EVALUATING THE COOLING POTENTIAL OF URBAN GREENERY: AN ENVI-MET SIMULATION CASE STUDY IN ITALY

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ABSTRACT

In recent decades, the urban heat island (UHI) phenomenon has become one of the main environmental challenges in urban areas. The intensification of temperatures in city centres, compared to surrounding rural areas, represents a concrete threat to public health, thermal comfort and urban sustainability. This paper discusses the use of the holistic three-dimensional software ENVI-met to evaluate how vegetation can mitigate UHI, focusing on a case study involving a parking lot near a supermarket in a municipality in the centre of Italy. It details the simulation process, including the selection of appropriate tree species, and two different arrangements within the parking area to enhance cooling effects. Simulations were carried out starting at 6:00 am for a duration of 24 hours, with the aim of evaluating the potential air temperature at 2:00 pm and the PMV and PPD comfort indices for the statistically representative summer and winter day; a comparison with the state-of-the-art with no greenery was then performed. The study emphasizes the importance of creating realistic models to assess temperature and comfort indices effectively. Results indicate that strategic planting can significantly lower temperatures and improve comfort levels in urban settings; it can be stated that the most suitable tree for the creation of a green parking lot is the Acer Campestre, thanks to its ability to lower the temperature by approximately 1.5°C and improve comfort indices; moreover, it is shown that the optimal arrangement of trees can significantly influence the microclimatic conditions of the parking lot.
Keywords: ENVI-met, UHI, outdoor comfort, urban greenery, temperature, comfort indices.

1 INTRODUCTION

Urban heat island (UHI) is one of the main problems related to urban heating, primarily due to the replacement of natural surfaces with artificial materials that absorb and release heat, leading to higher temperatures compared to surrounding rural areas. This phenomenon not only worsens the quality of life in cities but also increases energy demand for cooling buildings, with consequently significant environmental and economic impacts [1], [2].

Another important topic is the concept of outdoor comfort; it represents a multidisciplinary challenge, involving microclimatic, architectural, physiological, and psychological aspects, aimed at ensuring optimal living conditions in interior spaces but also in urban outdoor environments. Outdoor comfort is closely linked to individuals’ perception of thermal well-being, and its analysis requires the integration of various disciplines to adequately address the variables that influence it.

It is interesting and functional to consider that contemporary urban areas include not only city centres and residential neighbourhoods, but also industrial areas, parking lots, and commercial complexes frequented daily by workers and visitors. These areas are characterized by large, impervious surfaces (asphalt, roofs and yards) with low evaporation and high heat storage capacity, significantly contributing to the UHI.

Specific studies show that the surface temperature (LST) in parking lots can exceed that of surrounding green spaces by more than 6°C, as evidenced on a university campus in Saudi Arabia – where a LST of approximately 47°C was recorded in parking lots versus

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approximately 40°C in vegetated areas, an average difference of approximately 6.5°C in summer [3].

Furthermore, in Nagoya, Japan, traditional asphalt parking lot surfaces are responsible for increases in summer LST of up to 7.3°C; introducing greenery (grass and trees) can achieve maximum reductions of approximately 7.26°C for a single parking lot [4]. Simulations conducted with the software ENVI-met in Champaign Urbana (USA) indicate that increasing the albedo of a parking lot can lower the air temperature by about 1°C and improve the perceived thermal comfort (UTCI), mitigating the UHI effect at microscopic scale [5].

Finally, in an Italian case, the use of reflective or green pavements resulted in air temperatures up to 1.5°C lower than asphalt and in more favourable PMV indices during the hottest hours of the summer. This evidence supports the importance of considering industrial areas and parking lots in urban planning as significant contributors to UHI and objects for targeted solutions [6].

In this context, urban greenery plays a fundamental role in mitigating the effects of UHI and improving environmental comfort. Extensive research shows that the presence of trees and green spaces helps reduce outdoor temperatures through shading and evapotranspiration. These effects reduce the need for artificial cooling, with clear advantages in terms of energy savings and sustainability.

Numerous studies demonstrate that not only the quantity, but also the type of plant species and their spatial arrangement significantly influence the effectiveness of urban cooling. For example, a case study in Fuzhou, China, on three tree species, showed reductions in physiological equivalent temperature between 4.7°C and 5.3°C, correlating these differences with canopy density, leaf area index (LAI), and crown shape [7].

In Hong Kong, species with larger crown diameters and high LAI showed stronger cooling and humidifying effects, while Zhang et al. highlighted how increases in branch diameter/height ratio up to 8 can reduce mean radiant temperature by up to ~15°C in summer months [8]. In another research on 15 urban green spaces in the industrial district of Suzhou, the cooling capacity was found to be positively correlated with green area, tree cover density and mean LAI, while the shape of the green perimeter (perimeter–area ratio) negatively influenced the cooling [9].

Overall, this scientific evidence supports the importance of choosing tree species with broad canopies, high LAI, favourable crown structures and diverse compositions, as well as carefully planning their spatial arrangement, to maximize urban thermal mitigation.

To more accurately study and predict the impact of urban greenery on the city's microclimate, numerical modelling is a valuable tool. Advanced software such as ENVI-met allows for the simulation of three-dimensional environmental conditions, providing useful insights for urban planning and the implementation of effective climate adaptation strategies [10].

ENVI-met is one of the most widely used software for microclimate simulation in urban environments, thanks to its ability to model the interaction between surfaces, atmosphere, and vegetation at a local scale. Numerous studies have evaluated the validity of ENVI-met by comparing simulations with empirical data showing a good correlation especially given accurate inputs and settings [11]–[13].

These results, while highlighting some limitations in the representation of complex phenomena such as air flow or evaporative cooling, confirm the general validity of ENVI-met as a predictive tool for thermal comfort studies and urban design.

The aim of this work is to fit into this study context to verify the importance of the presence of vegetation in areas such as parking lots, examining the impact of both the type of trees and their spatial arrangement, on the ambient air temperature and on the thermal comfort perceived.

The study area was identified in a parking lot adjacent to a production facility and, consistently with previous research conducted by the authors [14], a statistical methodology was employed to select representative meteorological conditions for the simulation campaign. This approach enabled the identification of a typical summer day, from which temperature and relative humidity profiles, as well as wind speed and direction, were extracted.

Finally, the resulting output is presented through a series of colour maps illustrating the simulated distributions.

2 MATERIALS AND METHODS

The study was conducted using a supermarket parking lot as a case study. The parking lot is located on Via Musone in the municipality of Castelfidardo, a small town in the hilly hinterland of the Marche region with around 20,000 inhabitants (July 2025). This site was selected to ensure maximum adherence to a real-case context: as previously mentioned, parking lots adjacent to large commercial businesses are emblematic locations for studying the UHI effect, but they also offer good opportunities for vegetation addition.

The area was identified using Google Earth software first and then modelled in ENVI-met. Considering that the LITE version of the software allows grids of up to 50 × 50 cells, a rectangular portion measuring approximately 100 × 80 m was selected in the southern area of the parking lot. This allowed for the generation of a 50 × 40 grid with a spatial resolution of 2 m ($dx = dy = 2$ m). The modelled domain includes: a Digital Elevation Model (DEM) set to 10 m, a natural soil (default sandy loam, code = 00) with an albedo of 0.2 under the supermarket building, asphalt pavement (asphalt road, code = ST) with an albedo of 0.12 on the remaining surfaces, and two buildings 20 and 5 m high, respectively, both constructed with materials included in the software's standard database (default wall – moderate insulation). The domain is shown in Fig. 1.

For the vegetation, two tree species considered suitable for urban design in similar contexts were selected from the ENVI-met 'Albero' database, as highlighted in the 'Prontuario del Verde' of the Municipality of Vicenza and the Green Plan of the Municipality of Padua [15], [16]: Acer campestre (Field Maple), 10.45 m tall, and Catalpa Bignonioides, 6.48 m tall. Acer campestre is a native deciduous species with a dense, rounded crown, capable of effectively absorbing carbon dioxide and fine dust. Catalpa Bignonioides, on the other hand, is a now naturalized, fast-growing, non-native species that can reach 18 m in height. Its crown is thick and rounded, with very broad leaves (up to 25 cm), resistant to urban pollution and suited to various soil types.

For each of the two species, two alternative compositional schemes (shown in Fig. 2) were defined, consistent with good green parking design practices, thus generating a total of five simulated domains (the two arrangements of the two tree species and the state-of-the-art domain).

In the first layout, called 'type 0 layout' (Fig. 2(a)), a total of 42 trees were placed in an arrangement intended to provide the simulation with as much realism as possible. Referring to the figure, two lanes were left for car traffic and to leave free entry and exit to the supermarket itself, where functional areas for commercial activity must be provided. Instead, we imagine planting 18 perimeter trees, which will 'isolate' the parking lot and divide it from the road. Subsequently, five rows of five trees each are arranged, except for the one at the bottom of the figure, which has only four. Parking spaces are supposed to be created almost

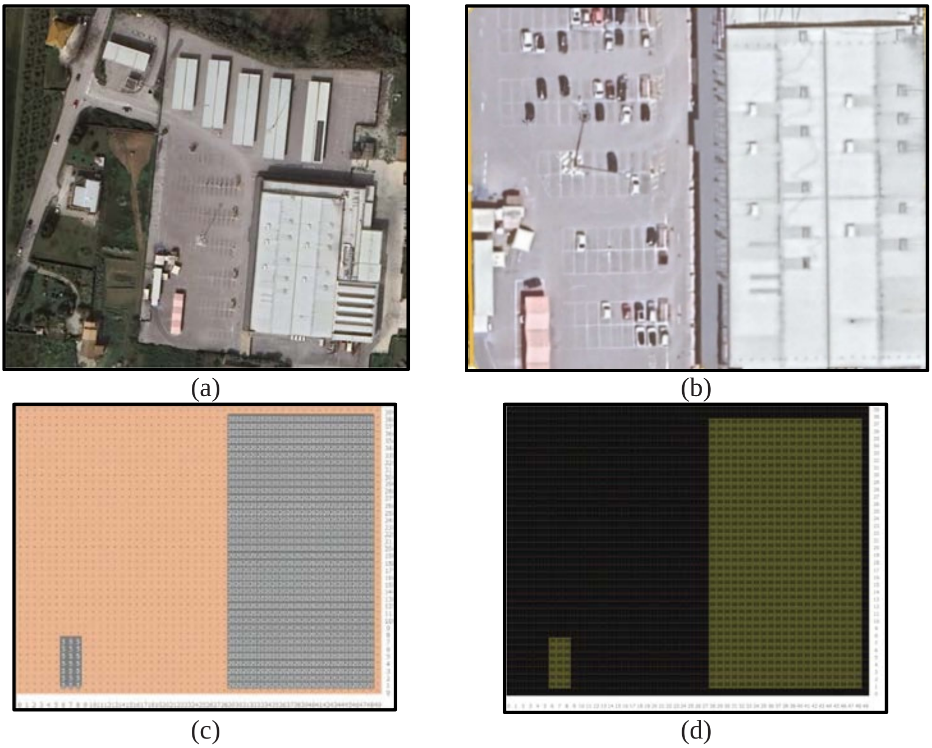


Figure 1: (a), (b) Aerial view of the parking lot and detail of the domain in Google Earth; (c) Domain in ENVI-met with representation of the buildings; and (d) The pavements.

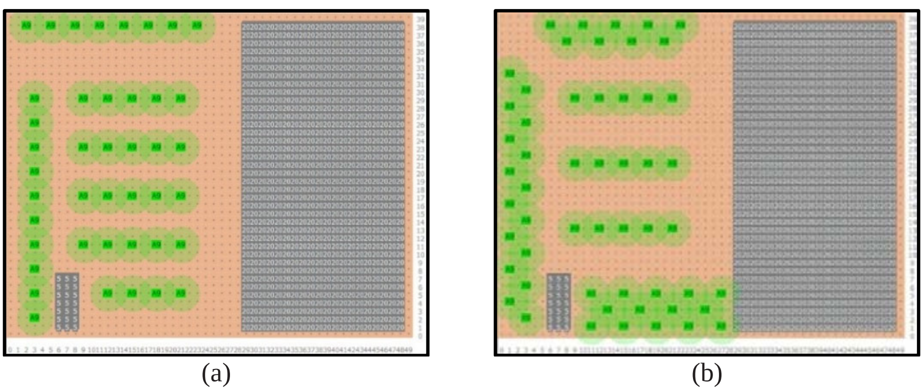


Figure 2: (a) Type 0 layout; and (b) Type 1 layout in ENVI-met.

everywhere, on the inside of the perimeter row and on both sides of the central rows. Within the rows, each tree is separated from the other by two cells, corresponding to 4 m. The central rows of trees, however, are spaced five cells apart, a distance equal to 10 m. To accommodate parking on both sides, it is necessary to assume that the orientation of the parking spaces will be slightly inclined and that only one-way traffic will be allowed.

The 'type 1 layout' (Fig. 2(b)) certainly reduces the number of parking spaces the parking lot can offer, but allows for the addition of more trees, a total of 54. Specifically, it reinforces the presence of perimeter and dividing trees.

The idea is to enhance the landscape role of trees within the parking lot, introducing a 'green fence' that creates a space separate from the urban context. The perimeter trees should visually create a kind of 'grove', which is why single rows of trees are not used, but rather double or triple rows, offset to convey the impression of a continuous green space.

For each domain, simulations for the summer season were run, each lasting 24 hours, starting at 6:00 am.

The simulations were evaluated primarily using the potential air temperature recorded at 2:00:01 pm, as well as the PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied) comfort indices. The PMV index represents the average rating of a group of people and provides an idea of how much the actual thermal situation perceived by an individual differs from their comfort level. The PMV index can range from +3 to −3, however, ENVI-met considers −4 and +4 as extremes for its calculation. The PPD index indicates the predictable percentage of people dissatisfied with the thermal conditions and is mathematically derived from the PMV value.

The simulation day was chosen based on the identification of the representative day, a statistical criterion that identifies the actual day (with data recorded by weather stations) whose hourly temperature trend deviates least from the seasonal average [17]. In operational terms, for each day, the sum of the standard deviation per hour compared to the other days was calculated, according to the formula:

$$A_{ij} = \sum_{k=1}^{24} (C_{ki} - C_{kj})^2 \quad (1)$$

where i, j = 1, 2, …; N = days; k = hour of the day, and C is the variable considered (temperature).

The vector:

$$A_i = \sum_{j=1}^{N} A_{ij} \quad (2)$$

allows us to identify the day with the minimum sum, that is, the most statistically representative day. The weather station chosen for applying this method was the one called 'Svarchi', closer to the domain area Via the SIRMIP-online portal of the Marche Region Civil Protection historical database [18]; 25 June 2023, has been identified as a representative summer day.

The boundary conditions for the simulations were generated using the 'simple forcing' method. As demonstrated in several studies, this technique yields satisfactory agreement between simulated and observed values. It achieves this by applying a forcing function to the temperature and humidity variables, assigning them the expected profile values for the selected reference period.

3 RESULTS AND FINDINGS

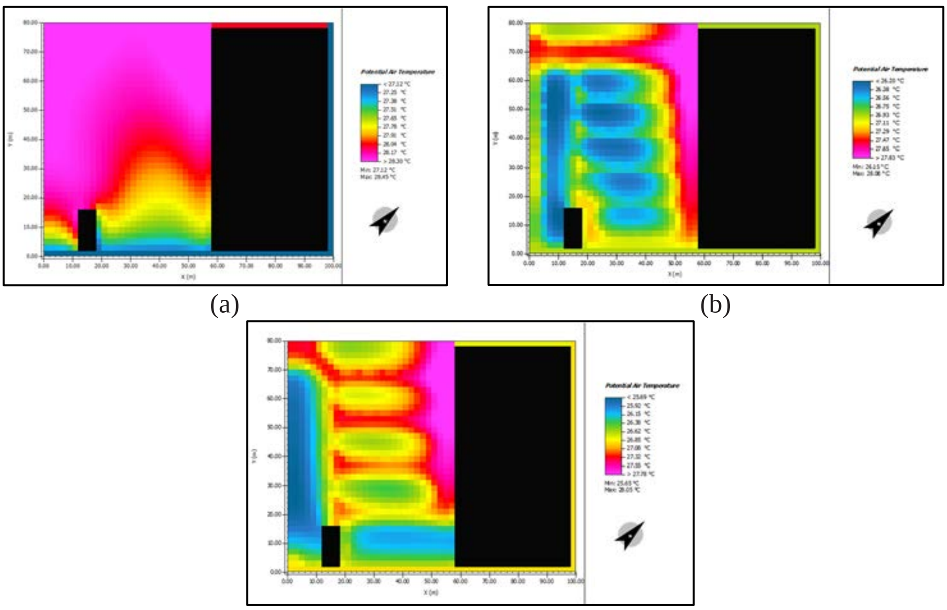
Below are the outputs, via colour maps, for the state-of-the-art and all the various simulations. First, a direct comparison is made between the state-of-the-art and the two layouts for the Acer Campestre, both for temperature and comfort indices. Second, a comparison is made between the state-of-the-art and the layouts for the Catalpa. A critical comparison will then be made for the best solution among those analysed.

3.1 Results for the state-of-the-art and simulations for Acer Campestre

3.1.1 Temperature

The outputs are shown at 2:00:01 pm, the time considered as severe for the UHI, in terms of potential air temperature, 1 m above ground.

Fig. 3(a), a state-of-the-art representation, shows a nearly uniform temperature distribution throughout the parking lot, with temperatures consistently above 27.12°C. Two-thirds of the area exhibit temperatures above 28°C, with a maximum of 28.45°C, shown in red and purple, respectively. The lowest temperatures occur in the southern area of the parking lot and near the buildings; they are represented by a colour that ranges from yellow to blue as the temperature decreases. It can be hypothesized that this distribution is due to geographic orientation, wind direction, and the placement of the buildings' shadows on the ground.



(a) (b) (c)

Figure 3: Potential air temperature output, Acer Campestre simulation. (a) State-of-the-art; (b) Type 0 layout; and (c) Type 1 layout.

Fig. 3(b), which shows the Acer Type 0 layout, has a temperature distribution consistent with the positioning of the trees. Where trees are present, temperatures are lower than in the areas devoid of vegetation. In areas with dense vegetation, a minimum temperature of 26.15°C is recorded, represented by the blue colour. In the upper part of the figure, the presence of the row of trees dividing the parking lot is less effective in mitigating temperatures, with values ranging from 26.75°C (green) to 27.29°C (yellow/orange).

Finally, in Fig. 3(c) (Type 1 layout), the output also shows a colour map consistent with the tree positioning. The lowest temperatures are around 25.7°C and are recorded on the southwest side of the parking lot. The highest recorded temperature is 28.05°C and, again, is found in the upper part of the grid, close to the building. The inclusion of trees, in this case, results in zones that differ by a maximum of 2.5°C. The temperatures under the tree row and in the path that passes between two rows differ by approximately 1°C.

3.1.2 Comfort indices

Regarding the PMV and PPD comfort indices of the state-of-the-art simulation (Fig. 4(a)), the graphical interpretation of the outputs also provides consistent results across the entire area, with PMV values consistently reaching 3.50 and PPD values above 94.27% (depicted by the purple colour in Fig. 4(a)).

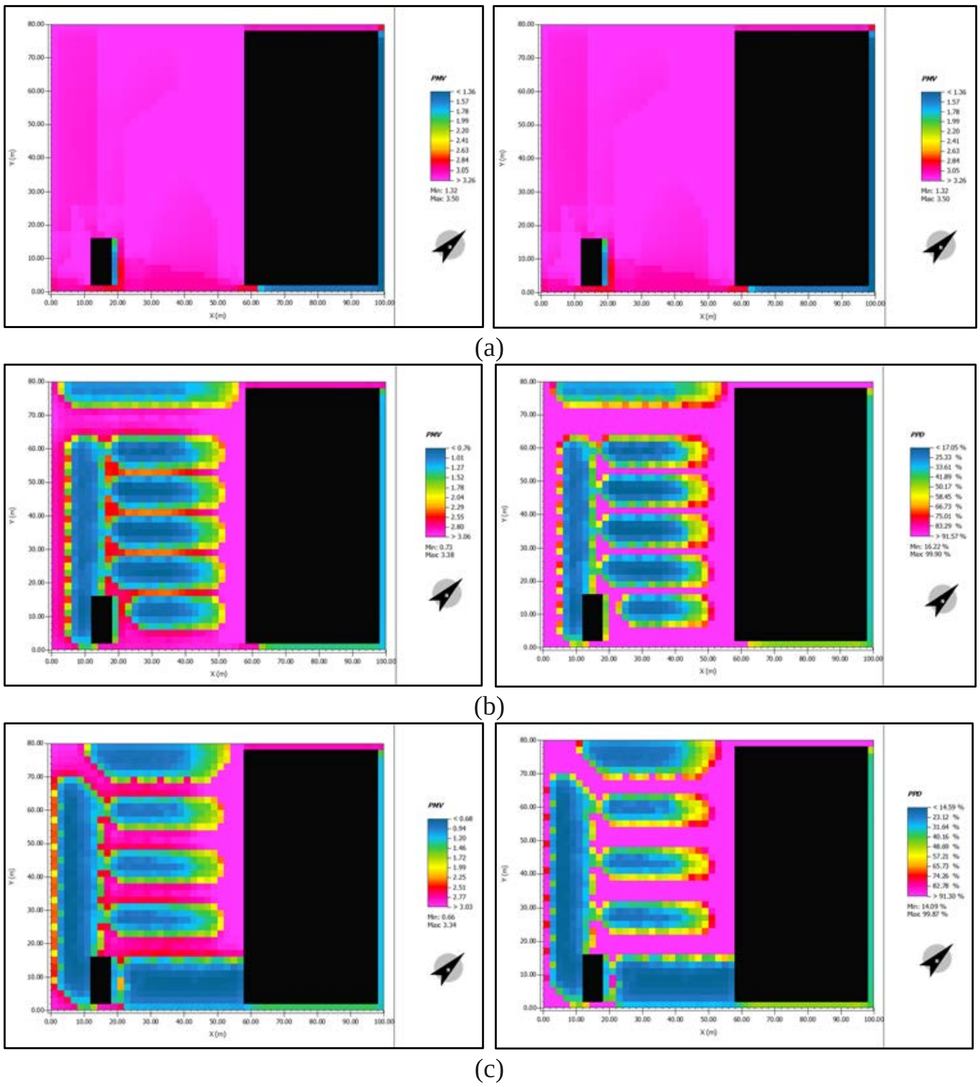


Figure 4: PMV and PPD comfort indexes outputs, Acer Campestre simulation. (a) State-of-the-art; (b) Type 0 layout; and (c) Type 1 layout.

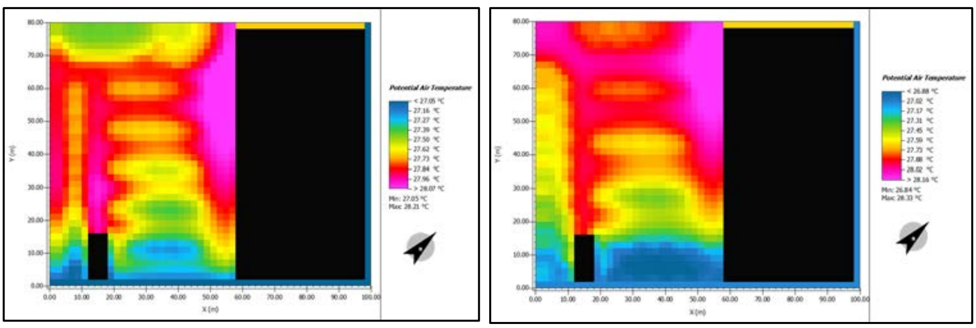
The simulation of Type 0 layout (Fig. 4(b)) provides significant improvements in the areas with trees, but a slightly improved situation in the areas without trees, compared to the state-of-the-art. As can be seen from the figures, the colour maps reflect the tree layout and indicate PMV values as low as 0.76 and PPD values less than 17.05%.

The simulation results for Type 1 layout (Fig. 4(c)) do not differ significantly from the previous one; areas are recorded with a maximum PMV equal to 3.34 and the dissatisfied rate is close to 100%. However, the perimeter 'groves' are particularly comfortable areas, with PMV values equal to 0.66 and PPD less than 15% even for medium-sized areas.

3.2 Results for the state-of-the-art and simulations for Catalpa Bignonoides

3.2.1 Temperature

The Type 0 layout provides the output shown in Fig. 5(a). The highest recorded temperature is higher than the same arrangement with Acer Campestre and tends to approach those of the state-of-the-art, reaching a maximum value of 28.21°C. Furthermore, the areas exceeding 28°C (purple colour), in addition to being, as before, close to the largest building, are also found on the paths between the rows of trees. Even the cooler areas seem to be affected by this phenomenon since they are confined to a smaller area and 1°C higher than the same arrangement with Acer Campestre, their positioning in the lower part of the grid remains unchanged.



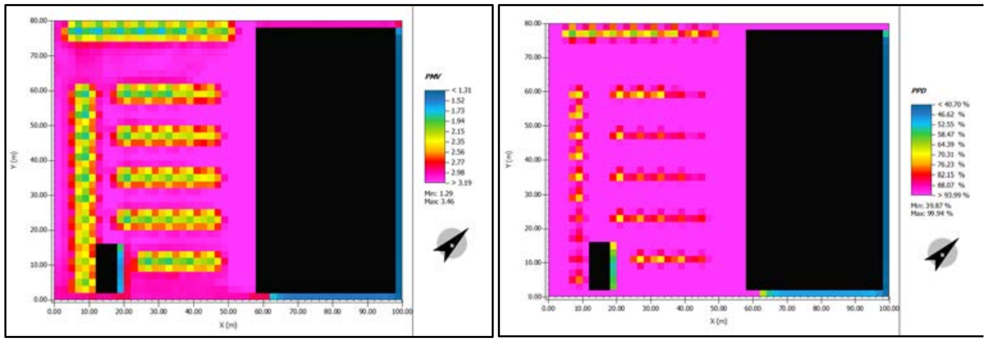
(a) (b)

Figure 5: Potential air temperature output, Catalpa Bignonoides simulation. (a) Type 0 layout; and (b) Type 1 layout.

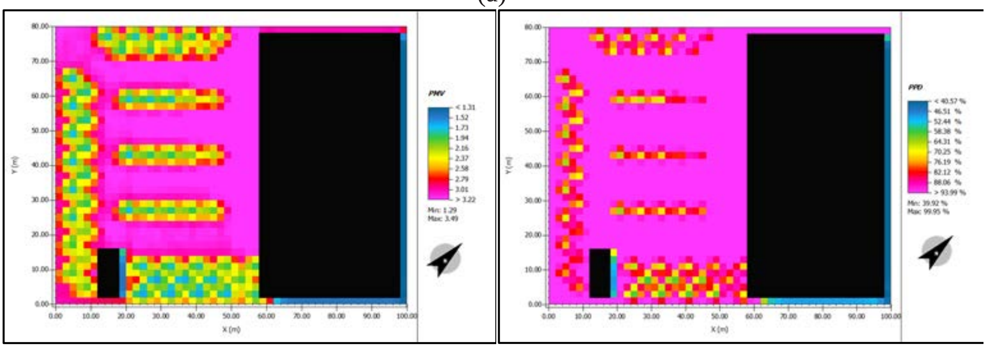
In Type 1 layout (Fig. 5(b)), the triple row of Catalpa trees brings the temperature below 27°C but is still far from the temperature of 25.7°C obtained with the Acer. In fact, the highest temperature recorded increases compared to the previous simulation, reaching 28.33°C. Overall, a temperature difference of 1.5°C is recorded, a value that is not inconclusive but still much lower than the 2.5°C observed in the simulation with the Acer Campestre in Type 1 layout.

3.2.2 Comfort indices

As shown in Fig. 6, the minimum PMV value increases, compared to the Acer Campestre, in the case of Type 0 layout (Fig. 6(a)) from 0.73 to 1.29, and the minimum PPD value from 16.22% to a value close to 40%.



(a)



(b)

Figure 6: PMV and PPD comfort indexes outputs, Catalpa Bignonoides simulation. (a) Type 0 layout; and (b) Type 1 layout.

In Type 1 layout (Fig. 6(b)), the PMV and PPD values remain virtually the same as the Type 0 layout simulation. In the actual parking area, a dissatisfaction rate of over 90% is recorded.

4 DISCUSSION

According to the simulations, some solutions, like the Type 1 layout with Acer Campestre (Fig. 3(c)), would appear to offer benefits to the car itself while parked, but less to human activity within the parking lot. It is evident, however, that the cited setting represents the best solution in terms of temperature reduction with respect to the state-of-the-art layout (reduction of almost 1.5°C for the minimum temperature).

For Type 1 layout with Catalpa tree (Fig. 5(b)), the results obtained are consistent with the reasoning used so far; this solution allows for a reduction in temperatures and over a larger area but mainly where the ‘groves’ have been set up, a sign that the number of trees is as important as a guarantee of efficiency as the arrangement and type.

The simulation of Type 0 layout with Acer Campestre (Fig. 4(b)) provides significant improvements, in terms of temperature, in the areas with trees, but a slightly improved situation in the areas without trees, compared to the state-of-the-art. The same is valid for the same layout for the Catalpa Bignonoides tree (Fig. 5(a)), confirming that the contribution of the trees to the air temperature is limited to their position. It is likely that the mitigating effect of this species is due more to their shading than to their evapotranspiration capacity.

Concerning the distribution of the comfort indices values, most of the parking area appears to have comfort indices that are unfavourable for human well-being in all the scenarios simulated.

Below are the tables showing the comparison between the temperatures for all the simulations and the state-of-the-art (Table 1) and the comfort indices (Table 2).

Table 1: Comparison of the minimum and maximum temperature between all the simulations and state-of-the-art.

	Tmin (°C)	Tmax (°C)
State of the art	27.12	28.45
Type 0 layout Acer Campestre	26.15	28.08
Type 1 layout Acer Campestre	25.65	28.05
Type 0 layout Catalpa Bignonoides	27.05	28.21
Type 1 layout Catalpa Bignonoides	26.84	28.33

Table 2: Comparison of the minimum and maximum comfort indices between all the simulations and state-of-the-art.

	PMVmin	PMVmax
State of the art	1.32	3.50
Type 0 layout Acer Campestre	0.73	3.38
Type 1 layout Acer Campestre	0.66	3.34
Type 0 layout Catalpa Bignonoides	1.29	3.46
Type 1 layout Catalpa Bignonoides	1.29	3.49

	PPDmin (%)	PPDmax (%)
State of the art	41.30	99.96
Type 0 layout Acer Campestre	16.22	99.90
Type 1 layout Acer Campestre	14.09	99.87
Type 0 layout Catalpa Bignonoides	39.87	99.94
Type 1 layout Catalpa Bignonoides	39.92	99.95

5 CONCLUSIONS

This case study identifies Acer campestre as the most suitable species for green parking areas, due to its capacity to reduce surface temperatures by approximately 1.5°C, its adaptability to urban soils, and the absence of fruits or flowers that may cause soiling. Its native status further supports its selection from an ecological perspective.

In terms of layout, the Type 1 layout, featuring a higher density of trees, proved more effective in lowering temperatures across the parking area. However, this comes at the cost of reduced parking capacity, highlighting the need to balance environmental benefits with urban functionality. Configurations such as perimeter planting and tree clusters (‘groves’) offer localized improvements in thermal comfort but require further planning to integrate with parking and social uses.

Overall, the simulation results align with existing literature, confirming initial hypotheses and reinforcing the role of urban greenery in mitigating the urban heat island (UHI) effect.

The use of such models represents a fundamental step for both their developers and end users, as the analysis results allow for improvements to the model itself and the development of more effective strategies. This study focuses on an infrastructure typical of urbanized areas, a parking lot, in a typical city in the coastal valleys of the Italian peninsula, making the results potentially applicable to other urban contexts with similar climate conditions, considering the strong and recognized validity of the model used.

Given the limitations of tree planting alone in fully asphalted areas, future studies should explore complementary strategies such as high-albedo pavements, green walls, green roofs, and vegetation's role in air pollution mitigation.

Simulations of areas such the one described in the present work could serve as an underrepresented yet policy relevant testbed, enabling systematic appraisal of design divers tree species and density, spacing and pavement materials to produce actionable guidance for decision-makers. Future developments could also include simulations over different seasons (winter, transition), considering leaf fall, seasonal albedo and solar radiation, and analyse the nighttime cooling capacity of various species.

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