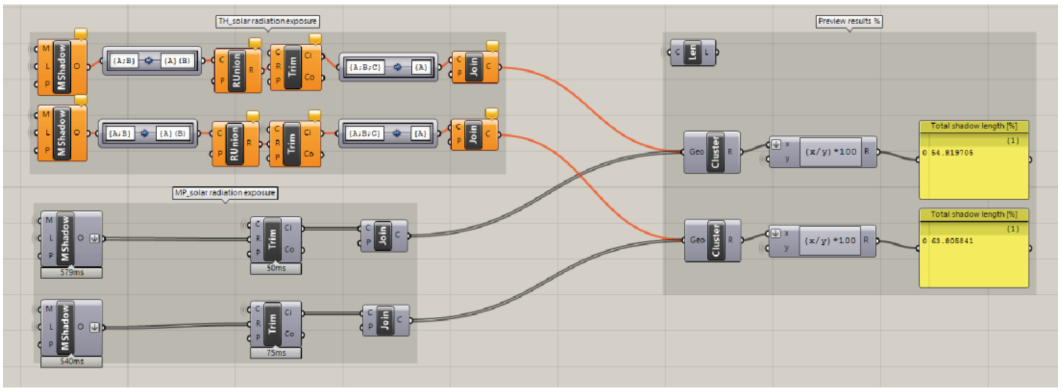


Figure 6.19 Simulation of solar radiation exposure of the centreline sidewalk on the two selected days; the panels on the right report the resulting shaded length [MP].

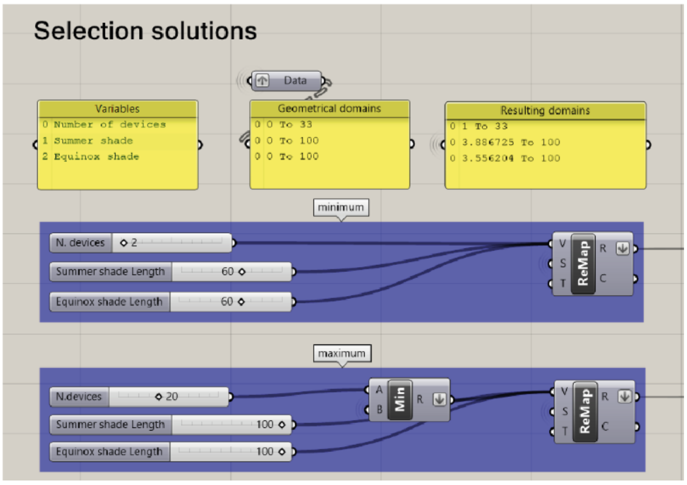


Figure 6.20 Definition of selection criteria, such as minimum and maximum number of devices and shading thresholds [TH].

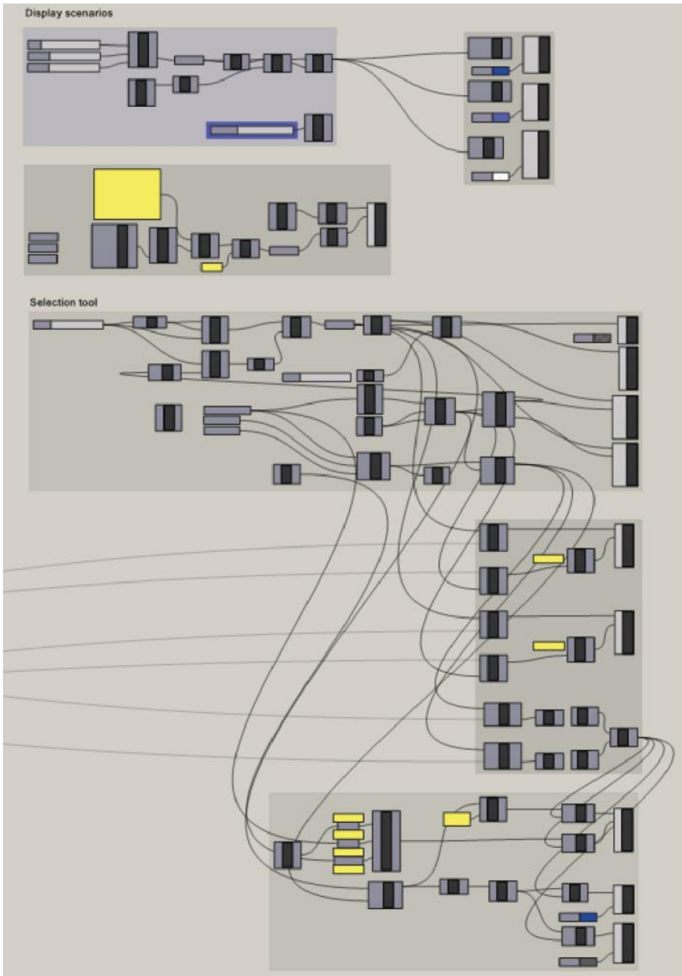


Figure 6.21 The design tool includes a graphics part to visualise results in the Rhino workspace. This code reports both the selection tool and the shading device configurations [TH].

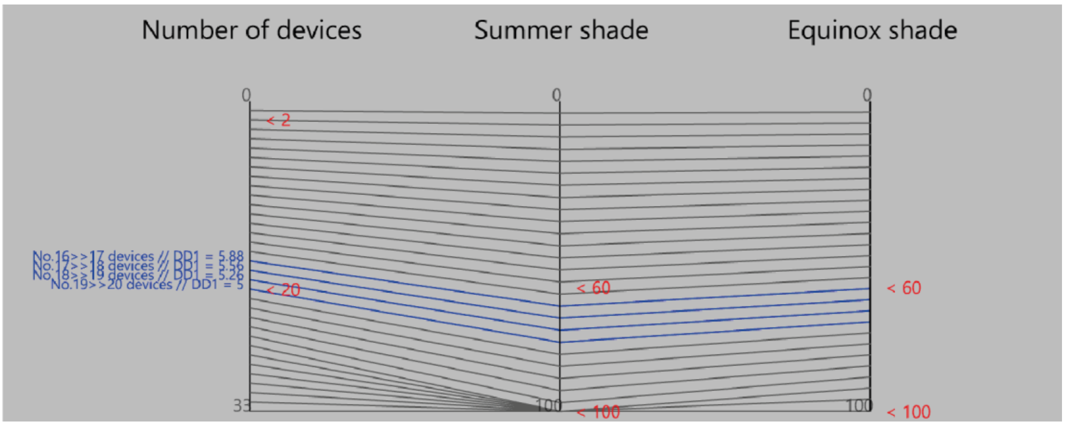


Figure 6.22 Visualisation of the selection tool [TH].

Figure 6.23 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].

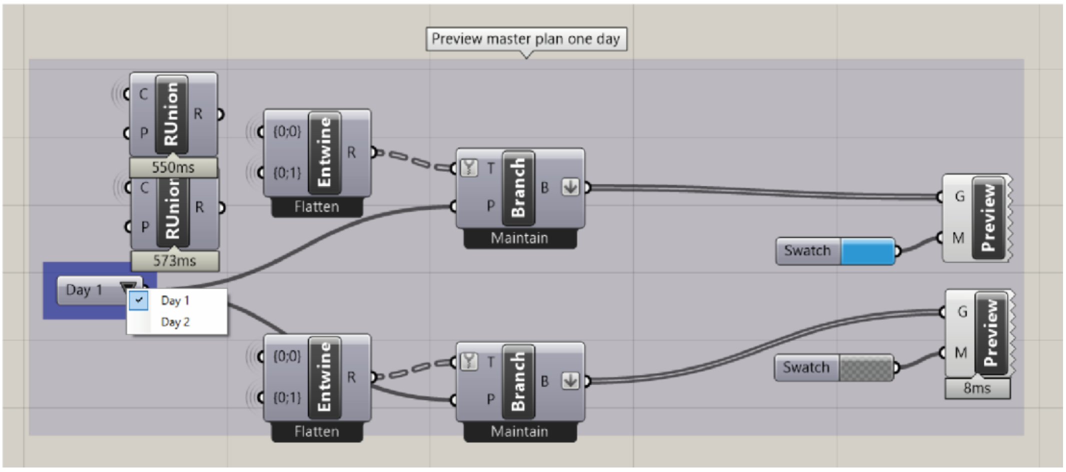
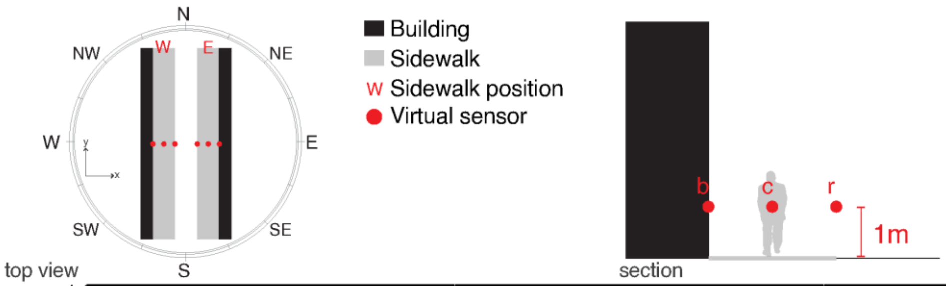


Figure 6.24 This cluster imports shadows in the Rhino workspace [MP].

Figure 6.25 Visualisation of the resulting shadows in the Rhino workspace [MP].

6.7.2. Appendix B

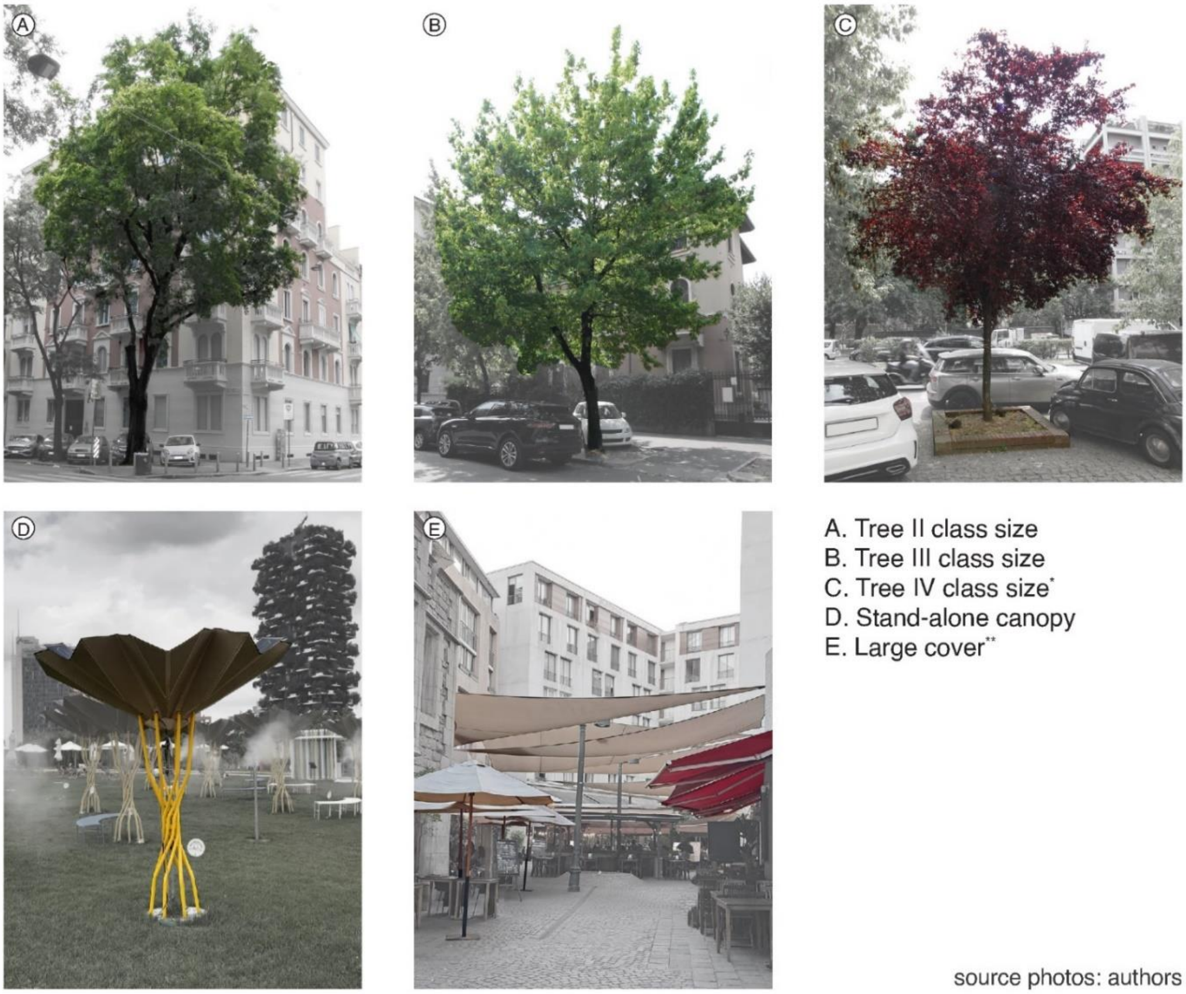


	10 am									1 pm									4 pm								
	UC 0.5			UC 1.0			UC 2.0			UC 0.5			UC 1.0			UC 2.0			UC 0.5			UC 1.0			UC 2.0		
	r	c	b	r	c	b	r	c	b	r	c	b	r	c	b	r	c	b	r	c	b	r	c	b	r	c	b
N	95	95	95	78	87	95	**45**	**55**	**62**	**95**	**95**	**95**	**68**	**84**	**95**		20	40	95	95	95	74	86	95	25	41	53
NE	95									**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.

Figure 6.26 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.

6.7.3. Appendix C



* 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.

Figure 6.27 Photographs of shading devices included in the library.

6.8. Contribution of this journal paper to this research

Shading pedestrian paths is strategically important to ensure accessibility and comfort for pedestrians in cities. Limited applicability of previous research about the effectiveness of natural and artificial shading devices in practice was found. In this chapter, a workflow to design effective installations of shading devices on sidewalks was proposed; 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; a performance of a 60% linear path in shade was set as the design goal. Based on solar radiation exposure of urban canyons, a time of 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 outcome of this paper fulfils the aim of the SOLOCLIM project of providing urban designers with solutions for urban climate adaptation. The theoretical knowledge assessed in Chapter 4 and the modelling method presented in Chapter 5 build a solid background to inform designers where the need for shading devices is localised; the proposed workflow materialises this design task, supporting practitioners in comparing proposals to develop an effective shading implementation project. In Chapter 7, the contribution of the three journal papers is collected into a single protocol formulated to allow practitioners to design effective solutions for shading pedestrian paths.

7. PROTOCOL FOR SHADING IMPLEMENTATION

7.1. Introduction

The three journal papers presented in the previous chapters provided extensive knowledge about the impact of solar radiation exposure on pedestrians, the critical role of solar radiation on the experience of diverse users walking on a pedestrian network, and the solutions available to reduce heat stress. To ensure that this research provides a valuable contribution to urban design practice, the knowledge gathered and methodology developed must be made available to practitioners. In fact, the best strategy to ensure effective results in terms of urban climate adaptation is to include the related processes in practice rather than delegating its investigation to dedicated phases of the workflow; this strategy is known as 'mainstreaming' (Uittenbroek et al., 2013). In this chapter, the material presented in the three journal papers is combined to formulate a protocol for the effective implementation of shading devices on pedestrian paths.

The protocol was developed specifically for urban planners and designers. It was formulated to be included in their daily practice and it allows them to analyse and evaluate design options of outdoor spaces with the goal of making them comfortable for users, throughout the year. The proposed workflow is shaped as an informative design tool to position a variety of shading solutions in master planning proposals. The protocol is organised to consider urban and climate data availability, operability into urban design workflows, and dissemination of microclimate knowledge. Multiple degrees of design optimization are provided in response to the level of expertise of urban designers and their familiarity with tools. Outcomes range from rule-of-thumb-like information to detailed modelling of shading devices, which enables wide accessibility and applicability of this research.

7.2. A protocol to design effective solutions for shading pedestrian paths

The protocol consists of two components; a methodology to effectively position shading devices based on the users' needs, and a design tool that enables the applicability of this methodology in practice. The methodology follows the analysis – evaluation – design iterative workflow presented in Chapter 6 for singular sidewalks. From this starting point, further work was done to allow designers to upscale the area of interest to analyse pedestrian networks at the neighbourhood scale; therefore, the modelling methodology presented in Chapter 5 was integrated into the code. Furthermore, in performing the evaluation phase, users of diverse walking abilities were considered to foster inclusivity in design (Chapter 4).

It is noted that the contribution of each paper to the protocol's workflow does not follow the order in which they were presented in this thesis, nor published. In formulating this research, the user was considered as the starting point, followed by an upscaling process leading to the analysis of a neighbourhood, and finally, the need to provide solutions to excessive exposure to DSR. Nevertheless, in developing the protocol, these activities were rearranged to build a systematic workflow to iteratively test design options. For this reason, the network dynamic analysis method presented in Chapter 5 was assigned to the first phase of the workflow, assuming that designers could benefit from investigating the DSR exposure of pedestrian paths as an initial step. Then, in the evaluation phase, it is suggested that the methodology of Chapter 4 is applied to set up a maximum threshold of DSR; this could inform designers in defining shading goals (Section 6.3.2.3). Finally, a catalogue of solutions would be used to propose effective positioning of shading devices.

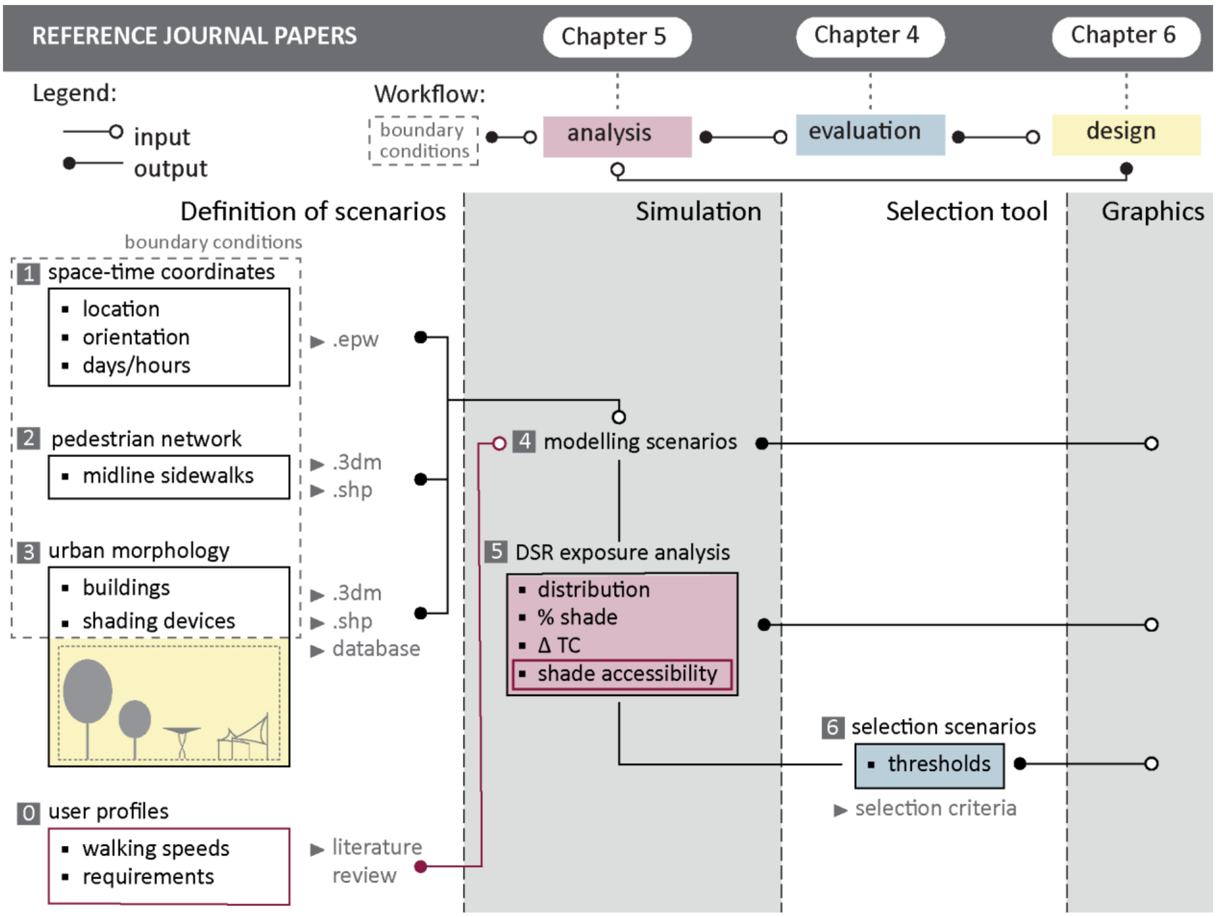


Figure 7.1 Schematic representation of the iterative workflow, highlighting the contribution of each chapter (i.e., journal paper) to it.

The development of the design tool expanded upon the Grasshopper code presented in Chapter 6, which was considered as a backbone to be implemented. In this extended version, additional clusters introduce the possibility of simulating experiences of diverse user profiles and performing the four direct solar radiation analyses presented in Chapter 5 (shading distribution, DSR exposure, ΔDC, and shade accessibility). Moreover, the winter solstice was included to allow urban designers to evaluate the amount of sun blocked during the cold season. An additional section about graphics was introduced so that designers could modify the visual representation of results; this falls into the effort to improve communication with professionals but also the wider public.

A screenshot of the Grasshopper code is presented in Figure 7.2. Of particular interest is the legend on the left, where the recurrent graphical elements adopted to improve the usability of the design tool by urban designers are collected. According to the workflow, the code is divided into four phases, which are explained in detail in the following sections. Only a selection of the screenshots of the Grasshopper code is shown in the following text; the complete code and associated procedures are presented in the protocol submitted as a deliverable for the SOLOCLIM project (Appendix A)[21].

[21] It should be noted that, as part of the project milestones program, the protocol was submitted in September 2023, while the relevant papers were published in 2024. Therefore, in a few cases, data and screenshots do not correspond to the results presented in this thesis. Nevertheless, since only minor changes were done, the overall protocol was confirmed valid after the peer review process of the journal papers.

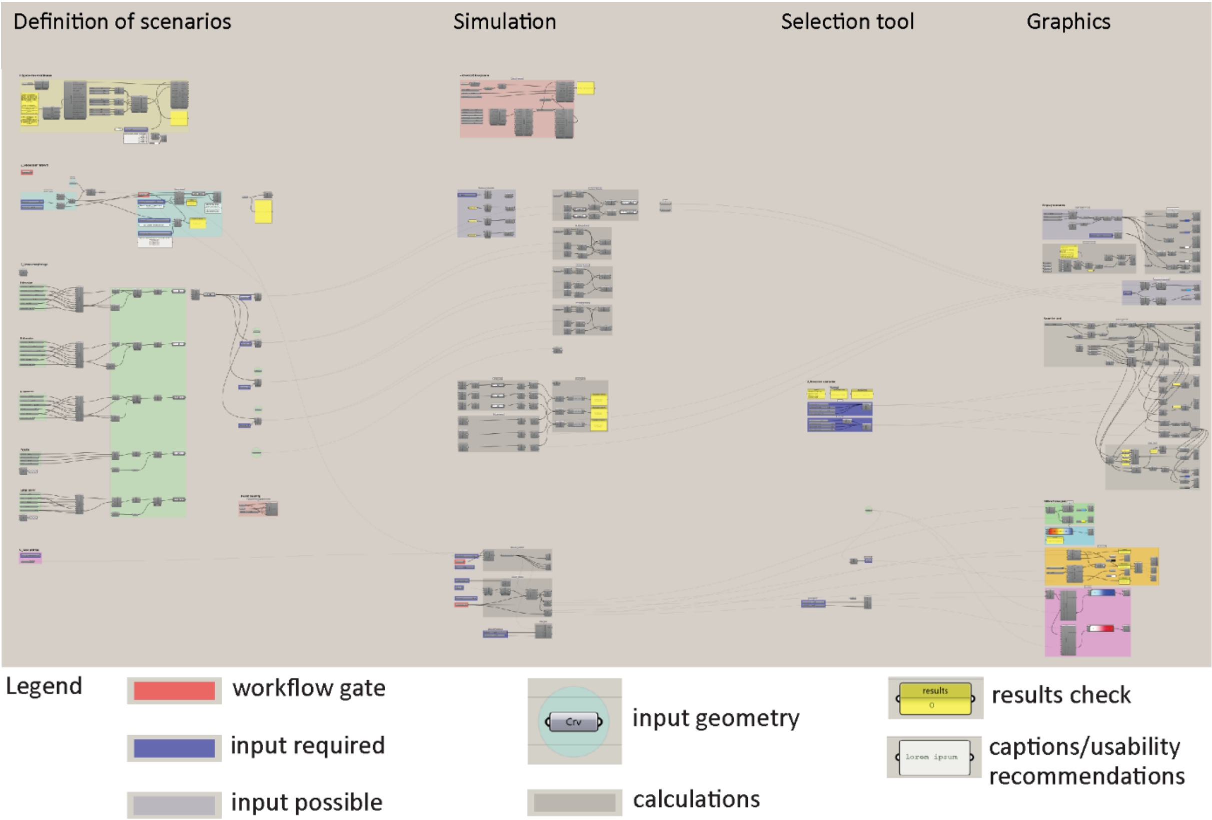


Figure 7.2 Screenshot of the design tool developed as a Grasshopper code.

7.2.1. Definition of scenarios

In this phase, designers could outline specific scenarios to analyse pedestrian networks in terms of solar radiation exposure. At first, meteorological data corresponding to the studied location are input into the code (Figure 7.3). Meteorological files can be downloaded from the EnergyPlus website for numerous locations around the world (EnergyPlus, n.d.). The files can be downloaded directly into Grasshopper via Ladybug tools; statistics about typical or extreme conditions are included in the meteorological file and can inform designers' choices. Alternatively, locations' coordinates or even sun ray vectors can be manually input in the Grasshopper code. Working with direct solar radiation, the position of the sun against the urban morphology is key. The code allows urban designers to change the orientation of the model, as part of the modelling task or for comparative purposes; an additional component to visualise the sun path is provided for reference. The analysis period corresponds to the day and hour combinations that are relevant for the performed analysis. In the default mode, the tool requires three day and hour combinations, ideally representing the same hour in three different seasons or three key hours on the same day. To prioritize people's activities at specific times, it is recommended to take into consideration daylight saving times in the selection phase.

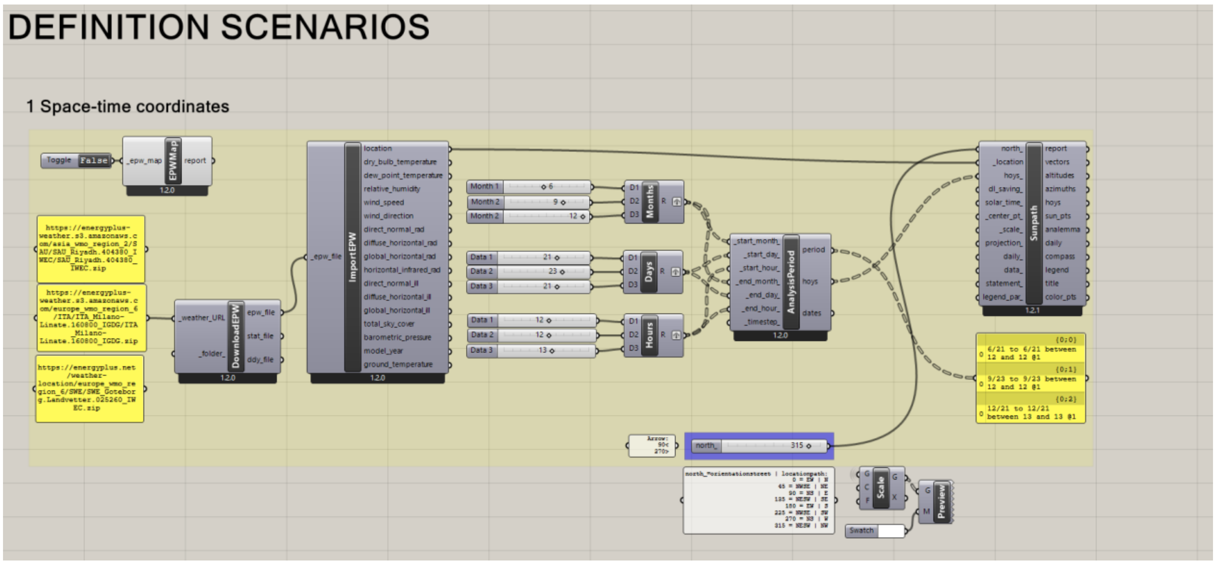


Figure 7.3 Screenshot of the Grasshopper cluster to select the space-time coordinates of the scenarios.

The pedestrian network is represented as one or multiple linear paths under investigation. An existing database (e.g., in shapefile format) can be imported via Grasshopper plug-ins, such as Urbano (Dogan et al., 2020). Sidewalks modelled in Rhino can be input as well. The sidewalks' system must be translated into a linear network; the midline of the sidewalk was selected to represent the considered surface as a segment of the network. To ensure model usability, cleaning the network is recommended, with specific attention to modelling a continuous network with accurate intersections and removing stubs; the network can be modelled in 3D.

Buildings and shading devices are modelled as surfaces and meshes in Rhino. In most cases, buildings are considered a static component of the urban environment because they are susceptible only to rare and/or limited changes. Municipalities increasingly provide open-source data in the shapefile format, with building height reported as an attribute. Using Grasshopper plugins such as Urbano (Dogan et al., 2020), it is possible to import building footprints and extrude them based on the height attribute. In addition, geometries modelled in Rhino can be selected as context; for reducing simulation time, it is recommended to simplify geometrical models keeping only the external shape. Shading 3D devices can also be modelled in Rhino, keeping in mind that all shading objects are considered exclusively in terms of morphology in the simulation phase. In Chapter 6, a catalogue of solutions was presented.

Inclusivity is a key factor in the proposed protocol, which encourages the identification of pedestrians that would use the analysed urban space; this is an endeavour to tailor the evaluation process based on diverse experiences of the urban environment. The design tool provides a list of the four user profiles presented in Chapter 5, which are characterised based on walking speed and ability to climb stairs and steep ramps. Selecting diverse user profiles impacts the spatial definition of scenarios by removing from the pedestrian network all segments resulting as non-accessible. Moreover, it is key for the shade accessibility analysis (5.3.3.3).

7.2.2. Simulation

The simulation section is where the calculation process takes place. As demonstrated by the results presented in the previous chapters, the input scenarios and design goals may differ consistently based on the scale of analysis, detail required, and resources available. Therefore, in order to adapt the direct solar radiation analysis accordingly, three workflows are defined as a combination of the direct solar radiation exposure analysis mode, divided into vector or raster, and the modelling scenarios mode, i.e., theoretical or master plan (Table 7.1). As regards the analysis mode, the term ‘vector’ refers to the analysis of a segment considered as a linear element, in which each point of separation between sun and shade is uniquely localised. Instead, the term ‘raster’ refers to the subdivision of each segment of the network into smaller segments, named ‘steps’; the DSR exposure is analysed for the midpoint of each step, therefore the analysis resolution depends on the length of the steps. In terms of modelling scenarios mode, the theoretical one allows urban designers to compare different urban morphology configurations on a standard linear street. Conversely, the master plan mode requires modelling one specific morphological scenario.

Table 7.1 Definition of three workflows based on DSR exposure analysis and modelling scenarios mode.

	Theoretical	**Master plan**
Vector	Workflow A	Workflow B
Raster	-	Workflow C

The workflow A corresponds to the exercise presented in section 6.4.2.3. The DSR exposure analysis is performed on a standard street with vector components. The Grasshopper component ‘Mesh Shadow’ projects the shadows on one plane; this affects the modelling of the street, which must be flat or inclined at a specific angle. Devices are positioned according to the defined scenarios. The goal is to compare the shaded length of a linear sidewalk resulting from the installation of one shading device at different distances, comparing results at three specific times. A screenshot of the outcome of this exercise visualised in the Rhino environment can be found in Figure 7.4.

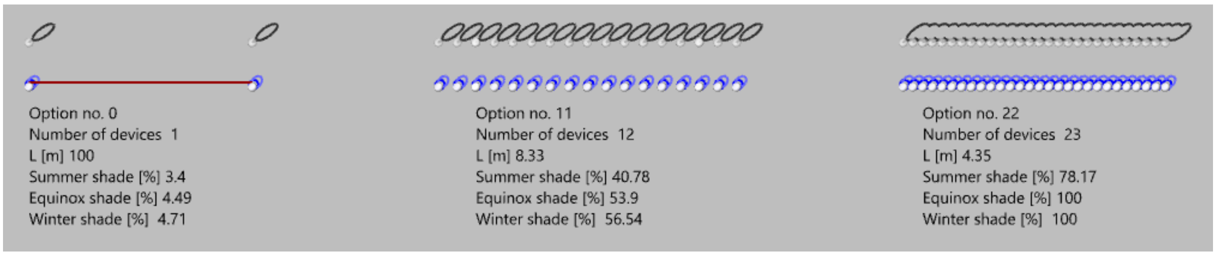


Figure 7.4 Screenshot of the outcome of the workflow A as visualised in the Rhino environment.

The workflow B analyses a specific street (or small group of streets) with vector components, as performed in Section 6.4.3. The projection plane must be planar, therefore only 2D analyses can be performed. In addition to buildings, different shading devices are positioned in the master plan. The shading devices from the provided library can be assigned to installation points. The goal is to compare the total shaded length of a pedestrian network as the result of a combination of shading devices and buildings. The pedestrian network is evaluated as whole segments, without dividing it into smaller lines; shadows are projected on a plane, and results are calculated in vector mode. The resulting outcome is highly precise but this extensive analysis requires huge simulation times, not suitable for practitioners. Therefore, the accuracy of results is traded with the possibility of performing only a general DSR exposure analysis, quantifying the percentage of shade and sun along a sidewalk (Section 5.3.3.1).

In the case of a 3D network analysed following the workflow C, the methodology is explained in Chapter 5. In this case, the opportunity to analyse 3D networks at the neighbourhood scale is traded with the level of accuracy of the results, because a raster analysis is applied. Additionally, only one day can be analysed at once; therefore, results on different days must be compared as printed maps. The four simulation analyses presented in Chapter 5 are included in the default code; distribution of shading; segmented solar radiation exposure analysis (in percentage); difference between the shortest and the most comfortable path; and shade and sun accessibility for diverse users. In this cluster, the code allows urban designers to modify the maximum steepness of the slopes walked by the users, adapting the network simulations to diverse walking abilities.

7.2.3. Selection tool

This section allows urban designers to evaluate the simulated results by comparing them with performance goals. The selection criteria could be the result of norms, guidelines, or preferences; the methodology developed in Chapter 4 could be used to set up thresholds of solar radiation exposure based on the presented user-centred approach. In the theoretical approach (workflow A), a limit to the number of shading devices installed can be specified, together with a minimum and maximum percentage of length to be shaded at all three times (Figure 7.5a). In the master plan design (workflow B), the tool presents the percentage of the pedestrian network in the shade on the three selected simulation hours. Finally, additional input data can be inserted for the 3D network analysis (workflow C). The area of interest for the simulation can be drawn, focusing the evaluation on segments within a specific perimeter. In the ΔDC analysis, combinations of origin and destination points can be manually inserted. As regards the shade accessibility analysis, it is possible to set a maximum threshold of time accepted before finding shade or sun (Figure 7.5b). The legends of the illustrated maps are set up to change according to the evaluation parameters and thresholds.

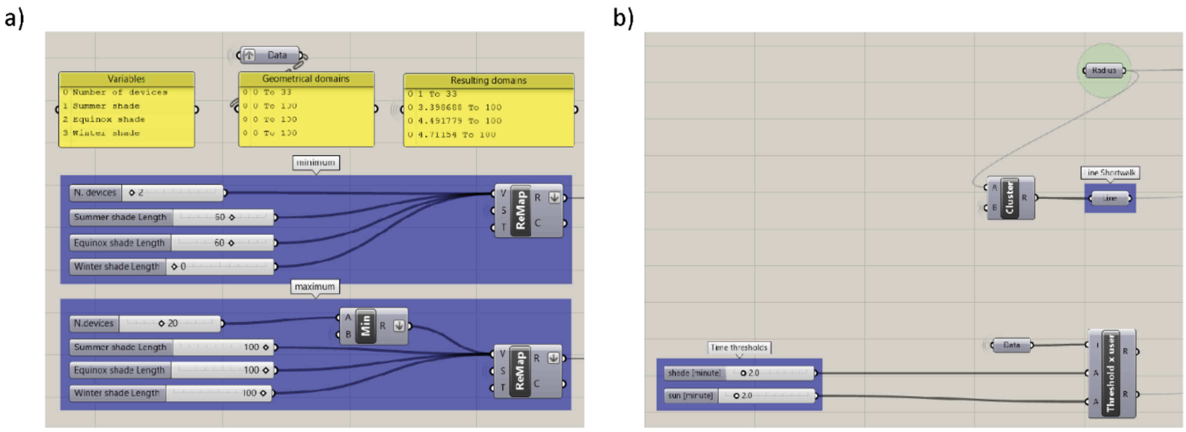


Figure 7.5 Screenshots from the evaluation section of the Grasshopper code; a) setting the design goals in the workflow A; b) from top to bottom, selecting an area of interest, the origin/destination paths, and a maximum threshold of accessibility time in the workflow C.

7.2.4. Graphics

This section is of utmost importance, as it allows one to effectively visualise results, which is critical to communicate the variations in the shading performance of diverse design proposals. Two examples are illustrated; the comparison of the shading performance of different devices configurations, following workflow A (Figure 7.6a); and a 3D visualization of results of workflow C (Figure 7.6b).

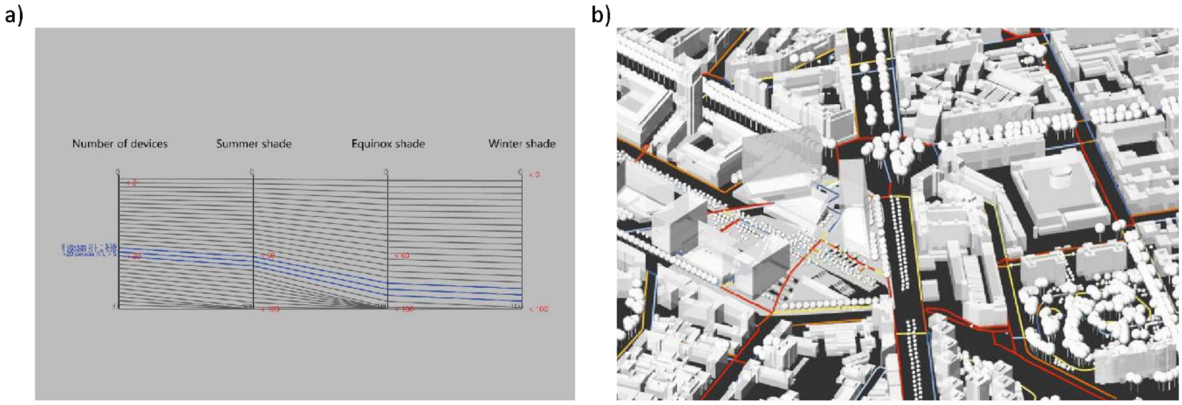


Figure 7.6 a) Visualisation of shading performances based on the distance between devices; b) 3-D visualisation of the direct solar radiation exposure of a pedestrian network.

A specific component is assigned to each step of the simulation and selection sections; urban designers can turn on and off the visualisation components, as well as modify them. Legend and drawing styles used in this thesis are included as default; designers with adequate expertise in Grasshopper can modify the graphic components in the code according to their preferences.

7.2.5. Principles and challenges in developing the Grasshopper code

In collecting the presented research into one design tool, some goals were defined beforehand; a clear layout, guiding users through the workflow steps; limited simulation times; and the opportunity to perform diverse exercises according to resource availability and level of detail (Table 6.4). The first goal was addressed by organising the code following the schematic representation of the iterative workflow (Figure 7.7). The use of recurrent graphical elements, including usability recommendations, aimed to provide valid information to the tool users. In terms of simulation times, the modelling and simulation methodologies were fine-tuned to keep processing times under 15 minutes; this threshold was assumed to be a valid compromise between detailed results and the need to fit into an iterative design process. The definition of two analysis methods, i.e., raster and vector, responds to this intent. In fact, the vector simulation mode was the preferred choice in terms of accuracy, and was applied in Chapter 6; nevertheless, in upscaling the DSR analysis at the neighbourhood scale, it became clear that the raster mode would bring benefits in terms of simulation time, together with the opportunity to model networks in 3D. Finally, the presence of multiple clusters under the same sections aimed at the implementation of diverse workflows within the same code. The flow of data is managed through a series of 'gates' (red rectangles in Figure 7.2) that activate clusters based on the selected workflow; the workflow-specific clusters are marked in Figure 7.7. In this way, one tool could be used for multiple design projects, moving from a preliminary assessment to the investigation of several design options based on user experiences.

As regards the selection of user profiles, the code is built to keep this activity optional; therefore, in the workflow, the cluster with user profiles built-in is labelled as step ‘zero’ (Figures 7.1 and 7.7). This choice aimed to make clear that the adoption of diverse pedestrians’ perspectives is not mandatory in using the protocol, yet it should be considered as an innovative source of information that would have a relevant impact on the results of the design process, starting from modelling the pedestrian network according to the user’s walking abilities.

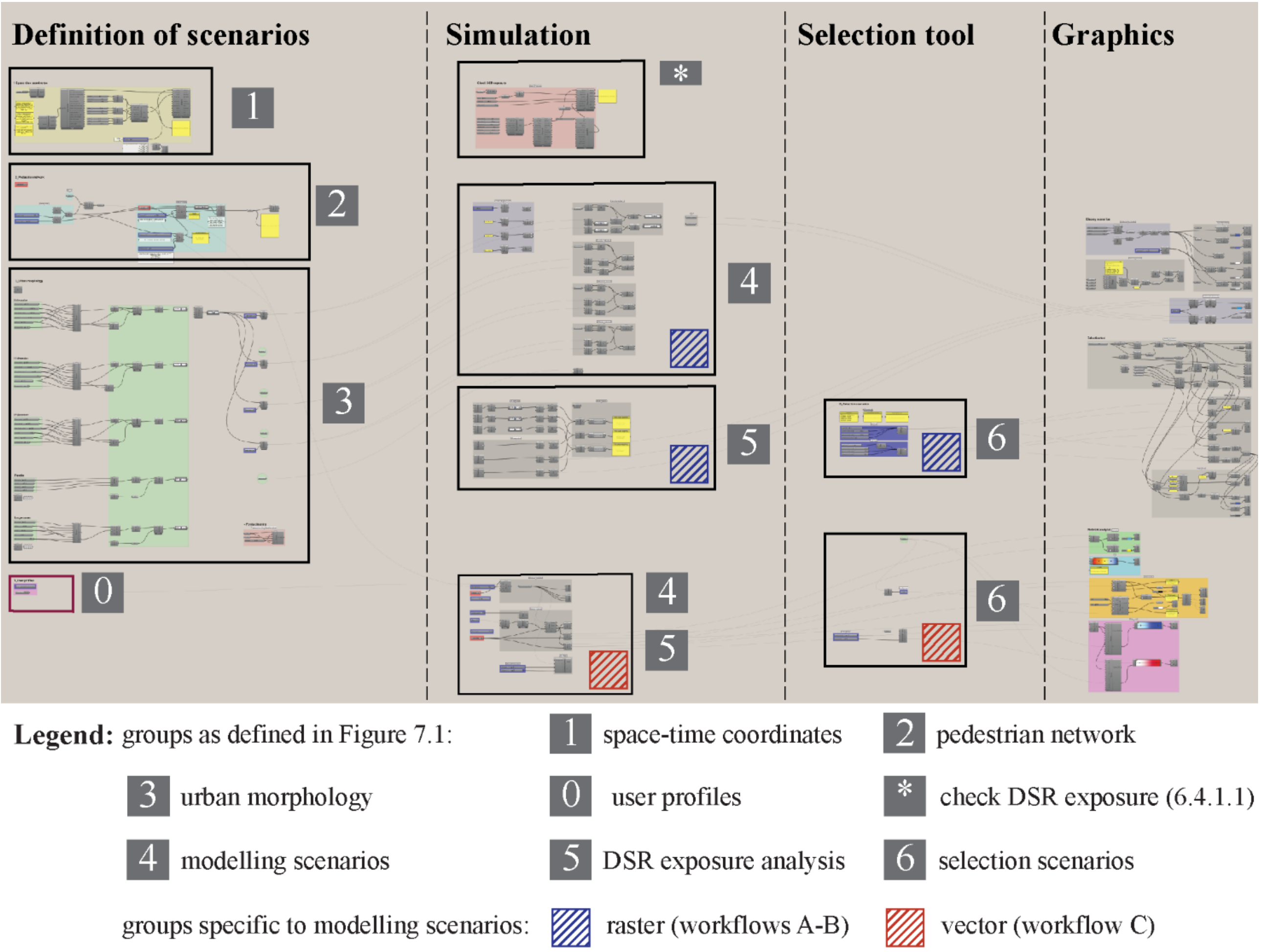


Figure 7.7 Overlay of the schematic representation of the workflow (Figure 7.1) and a screenshot of the Grasshopper code (Figure 7.2).

7.3. Conclusions

As highlighted in Chapter 1, the final outcome of this research is a protocol to design effective solutions for shading pedestrian paths, specifically formulated for urban designers. This protocol collects the work presented in the previous chapters in a systematic way so that a coherent design workflow for urban designers is proposed. The workflow presented in Chapter 6, including the principles and practical solutions presented, was the foundation of the final protocol, and research about diverse users and systematic analysis of pedestrian networks was inserted as features.

The iterative workflow enables urban designers to analyse, evaluate and design the shading devices' configuration within the design process rather than the conventional way of performing modelling exercises separately to assess environmental issues. The opportunity to evaluate theoretical urban canyons and a real case study sidewalk allows for implementing DSR exposure analysis in urban design with various levels of detail. Three results of this protocol are highlighted; a structured layout that guides the designer according to the workflow; a time-efficient workflow suitable for urban design practice; and the possibility to perform different exercises with the same Grasshopper code. Additionally, the research presented in the previous chapters forms a consistent body of information to support the selection of simulation methods and design goals. Finally, a key innovation of this protocol is the inclusion of user profiles for pedestrians of diverse walking abilities. The possibility to switch between user experiences is embedded in the design tool, encouraging urban designers to evaluate how DSR exposure of pedestrian paths impacts multiple user experiences. Design proposals could therefore be adapted to respond to various needs, fostering inclusivity in urban design.

8. CONCLUSIONS

8.1. Introduction

This research addressed the implementation of climate-responsive systems at the master planning scale as part of the SOLOCLIM project. The topic outlined was narrowed down to the effective positioning of shading devices to shade pedestrian paths, emphasising the opportunity for designers to impact positively on the experience of outdoor spaces through the manipulation of solar radiation exposure. Additionally, the focus on users of diverse walking abilities led to addressing how diverse pedestrians would be impacted by the exposure to the sun and the availability of relief spots, fostering inclusivity in urban design. This research was developed as a thesis-by-publications; three papers were published in peer-reviewed journals, and work-in-progress presentations were delivered in four international conferences (Appendix B).

This chapter begins with addressing the research questions formulated in Chapter 1, and highlighting the answers provided through this research. Then, the contribution of this research is placed within the large context of climate-responsive design, illustrating how the developed strategies and methods could be applied to diverse meteorological variables. Finally, the limitations of this work and future directions that could be pursued are outlined, emphasising the relevance of this topic in the field of urban design.

8.2. Results of this research

First, it should be noted that the opportunity to test the developed outcome within a project under development at the industry partner greatly contributed to this research, facilitating the engagement with different stakeholders. Conversations with professionals helped in shaping research questions, directing the focus on strategies useful in practice and enabling the representation of their interests in the design process. Furthermore, presenting advancements of this research to professionals involved in the project, and in the urban design field in general, supported the definition of realistic scenarios, highlighting relevant challenges in the application of climate-responsive strategies.

The outcome of this research can be associated with three dimensions, concerning human physiology, user experience, and design. The first one refers to the innovative approach adopted in evaluating the impact of DSR on people based on their physiology and activity; considering the users as the starting point for this analysis led to proposing a method to link design outcomes with people's needs for shading. As regards experience, analysing shading in a neighbourhood, coupled with the definition of different walking speeds and abilities, allowed the simulation of diverse walking experiences throughout the year. Finally, the largest contribution to the professionals' field is the development of a workflow, with the related design tool, to allow for the implementation of the knowledge gathered in practice. The combination of these three perspectives answers the three research questions formulated in Section 1.4.

- What is the impact of the solar radiation load on pedestrians?

This question was addressed from a physiological and physical perspective. The theoretical framework proposed in Chapter 4 isolated the impact of DSR on the human energy balance in terms of heat load. The method was applied to two user profiles of different characteristics; as a result, the young adults were associated with an energy budget to cope with heat stress three times higher than the elderly people. This confirms the greater vulnerability of the elderly during hot periods, and it could be located within an assessed research field studying the morbidity and mortality during heat waves (see, for example, Baccini et al., 2008; Dodman et al., 2022).

As illustrated in Figure 5.8 and Section 5.7.3-5, the impact of solar radiation on a pedestrian is not limited to the resulting heat load. The different walking speeds, and possible limitations in mobility, could worsen the harmful impact of walking in the sun during heat stress periods. Even though the level of accessibility of sidewalks is not directly connected to microclimate, the analysis presented in Section 5.4.5 shows that the combination of the two issues might threaten vulnerable people's health and comfort. For instance, the walking speed of a pedestrian using an assisting device was assigned a value equal to half the one associated with standard pedestrians. If an elderly person with a cane and a young one were walking the same path simultaneously, not only the older pedestrian would have less energy available to cope with the absorbed heat than a young adult, but they would also walk in the sun double the time. This situation could be even worse if elderly people were forced to take a longer path to avoid barriers such as the stairs, which highlights the importance of accessibility in designing pedestrian paths.

- How does the user experience on a pedestrian network change based on its solar radiation exposure?

Besides the components related to personal characteristics, discussed in the previous paragraph, this research focused on the impact of solar radiation on a pedestrian network intended as an infrastructure. The hypothesis that a system of sidewalks is perceived differently according to the presence of shading was supported through literature (Section 2.5.2). The contribution of this research is the systematic modelling methodology to simulate DSR exposure on pedestrian networks, with additional components to test routes chosen by pedestrians if walking in the sun or shade was considered a priority. Focusing on detailed 3D modelling of the urban morphology and the pedestrian network improved the accuracy in simulating user experiences based on solar radiation exposure.

In Chapter 5, maps illustrating the dynamic character of DSR on a network are reported. These maps show that especially on very hot or cold days, the foot traffic on sidewalks is expected to substantially change at different hours. This might seem obvious information, but nevertheless the implications of this are crucial. For instance, results of the shading analysis could be used to highlight 'protected' paths connecting relief spots such as parks; points of interest like pharmacies; and places where people are expected to queue, e.g., near streetlights and street food vendors. In Figure 5.6, the simulation of three origin-destination paths illustrates the impact of seeking shade in route choice; this tool could be useful to prioritise shading installations to shorten the ΔDC variable, evaluating design proposals via graphs of Figure 5.7. Furthermore, it demonstrates that time-driven pedestrians, who are expected not to change routes because of uncomfortable exposure to the sun, experience the same path differently based on the shading pattern on the sidewalks.

- How to make the effective implementation of shading solutions accessible for practitioners?

This research question resulted in focusing on two aspects of the research: the effective implementation of shading devices and the usability of the design tool by designers. The first one refers to compiling the catalogue of solutions complete with installation guidelines (Figure 6.4). The selection of shading devices available for designers was performed based on the location and existing products. Using Milan as a case study, the installation guidelines were defined in accordance with the Municipality regulations to ensure the feasibility of the design proposals. The modelling strategy of selecting real trees planted in the city of Milan was also guided by this objective. In the end, even in projects where resources are limited, extracting information from Figure 6.5 allows urban designers to propose effective shading solutions.

The protocol developed to effectively position shading devices in master planning proposals is formed of an iterative workflow complemented by an informative design tool (Chapter 7). In developing this protocol, usability, in terms of computational time, modelling process, and communication of results, was prioritised. The final outcome fulfilled these requirements as follows. The computational time was reduced by adopting efficient modelling strategies, and in some cases, reducing the accuracy of results in favour of the possibility of iteratively testing different scenarios. The simulation times in Chapter 6 were below one minute; in the case of network simulations, the longest ones were the shade accessibility analysis (section 5.4.5), with a maximum time of 15 minutes. These results were considered feasible for practitioners, allowing them to perform numerous simulations without putting on hold the design process. In many cases, the modelling process required manual adjustments of the imported data. Nevertheless, the integration of the design tool with the software used by practitioners was accounted as a positive aspect in terms of usability. Finally, specific research was performed about communication of results. When discussions with professionals led to establishing effective illustration strategies, these were included in the Graphic section of the design tool as default.

8.3. Overall contribution to the field of climate-responsive urban design

This research focused on direct solar radiation because its impact on the human heat balance has been demonstrated as a key factor in encouraging or hindering walking in cities. The choice to isolate one climate-responsive system enabled the proposal of practical solutions to one challenge, ensuring the effective performance of proposals and usability by practitioners. Nevertheless, the review presented in Chapter 2 identified outdoor thermal comfort as a theme of complex nature; similarly, many challenges can be found within the urban environment. The principles and concepts adopted in this research respond to the solution-oriented approach promoted by SOLOCLIM and are valid for addressing responsiveness to diverse variables. In fact, the proposed methodology is suitable for developing twin protocols assessing different microclimatic components. To demonstrate its versatility, here an example considering wind speed is outlined. The theoretical assessment of the impact of wind draughts on the outdoor thermal comfort of diverse users would be performed starting from the energy balance, estimating the heat transferred via convection. Wind patterns would be simulated via tools compatible with Rhino, e.g., the Grasshopper plug-in *Butterfly* (n.d.). Finally, a catalogue of solutions with installation guidelines to preserve wind speed when beneficial, and block it in cold conditions, would be created.

The choice of using Rhino tools represents a key advantage in systematically applying the proposed approach to climate-responsive urban design, intended as the combination of solutions to adapt to various microclimatic components. Since Grasshopper plugins are widely assessed to simulate many meteorological variables, as well as building energy analysis, the outcome of this research is suitable to be considered as a component of a large modelling and simulation system. Applying the methodology presented in this research to diverse layers of outdoor spaces has the potential to enable the creation of a multi-layer overview of urban microclimate for designers to define priorities and test solutions. Furthermore, it supports the solution of contradictory results; for example, solutions to tackle excessive exposure to solar radiation, like planting shading devices and trees, could act as a barrier for wind speed, which contributes positively to outdoor thermal comfort in heat stress conditions (de Abreu-Harbich et al., 2015). The systematic combination of sun and wind requirements enables the development of solutions responsive to both microclimatic variables. This research contributes to the development of this multi-faceted design by proposing a systematic methodology to evaluate solutions based on the simulated performance.

The trend of evaluating design based on performance has led to the definition of performance-based verification systems such as LEED (USGBC, n.d.), WELL (International WELL Building Institute, n.d.), and BREEAM (BRE, n.d.). The parametric approach adopted to install shading devices moves forward in this direction, making performance driving the design process. The recent development of digital parametric tools to generate urban morphology (ÇalıŞKan, 2017; El Dallal & Visser, 2017) reinforces the relevance of the adopted strategy. This research proposed a parametric approach to urban design, yet the maps kept a key role, both for visualising results and communicating design choices. Furthermore, modelling in Rhino enables the possibility of visualising design proposals in 3D, simulating the perspective of pedestrians. This is a key advantage in parametric modelling, stressing the importance of moving across scales, always with the user at the centre of the approach.

Focusing on the human dimension led to shifting the focus from the city to the people; this change of paradigm modifies the top-down planning approach well-established before, adopting an upscaling design process that identifies people as the starting momentum. The critical goal of prioritising the user experience in design processes is increasingly present in research about thermal comfort (Chokhachian et al., 2017; Vasilikou &

Nikolopoulou, 2020), emphasising the relevance of this theme. Results of this research are directly linked to urban theories such as the 15-minutes city concept and provide potential integration of climate-responsiveness into mobility analysis. Positioning the user at the centre even generated questions about how pedestrians of diverse walking abilities would experience the same outdoor space; results presented in Chapters 4 and 5 are a critical example of how to foster the adoption of diverse perspectives in climate-responsive urban design.

The knowledge first gathered, then developed, in this research is a contribution not only for urban design but also for the development of travelling applications. Barcelona Regional (n.d.) created a web map that compares sun exposure of walking paths at three different times of the day. The route modes are defined as 'the shortest path', 'the shady path' and 'vampire mode on', which maximises the shading; the web users can also locate drinking fountains and shelters. Similarly, the EXTREMA Global Mobile App was developed to inform users about shaded streets and cooling spaces; in September 2024, it covered four cities, including Milan (ARTi Analytics BV, n.d.). The characterisation of pedestrians based on their physiology and walking abilities finds application in these mobile tools, fostering the implementation of the inclusivity component.

8.4. Limitations and future directions

The focus on the accessibility of results by practitioners led to prioritising usability over accuracy. As reviewed in Chapter 2, the climate adaptation topic is vast, and microclimatic conditions result from the combination of diverse microclimatic components that vary differently in time and space. This research narrowed down the focus to direct solar radiation exposure, a variable that designers can manipulate in practice; nevertheless, results presented in this thesis must be considered as part of the larger context of climate-responsiveness. A future direction of research might be the adaptation of the proposed protocol to diverse meteorological variables, as described for wind speed in Section 8.3. Additionally, even though solar radiation has a prominent role in outdoor thermal comfort and microclimatic conditions, further studies should 'weight' the results of this thesis compared to other variables and interests, with the goal of assessing the systematic implementation of multidisciplinary knowledge in urban design.

The methodology to define user profiles by reviewing the literature can be considered as a first step. In this research, this method was used specifically to simulate a process adopted in practice, but it is acknowledged that there is room for further research. Specifically, observational campaigns would provide more data about pedestrians' habits linked to solar radiation exposure, as performed by Melnikov et al. (2022). Surveying people also proved to be an effective method to relate observed behaviours with people's perception, providing relevant insights to understand the subjective component of thermal comfort (Faustini et al., 2020; Labdaoui et al., 2021a). Gathering first-hand feedback about outdoor thermal comfort and physiological characteristics could be used to validate the definition of user profiles, providing also information to enlarge the group of user experiences analysed. Additionally, surveys would allow for the inclusion of cultural aspects, following the approach of Aljawabra & Nikolopoulou (2018).

The selection of the case study city was driven by the opportunity to test the proposed methodology on a real case study project. Additionally, the city of Milan provided useful insights in terms of population, being the second most populated city in Italy, and climate change, having experienced an increasing number of heat waves in the last years (Municipality of Milan, 2022a). In the wake of global warming, shading solutions are increasingly needed worldwide, yet a particular mention must be given to arid climate zones; this is validated by the fact that the shading goals reported in Chapter 6.2 are defined by cities where summers are hot and dry. Future research could be performed to systematically compare the effectiveness of shading devices based on different latitudes; tables like the one reported in Figure 6.5 could be created for various cities. A critical study to inform decision-making about shading goals would be comparing the impact of solar radiation on pedestrians in different climate zones. The methodology in Chapter 4 was developed to inform practitioners in this regard, but more research is needed to adapt the defined thresholds in diverse environmental and microclimatic contexts.

The systematic approach of this research to solar radiation exposure makes room for future developments. In fact, its contribution is not limited to innovative tools for positioning shading devices into master planning projects using a user-centred approach. From a more strategic perspective, it developed a methodology for isolating the impact of one variable of the urban context on people, making the related knowledge accessible for professionals, and providing them with tools to design beneficial solutions, leading to a tangible positive change. In light of that, both the protocol for shading implementation and the methodological approach adopted to quantify the impact of solar heat load on people could be adapted to multiple factors, not necessarily related to climate. The systematic overlay of interests placed on urban spaces would support stakeholders and decision-makers in designing comfortable and inclusive public spaces.

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APPENDICES

Appendix A: Protocol for the implementation of shading solutions in outdoor spaces

In this section, the protocol submitted as a deliverable for the SOLOCLIM project is presented.

SOLUTIONS FOR OUTDOOR CLIMATE ADAPTATION

Improving microclimate inclusivity of pedestrian paths

Protocol for the implementation of shading solutions in outdoor spaces

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The work on climate-responsive systems carried out during this PhD research is collected into a protocol developed specifically for urban planners and designers. It has been formulated to be included in their daily practice and it allows them to analyse and evaluate design options of outdoor spaces with the goal of making them comfortable for users, throughout the year. The proposed workflow is shaped as an informative design tool to position a variety of shading solutions in master planning proposals. Direct solar radiation is investigated because of its major impact on human heat balance and its interaction with urban morphology – a component that designers can manipulate during the design process. The definition of the protocol considers urban and climate data availability, operability into urban design workflows, and dissemination of microclimate knowledge. The protocol is structured to provide multiple degrees of design optimization in response to the level of expertise of urban designers and their familiarity with tools. Outcomes range from rule-of-thumb-like information to detailed modelling of shading devices: this enables wide accessibility and applicability of this research.

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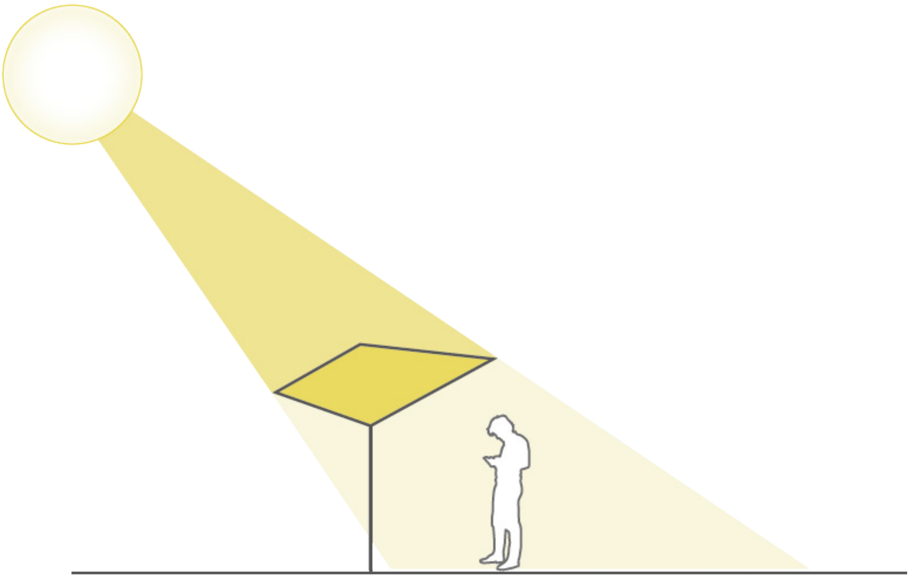


INTRODUCTION

Walkability and direct solar radiation

The 15-minute city concept (Luscher 2020) argues for comfortable and safe walking environments; because of world population growth and urbanisation trends (UN DESA 2019), the number of people that would benefit from comfortable urban pedestrian paths is increasing.

Microclimatic conditions of pedestrian paths deserve critical attention because walking is impacted by environmental factors whether it is for recreational purposes, to exercise or as a means of travelling (Forsyth 2015). Santucci et al. (2020) defined walkability as the combination of health, safety, and vitality; the walking activity is strictly dependent on the quality of the public realm. In their review of definitions of walkable spaces, Forsyth (2015) cited climate as a factor influencing walking activity. Climate walks highlighted the impact of variations in dense urban morphology on thermal pleasantness (Santucci et al. 2020; Vasilikou and Nikolopoulou 2020). Literature has presented associations of thermal stress with increasing perceived travel time (Rakha 2015) and walking speed (Bosina and Weidmann 2017; Mouada et al. 2019).

Inclusivity in the design of pedestrian paths

The human factor is often overlooked in urban climate mitigation strategies, even if cities are hubs where daily choices impact people and their environment (Kaltsa 2016). The human dimension requires its due space, moving the focus from the city to the people: this change of paradigm calls for design-goal-oriented workflows to improve accessibility to outdoor public spaces: it is an opportunity to foster inclusivity in cities, thinking about people with diverse needs and peculiarities.

Elderly people are considered among the most vulnerable users in cities, especially during hot summer days (Dodman et al. 2022): this is critical since the United Nations has listed population ageing among the world demographic megatrends, defining it as an unprecedented phenomenon (UN DESA 2019). The elderly are recommended to walk because walking is a moderately intense physical activity that indirectly reduces health risks due to heat stress (Dodman et al. 2022). Mobility declines with age: this can be a barrier in case of uncomfortable microclimatic conditions because it would impede moving in search of restoration (Kabisch et al. 2017). Furthermore, lower walking speeds reduce the number of accessible facilities within the beforementioned 15-minute radius.

Together with the elderly, children are another vulnerable user group experiencing cities (Kabisch et al. 2017). The urban environment might be challenging for the youngest pedestrians: Urban95 shed light on infants, toddlers and caregivers (ITCs), listing continuous sidewalks, the presence of resting points and safe paths among indicators of good quality neighbourhoods for their needs (Urban95 2019b). Growing up, comfortable walking paths would encourage children to walk to and from school (White et al. 2017): since children and infants are more vulnerable to the impact of extreme heat (Vanos et al. 2018), it is mandatory to adopt their perspective in evaluating pedestrian paths.

Problem statement

The provision of shade on walking paths is one of the most effective strategies to improve pedestrians' comfort in summer sunny conditions (Labdaoui et al. 2021; Pearlmutter et al. 2007; Sanusi et al. 2017). The shade provided by buildings is the most beneficial for thermal comfort (Middel et al. 2021); in its absence, natural and artificial shading devices can be strategically installed. Trees are considered a critical strategy for improving thermal comfort (Nasrollahi et al. 2020). In addition to trees, artificial shading devices such as overhead covers (Lee et al. 2020; Shashua-Bar et al. 2011) and stand-alone canopies (Palomo Amores et al. 2023) can be used to screen urban streets from solar radiation (Middel et al. 2021). Natural and artificial shade can also be combined, as demonstrated by Peeters et al. (2020) simulating a pergola covered with vegetation.

The installation of trees is subject to a variety of factors: economic, cultural, ecological, and aesthetic (de Abreu-Harbich et al. 2015). Trees in urban environments are valued by people because of their aesthetics (Klemm et al. 2015), and their impact on reducing direct solar radiation which critically contributes to outdoor thermal comfort (Kenny et al. 2008; Shashua-Bar et al. 2011). 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. Recent findings highlighted that if trees are planted close to walking paths, but without shading pedestrians, they rather contribute to thermal stress through the emission of longwave radiation (Park et al. 2019). Therefore, a systematic approach to position shading solutions is needed to avoid detrimental effects.

A solution to implement shading devices in outdoor spaces

The best strategy to ensure effective results in terms of urban climate adaptation is to include the related processes in practice rather than delegating its investigation to dedicated phases of the workflow; this strategy is known as 'mainstreaming' (Uittenbroek et al. 2013). Keibach & Shayesteh (2022) evaluated software tools for climate adaptation planning based on six characteristics: functional suitability, reliability, performance efficiency, usability, compatibility, and information quality. Limited compatibility and interoperability of software result in time-consuming operations (Diéguez et al. 2017), which might discourage microclimatic analyses at the early stages of the design process. Therefore, compatibility with other software or processes, and performance efficiency become key in applying microclimate analysis to urban design. To ensure the relevance of the protocol to urban designers, tools predominantly used by architects and urban designers in practice were selected. The target of this protocol was professionals working at the street scale, therefore it was developed in Grasshopper (GH), the visual scripting interface for Rhinoceros. Within the Rhino environment, urban designers accurately model urban morphology in 3D (a critical feature in shadow studies) without the need to remodel geometries, as well as modify and test design options with limited simulation time (Keibach & Shayesteh 2022).

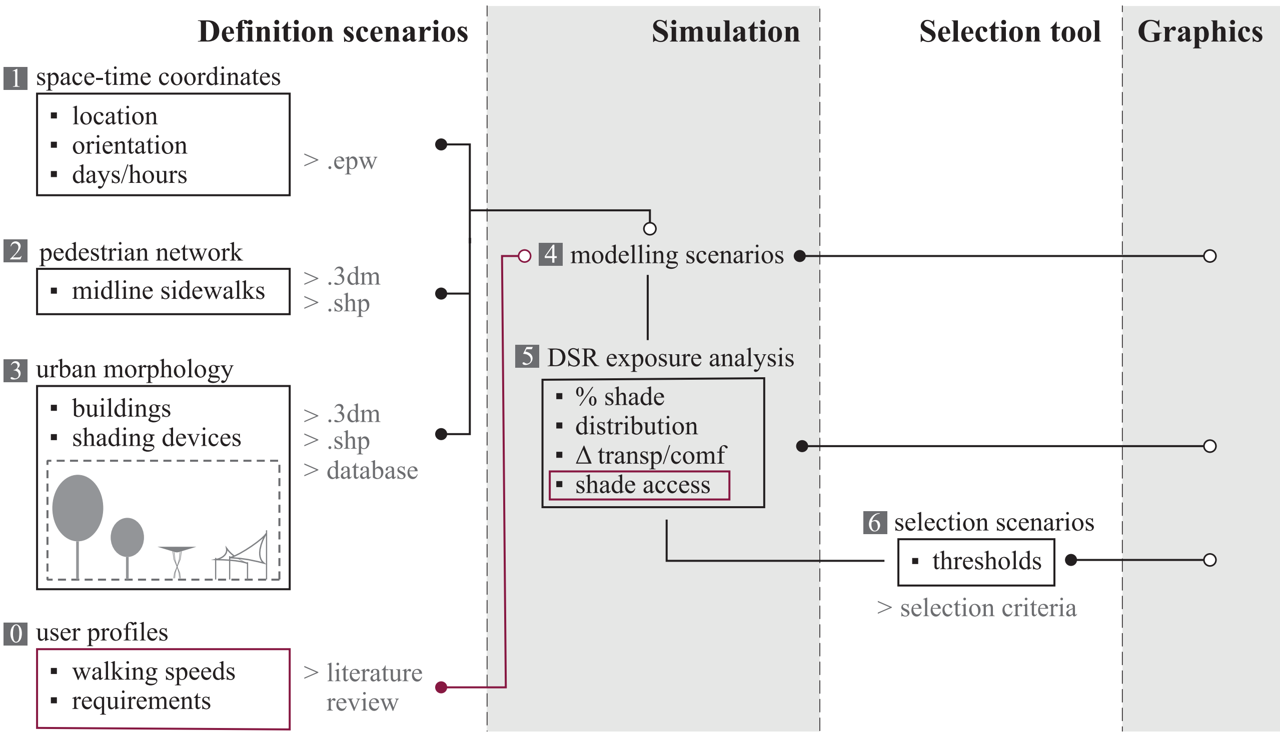
This protocol was developed for urban designers to design effective installations of natural and artificial shading devices to shade pedestrian paths. This approach was shaped as an iterative workflow that enables urban designers to analyse, evaluate and design the shading solutions within the design process rather than the conventional way of performing modelling exercises separately to assess environmental issues. At first, the proposed design tool is presented, alongside materials required and default settings. Three design exercises are then illustrated step-by-step, with the double objective of presenting possible applications of the protocol and providing detailed guidance in using the tool. Finally, diverse applications to urban design practice are proposed in accordance with resources availability and the required outcome.

DESIGN TOOL TO POSITION SHADING SOLUTIONS IN OUTDOOR SPACES

Structure of the protocol

The protocol for the implementation of shading solutions in outdoor spaces relies on a design tool developed in GH for effectively positioning shading devices. The term 'design tool' is a reference to the work by Ratti (2002: 9), who proposed 'a simple reactive tool, allowing for comparison of different architectural and urban options'. To structure it, the Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC), organised in inventory, calculation, and goal setting, was taken as a reference (Fong et al. 2021). Thus, three sections were defined: definition of scenarios, simulation, and selection tool. In the first one, materials are assembled and selected to define the case study project. In the simulation phase, the direct solar radiation (DSR) exposure of modelled scenarios is analysed; finally, the selection tool is used to compare the shading performance against design criteria. Additionally, the graphics section ensures meaningful communication of results. Each section is populated with groups of clusters, referring to specific steps in using the design tool: the sequence of steps aims at selecting the most suitable design proposal to shade sidewalks when pedestrians most need it. Figure 1 reports the structure of the design tool, including input data required to model scenarios; in the following pages, each section of the tool is illustrated.

Figure 1: Structure of the design tool for an effective installation of shading devices. Each black rectangle corresponds to a group of clusters in the GH code. Grey arrows highlight input data by designers; black and white dots represent the output and input data of groups, respectively.



DEFINITION OF SCENARIOS

In this phase, the scenarios to analyse pedestrian networks in terms of microclimate inclusivity are defined. Designers have the opportunity to outline specific scenarios to be addressed in their practice and analyse either theoretical sidewalks or ‘real’ master planning proposals.

1. Space-time coordinates

Microclimatic conditions in the urban environment change on a seasonal, daily and hourly basis. The first step requires the selection of the microclimatic conditions to address in the design phase, based on the goal stated at the beginning of the process. At first, meteorological data corresponding to the studied location are input into the code.

LOCATION

Meteorological files can be downloaded from the EnergyPlus website for numerous locations around the world (https://energyplus.net/weather). The files can be downloaded directly into GH via Ladybug; statistics about typical or extreme conditions are available on EnergyPlus and can inform designers' choices. Alternatively, sun ray vectors can be manually input in the GH code.

ORIENTATION

Working with direct solar radiation, the position of the sun against the urban morphology is key. The code allows urban designers to change the orientation of the model, as part of the modelling task or for comparative purposes; an additional component to visualise the sun path is provided for reference.

DAYS/HOURS

The analysis period corresponds to day/hour combinations that are relevant for the performed analysis. In the default mode, the tool requires three day/hour combinations, ideally representing the same hour in three different seasons. To prioritize people's activities at specific times, it is recommended to take into consideration daylight saving times in the selection phase.

2. Pedestrian network

The pedestrian network is represented as one or multiple lines under investigation. An existing database (e.g., in shapefile format) can be imported via GH plugins, such as Urbano (https://www.urbano.io/). Sidewalks modelled in Rhino can be input as well.

Based on the design goal, two modelling options are available:
- Theoretical mode: various shading devices installation proposals are analysed and compared for the same standard street.
- Master plan mode: a specific master plan is modelled and analysed, therefore streets are not standardised but refer to specific paths in the context.

MIDLINE SIDEWALKS

The sidewalks system must be translated into a linear network: the midline of the sidewalk is selected to represent the considered surface as a segment of the network. To ensure model usability, cleaning the network is recommended, with specific attention to modelling a continuous network with accurate intersections and removing slubs. According to the adopted workflow, the network must be modelled as bidimensional or can be modelled in 3-D.

3. Urban morphology

The interaction between urban morphology and sun rays impacts the exposure of pedestrian paths to DSR. In this protocol, the term ‘urban morphology’ includes buildings and shading devices, modelled as surfaces in Rhino.

BUILDINGS

It is considered a static component of the urban environment because it is susceptible to rare and/or limited changes. Municipalities increasingly provide open-source data in *.shp* format, with building height reported as an attribute. Using GH plugins such as Urbano, it is possible to import building footprints and extrude them based on the height attribute. In addition, geometries modelled in Rhino can be selected as context.

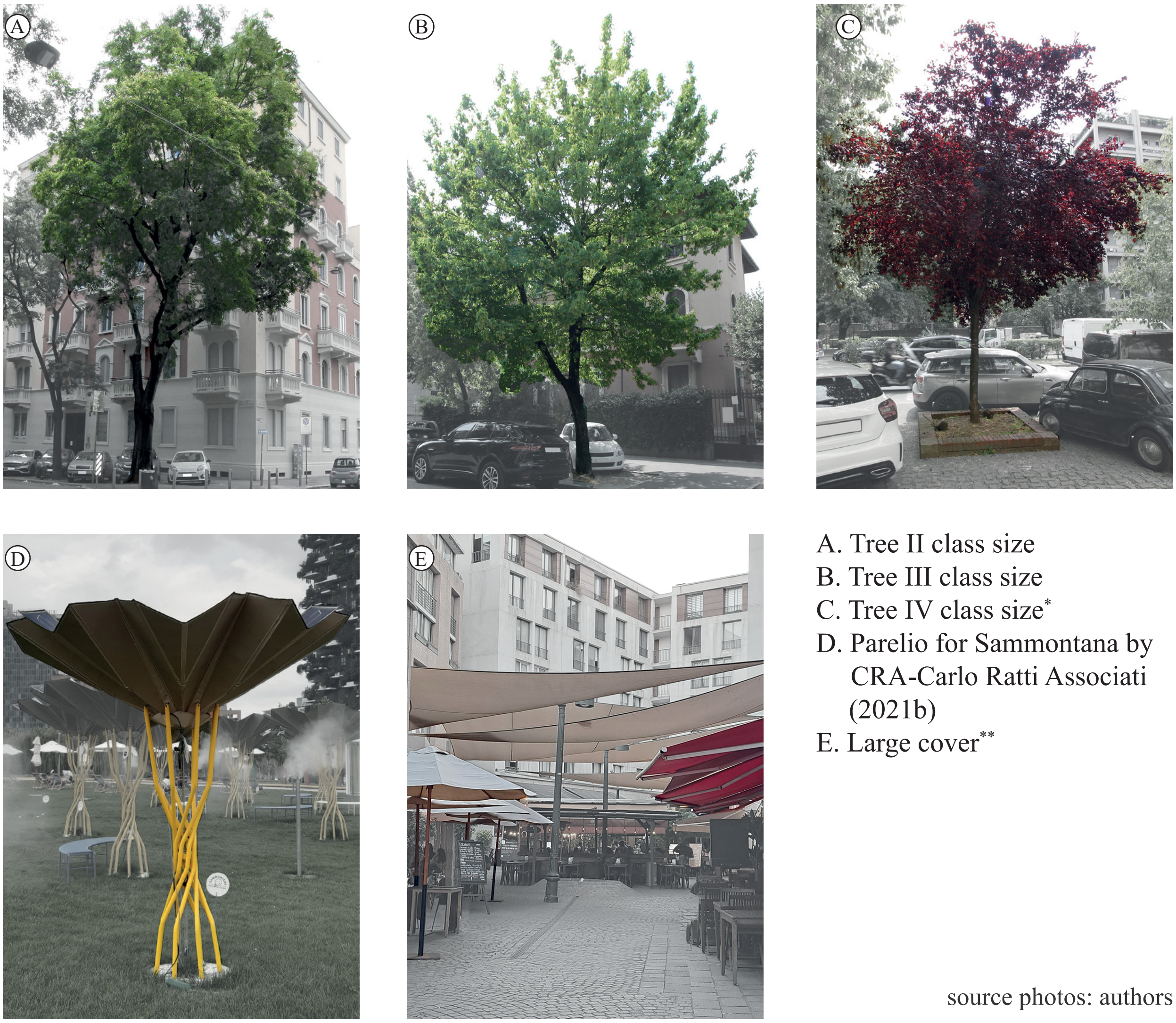
SHADING DEVICES

A catalogue of shading devices is presented, with the potential to implement new solutions. Devices are considered exclusively in terms of morphology, focusing on their overall dimensions.

Trees are 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 is modelled as a spheroid blocking sun rays, as the focus is on identifying the exact location of the shading effect; removing the canopy in winter is possible. Artificial devices, even of complex shapes, can be included in the catalogue.

In default mode, a library of three natural and two artificial shading devices is provided (Figure 2). Trees were modelled after specific plants included in the census database of the Municipality of Milan (Table 1). The modelled artificial devices represented two different typologies of intervention: the punctual installation of objects, i.e. the stand-alone device Parelio by CRA - Carlo Ratti Associati (2021b), an umbrella-shaped structure able to convert solar energy into electricity through the foldable photovoltaic panels installed on top; and a large textile cover to be installed above pedestrian paths, specifically a rectangular canopy 2.2 m high connected to the ground at a 3 m interval.

Figure 2: Photographs of shading devices included in the provided catalogue.



A. Tree II class size
B. Tree III class size
C. Tree IV class size*
D. Parelio for Sammontana by CRA-Carlo Ratti Associati (2021b)
E. Large cover**

source photos: authors

* The tree in the picture is not the one reported in Table 1 because of limitations during field visit.
** Various examples of large textile covers, which serves as an inspiration for designers.

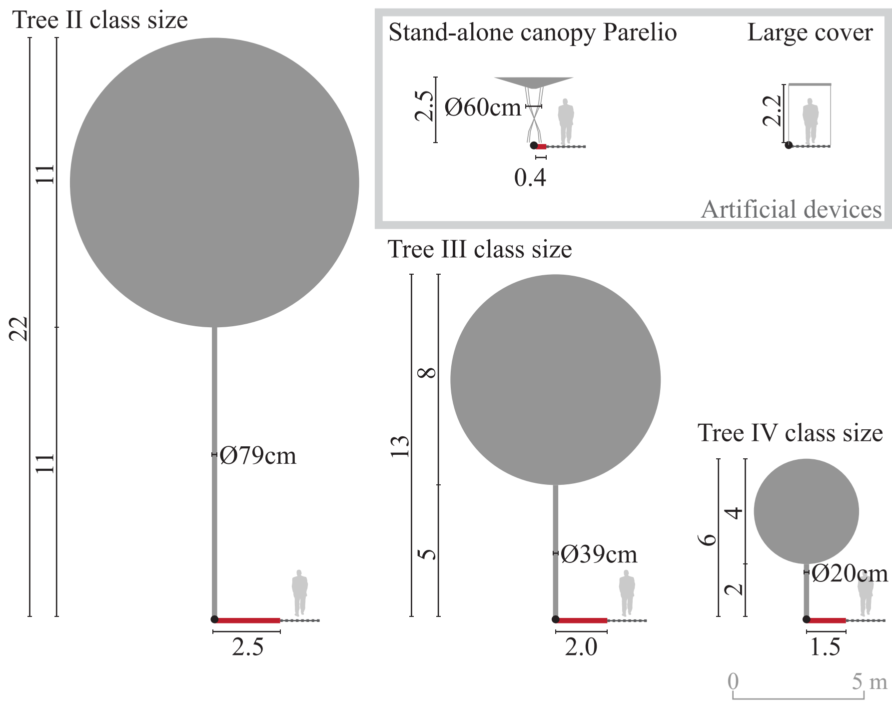
Table 1: References of trees included in the catalogue.

Class size	**Maturity height**[1] **[m]**	**Specie**[1]	**Canopy shape**[1]	**Tree ID**[2]
II	15-25	*Celtis australis*	Sphere	13875
III	8-15	*Acer negundo*	Sphere	134302
IV	<8	*Prunus cerasifera*	Sphere	37367

[1] (Municipality of Milan & AMAT 2021); [2] (Municipality of Milan n.d.-b).

The library was complemented with a suggested minimum distance between the devices and the sidewalk edge (DS) if required. For trees, this buffer zone was identified based on indications specified in Municipality of Milan (2022): it corresponded to a circle, with the trunk at the centre, of radius determined by the class size. The selected values referred to the portion of the ground in which roots could grow. For artificial devices, the suggested DS distance corresponded to the space occupied by the structure. Figure 3 illustrates the catalogue of devices, complemented with suggested minimum DS distances.

Figure 3: Catalogue of shading solutions included in the code. Red lines refer to the recommended minimum distances between the device and the sidewalk edge (DS).



0. User profiles

Inclusivity is a key factor in the proposed protocol, which encourages the identification of pedestrians that would use the analysed urban space and the following endeavour to tailor the selection process based on their diverse experiences of the urban environment.

WALKING SPEED

Walking speed differs based on the physical and behavioural components of pedestrians. In default mode, four users of diverse walking abilities are modelled: standard pedestrians, individuals in a wheelchair, pedestrians using assisting devices (cane, crutch, walker), and ITCs (infants, toddlers and caregivers). The respective walking speeds are determined from the literature and collected in Table 2. Selecting one user profile allows one to tailor the shade accessibility analysis to the appropriate walking speed, converting metric distances in time necessary to walk from one point of the pedestrian network to another.

Table 2: Walking speeds for users of different physical abilities.

User	Speed (m/s)	Speed (m/minute)	Adapted from
standard	1.34	80	(Bosina & Weidmann, 2017)
wheelchair	1.08	65	(Oxley et al., 2004)
assisting device	0.72	43	(Oxley et al., 2004)
ITCs	0.50	30	(Urban95, 2019a)

REQUIREMENTS

Additional mobility requirements can be included in defining scenarios. For example, a maximum slope, which can be defined according to local legislation, can be associated with individuals using a wheelchair: segments above the defined steepness are then removed from the network. The result of the first section is a pedestrian network model surrounded by urban morphology.

SIMULATION

4. Modelling scenarios
5. DSR exposure analysis

The simulation section performs direct solar radiation analyses based on input scenarios and design goals. Three workflows are defined by combining the DSR exposure analysis mode, i.e., vector or raster, with the modelling mode, i.e., theoretical or master plan (Table 3).

Table 3: Definition of three workflows based on DSR exposure analysis mode and modelling strategy.

	Theoretical	Master plan
Vector	Workflow A	Workflow B
Raster	-	Workflow C

Workflow A

The DSR exposure analysis is performed on a standard street with vector components. The street is flat, therefore the analysis is performed on one plane: shadows are projected on a defined horizontal plane and devices are positioned according to the defined scenarios. The goal is to compare the shaded length of a linear sidewalk resulting from the installation of one shading device at different distances, comparing results at three specific times.

Workflow B

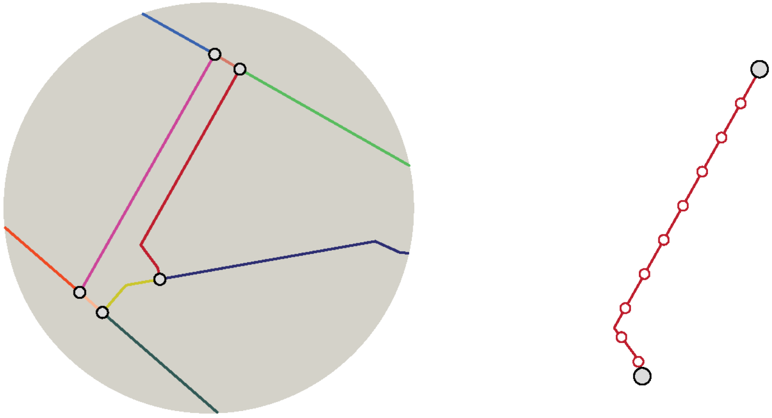
The DSR exposure analysis is performed on a specific street (or group of streets) with vector components. The projection plane must be planar, therefore only 2-D analyses can be performed. In addition to buildings, different shading devices are positioned in the master plan. The shading devices from the library can be assigned to installation points. The goal is to compare the total shaded length of a pedestrian network as the result of a combination of shading devices and buildings.

Workflow C

A 3-D network is segmented at first only at intersections. The term ‘raster’ analysis mode refers to the subdivision of each segment of the network into smaller segments, named ‘steps’ (Figure 4). Then, the DSR exposure of each step is analysed with the obstructions method. The height of analysis is set in the segmentation component, therefore it is recommended to set to zero the modelling projection plane used in workflows A and B.

Figure 4: Definition of two segmentation modes of the pedestrian network: a) segmentation at intersections; b) subdivision of each segment in steps.

a) b)



The opportunity to analyse large tridimensional networks is traded with the accuracy of the results. Additionally, only one day can be analysed at once.
Four analyses are included in the default code:

- % shade > each segment of the network is classified based on the percentage of shaded length;
- Distribution > each segment of the network is classified based on how frequently shaded/sunny conditions change.
- Δ transp/comf > for a given origin/destination combination, this cluster compares the shortest and the most shaded paths.
- Shade access > based on the selected user profile, at each step of the network, the distance to the closest step at the opposite condition is calculated in terms of time. For example, if a step is classified as 'sunny', the shortest distance to walk to find shade is defined.

In this group is also possible to modify walking speed on stairs to differently weigh segments above a selected inclination: in default mode, the value of 43 m/minute for standard pedestrians is selected. This value refers to the horizontal walking speed; it is assumed valid for pedestrians climbing and descending stairs and was estimated based on literature (Fujiyama & Tyler 2004; Kretz et al. 2008).

SELECTION TOOL
6. Selection scenarios

This section allows urban designers to define thresholds for evaluating the results of the simulation section. In the theoretical approach (A), a limit to the number of shading devices installed can be set up, together with a minimum and maximum percentage of length to be shaded on all three times. In the master plan design (B), the tool presents the DSR exposure of the pedestrian network on the three times. Finally, additional input data can be inserted for the 3-D network analysis (C), such as an area of interest, performance thresholds in terms of DSR exposure, and origin-destination combinations.

GRAPHICS

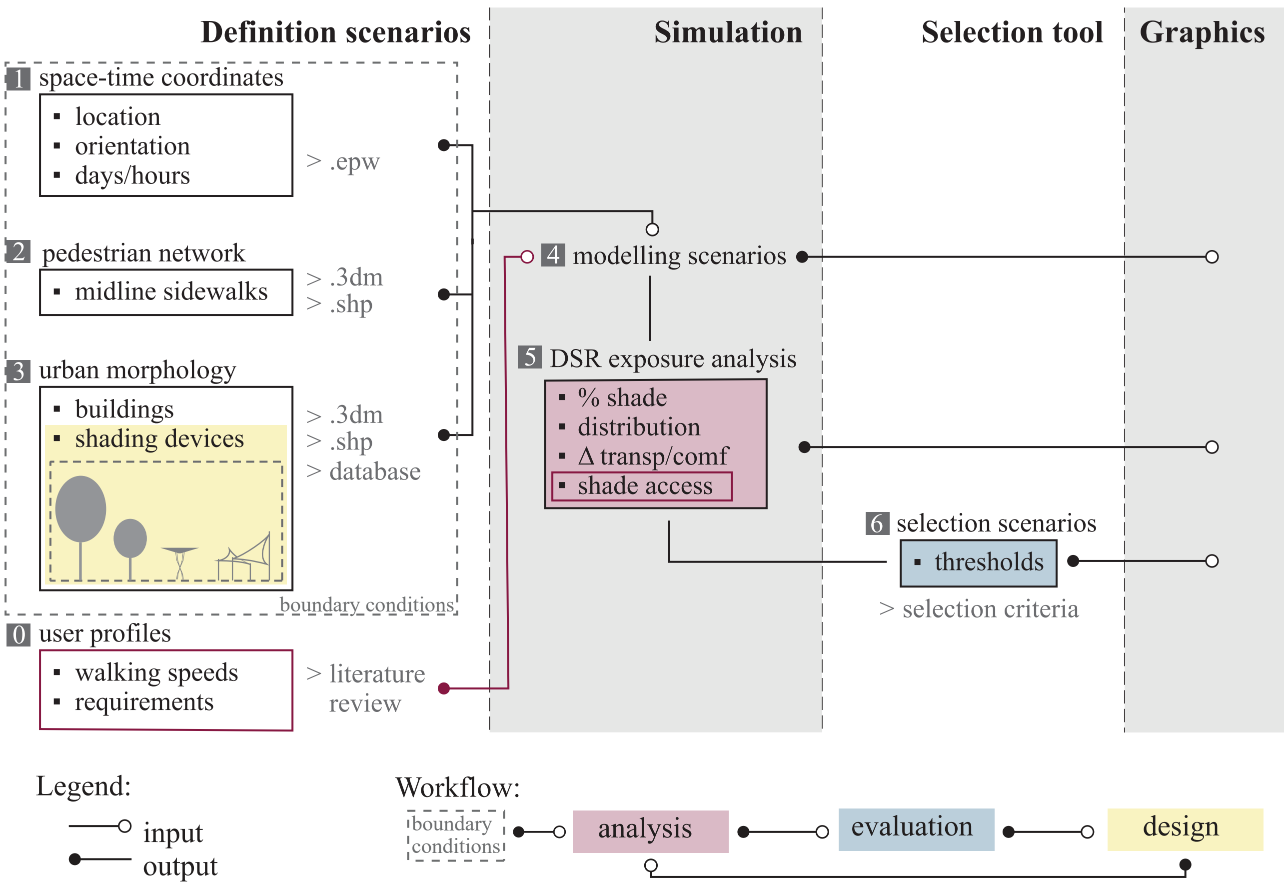
This section is of utmost importance, as it allows one to effectively visualise results. A specific component is assigned to each step of the simulation and selection sections; urban designers can turn on/off the visualisation components, as well as modify them. Legend and drawing styles reported in this report are included as default.

THREE DESIGN EXERCISES PERFORMED WITH THE DESIGN TOOL

Presentation of the iterative workflow

The protocol for the implementation of shading solutions in outdoor spaces presents a rigorous approach to setting up various scenarios for evaluating DSR exposure based on different hour and day combinations, urban morphology, and shading solutions available. To make the best use of this tool, an iterative workflow is recommended: it is divided into analysis, evaluation of results and design. At first, the so-called 'boundary conditions' must be set, which correspond to the existing scenario or the first design proposal. Once the DSR exposure analysis has been performed, the selection tool is used for the evaluation process. Selection criteria are used to compare results with design goals or requirements, evaluating the analysed scenario. If necessary, urban designers can design and test new scenarios. For existing urban morphologies, the design tool allows urban designers to test shading device configurations to fulfil selection criteria; if master plan proposals are evaluated, buildings can also be rearranged to find the best configuration for benefit outdoor spaces as well as indoor occupants.

Figure 5: Scheme illustrating the iterative workflow proposed to use the protocol for an effective installation of shading devices.



GH code explanation

Figure 6a presents a high-resolution screenshot of the GH code. The legend on the left provides information about how the design tool is organised: coloured boxes highlight the input data required, while panels are used to visualise intermediate results and provide suggestions to urban designers. In Figure 6b, the schematic representation of the design code (Figure 1) is overlaid on Figure 6a. This figure serves as a wayfinder in the GH canvas: the navigator is always reported in the following pages.

Figure 6a: Screenshot of the GH code.

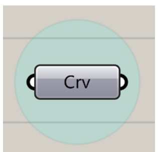
Legend

Colours are assigned to groups reported in Figure 6b. Additionally, recurrent graphical elements are adopted to improve the usability of the GH code by urban designers:


workflow gate

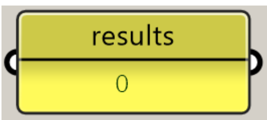

input required


input possible



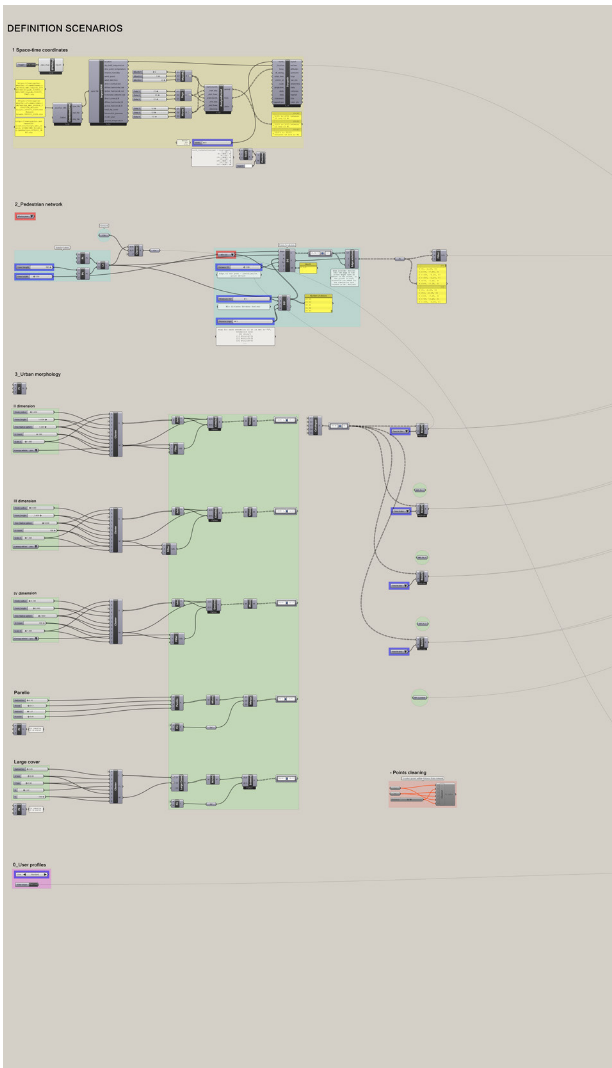
input geometry


calculations



results check

captions/
usability tips



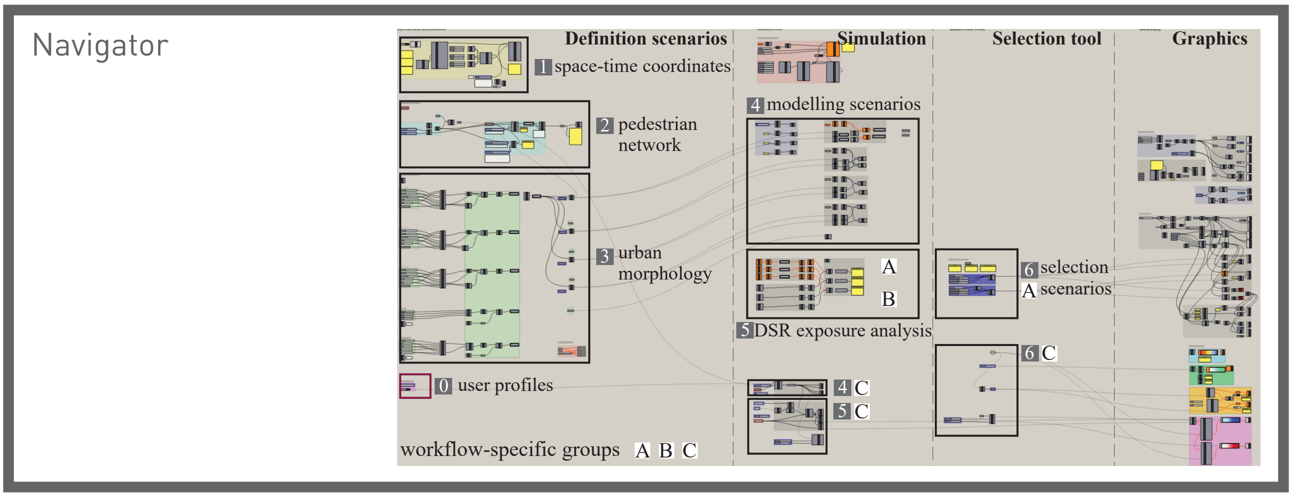
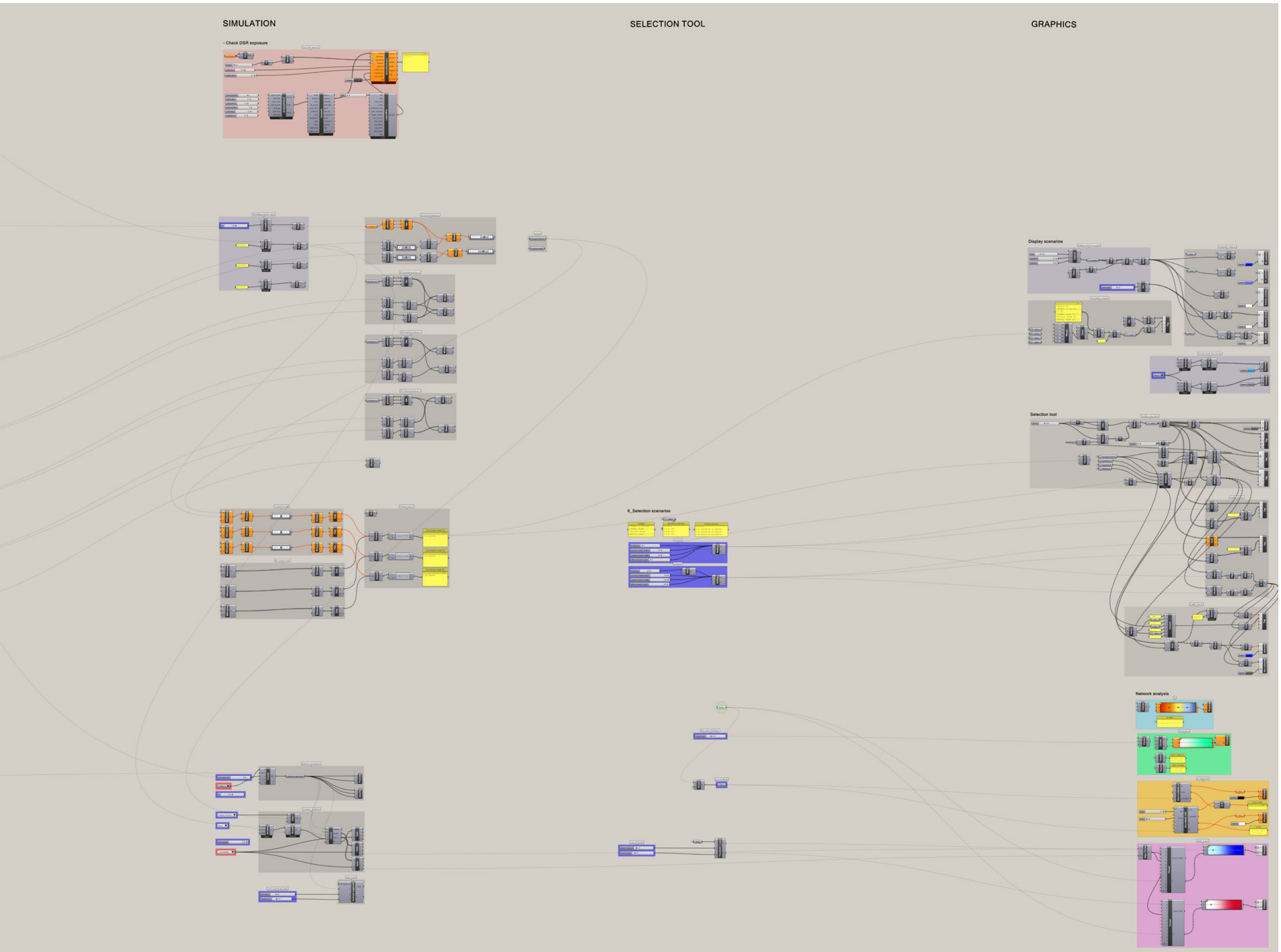


Figure 6b: Overlay of the schematic representation of the design tool on the GH code to visualise the position of each group in the GH canvas.



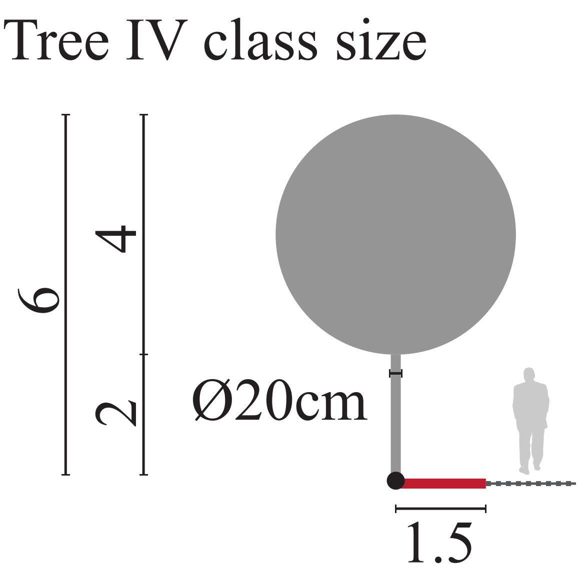
In this section, the three workflows reported in Table 3 are presented as design exercises and illustrated step-by-step. At first, a brief introduction of the case study and the design goal are outlined; then, the relevant parts of the code are selected, and pictures of the output of the design tool are presented.

Design exercise 1

WORKFLOW A – Selecting a shading solution for a theoretical sidewalk
A theoretical sidewalk located in the city of Milan (IT) was simulated. The sidewalk was of standard length (100 m) and 1.5 m wide; it was located in the NW position of an NE-SW oriented urban canyon. The goal of this exercise was to define the number of tress IV class size that would allow a minimum shaded length of 60% at 1 pm during the summer solstice and autumn equinox; the winter solstice day was analysed to evaluate whether shadows would land on the sidewalk in the coldest season when direct solar radiation on pedestrians would be beneficial.

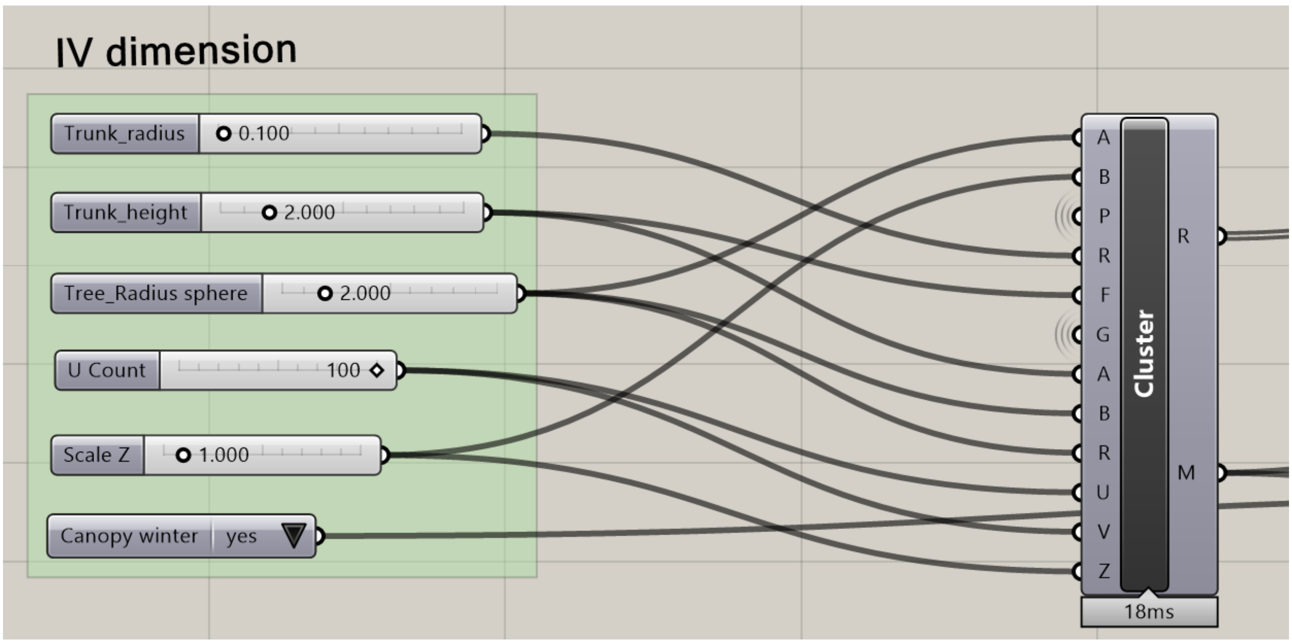
Figure A-0

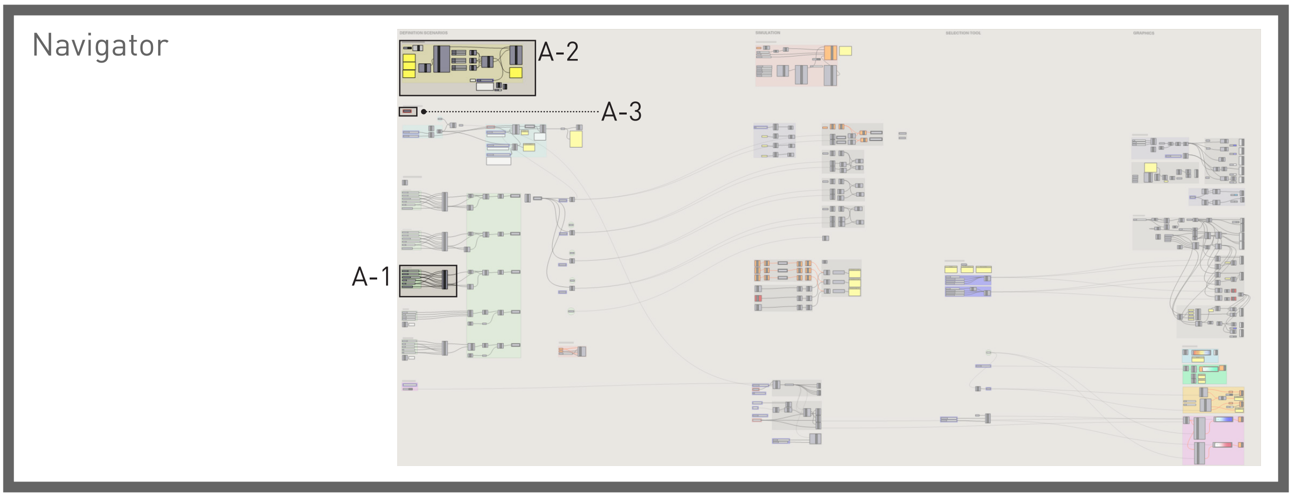
The analysed solution is a tree IV class size included in the default library of shading devices. Dimensions are reported for reference.



Each tree of the library is modelled parametrically: dimensions can be changed to implement additional or different tree morphologies. Additionally, the canopy of the tree can be removed in winter.

Figure A-1





The selected location was Milan; specifically, the *.epw* file refers to the station of *Milano-Linate.160800*. The selected days were defined as the analysis period: it should be noted that in summer, hours were selected based on daylight saving times. Finally, the orientation was set to 315°, as explained in the white box reported in the code.

▼ Figure A-2

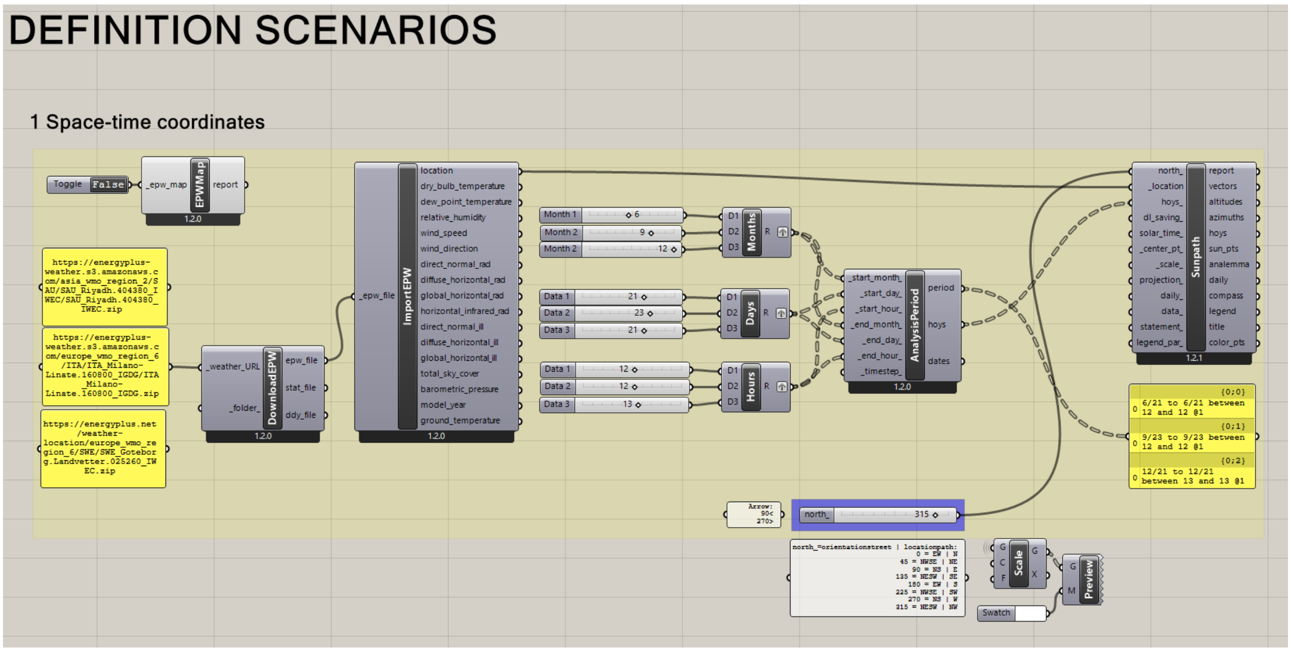


Figure A-3 ▶

The code was set to ‘theoretical’ mode: this enabled the clusters to compare design scenarios referring to one specific solution positioned at different distances.

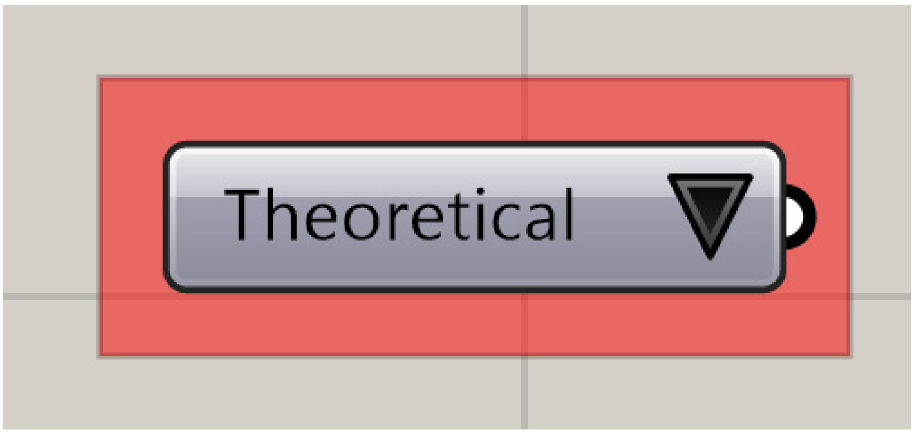


Figure A-4

Dimensions of the theoretical sidewalk were input in the code in the cluster 'standard street'.

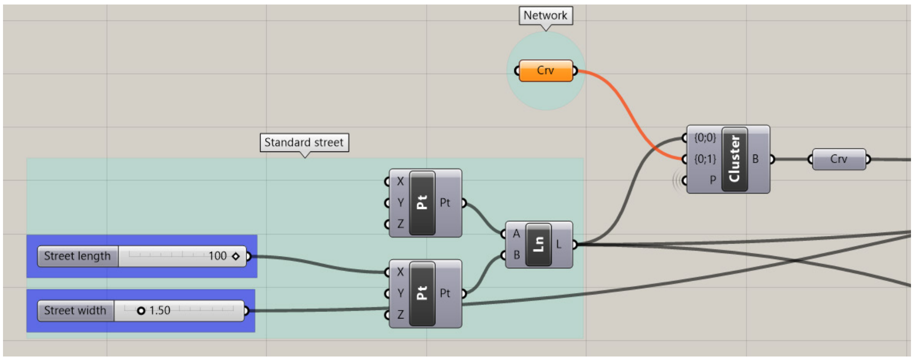
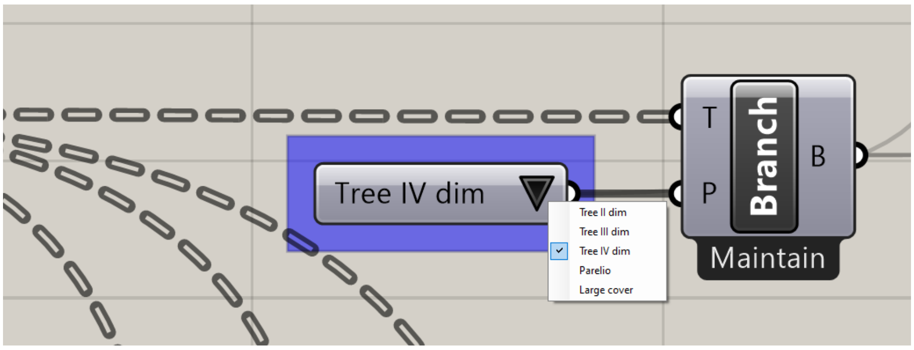


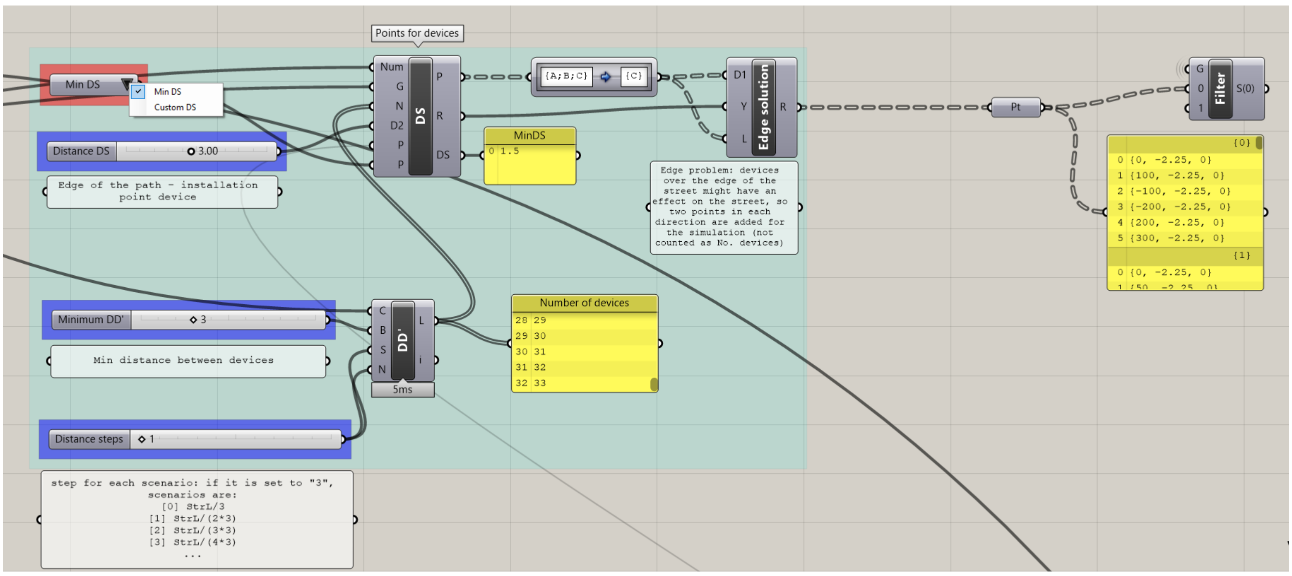
Figure A-5

The shading device was selected from the default library; in this case, it was a tree IV class size. Five solutions are available in the dropdown list.



Parameters about the installation of the tree and the number of scenarios to model were input in the code. As regards the distance between the tree and the edge of the sidewalk, two options are available: selecting the minimum distance recommended (Min DS), in this case by the Municipality of Milan (2022), or setting a customised distance (Custom DS). In this case, the first option was selected. Then, the minimum distance between devices (DD') was inserted (twice the distance between device and sidewalk edge, i.e., 3 m). The number of scenarios refer to how many design options will be simulated; in this case, the maximum number allowed by the minimum distance resulted in a total of 33 options to be tested.

Figure A-6



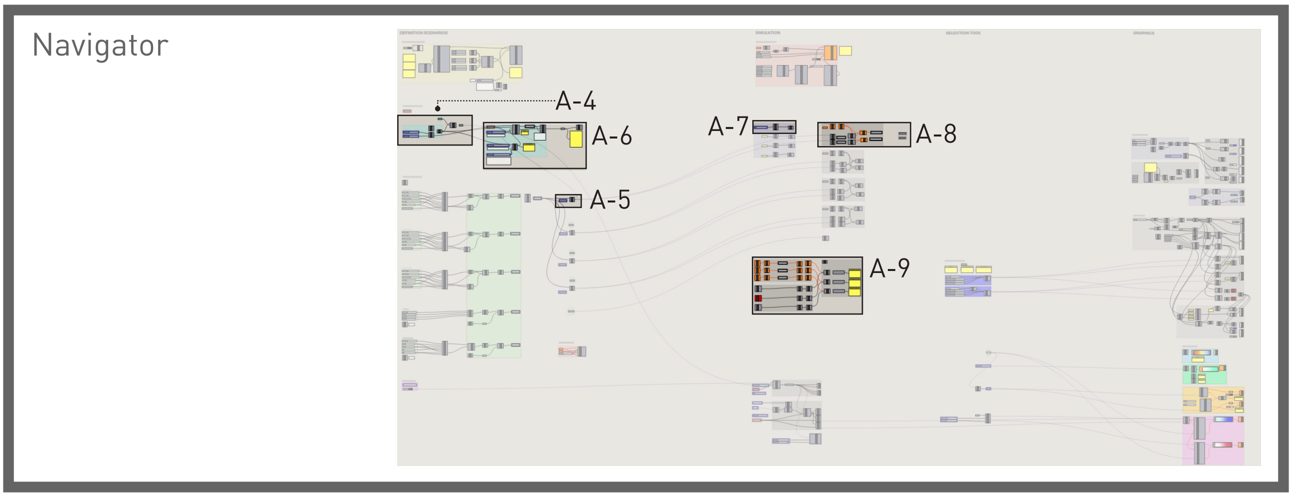


Figure A-7

In the Simulation section, the height of analysis was set to 1m[1].

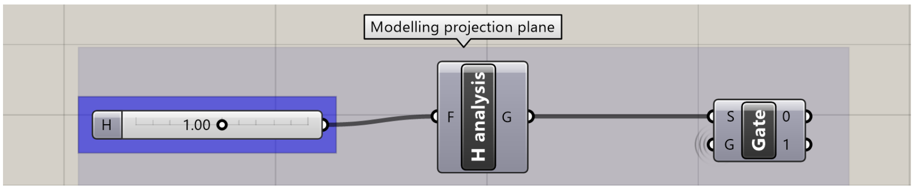
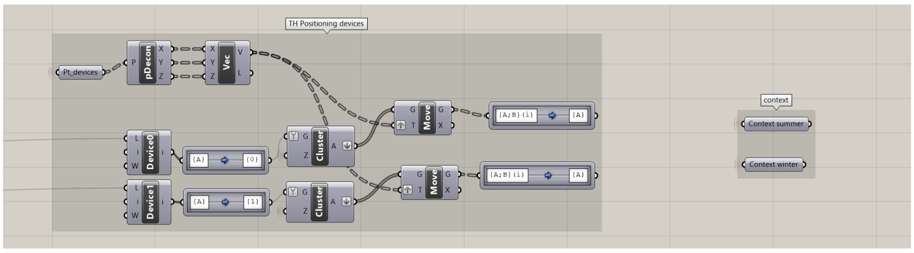


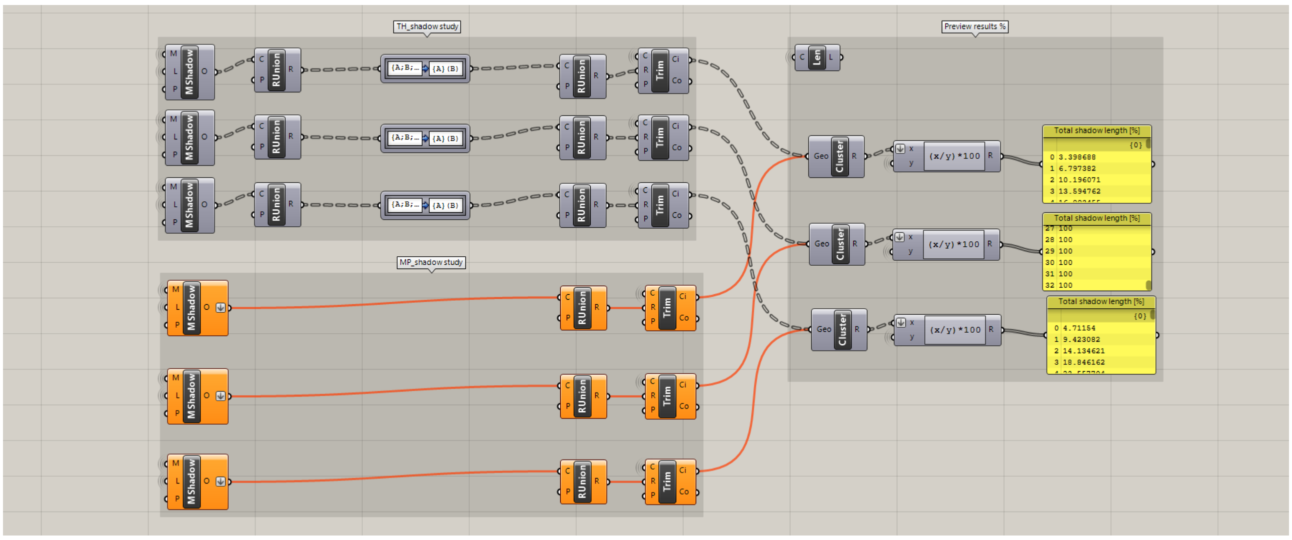
Figure A-8

The devices were positioned on points defined in Figure A-6, and summer and winter contexts were created.

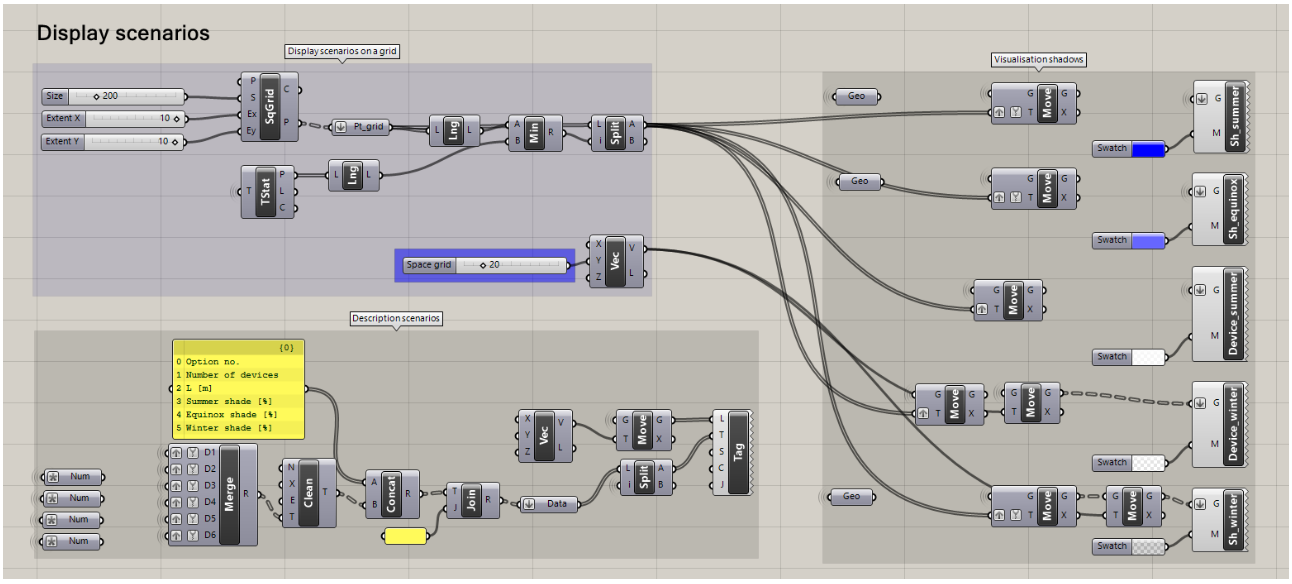


The simulation components calculated shaded lengths for each scenario/time combination, and a preview of results could be read in the panels at the end of the section. This cluster uses a vector mode to project shadows on the specified plane; then, the sidewalk curve is trimmed using the shadow curves. Highly-precise shadow simulations are thus performed by accurately considering the shape of shading devices.

Figure A-9



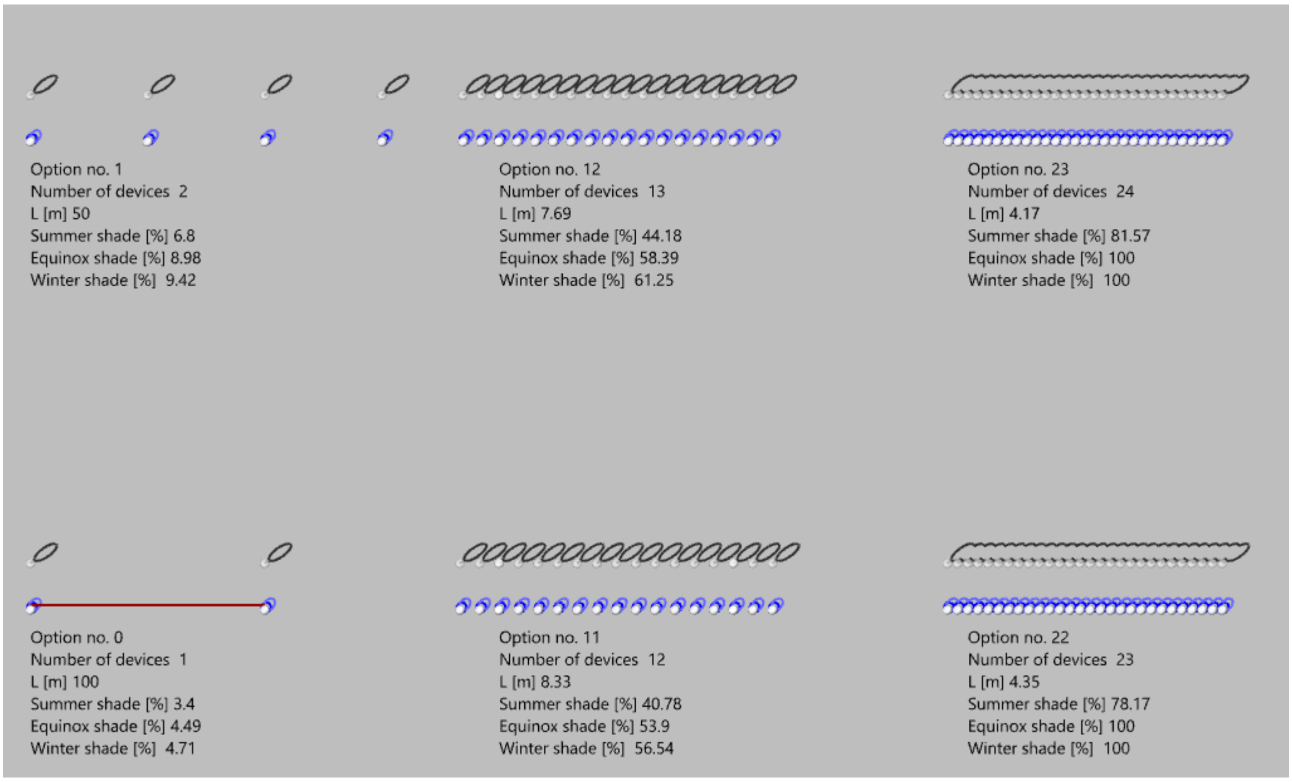
[1] This value was selected because it is representative of the centre of gravity of an average standing adult (Matzarakis et al. 1999), while accounting for a diverse range of users, as it approximates the suggested height for designing for toddlers (Vincelot 2019) and the floor-to-head height of a person on a wheelchair (Jarosz 1996).



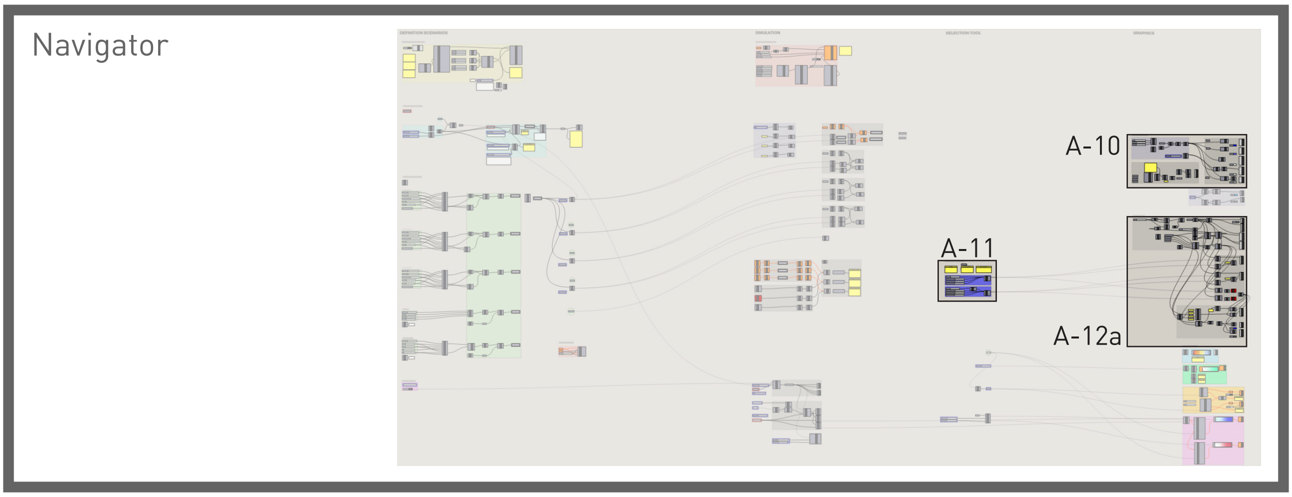
▲ Figure A-10a

All option were visualised through the Graphics section[2]. Figure A-10a reports the default settings to compare scenarios; FigureA-10b is a screenshot of the Rhino workspace in which all options were previewed, together with a brief description of results. Summer shadows are drawn in blue, light blue corresponds to the autumn equinox, while the winter scenarios are drawn on top. Urban designers with expertise in GH could modify the graphic components, e.g., changing the displayed colours or the matrix disposition of the solutions.

▼ Figure A-10b

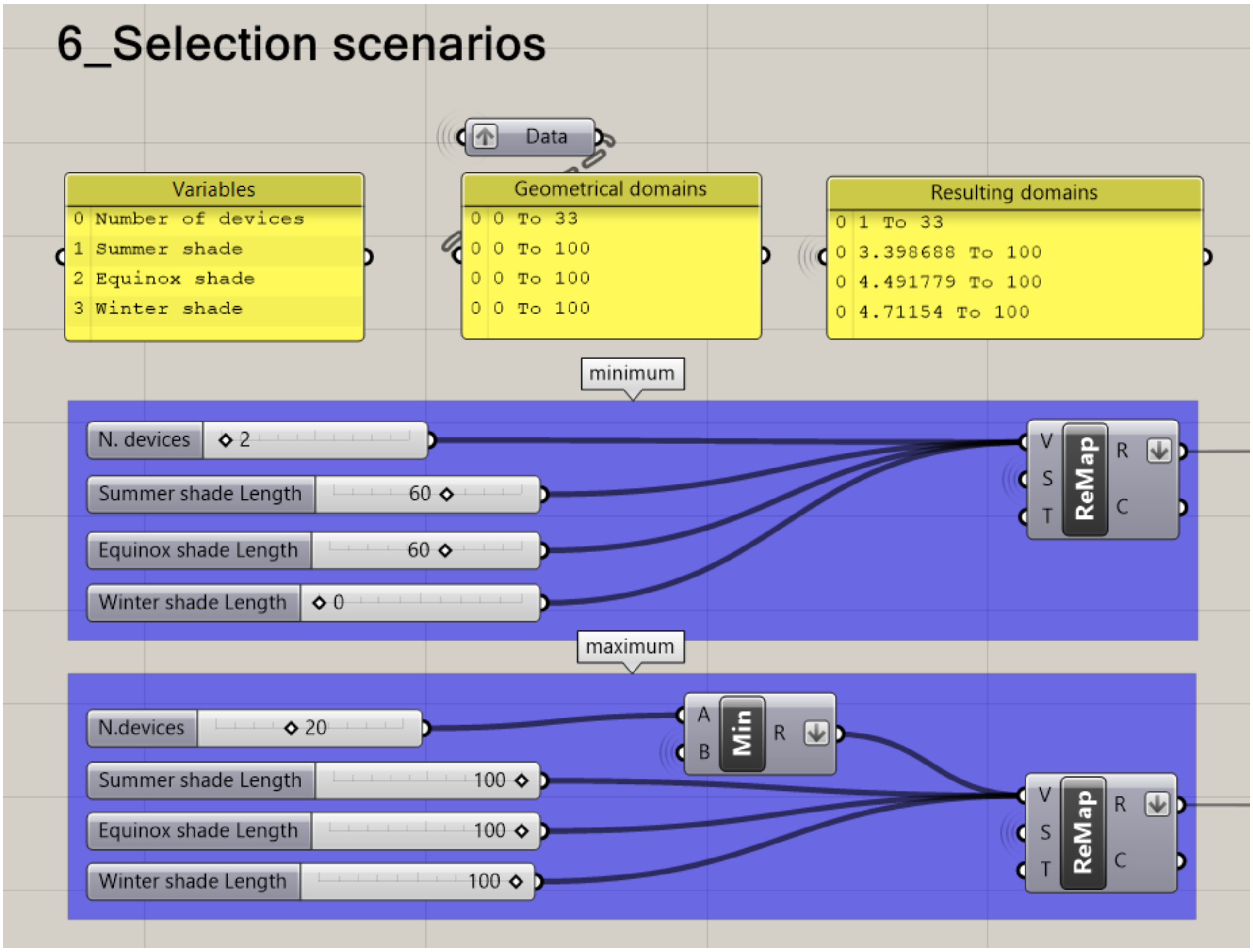


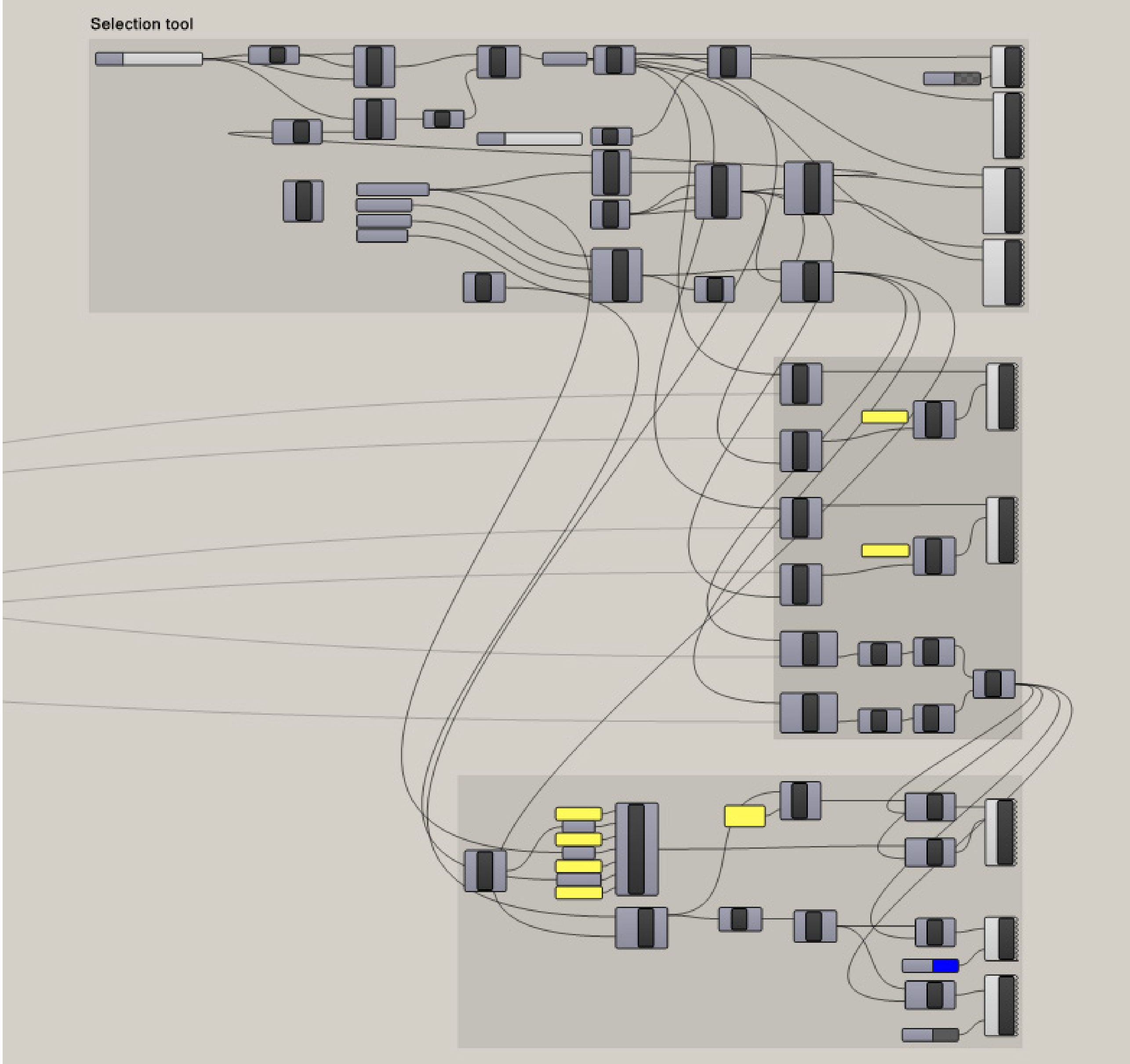
[2] The graphical part of this design tool was developed following the tutorial provided by Digital Design Unit – TU Darmstadt (2020, June 30): 'Generative Design in Grasshopper' [Video]. YouTube. https://www.youtube.com/watch?v=-HLRtXSG7fQ (and following)



The Selection tool allows urban designers to set performance threshold for evaluating results. To inform the decision, panels on top summarise the available range of performances: ‘geometrical domains’ refers to the minimum and maximum results that could be potentially obtained, while ‘resulting domains’ reports the actual range of outcome results. For this exercise, the minimum shaded length on both summer solstice and autumn equinox was set to 60%. As regards the number of devices, a limit of 20 was set to simulate resources constraints from the investors’ side.

▼ Figure A-11

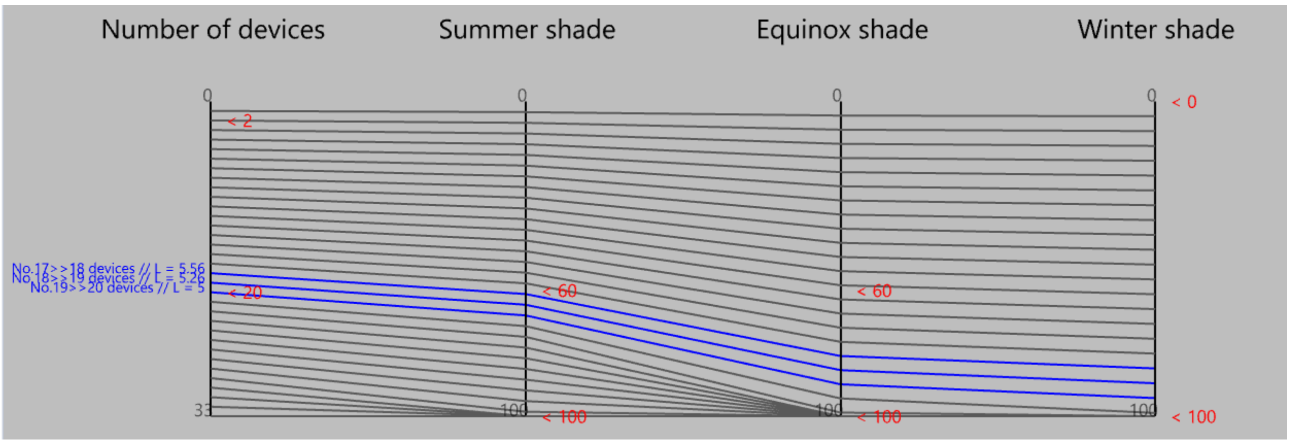




▲ Figure A-12a

Another group of clusters in the graphic section draws the selection tool in the workspace; the final result is illustrated in Figure A-12b. Each horizontal line refers to one scenario option defined in the first section. The red arrows represent the selection criteria set on GH, against the respective axes. Options that fit all selection criteria are coloured in blue, and a brief description for reference is written on the left.

▼ Figure A-12b

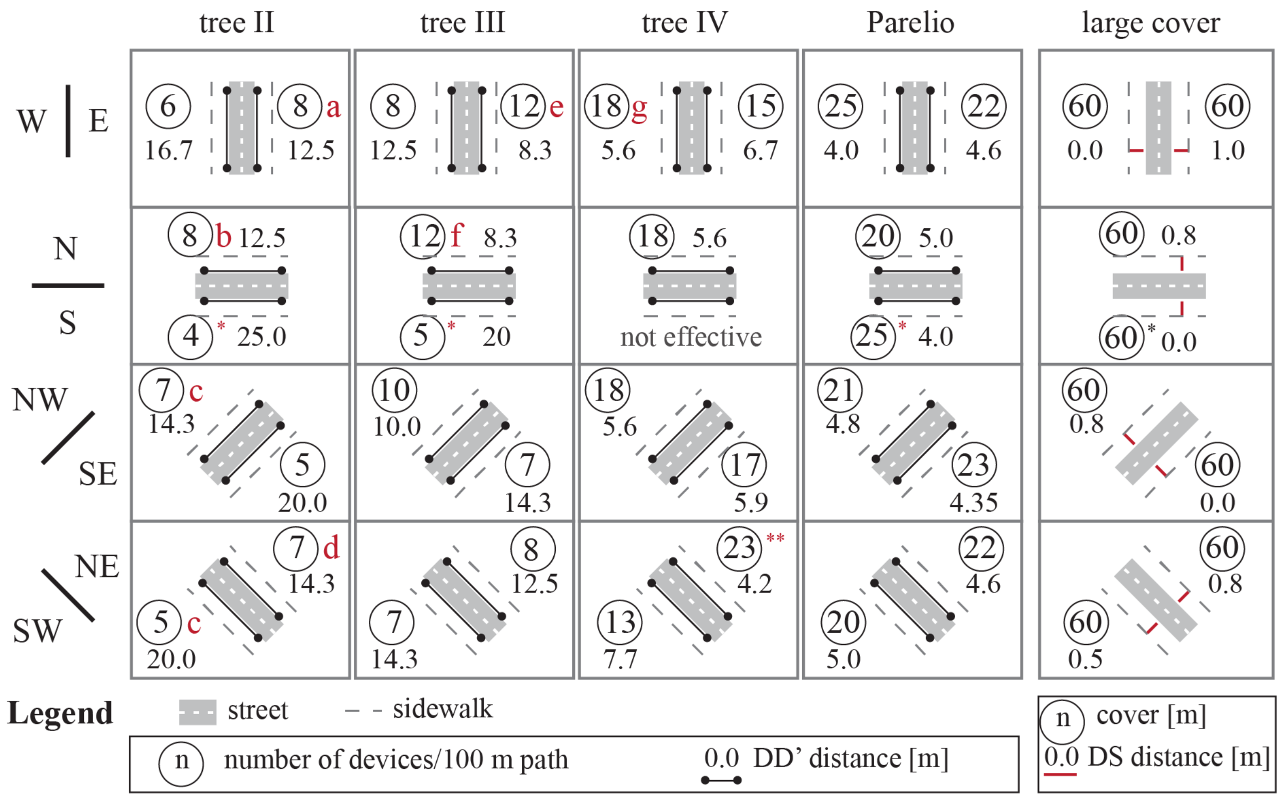


Based on the outcome of this exercise, an amount of 18 trees IV class size every 100 m was recommended to shade a NW sidewalk in Milan. The running time of the code was less than one minute, which makes it a valuable tool for urban designers.

The same design exercise was replicated for all five shading devices included in the catalogue, positioned to shade eight sidewalks of different orientations. Three hours were tested (i.e., 10 am, 1 pm and 4 pm) to detect when shade was most needed: each sidewalk orientation was threfore assigned a worst-case scenario hour. To ensure effectiveness, the distance between devices and the sidewalk edge was adapted for each device/orientation combination. The results were collected into a table providing rule-of-thumb-like information to estimate the amount of solutions required to shade pedestrian paths by 60% of their length (Figure A-13).

Suggested number of devices and distances to shade 60% of the sidewalk on the respective worst-case scenario hour. Red notes refer to modified DS distances to effectively shade sidewalks.

Figure A-13



modified DS distances: a 11.5 m rather than 2.5 m; b 9.5 m rather than 2.5 m;
c 8.0 m rather than 2.5 m; d 4.5 m rather than 2.5 m;
e 4 m rather than 2 m ; f 3 m rather than 2 m ;
g 0.75 m rather than 1.5 m.

* effective on 21 June, not 23 September. ** if g: (16), 6.3

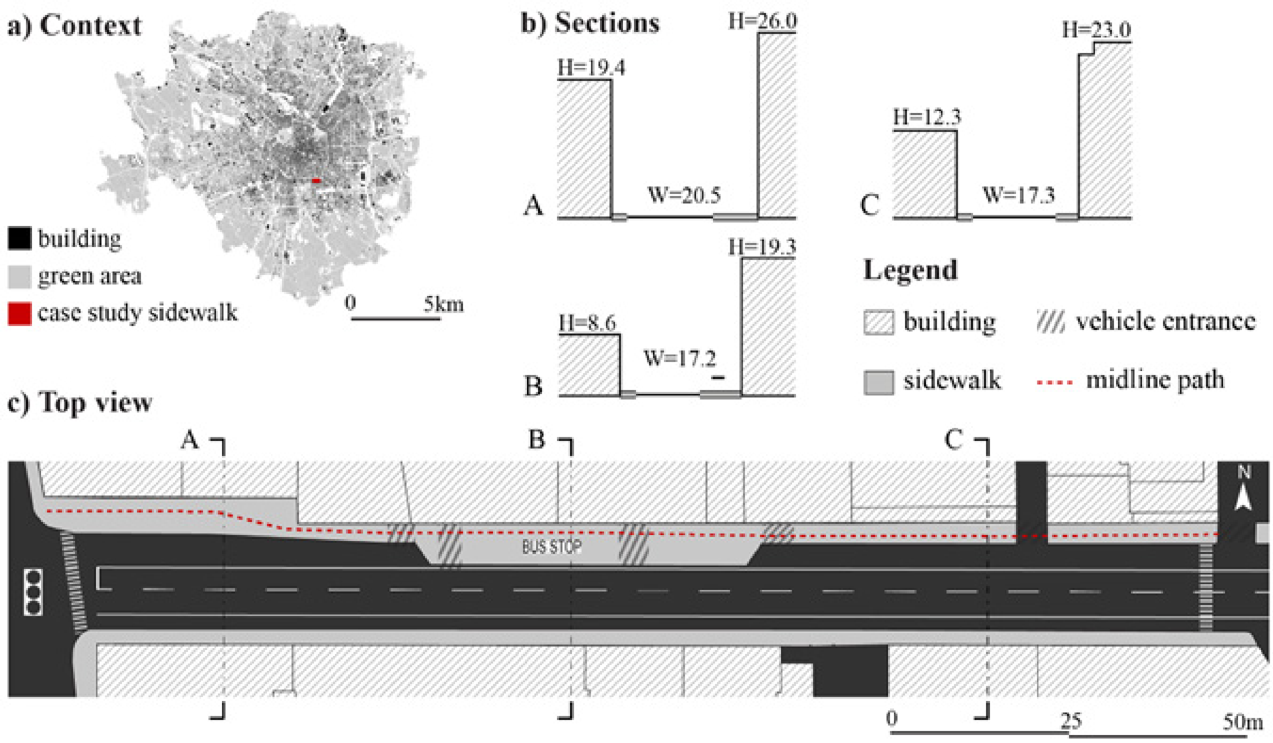
Design exercise 2

WORKFLOW B – Positioning shading devices from the library into an urban design proposal

Moving from theoretical urban canyons to real case studies, the protocol was applied to simulate a master plan proposal in Milan. Specifically, an urban canyon was analysed. Sidewalk N was considered a critical case study to focus on because the corresponding urban canyon orientation E-W has been extensively reported as the worst orientation for thermal comfort conditions during the day (Jamei et al. 2016). A representative sidewalk in Milan was modelled: it is situated on the northern side of via Sabotino, in the southern part of the city (Figure B-0). 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 2.00 to 6.00 m, widening with respect to the bus stop. The H/W ratio resulted in about 1.0, being the width of the canyon about 17.00 m and the average height of buildings 16.80 ±7.40 m (data source: Municipality of Milan, n.d.-a).

Presentation of the case study sidewalk in Milan (IT): a) location of the sidewalk in the city; b) sections and c) top view of the case study urban canyon.

Figure B-0



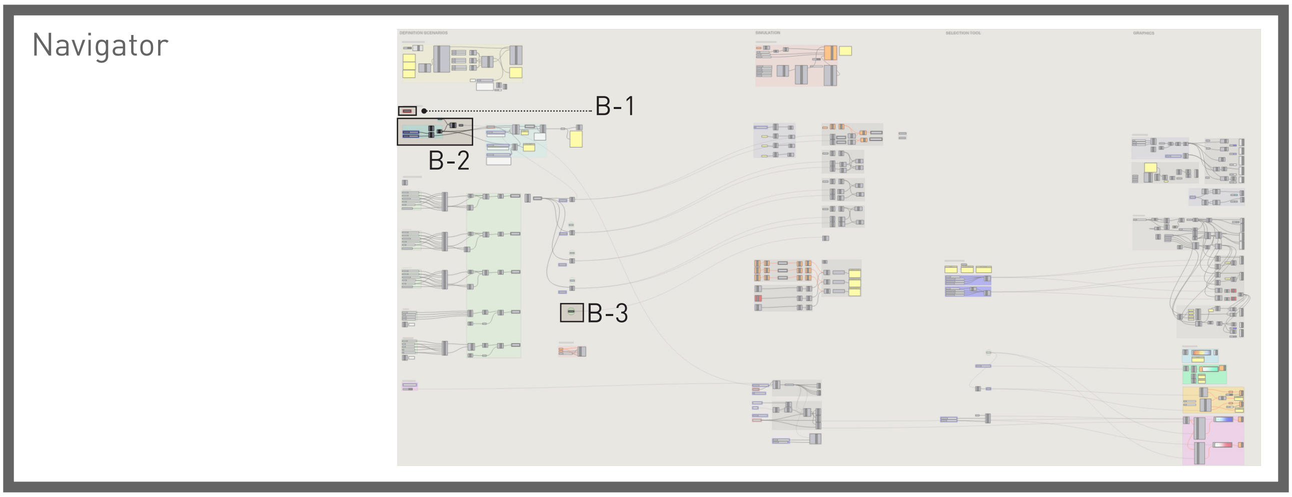


Figure B-1

The code was set to 'master plan' mode: in this way, multiple geometries were included as context, and one design scenario per day was modelled.

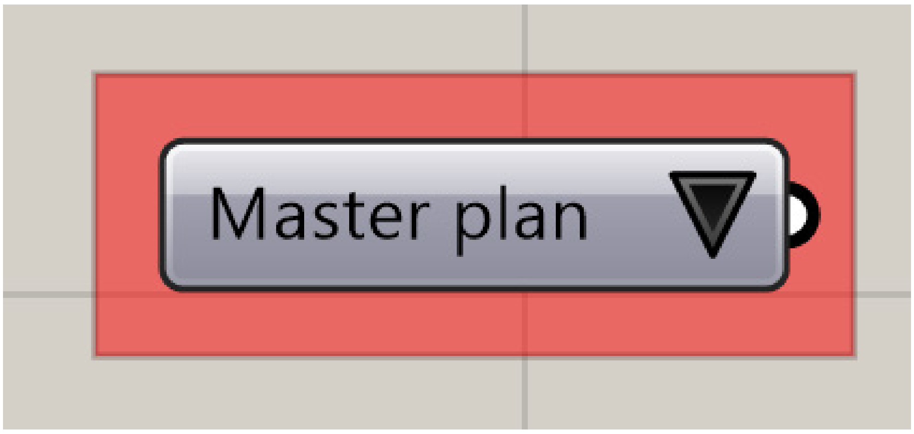


Figure B-2

The midline of the sidewalk was input as the pedestrian network (curve in 'Network').

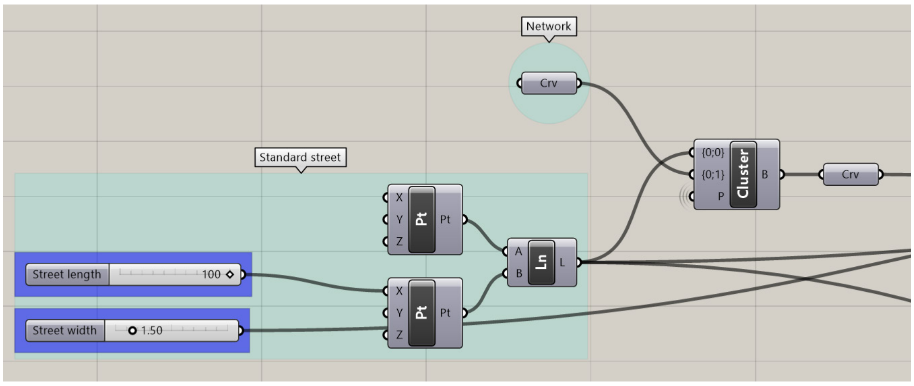
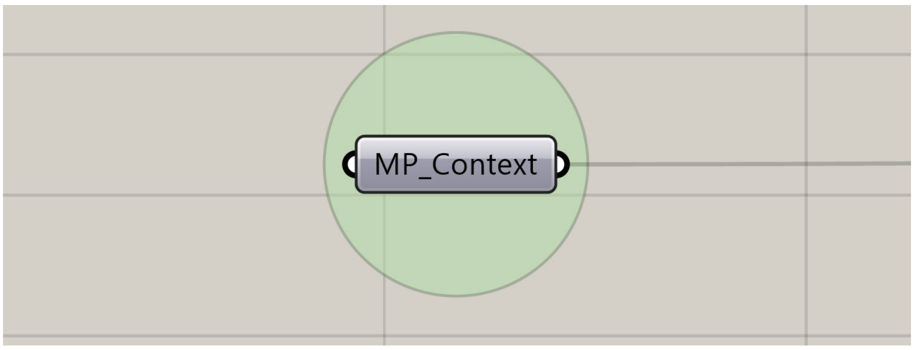


Figure B-3

Buildings were modelled as extruded polisurfaces: all elements were input as context.



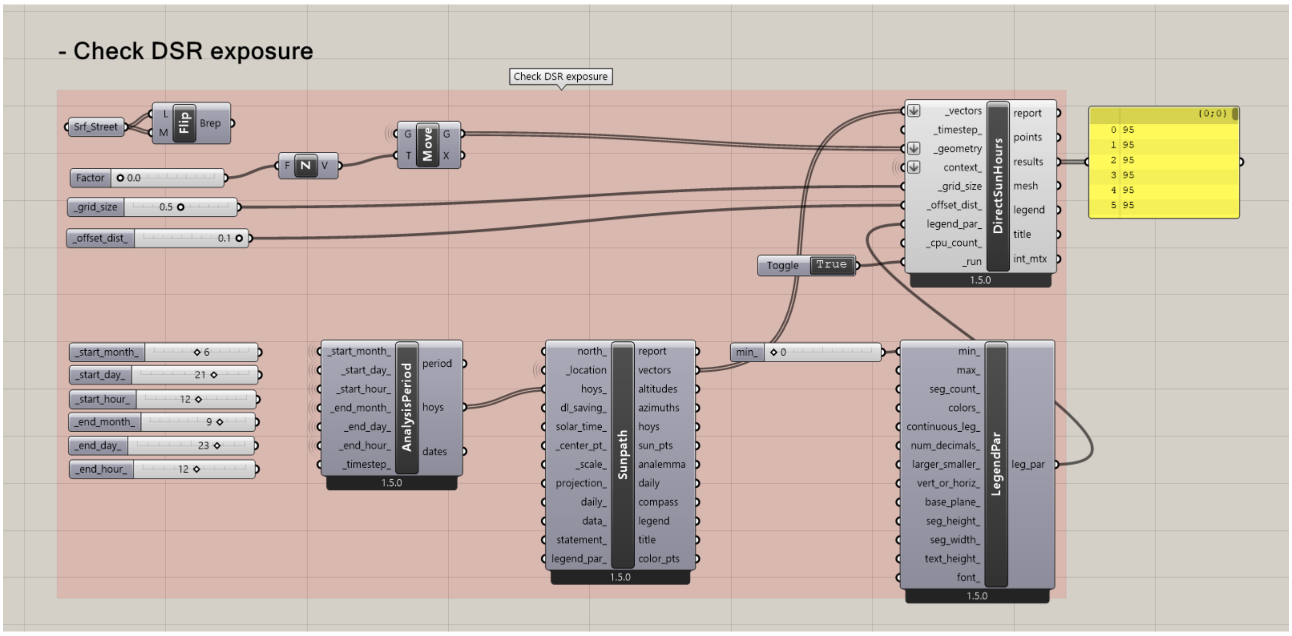


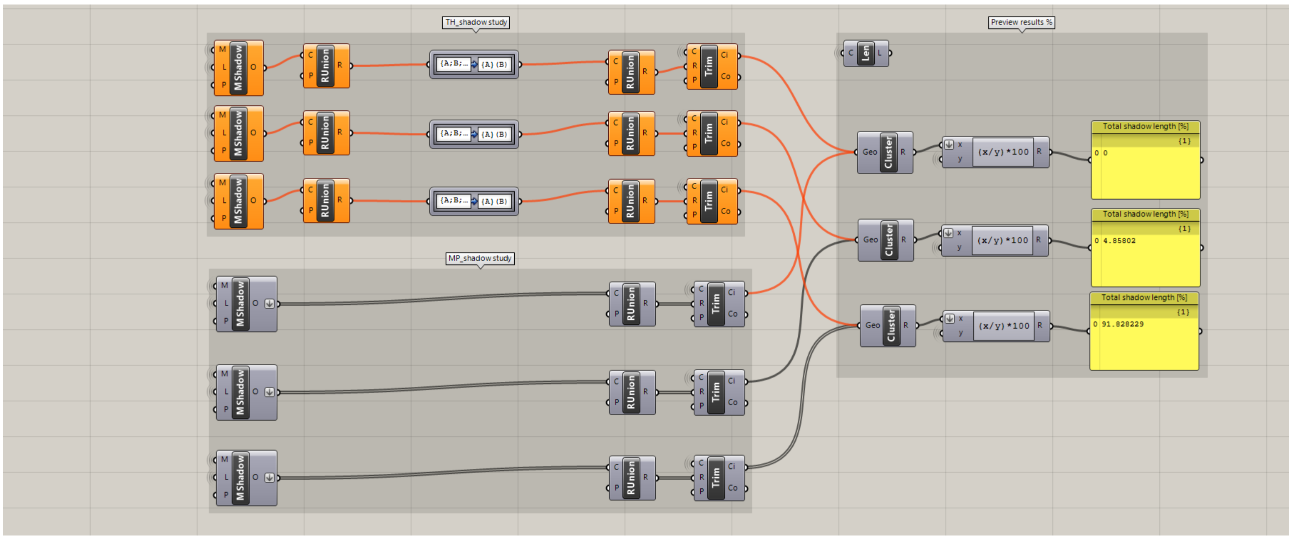
Figure B-4a

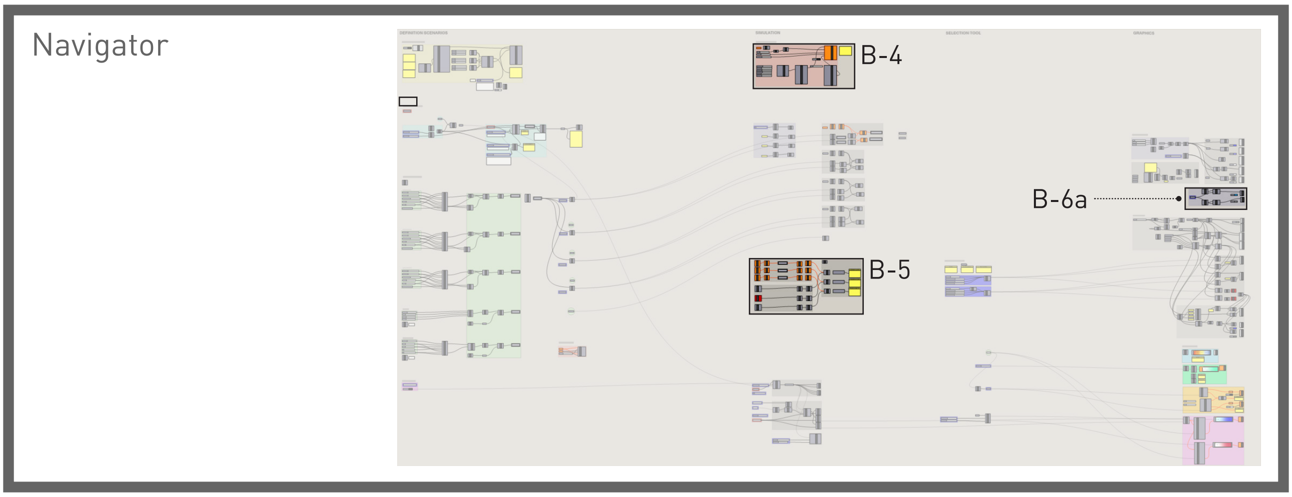
The analysis period was kept as the previous exercise; additionally, a boundary condition analysis was performed to confirm DSR exposure of the sidewalk at the selected hour (1 pm). The simulation height was kept at 1 m. Considering the entire sidewalk area as a surface and buildings as shading context, the DSR exposure was simulated every day from 21st June to 23rd September, for a total of 95 days. Results confirmed the need for shade at 1 pm because all days resulted in the sun; Figure B-4b presents the results.

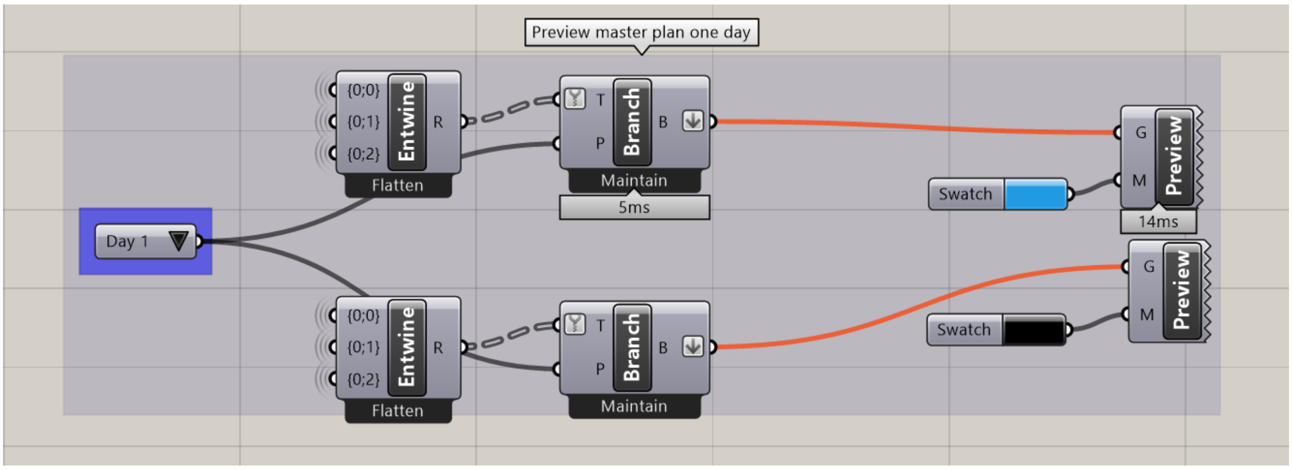
Figure B-4b

The DSR exposure simulation was performed through the ‘MP shadow study’ group, and the resulting shaded lengths were reported in the panels on the right.

Figure B-5







▲ Figure B-6a

A preview of the existing context and simulated shadows is available in the Graphics part (Figure B-6a); Figure B-6b is a screenshot of the resulting Rhino workspace on the summer solstice (top view). The sidewalk line was drawn in red.

▼ Figure B-6b

Class size IV trees were selected as suitable for the case study sidewalk based on the space available. According to Figure A-13, for shading 60% of the path length, 30 trees should have been positioned. Nevertheless, for a range of reasons such as preserving access to driveways, preventing obstacles near the crossroad, and keeping access by ramps to the bus stop, it was not possible to exclusively adopt trees as a strategy. Therefore, artificial devices were additionally used in proximity of two key points, the streetlight, where pedestrians were expected to wait under the sun, and the bus stop, to preserve its accessibility.

Figure B-7

The installation points for each device were positioned in Rhino and inserted into the 'MP_PT_n' components in GH; the code associated each device to the respective installation points (devices are reported on the right for reference).

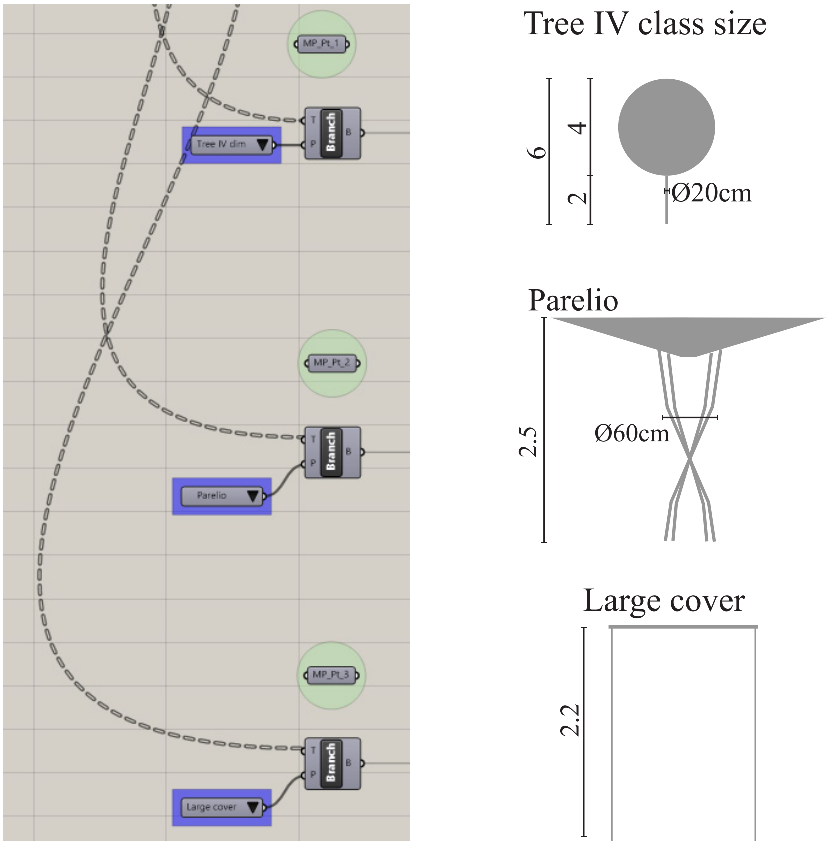
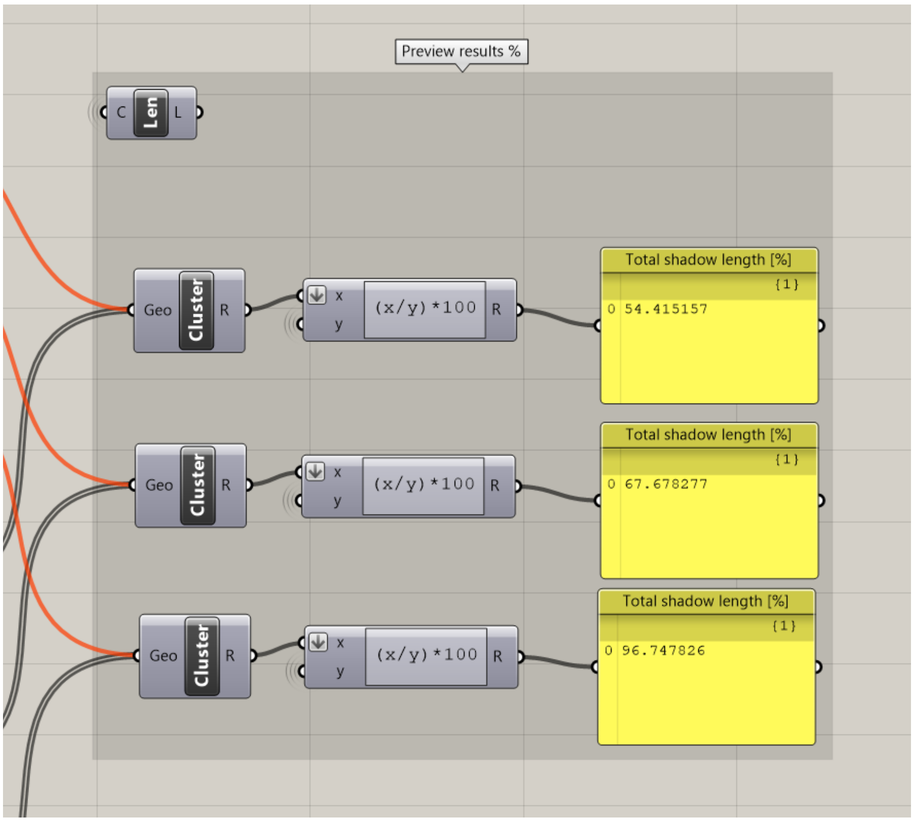
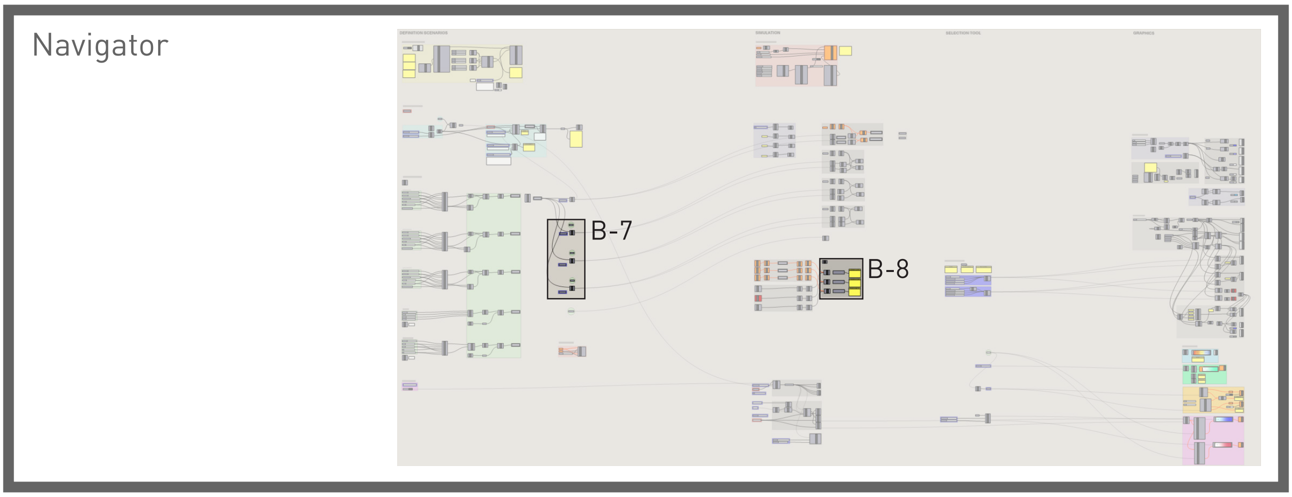


Figure B-8

Various combinations were iteratively tested, and resulting shaded lengths were visualised in the panels on the right.

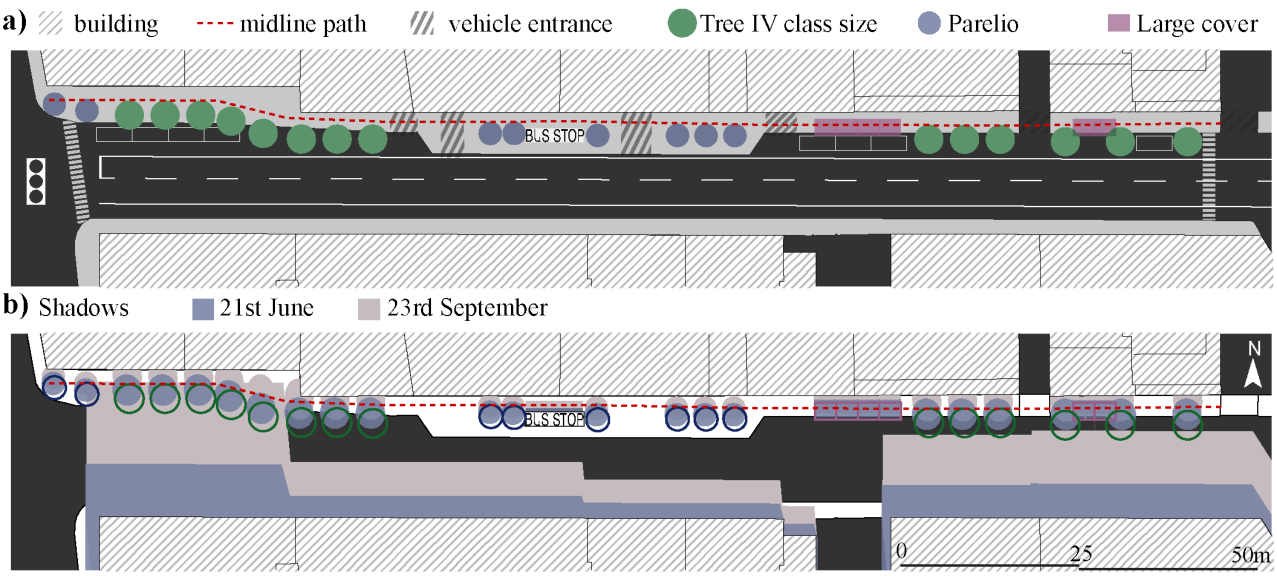




The final design proposal consisted of 14 class size IV trees, 8 Parelio devices and 18 m of large cover. In total, 54% and 68% of the path resulted in shade during the summer solstice and autumn equinox, respectively, at 1 pm. It should be noted that, if the bus stop shelter was modified to shade the pedestrian path behind it, the minimum threshold of 60% could be achieved on 21st June as well.

Final design proposal developed through the design tool: a) location of shading devices; b) shadow analysis on extreme summer season days.

Figure B-9



WORKFLOW C – Performing direct solar radiation exposure analyses on an extensive pedestrian network

The protocol was applied at the neighbourhood scale, with the objective of analysing the DSR exposure of an extensive pedestrian network. This exercise started from the metro station 'Lodi' in Milan (IT): it was selected because adjacent to a railway yard object of a redevelopment project involving the industry partner CRA—Carlo Ratti Associati (2021a), the Parco Romana master plan (Figure C-0a). The presented design proposal was a preliminary submission for the Municipality of Milan; changes were possible because of the still ongoing authorisation process. The area under consideration was the eastern part of the master plan, which will mainly host offices. Buildings are located around an elevated square, above the railway line; access to the square is by stairs, elevators and ramps. The designers' proposal locates various trees in the central part of the square, as part of an urban forest in the east-west direction (the so-called "Suspended Forest"). The presence of the metro station to the north and buildings of broad interest to the south (e.g.: Fondazione Prada) led designers to propose the creation of new connections in the north-south direction.

A catchment area of a radius of 400 m (corresponding to a 5-minutes walk of standard pedestrians) around the metro station accesses was set to define the network of interest. The pedestrian network was modelled from imported *.shp* geometries describing sidewalks and buildings of the existing urban morphology; the Parco Romana master plan area was imported from the designers' model developed in Rhino. The midlines of sidewalks were drawn in Rhino; because of 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. Lines were used to model the slopes of stairs (Figures C-0b and C-0c).

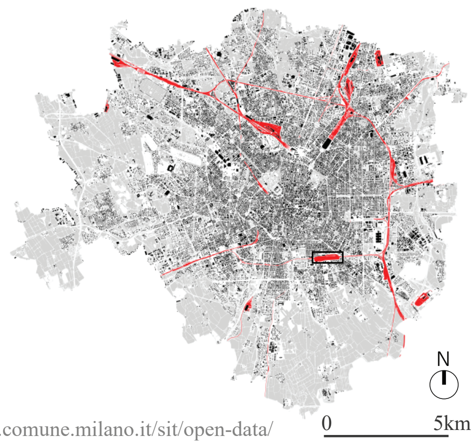
Figure C-0a

Position of the Parco Romana master plan area in the city of Milan.

PORTA ROMANA DISTRICT

Milan (IT)

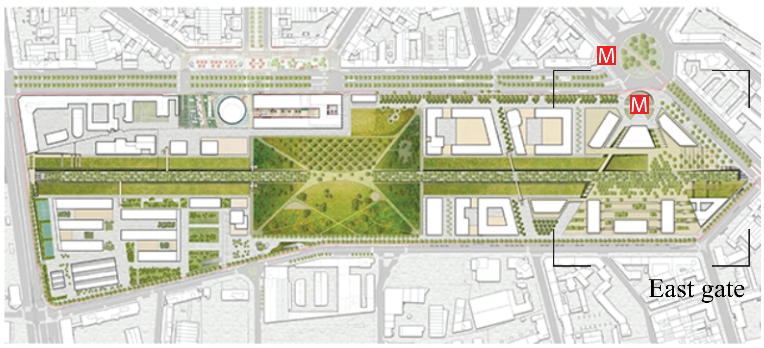
45.45 N, 9.21 E



source: https://geoportale.comune.milano.it/sit/open-data/

PARCO ROMANA MASTER PLAN

status: design



source: https://scaloportaromana.com/en/il-progetto/parco-romana   M metro station

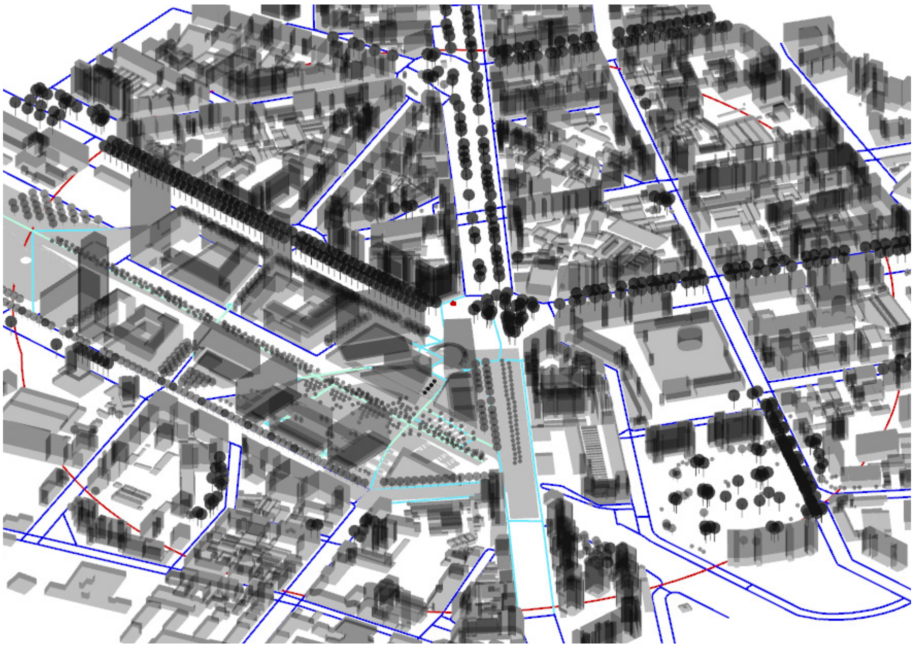
Figure C-0b

Top view of the case study area. The red curve encloses the area of interest, selected within a 400 m radius around two accesses to the metro station (marked with red dots).
The pedestrian network was divided into three layers:

- ground level (z=0)
- elevated space of the Parco Romana master plan (z= 7.7m)
- ramps, stairs and inclined paths

Figure C-0c

Isometric view of the case study area.

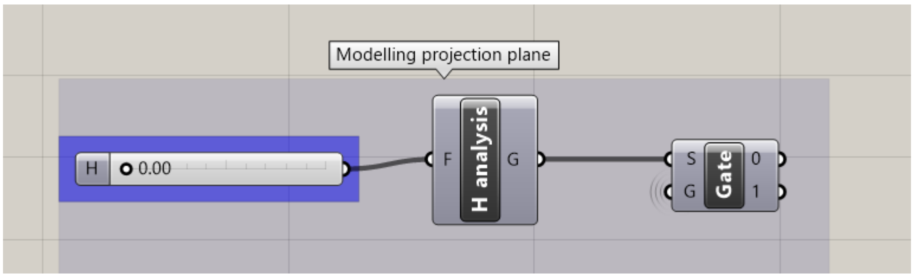


The protocol allowed urban designers to perform multiple analyses on a pedestrian network, evaluating its shading performance in summer and producing a baseline scenario to propose further shading devices installations. Trees of different class sizes were positioned in Rhino according to the designers' model (Parco Romana master plan) and the Municipality material (Municipality of Milan n.d.-a; n.d.-b). Then, the DSR exposure of the pedestrian network was analysed; in this exercise, only results reffering to the 21st June at 1 pm are presented. Additionally, to select where shading devices would be needed, the perspective of four users of diverse walking abilities was simulated: this fostered inclusivity in the evaluation phase.
This last design exercise produced maps that form a baseline to propose solutions; in the design phase, both workflows A or B could be followed.

The modelling phase was similar to the one previously presented (Worflow B): buildings and shading devices (trees) were inserted in the model, and the pedestrian network was built collecting curves in the appropriate component (Figure B-2). For this exercise, because of the complexity of the 3-D network and the high computational time required by vector analysis, the ‘raster’ DSR exposure analysis mode was used.

Figure C-1

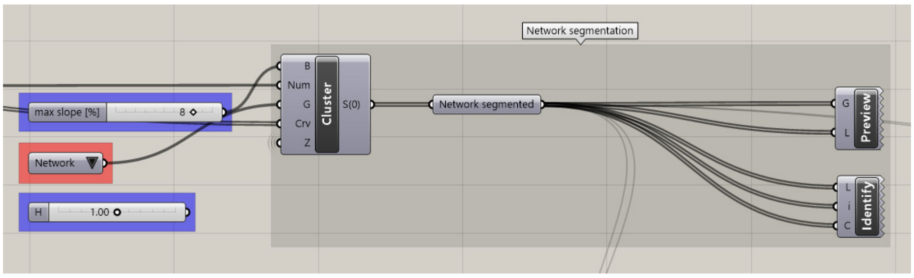
The height of the projection plane was set as null because of the different simulation mode adopted for 3-D networks.



Then, the network was segmented at each intersection. This is a critical step to ensure the usability of the network in terms of wayfinding: for this reason, specific attention was paid to ensure a continuous network with nodes connecting segments.

Figure C-2

After setting the simulation cluster to ‘Network’, the projection height was set to 1 m.

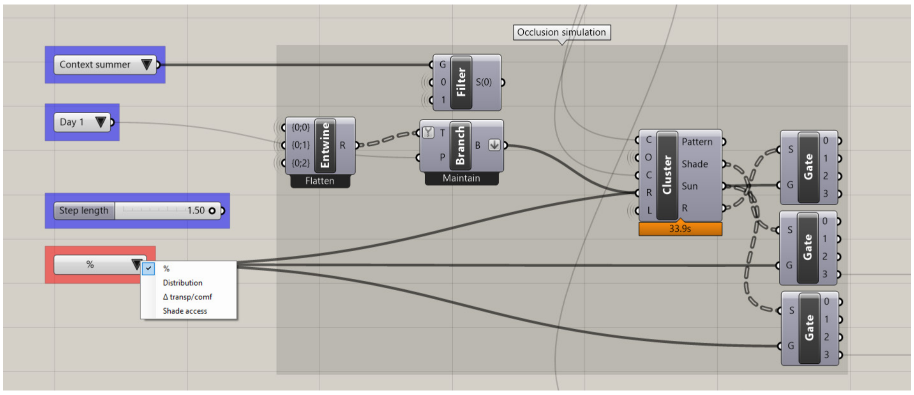


In Figure C-2, the term ‘max slope’ refers to the threshold of steepness beyond which a segment was classified as not accessible to certain user profiles; the value of 8% was selected according to the Italian legislation[1]. This procedure will be useful in following steps.

To analyse the DSR exposure of a 3D pedestrian network without excessive computational time, a strategy more similar to a raster than a vector approach was selected. Each segment of the network was subdivided at a constant distance, creating smaller segments (‘steps’). The centre point of each step was then processed in GH with the ‘Occlusion’ component, which determines whether a point in space is exposed to the sun or shaded by the context. If small steps are adopted, results can be considered a good approximation of results that could be obtained in vector mode.

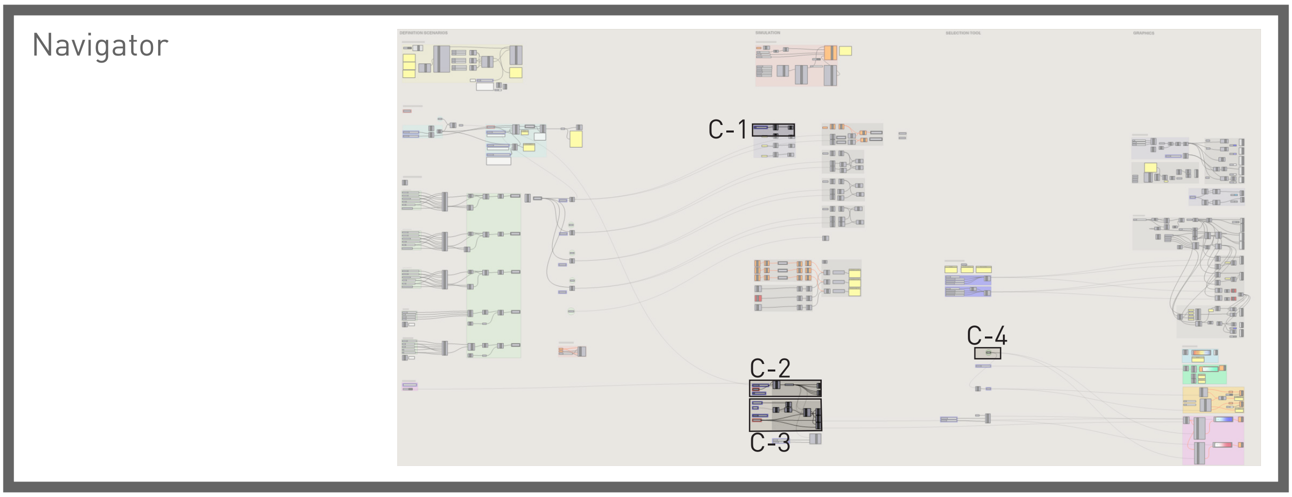
Figure C-3

The first day simulated was selected; the step length was set to 1.5 m[2]. The dropdown menu allows urban designers to select the analysis of interest.



[1] DM 14 June 1989, n. 236

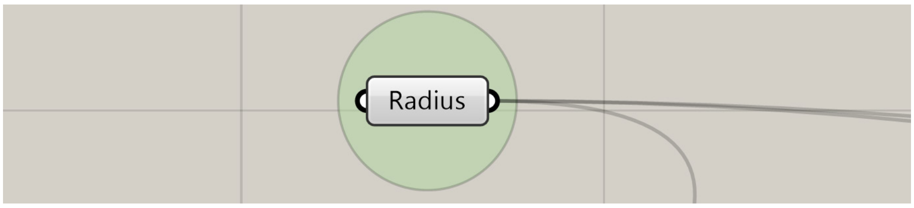
[2] This value was selected based on the stride measure, i.e., ‘two consecutive heel strikes’ of the same foot. It refers to a pedestrian walking at 80 m/minute, with a step length of 0.73 m (Buddhadev et al. 2020; Sekiya et al. 1997).



Finally, a curve representing the catchment area under investigation was imported into the selection tool; it allows urban designers to analyse only relevant network segments, avoiding unnecessary calculations. This component does not trim the curves so that the network aspect and functionality are preserved.

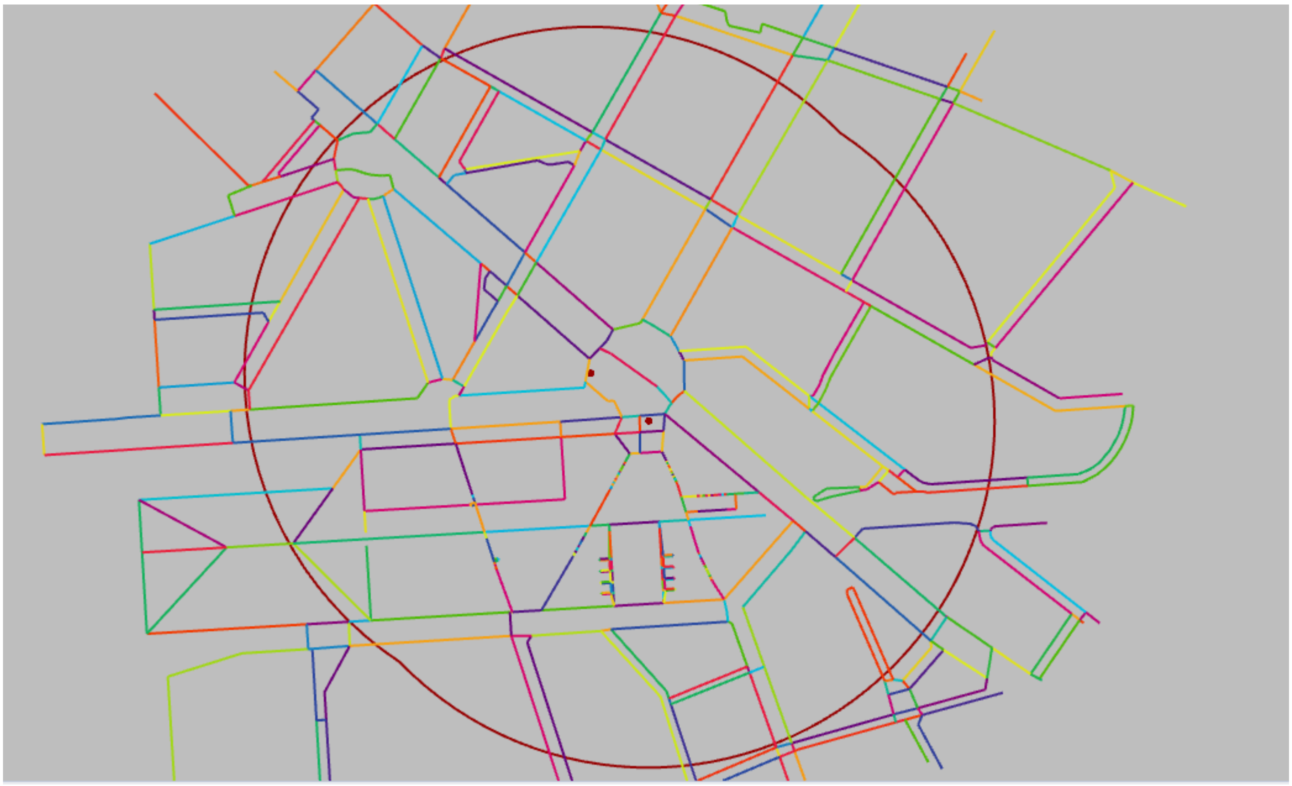
Figure C-4

Curve to select network segments of interest.



A preview of the pedestrian network is available in the component of Figure C-2: random colours are assigned to each segment to allow urban designers to verify the simulation results before performing DSR exposure analyses.

Figure C-5



At first, each segment of the network (in between intersections) was coloured based on the DSR exposure.

Figure C-6a

The % analysis refers to the percentage of shade of each network segment.

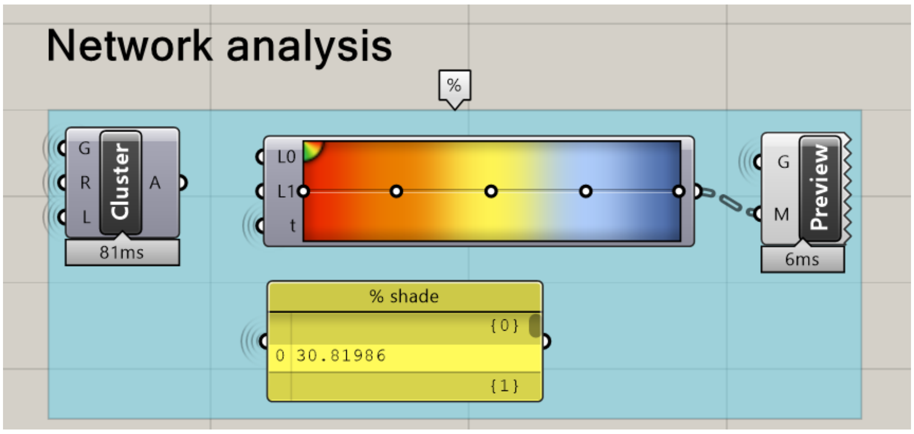
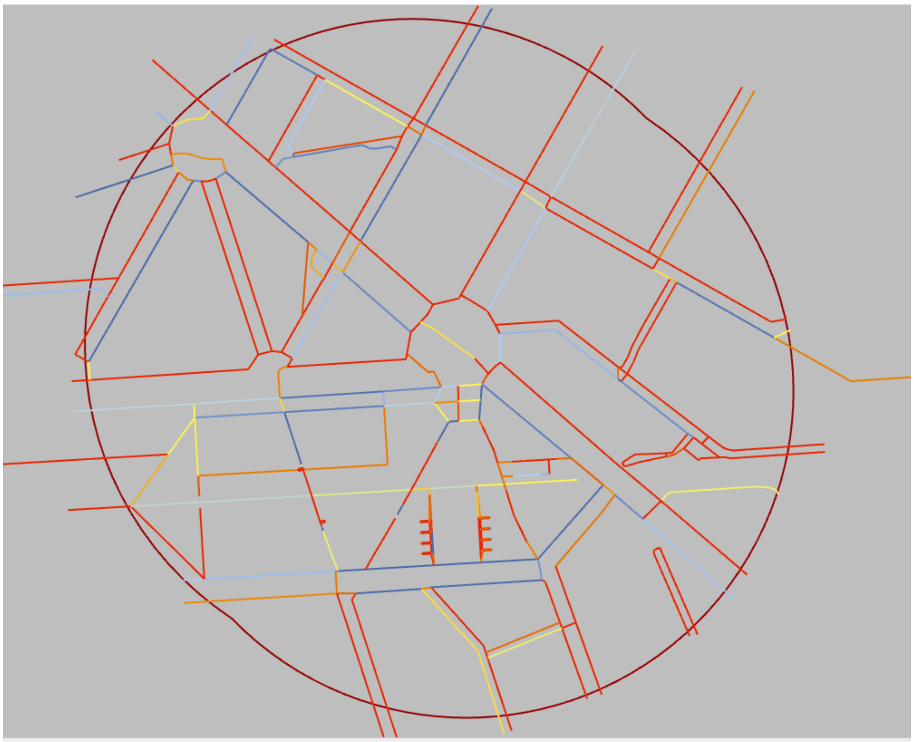


Figure C-6b

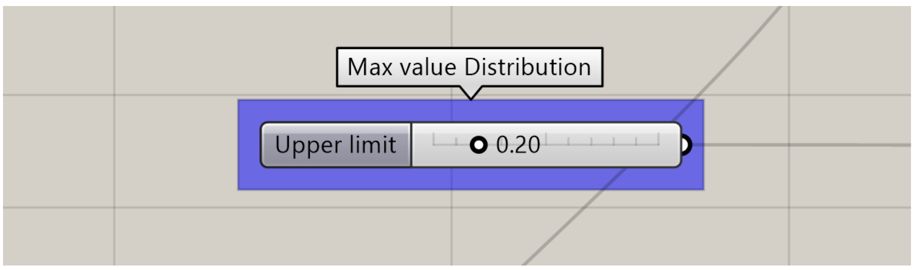
Screenshot of the Rhino workspace, where the % analysis map and the radius of analysis are pictured.

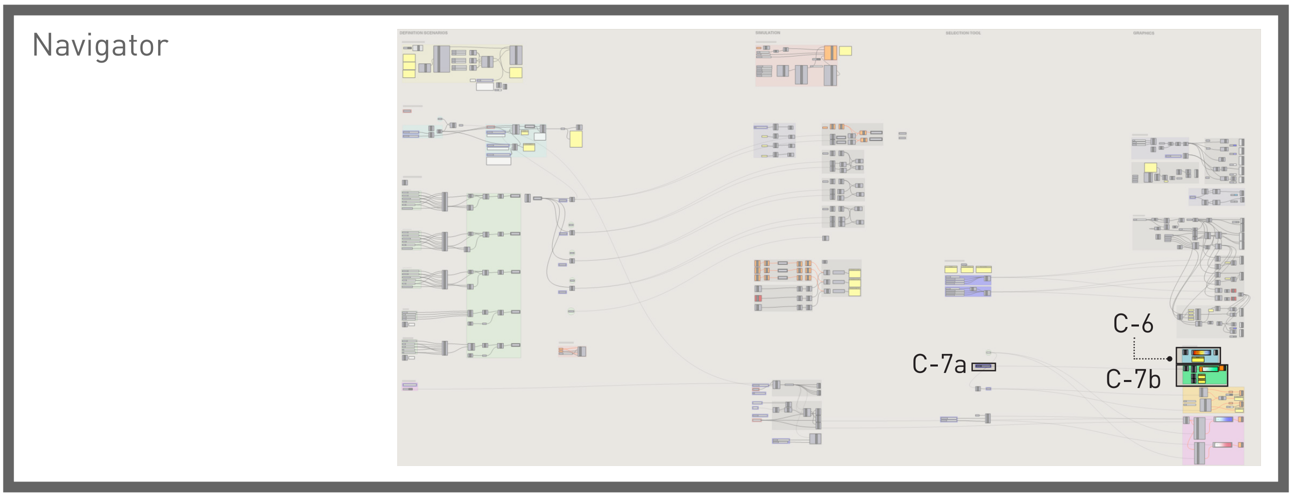


The first analysis showed the ratio between the shaded and sunny steps of each network segment. This is already critical, yet the distribution of shade must be considered in positioning shading devices. The second analysis performed aimed at classifying network segments based on how often the shaded/sunny condition would change along the path. A maximum value of interest was set, and segments were coloured based on DSR exposure diversity. The combination of these two analyses provides meaningful information for designing shading devices installations, making sure to interrupt long paths exposed to DSR with shaded spots.

Figure C-7a

The maximum value to visualise for DSR exposure distribution was set to 20%, meaning that 1/5 of the steps recorded a change in the DSR exposure status.





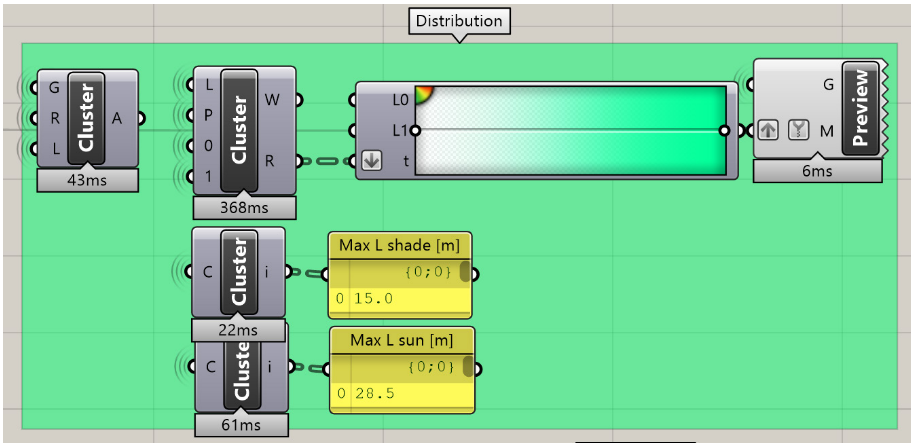


Figure C-7b ▶

This cluster estimates the diversity measure of each network segment; maximum distances in shade and sun are also reported in the panels.

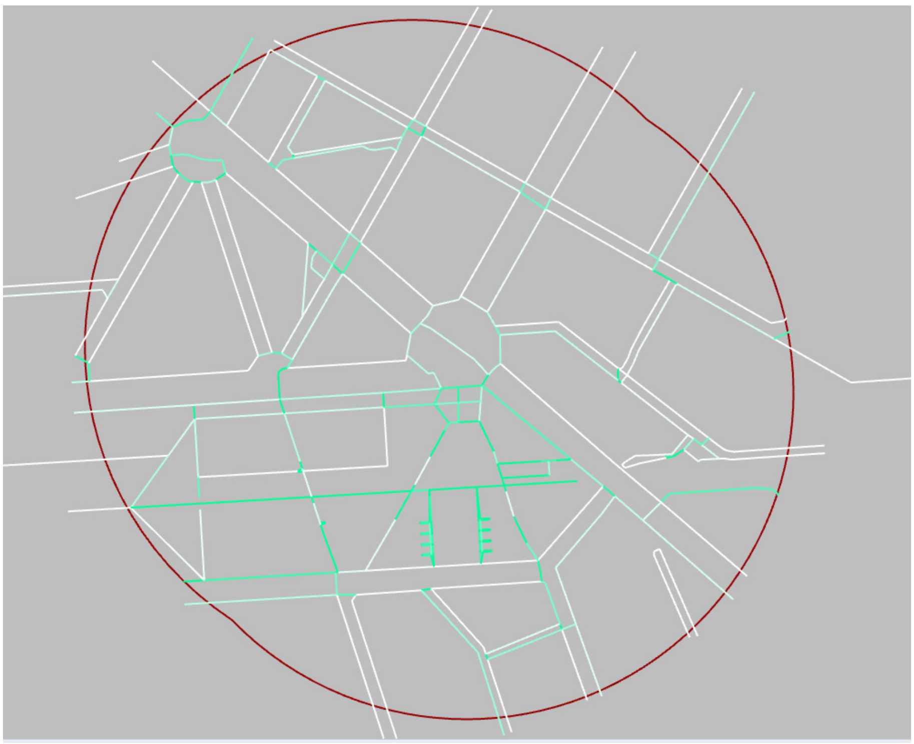


Figure C-7c ▶

Screenshot of the Rhino workspace where the diversity map is reported. In green network segments, the sequence of shaded and sunny segments changes more often than in white ones, meaning a larger DSR exposure diversity of the path.

The next analysis compared the shortest path with the most shaded one, for the same origin/destination trip.

Working with path finding, stairs length was adjusted in defining the scenarios. Stairs were identified as inclined segments steeper than 20°; the horizontal length was increased to simulate a lower walking speed, and it was set to 1.9 as the ratio between walking speed on a flat surface (80 m/minute) and stairs (43 m/minute) for standard pedestrians.

▼Figure C-8a

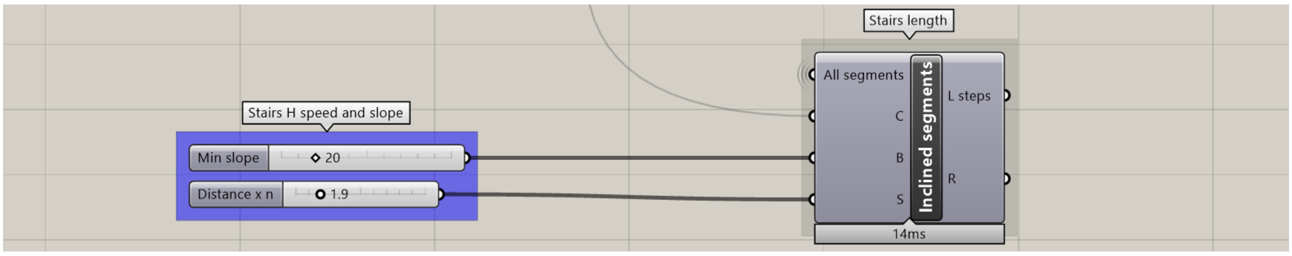


Figure C-8b ▶

A line connecting an origin and a destination was input in the code.

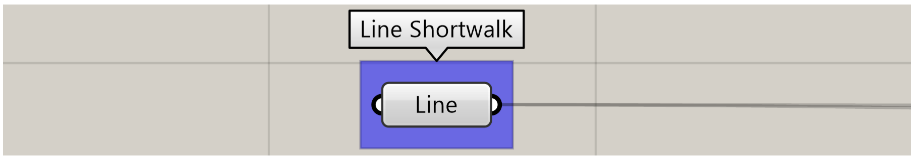


Figure C-8c ▶

The shortwalk component was used to compare the shortest path connecting the selected O/D points with the most shaded one. Statistics are reported in the panels.

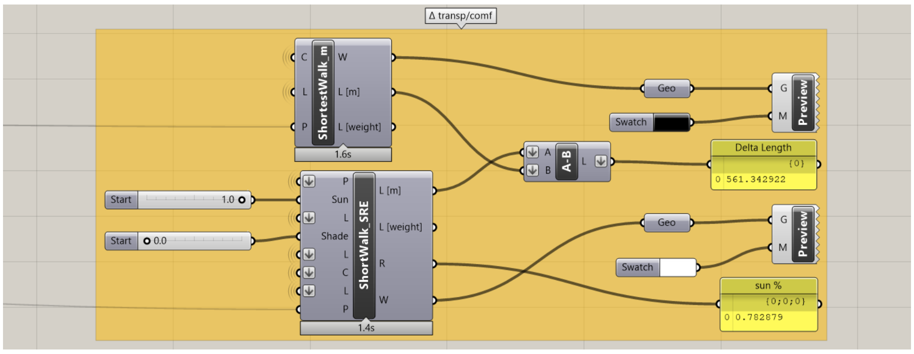
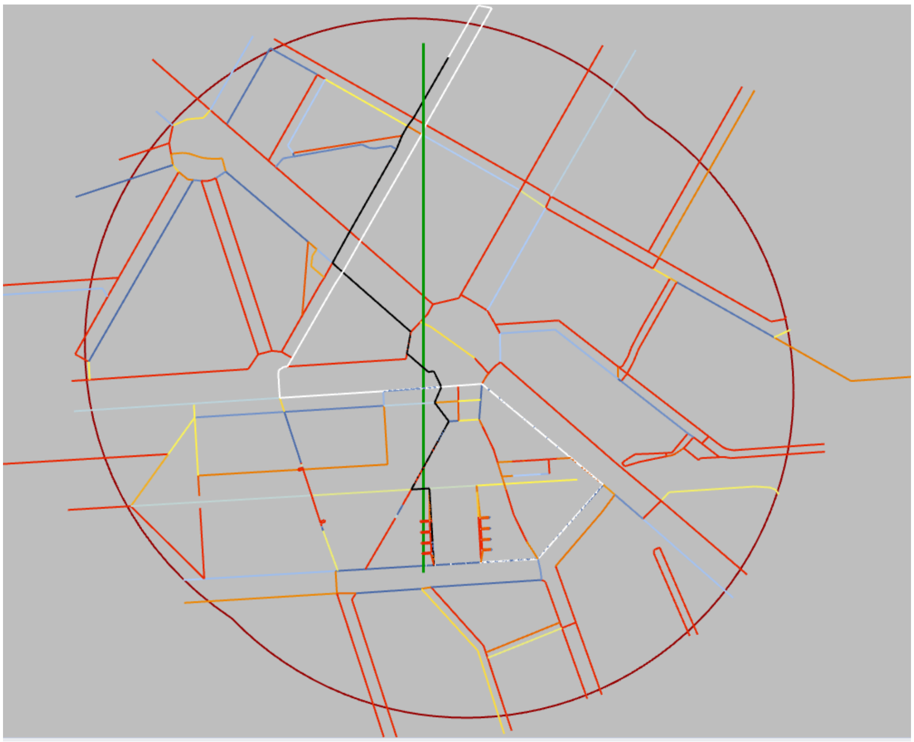
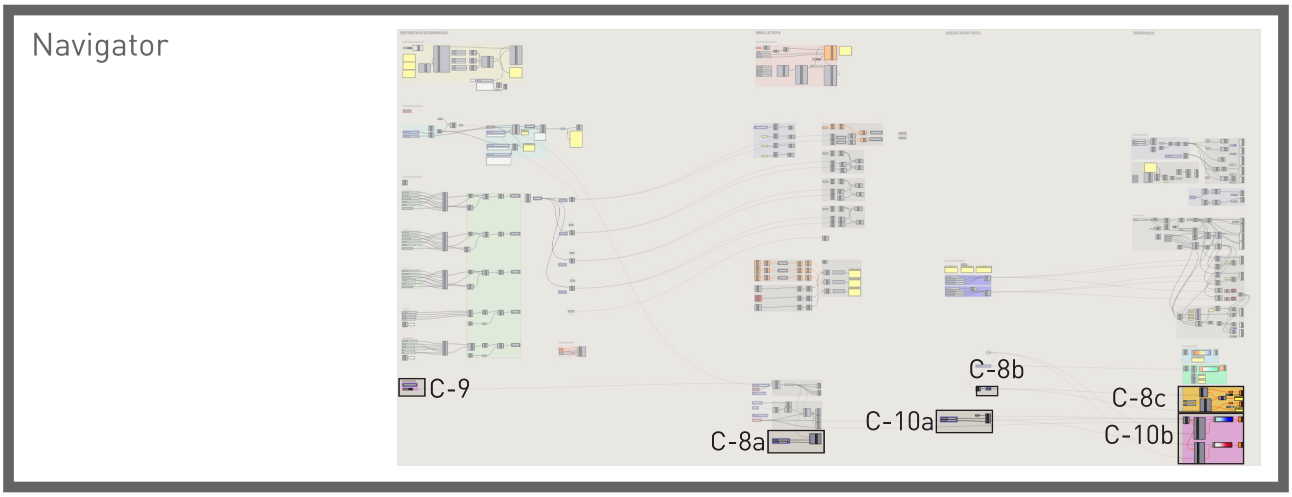


Figure C-8d ▶

Screenshot of the Rhino workspace in which the two paths are reported within the analysed network (colours refer to Figure C-6b). The shortest path is reported in black, and the most shaded one in white.



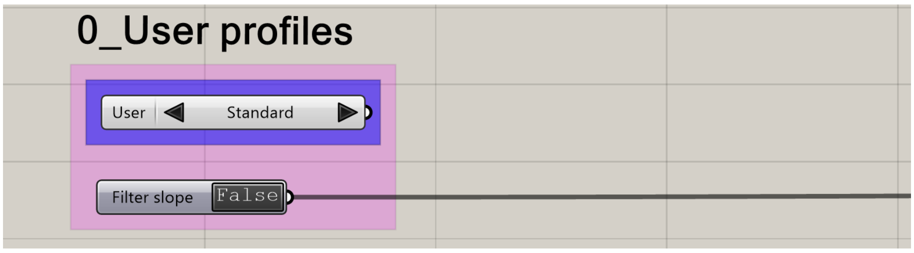
The same methodology was applied to analyse the performance of the pedestrian network within the area of interest. All the points where network segments intersected the radius of interest were connected to the closest metro station access; then the analysis was repeated. On average, the most shaded path was 32% longer than the shortest one, and the average shaded length of the most shaded one was 70%.



The last analysis adopted the point of view of four users of diverse walking abilities to evaluate the level of accessibility to shade provided by the pedestrian network.

Figure C-9 ▶

Shade accessibility analysis started by selecting a user profile among the four proposed. The boolean toggle was used to remove steep paths.



In the selection tool, a time threshold for changing the DSR exposure status is set: in this exercise, it was set to one minute for both shaded and sunny steps.

▼**Figure C-10a**

Figure C-10b ▶

This cluster performs the shade and sun accessibility analysis. For each step, the closest point (on the network) in which the DSR exposure status changed was defined; diverse colour legends were adopted for shaded and sunny steps.

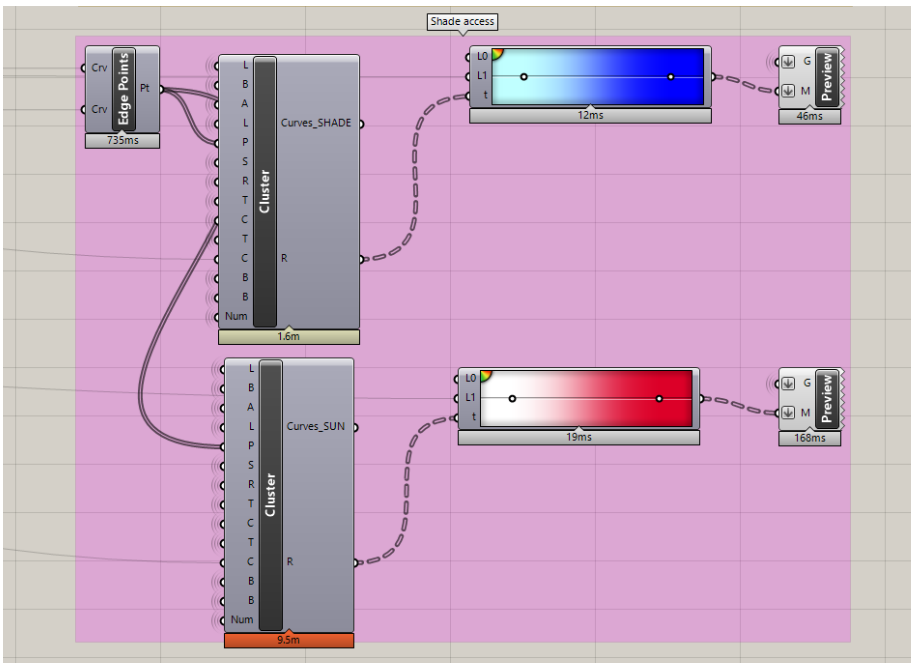


Figure C-11a

Shade accessibility map for a standard pedestrian.

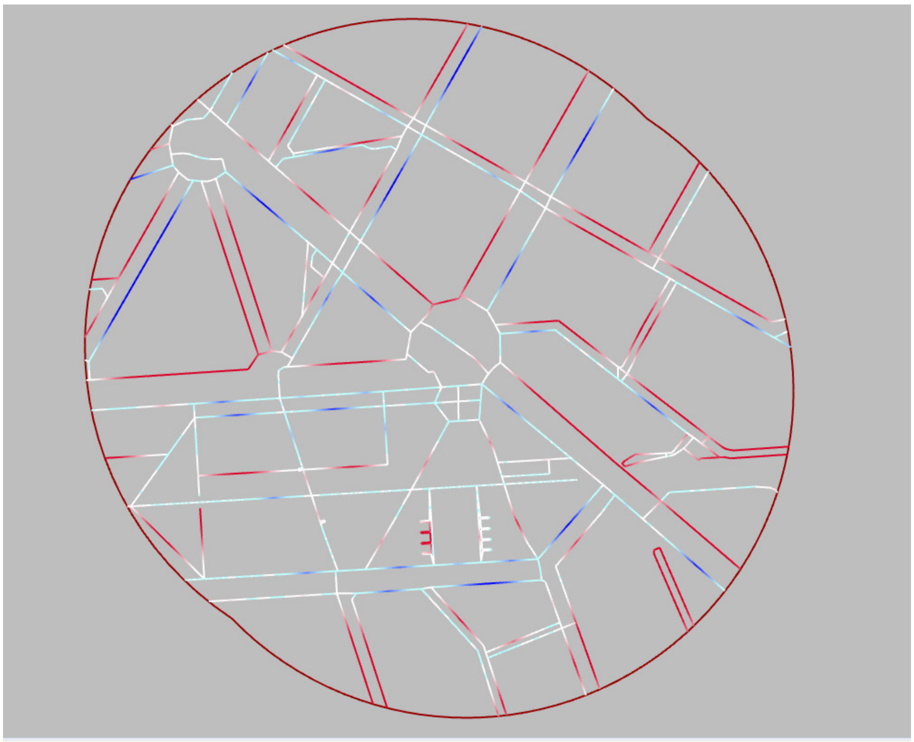


Figure C-11b

3D visualisation of the shade accessibility network for a standard pedestrian

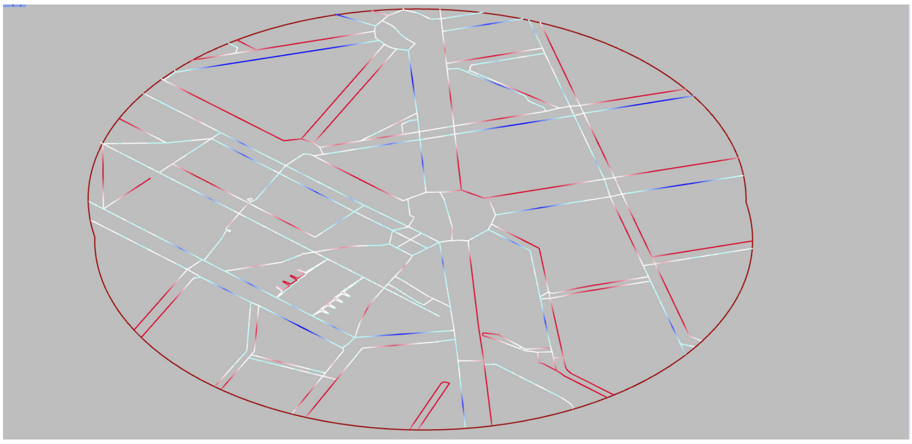


Figure C-12

Shade accessibility map for a user in a wheelchair. The network was filtered to remove slopes steeper than 8%: therefore, stairs were removed from the network in calculating shade accessibility. This could be observed in the Parco Romana master plan, where stair steps are missing, and points in between stairs are isolated.

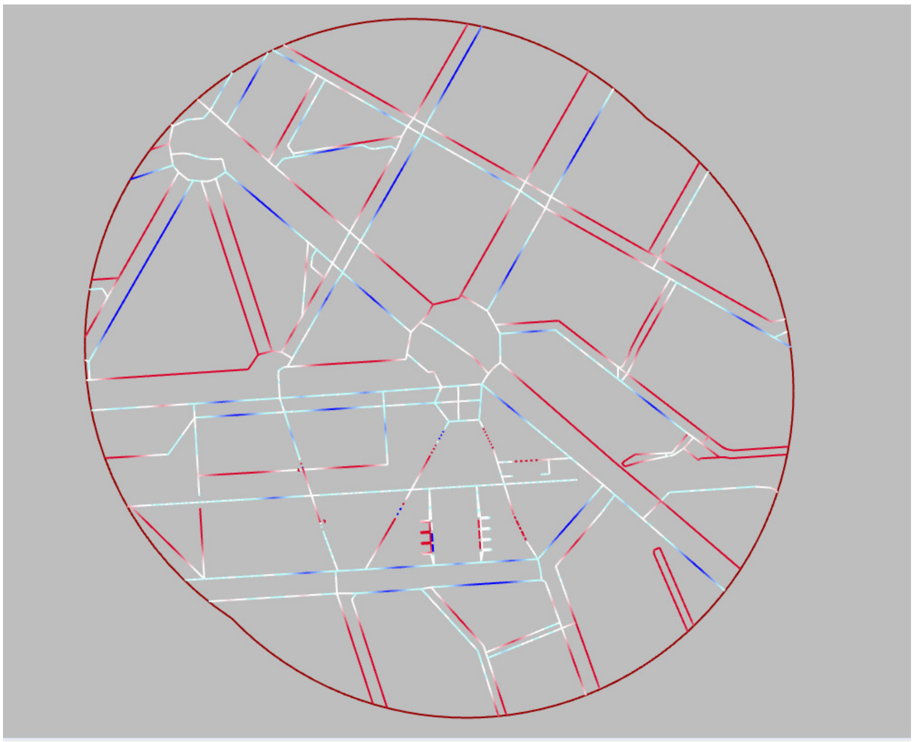


Figure C-13 ▶

Shade accessibility map for a pedestrian using an assisting device; the network was filtered from slopes larger than 8%.

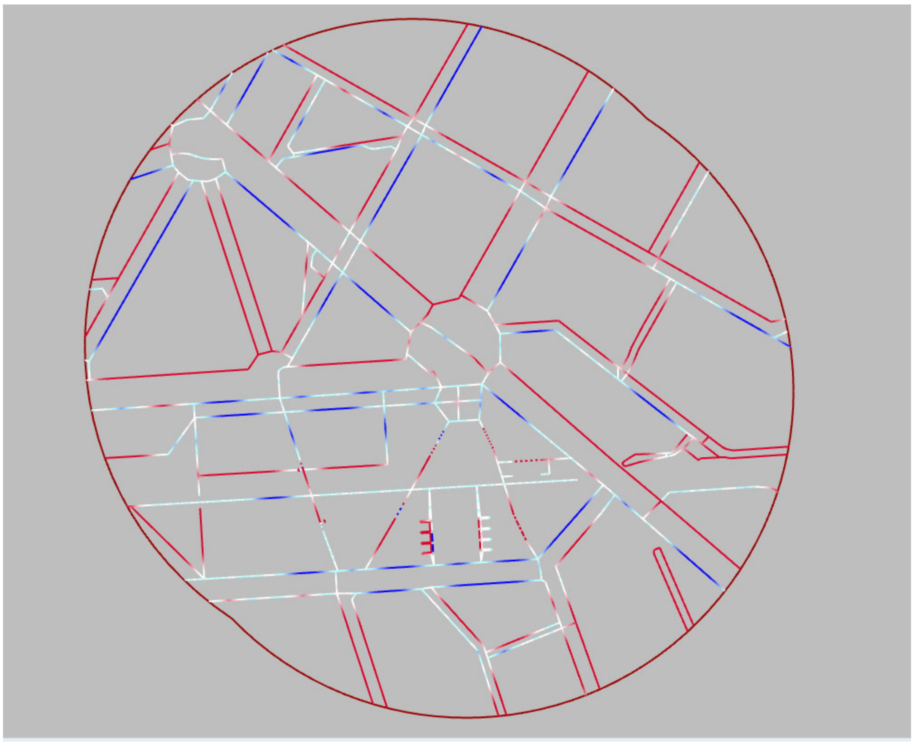
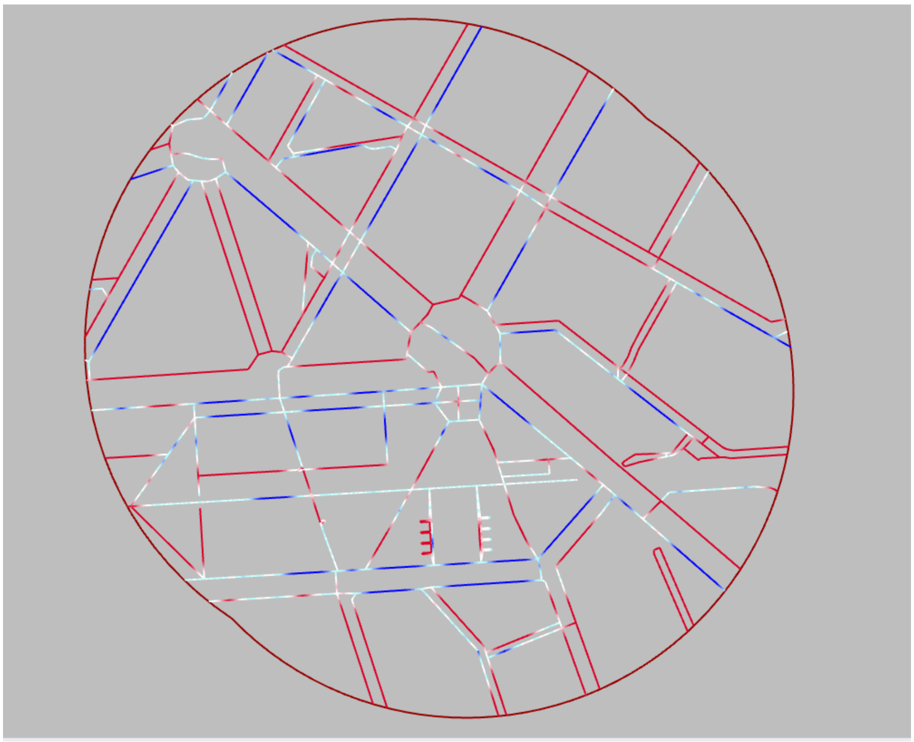


Figure C-14 ▶

Shade accessibility map for ITCs (infants, toddlers and caregivers).



Previous simulations were completed in a few minutes. The shade accessibility simulations required a larger computational time; nevertheless, the threshold of 15 minutes was never exceeded. Given the elevated complexity of the master plan, in terms of 3-D pedestrian network and context, this result makes the design tool a valuable instrument to implement microclimate inclusivity analysis in urban design practice.

Starting from the DSR exposure of the pedestrian network, a total of four analyses were performed (% shade, distribution, Δtransp/comf and shade access), each one providing a different perspective on the travelling experience of users. The combination of results could set the canvas to design shading interventions, ensuring good coverage of paths, sensible distribution of relief spots, and emphasis on how a pedestrian network serves users of diverse walking abilities.

APPLICATIONS IN URBAN DESIGN PRACTICE

In the previous section, the design tool was applied to three design exercises. In Figure 7, 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 workflow is followed. The horizontal axis refers to the specificity of results, ranging from rule-of-thumb-like information formulated based on theoretical case studies to ad-hoc proposals tailored to specific projects. The four applications were defined based on work presented in the previous section and are described in Table 4.

Figure 7: Position of four applications against increasing resources deployed and narrowing outcome application. Dark grey boxes refer to Table 4.

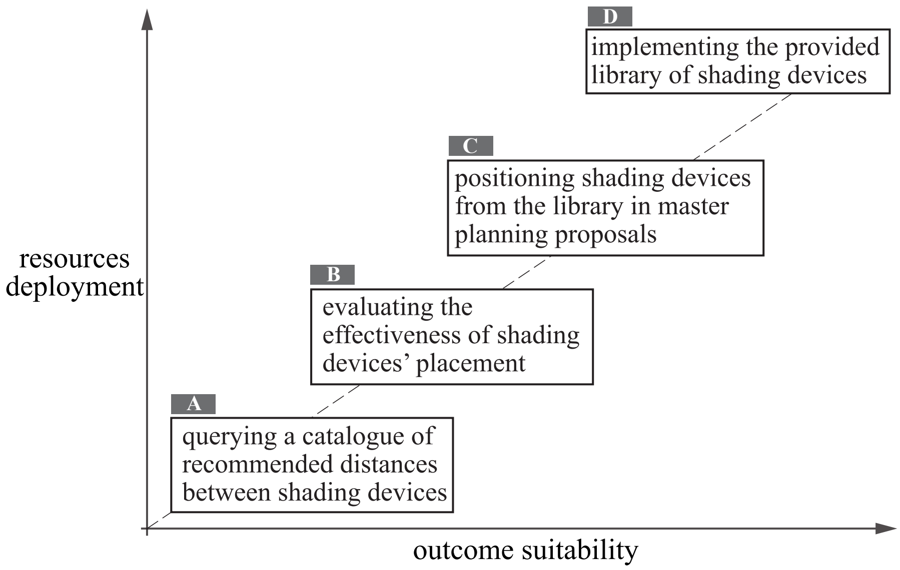


Table 4: Applicative processes of the protocol to urban design.

	Applicative process	Description
A	Querying a catalogue of recommended distances between shading devices	A table created through workflow A (Figure A-13) would allow urban designers and decision-makers to extract rule-of-thumb-like information for positioning shading devices in cities according to pre-selected shading performances.
B	Evaluating the effectiveness of shading devices' placement	Urban designers can inquiry and consequently updating minimum installation requirements based on target performances, finding the most suitable recommendations based on location and selection criteria.
C	Positioning shading devices from the library in master planning proposals	The design tool allows urban designers to evaluate urban morphology modelled in Rhino, position shading devices and simulate DSR exposure of pedestrian paths within the design process.
D	Implementing the provided library of shading devices	The library can be expanded with new shading devices, complemented with all relevant parameters necessary for evaluating their effectiveness in shading pedestrian paths.

CONCLUSIONS

Summary of the protocol

This research developed a protocol to implement shading solutions in outdoor spaces, specifically on pedestrian paths. Pedestrians were central in evaluating sidewalks; microclimatic conditions were considered as an infrastructural component of the urban environment, subject to requirements and design guidelines. The iterative workflow enables urban designers to analyse, evaluate and design the shading solutions' configuration within the design process rather than the conventional way of performing modelling exercises separately to assess environmental issues.

The protocol relies on a design tool shaped as a GH code: it allows urban designers to test various configurations of natural and artificial devices to shade pedestrian paths based on location, urban morphology, and orientation. A library of shading devices, created for the city of Milan, is provided; multiple natural and artificial shading devices, complete with installation requirements, could be added. In fact, 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.

Key features of the protocol

The opportunity to evaluate theoretical urban canyons and a real case study sidewalk allows for implementing DSR exposure analysis in urban design with various levels of detail. Three results of this protocol are highlighted: the time-efficient workflow suitable for urban design practice; the step-by-step presentation of three design exercises; the consistent body of information to support the selection of design goals.

Finally, the key innovation of this protocol is the provision of user profiles for pedestrians of diverse walking abilities. The possibility to switch between user experiences is embedded in the design tool, encouraging urban designers to evaluate how DSR exposure of pedestrian paths impacts multiple user experiences. Design proposals could therefore be adapted to respond to various needs, fostering inclusivity in urban design.

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Appendix B: Conference presentations

B.1. Users' comfort as an urban design variable: people and microclimate define priorities in outdoor spaces

Oral presentation: Tomasi, M., Nikolopoulou, M., Giridharan, R., Romero, J. C. & Löve, M. (2022). International Urban Planning and Environment Congress. Tartu, 29 July – 1 August 2022.

ABSTRACT

The COVID-19 pandemic has demonstrated the importance of outdoor public spaces for people; this emphasises the need for urban design methods increasingly focused on users. Microclimate considerably impacts people, affecting their experience of outdoor spaces. Multidisciplinary approaches are needed to implement scientific knowledge into urban design: innovative tools developed at the interface between academia and industry would allow urban designers to propose climate- and users-responsive outdoor spaces. This contribution explains a methodology to improve users' comfort in outdoor spaces. The specific aim is to investigate solar exposure of users' walking paths to underpin temporary and permanent measures to provide shadow for pedestrians in uncomfortable conditions. The methodology is tested on a new development in Milan (IT), in collaboration with the industry partner. Space Syntax theory is applied to prioritize users' paths within the pedestrian network. By overlaying solar exposure and spatial relations, valuable insights are obtained to define static and temporary uses of the space and to fine-tune the location of vertical elements to protect people. The changes in the direction of the sun rays contribute to the proposal of flexible and dynamic spaces. Different scenarios are investigated: users' comfort is the main variable considered in the evaluation of the design proposals. The project illustrates the outcome that can be obtained when urban design gives priority to users' comfort over other variables accounted for in practice. The result is a tool for urban designers to design comfortable outdoor spaces through the critical implementation of microclimate information into their work.

Keywords: outdoor spaces, solar radiation, pedestrians, user experience, multidisciplinary design

B.2. Pedestrians' comfort as a priority for urban design: a case study in Milan (IT)

Poster presentation: Tomasi, M., Nikolopoulou, M., & Löve, M. (2022). International Association for Urban Climate (IAUC) virtual poster conference. [Online], 30 August – 1 September 2022.

ABSTRACT

The COVID-19 pandemic has demonstrated the importance of outdoor public spaces for people. Since microclimate considerably impacts people, affecting their experience in outdoor spaces, additional attention should be paid to the climatic conditions of the urban space. For necessity or leisure, most people spend time walking outside every day; this activity demands particular attention from urban designers and municipalities, especially during exceptional conditions such as heat waves. Multidisciplinary approaches are needed to implement scientific knowledge into urban design: this can be done through innovative tools for practitioners and decision-makers to propose climate- and user-responsive outdoor spaces. This contribution draws attention to the importance of providing comfortable and safe paths for users, analysing sidewalks from the microclimatic perspective. Specifically, investigating solar exposure of users' walking paths leads to the design phase, in which temporary and permanent solutions to shade pedestrians are proposed. The methodology is tested on a new development in Milan (IT), in collaboration with the industry partner. The pedestrian network is previously classified to prioritize the design intervention on the most used pedestrian paths. By overlaying solar exposure and spatial relations, valuable insights are obtained to define short- and long-term solutions to protect people from solar radiation-related risks. The changing direction of the sun rays contributes to flexibility and dynamism in outdoor spaces. Different scenarios are investigated, and the design proposals are evaluated based on the user experience. The research illustrates the outcome that can be obtained when users' comfort is among the priorities of urban designers. The result is the application of a tool developed for both urban designers and municipalities, to implement microclimate information into the outdoor spaces design process.

B.3. Walkability and solar radiation exposure for diverse users: climate-responsive urban design to enhance accessibility to outdoor spaces

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ABSTRACT

Urban designers can contribute to improve microclimatic comfort by adapting outdoor spaces to users' need for comfortable and safe microclimatic conditions. The proposed methodology evaluated outdoor spaces from the user experience point of view, focusing then on pedestrians. Walkability was evaluated through analysis of exposure to solar radiation, along with the time pedestrians of different physical abilities would take on the paths. Overlaying walking speeds with solar radiation exposure maps enabled designers to evaluate how much time pedestrians would spend under the sun. Time graphs presented sunny and shaded time along the paths; the total time spent in each condition was then calculated. The methodology was tested on a case study master plan. Testing different spatial configurations of shading devices enabled the optimization of the design, considering users' need for shaded or sunny places, according to different seasons. The installation of shading devices in summer increased the time spent in the shade by 55% for pedestrians walking with an assisting device. The proposed tool aims to give priority to users' comfort in urban design practice. The additional focus on users with different physical abilities contributed by drawing attention to more inclusive cities.

Keywords: solar radiation, walkability, climate-responsive, user experience

B.4. Designing for users: a decision-making tool for positioning shading solutions in master planning

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ABSTRACT

While the COVID-19 pandemic has strengthened the importance of outdoor spaces, the 15-minute city concept has drawn attention to the need for comfortable walking paths. Solar radiation exposure plays a key role in people's outdoor experience: urban designers' challenge is improving pedestrians' safety and comfort in response to it. To succeed in this challenge, a comprehensive approach is needed: the combination of expertise in diverse fields can implement scientific knowledge into urban design, having a significant impact on practice. The outcome of this research, carried out between academia and industry, is an informative decision-making tool to position a variety of shading solutions in master plan proposals. It has been formulated as a protocol for urban designers to be included in their daily practice: based on tools already used by professionals, it allows them to analyse and evaluate design options of outdoor spaces with the goal of making them comfortable for users, throughout the year. Solar radiation is investigated because of its major impact on human heat balance and interaction with urban morphology – a component that designers can manipulate during the design process. The definition of the protocol considered urban and climate data availability, operability into urban design workflows, and dissemination of microclimate knowledge. The workflow is structured to provide multiple degrees of design optimization in response to the level of expertise of urban designers and their familiarity with tools. Outcomes range from rule-of-thumblike information to detailed modelling of shading devices: this enables wide accessibility and applicability of the research. The methodology has been prototyped using the city of Milan (IT) as a case study; further results are provided for cities at different latitudes. The presented decision-making tool is relevant to support urban practitioners in adopting a climate- and users-responsive approach for positioning shading solutions in their urban design proposals.

Keywords: outdoor spaces, solar radiation, pedestrians, user experience, multidisciplinary design