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Potential of Nature-Based Solutions to Diminish Urban Heat Island Effects and Improve Outdoor Thermal Comfort in Summer: Case Study of Matadero Madrid

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Abstract: Urban heat island effects and climate change are climatic phenomena responsible for periods of extreme heat in summer which severely impact citizens' well-being and health. In this alarming context which questions the livability of our cities, Nature-Based Solutions (NBSs) are considered an unavoidable component of the complex strategy in diminishing urban temperatures. The present work aims to show the relevance of NBSs in urban temperature regulation through the estimation of their potential to improve outdoor thermal comfort of the heritage site Matadero Madrid. To this end, this article evaluates the effects of a scenario combining different solutions including NBSs and identifies which solutions are the most effective. The results show that this scenario has an impact on direct solar radiation and wind speed but does not affect air temperature and relative humidity. Furthermore, even if this scenario combining a fabric canopy, tree canopy, and green area significantly improves thermal conditions, it does not allow us to reach an optimal level of thermal comfort for visitors. To consider the implementation of more meaningful interventions, existing legal, administrative, and cultural limitations of the case study should be omitted. This would enable us to identify which restrictions could be adapted, thus unlocking the adaptation potential of Matadero Madrid.

Keywords: outdoor thermal comfort; urban heat island; historic building; climate change; nature-based solutions; mitigation strategy

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1. Introduction

Climate change is a complex phenomenon which exerts numerous direct and indirect impacts [1], of which the most widely known are the increase in temperature and the increment in extreme natural events [2,3]. In this context, urban areas constitute particularly vulnerable places, as consequences of climate change severely impact citizens' well-being and health on a daily basis [4]. One of these consequences is the occurrence of heat waves in the summer season which, in cities, is amplified by the Urban Heat Island (UHI) effect [5]. In these periods of extreme heat, outdoor thermal comfort can reach critical levels, notably in Mediterranean cities [6]. This alarming situation brings us to question if cities like Madrid, Lisbon, or Roma, European centers of power, population, and economy growth, will be still livable in some decades' time. This concern is part of the 2030 Agenda for sustainable development and the Sustainable Development Goals (SDGs), as it is connected to SDG3 "ensure healthy lives and promote well-being for all at all ages", SDG11 "make cities and human settlements inclusive, safe, resilient and sustainable", and SDG13 "take urgent action to combat climate change and its impacts" [7].

In the search for technologies and strategies to diminish UHI effects and improve outdoor thermal comfort, Nature-Based Solutions (NBSs) are considered a key principle [8].

NBSs are defined by the European Commission as solutions "inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social, and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes, and seascapes, through locally adapted, resource-efficient, and systemic interventions" [9]. It has been widely demonstrated that the integration of NBSs in cities enables us to mitigate the UHI effect and cool down air temperatures [10]. Furthermore, these solutions permit us to design outdoor spaces that are both attractive and comfortable for citizens [11].

Despite the recognition that NBSs could offer more opportunities and space for bringing nature into cities, there has been limited consideration of this aspect for urban protected areas [12]. Existing studies tend to focus on spaces with low or no degrees of heritage protection such as city squares [13], urban streets [14], or residential areas built in the last few decades [8]. Indeed, heritage sites are more challenging spaces to enhance in terms of the sustainability and thermal comfort. Architectural restrictions, conflicting opinions, possible damage to vulnerable historic materials . . . all of these barriers are currently restraining the inclusion of built heritage in the NBS agenda. However, built heritage is a valuable and extensive component of Mediterranean cities and, in that sense, they should be part of NBSs strategies to enabling the development of a more connected green infrastructure network [15].

The following study of Matadero Madrid, a heritage site in the city of Madrid, aims to contribute to this research on NBSs within the heritage sector. This cultural and historical site is well known in the city for activities organized in its outdoor ambits—concerts, festivals, markets, and movies—but during summer periods, extreme temperatures make it impossible to use during most of the day. This work constitutes one of the outputs of "Matadero Acción Mutante" (in English "Matadero Mutant Action"), a project launched in 2018 which focuses on the design of NBSs that could reverse UHI effects in Matadero Madrid. The Universidad Politécnica de Madrid (UPM) participated in this initiative, organizing work sessions with scientist and artists in order to unlock creativity and boost innovation [16]. This study aims to show the relevance of NBSs in urban temperature regulation within heritage sites and addresses this issue with a scientific approach which has been enriched through dialogue with artists and designers during the work sessions of "Matadero Acción Mutante".

This article first analyses the current microclimate of Matadero Madrid by means of an experimental campaign and then proposes and simulates a mitigation scenario including NBSs to improve thermal comfort. The numerical modeling and simulation are executed with ENVI-met, and the results obtained are compared with the existing situation. The design of a realistic mitigation scenario for a heritage site is a process which requires detailed climate data (direct solar radiation, air temperature, relative humidity, and wind speed) and knowledge of legislation on the historical heritage of the specific context. This complexity can prevent public authorities from investigating possible solutions, and the present work, through the simulation of a concrete scenario, seeks to help policymakers by exploring possibilities and giving them recommendations. As a result, the current article evaluates if the solutions implemented in the mitigation scenario permit us to improve thermal comfort and identifies which ones are the most effective.

The remainder of this article is organized as follows. Section 2 presents the case study of Matadero Madrid and describes the methodology used in this study. Then, the results of the mitigation scenario are presented in Section 3 and discussed in Section 4. Finally, conclusions are drawn in Section 5.

2. Materials and Methods

2.1. Case Study: Matadero Madrid

2.1.1. Presentation of the Case Study

The case study of this paper focuses on Matadero Madrid, a former slaughterhouse which has been converted into an arts center in the last few decades (Figure 1). It was at the end of the 19th century when the Madrid authorities began to think about the creation of an industrial slaughterhouse that would supply the whole city. With the Arganzuela district chosen as the ideal location and Luis Bellido as the architect, in 1911, the construction of this complex began. The slaughterhouse, which was inaugurated in 1925, has been in operation for approximately seven decades, until 1996, when it was finally closed [17].

In 2005, it was established that part of the complex would be converted to host cultural activities under the direction of the Arts Department of the Municipal Council of Madrid. The rehabilitation process of the indoor and outdoor environments was initiated this same year and lasted until 2014. The artistic and cultural activities of Matadero Madrid, which began in 2006 with the first call of "Ayudas a la Creación" (in English, "Aids to [Artistic] Creation"), aim to support and make visible contemporary artistic creations. Nowadays, Matadero Madrid occupies part of the set of pavilions designed by Luis Bellido at the beginning of the 20th century and, in addition to its cultural and artistic activities, also serves as a recreational space for citizens [18].

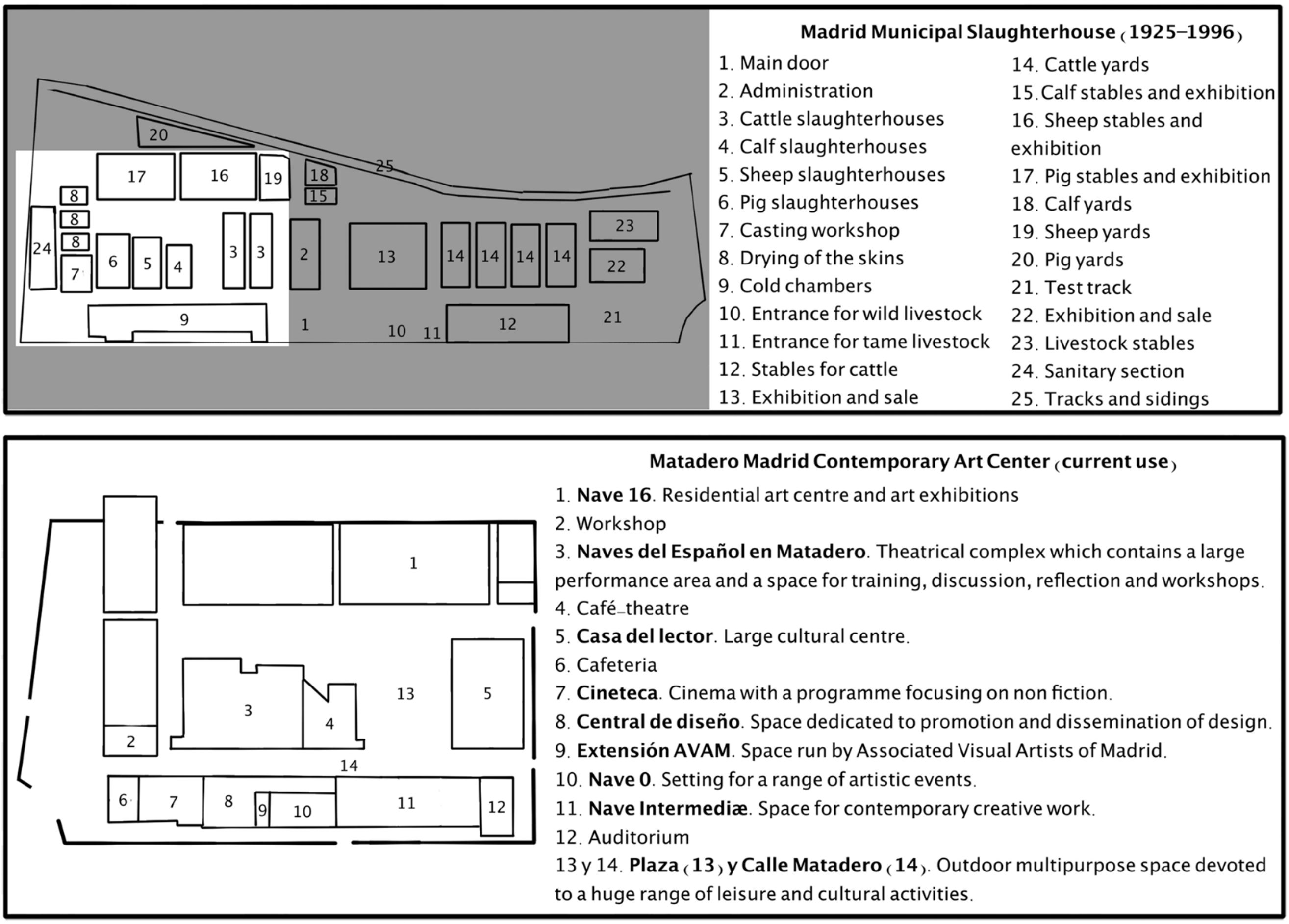

Figure 1. Past and present configurations of Matadero Madrid, compiled by authors based on [19].

Particularly from May to September, a lot of activities take place in the outdoor compounds of the center, such as concerts, artisanal markets, music festivals, or an open-air cinema. Thanks to its proximity to the Madrid Rio park, Matadero Madrid has become one of the main cultural spots of the city during the spring and summer periods. In 2019—the reference year chosen for the study—54,000 people attended the music concerts of the center [20]. In this sense, Matadero Madrid constitutes a successful example of reconversion and urban regeneration, from productive to community purposes. However, in the last few years, the extreme climatic conditions of Madrid in summer are preventing the use of those outdoor spaces during most parts of the day and, consequently, are reducing the number of activities hosted by the cultural center. Indeed, Plaza Matadero and Calle Matadero, the outdoor compounds where most of the cultural manifestations occur, have conserved the refined historical esthetic of an industrial park, with wide open spaces, clay pavements, and a total absence of trees or vegetations. Hence, these heritage spaces that do not include cooling assets and components become unlivable during extreme heat periods. In this context, the study of methods and means of improving Matadero Madrid's outdoor thermal conditions during summer not only appears necessary to ensure its future as a cultural center, but also represents an opportunity to explore the conflicts that can appear between cultural heritage regeneration and the adaptation of cities to climate change. Section 2.1.2 describes the climatic conditions and specificities of Madrid to provide a further understanding of the current situation and challenges.

2.1.2. Climatic Conditions of Madrid

According to the Köppen classification, the province of Madrid is characterized by a Csa type of climate: "C" meaning temperate, "s" meaning dry summer, and "a" meaning hot summer [21]. However, this climate shows variations across the province, which are due in particular to the terrain's morphology, anthropic activities, and human settlements [22]. In the specific case of the city of Madrid, the climate is strongly affected by the phenomenon of UHI, i.e., the local increase in temperature produced by urban agglomeration [23]. The UHI phenomenon is a common issue around the world which has been known for almost a century [24] and is caused by numerous factors, including the greenhouse gas accumulation in cities. In that sense, global climate change and the UHI phenomenon have synergetic effects which lead to an intensified increase in normal temperatures in cities. Indeed, as climate change causes a serious increase in the frequency, magnitude, and duration of extreme heat events, the magnitude of the UHI phenomenon is intensified during periods of heat waves [25].

Furthermore, as it relies on many parameters, the UHI phenomenon does not affect homogeneously the different urban spaces of the city. A comparison of the temperature measured by three urban weather stations of the center and south parts of Madrid (including one localized near Matadero Madrid) during the years 2019 and 2020 shows that the temperature variation may reach 3 °C degrees, and thus demonstrates the difficulty of establishing detailed patterns of temperature for the whole city. Therefore, in order to study climate mitigation possibilities and their impact on meteorological parameters like temperature, it is necessary to base the analysis on climate data of the specific location, in our case Matadero Madrid [26].

2.2. Methodology

2.2.1. General Methodology

The objective of this paper is to estimate the potential of NBSs to improve the urban outdoor thermal comfort of two spaces of interest in Matadero Madrid: Matadero Street and Matadero Square. With that aim, a methodology based on experimental measurements and numerical analysis has been developed. The implemented methodology consists of four successive steps that can be summarized as follows—each one being then further described in a dedicated section:

1. Experimental measurements and analysis of Matadero Madrid's microclimate (see Section 2.2.2) to quantify and characterize the climate conditions of the case study, identify the outdoor spaces most affected by thermal stress, and provide data for the numerical model's validation.
2. Numerical modeling in ENVI-met version 4.4.6 and validation of the software for our case study (see Section 2.2.3). The buildings, surfaces, and vegetations of the site are modeled in ENVI-met. A simulation of the model is executed for one week of the summer period and numerical microclimatic data are compared with on-site measurements in order to validate and calibrate the ENVI-met model.

3. Research and selection of solutions to improve thermal comfort within the outdoor compounds of Matadero Madrid (see Section 2.2.4). This phase focuses on the identification and testing of potential microclimate mitigation strategies that could be implemented in Matadero Madrid. The solutions are first selected among the most used in similar microclimate conditions and combined into a mitigation scenario. The scenario is then modeled and simulated in ENVI-met.
4. Evaluation of the mitigation scenario. The impact of the selected mitigation strategy on the climatic parameters and outdoor thermal comfort is assessed and compared to the initial scenario.

2.2.2. Experimental Measurements and Analysis of Matadero Madrid

A monitoring campaign was carried out from July 2018 to July 2021 to study the climate conditions of the case study area and to provide reference data for the correct calibration of the numerical model. This campaign was based on two data collection methods.

First, air temperature and relative humidity were retrieved by on-site sensors installed in the context of the project "Matadero Acción Mutante". Sensors "HOBO Pro v2 logger" were placed in the three locations of the outside ambits of Matadero Madrid shown in Figure 2.

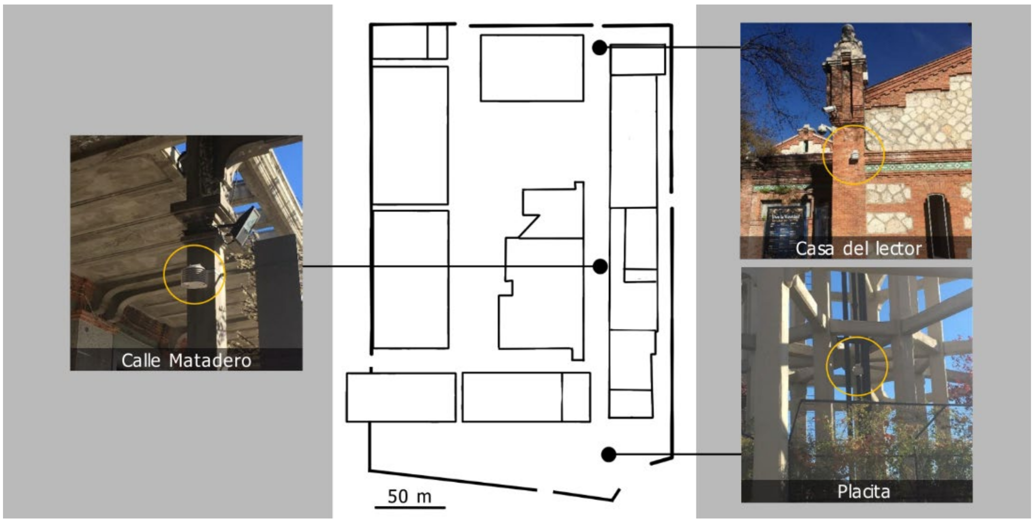

Figure 2. Locations of the three sensors (indicated with a yellow circle) installed in the outside ambits of Matadero Madrid, compiled by the authors.

These sensors for air temperature and relative humidity enabled us to acquire and store data every five minutes. Their specifications are presented on Table 1.

Table 1. Specifications of the sensors HOBO Pro v2 logger, measuring air temperature and relative humidity.

	Air Temperature	Relative Humidity
Operation range	−40 to 70 °C	0 to 100%
Accuracy	±0.2 °C from 0 to 50 °C	±2.5% from 10% to 90%, to a maximum of ±3.5% in the full range
Resolution	0.02 °C at 25 °C	0.03%

Then, wind and solar radiation hourly data were collected from a close urban weather station located in the Municipal District Office of Villaverde, indicated in Figure 3 [27].

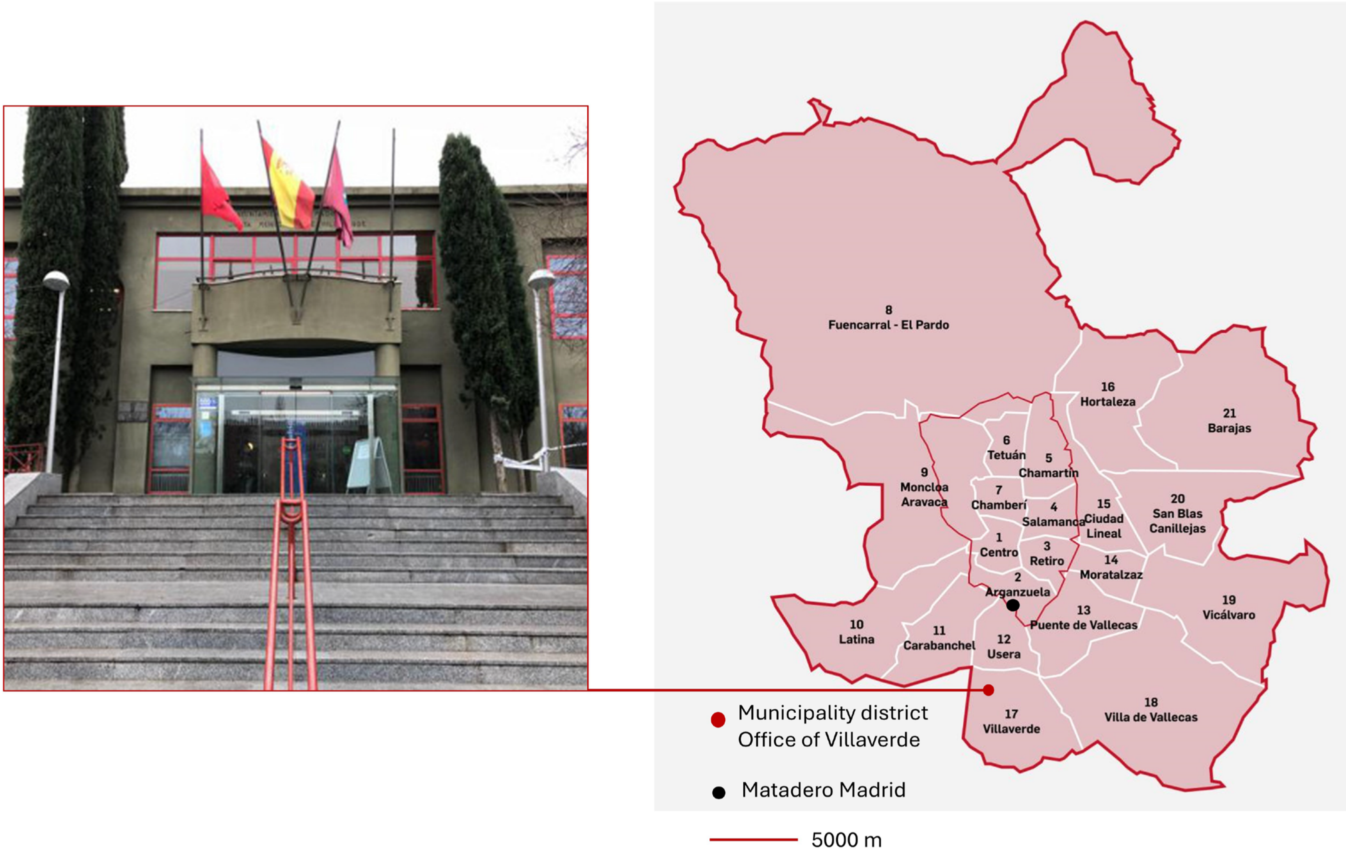

Figure 3. Urban weather station measuring wind and solar radiation, compiled by authors based on [28,29].

2.2.3. Numerical Modeling in ENVI-Met and Validation of the Software

Traditionally, assessing the thermal effect of mitigation scenarios was achieved using field monitoring approaches with relevant meteorological instruments. With significant advancements in computation resources in recent decades, numerical simulation has gradually become one of the principal research approaches [30]. In the field of mitigation scenario by means of NBSs, Energy Balance Model (EBM)-based models and Computational Fluid Dynamic (CFD)-based models are commonly used in numerical simulation applications [31]. Compared to EBM-based models, CFD-based models have a higher resolution [32] and have been applied in more urban NBS-related studies [31]. ENVI-met is a holistic three-dimensional microclimate CFD-based model widely used for vegetation thermal effect simulations, particularly to assess the effectiveness of urban planning measures to tackle the UHI problem in a variety of climate contexts [33]. Therefore, in this work, ENVI-met version 4.4.6 was chosen to carry out the numerical modeling and simulations of the case study.

To that end, Matadero Madrid, in its current state, is first modeled based on original buildings plans and satellite photographs. The model is executed using ENVIguide, the simulation program of ENVI-met. The week chosen for the simulations is from the 22nd to the 29th of July 2019, the hottest week in Madrid [34]. The simulation outputs include climatic parameters for each grid point and the calculation of bio-meteorological parameters such as the Mean Radiant Temperature (MRT) or Predicted Mean Vote (PMV) [35].

Then, the results of the simulation are used to validate the software for the case study. For this purpose, for the whole week, measured and simulated data for the main four climatic parameters with an impact on outdoor thermal comfort, i.e., air temperature, relative humidity, wind speed, and direct solar radiation, are compared.

For air temperature and relative humidity, the Mean Absolute Error (MAE) between the experimental data and the numerical results is calculated. As shown in Table 2, ENVI-met estimates the air temperature with an MAE of about 11.8% and the relative humidity with an MAE of about 22.5%. While the air temperature has an acceptable MAE (about 10%), the relative humidity error is about two times higher than the usual magnitude of error considered acceptable for numerical simulations [36]. However, considering that relative humidity is complex to estimate with precision [37], the fact that the program reproduces the trend of the measured values is sufficient for the purposes of this study.

Table 2. MAE for air temperature and relative humidity, compiled by authors.

	MAE (%)
Air temperature	11.8
Relative humidity	22.5

Indeed, in the case of solar radiation and wind speed, the data are measured by an outside meteorological station located in Villaverde at 4800 m from Matadero Madrid, which thus does not take into account local specificities and physical parameters of the case study. Therefore, in this case, the order of magnitude of the data is more evidential than its precise values and evolutions, and it is thus not considered relevant to calculate the associated MAE

The comparison of experimental and simulated data is performed by means of graphical representation. Figure 4 shows that except for the location "Placita", the same order of magnitude is observed between the simulated and measured wind speed. This difference can be explained by the location of the sensor, which is protected from the wind by Matadero Madrid's tower and nearby trees. Figure 5 shows that for direct solar radiation, the data simulated are similar to the data measured by the meteorological station. The differences that can be observed at some points of the days are due to the shadows caused by the different obstacles located within Matadero Madrid's outdoor compounds (trees, buildings, etc.).

The performance of ENVI-met is therefore validated for Matadero Madrid in the context of UHI analysis and outdoor human thermal sensation calculations.

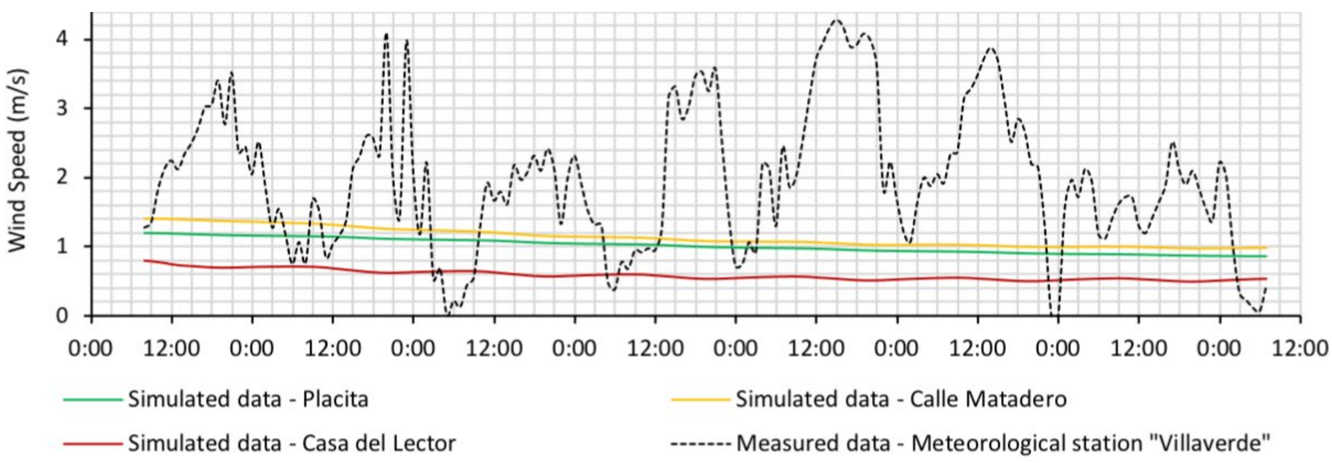

Figure 4. Comparison between measured and simulated data for wind speed, compiled by authors.

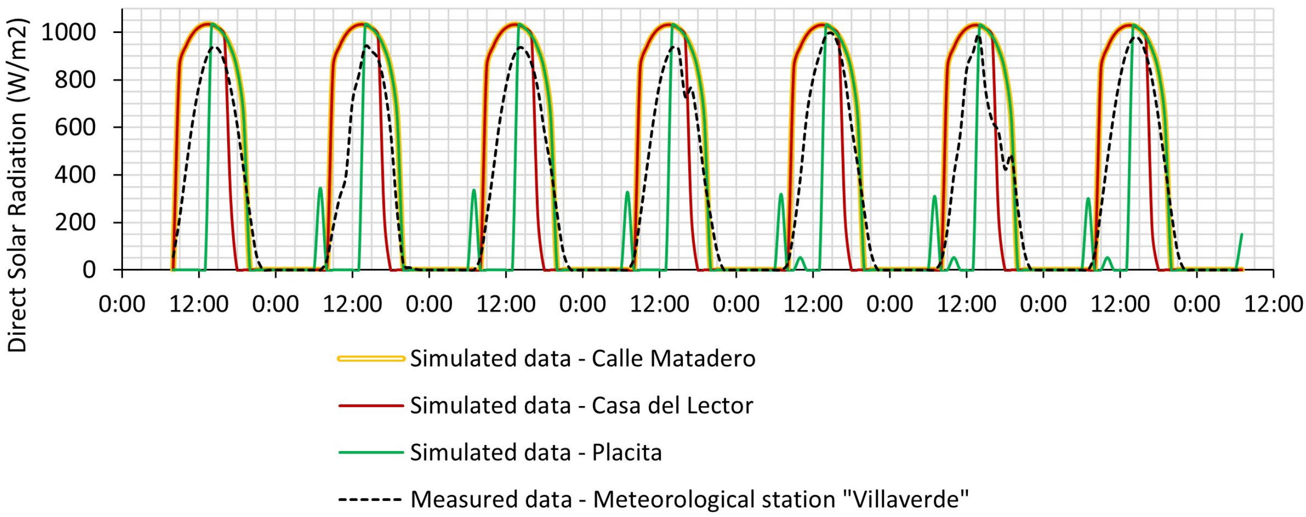

Figure 5. Comparison between measured and simulated data for solar radiation, compiled by authors.

2.2.4. Research and Selection of Mitigation Solutions

High urban ambient temperatures have a serious impact on citizens' life and the overall environmental quality of cities [25]. The purpose of this study is to explore ways of mitigating the UHI phenomenon and improving the thermal comfort within the outside compounds of Matadero Madrid.

Before presenting the chosen technologies and the mitigation scenario, it must be emphasized that Matadero Madrid, because of its historic value, is a protected site and therefore does not allow for all types of constructions. The degree of protection applied to Matadero Madrid's buildings is "Structural" (level 2) and involves the conservation of both its volumetry and its most distinctive architectural elements [38]. Consequently, NBSs like green roofs and façades cannot be implemented as they would modify and hide the architectural characteristics of the buildings.

In that context, this study analyses a possible scenario based on three technologies: two NBSs, the green resting area and the tree canopy; and a non-natural solution, the fabric canopy. On the one hand, the tree and the fabric canopy are two solutions with the same main purpose: to shadow streets and squares that would be therefore cooler than surfaces without protection. On the other hand, the evaporative cooling capacities of grass fields and trees constitute an additional benefit that helps in urban heat mitigation and improvement in the thermal environment [39]. Previous studies have shown that a combination of these technologies could have a synergistic positive effect on outdoor thermal comfort [40,41]. Therefore, for the design of the mitigation scenario, particular attention is paid to maximize the combination of shading technologies and grass fields (fabric canopy or trees), always taking into account limitations like space use and protected buildings. The mitigation scenario focuses on the modification of two emblematic spaces of Matadero Madrid: the "Calle Matadero" and the "Plaza Matadero" (Figure 1). In relation to the possible limitations related to space use, it has been considered that "Plaza Matadero" hosts many cultural and community activities throughout the year (i.e., concerts, marketplaces, and events), which implies that the main part of the square must be free of shadowing assets for specific occasions. For this reason, in the proposed scenario, while the "Calle Matadero" is shadowed by means of trees, for the main part of the square, the shadow is proportionated by means of a removable fabric canopy. The selection of mitigation solutions and the proposed scenario are presented in Figure 6.

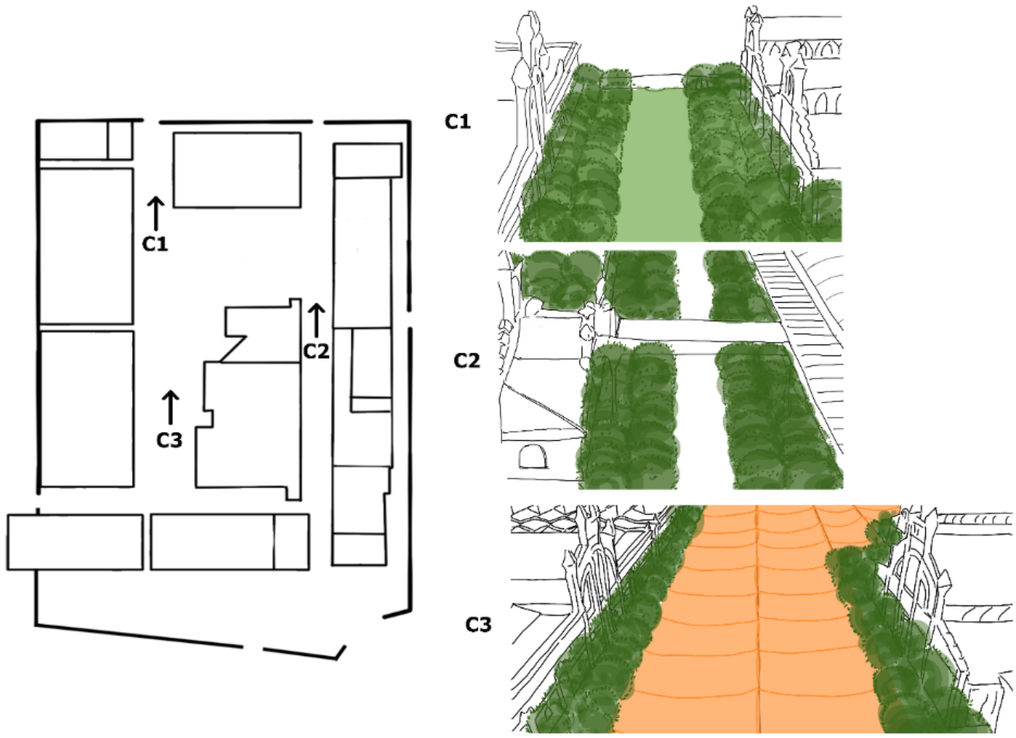

Figure 6. Presentation of the scenario assessed in this study, compiled by the authors. C1, C2, and C3 are section perspectives of the architectural plan, that enable to better visualize the different solutions.

2.2.5. Evaluation of the Mitigation Scenario

The evaluation of the impacts of the scenario is based on the calculation of outdoor thermal comfort, which is predominantly and tacitly associated with the UHI phenomenon. Thermal comfort is based on a combined effect of physical and climate parameters and therefore cannot be estimated only by means of climatic data [27]. Therefore, in this paper, the case study compares the present configuration of Matadero Madrid with the mitigation scenario by taking into consideration the PMV model, the most widely used index to evaluate outdoor thermal comfort [42].

PMV is defined as the average thermal sensation vote of a group of people [43]. The model is based on the human energy budget under steady-state thermal conditions and calculated with climatic and human parameters [44]. An outdoor thermal comfort comparison is performed by using the biomet tool of ENVI-met which enables us to calculate and represent the PMV for a specific person. For this study, the default data of the program have been used as input parameters.

PMV is calculated on the basis of four measurable quantities (air velocity, air temperature, MRT, and relative humidity) and two expected parameters (clothing and metabolism rate). The MRT summarizes all short-wave and long-wave radiation fluxes reaching the human body [45] and thus is directly dependent on solar radiations. Concerning the PMV scale, it ranges between −5 (extremely cold) and +5 (extremely hot), where 0 is the thermal neutral (comfort) value. It should not be forgotten that the PMV is a function of the local climate, and its values can differ from the interval (−5) ÷ (+5) [44].

To evaluate the effects of the mitigation scenario, the PMV is simulated for two days (22nd and 23rd of July 2019) and studied at four points distributed among the two selected areas, "Plaza Matadero" and "Calle Matadero", for the initial scenario and the mitigation scenario (Figure 7).

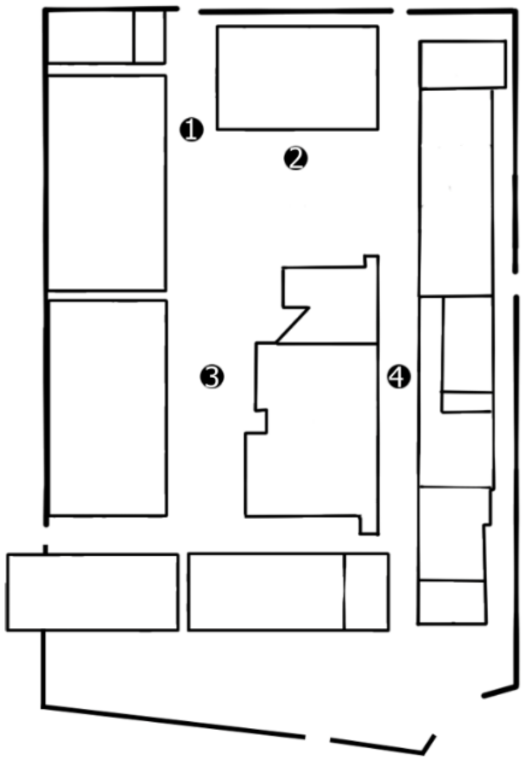

Figure 7. Locations of the four measuring points, identified thanks to the numbers indicated on the figure, at which the effects of the mitigation scenario are studied, compiled by the authors.

3. Results

3.1. Impact on Climatic Parameters

Although climate parameters taken separately do not give enough information to evaluate the impact of the mitigation scenario on thermal comfort, four of them (air temperature, relative humidity, wind speed, and direct solar radiation) do have an important and direct influence on it [46]. Therefore, as climate parameters are easier to measure and comprehend than thermal comfort indexes, it is still relevant to study how different solutions and scenarios may impact climatic parameters and consequently thermal comfort. Figures 8–11 show the climatic results obtained at the different measuring points of the model for the initial situation, shown in black, and the mitigation scenario, shown in blue, for the 22nd and 23rd of July 2019.

First, for all of the measuring points, there is no significative difference between the air temperature of the mitigation scenario and the one of the initial situation. Moreover, regarding relative humidity, the values obtained for the mitigation scenario are slightly higher than those of the initial situation. Concretely, the difference between the two scenarios is maximal before 12 h, reaching a value between 1 and 4%, then decreases until reaching a value close to 0 after 21 h. For some of the measuring points (n° 2 and n° 4), the difference increases again between 18 h and 21 h, reaching a value between 1 and 2%. Next, for all of the measuring points except the third one, the wind speed in the mitigation scenario is lower than that in the initial situation due to the presence of obstacles (trees and fabric canopy) which reduce wind speed [47]. The difference is about 0.3–0.4 m/s. For the third measuring point, the wind speed of the mitigation scenario is slightly higher than that of the initial situation. Finally, with regard to direct solar radiation, there is an important difference between the two scenarios, for all measuring points. The direct solar radiation of the mitigation scenario is lower due to the presence of shadowing assets. Furthermore, its evolution directly depends on the hour of the day: when the sunlight is blocked by trees or the fabric canopy, the direct solar radiation is low (about 200 W/m^2) or null, whereas when the sunlight is not blocked, the direct solar radiation is equal to that of the initial situation.

These first results show that the technologies implemented in the mitigation scenario have an impact on some climatic parameters of Matadero Madrid. On the one hand, air temperature and relative humidity are almost not impacted by these technologies. On the other hand, the initial situation and mitigation scenario present significative differences in terms of direct solar radiation and wind speed, which vary depending on the measuring point considered. However, whereas direct solar radiation is responsible for increasing thermal sensation [48], wind speed is responsible for a cooling effect, as long as the air temperature is lower than body temperature, i.e., 37 °C [49]. Therefore, the reductions in both direct solar radiation and wind speed have opposite effects, and it is not possible to qualitatively estimate the possible impact of the combination of these climatic changes on outdoor thermal comfort without studying specific indexes, e.g., the PMV.

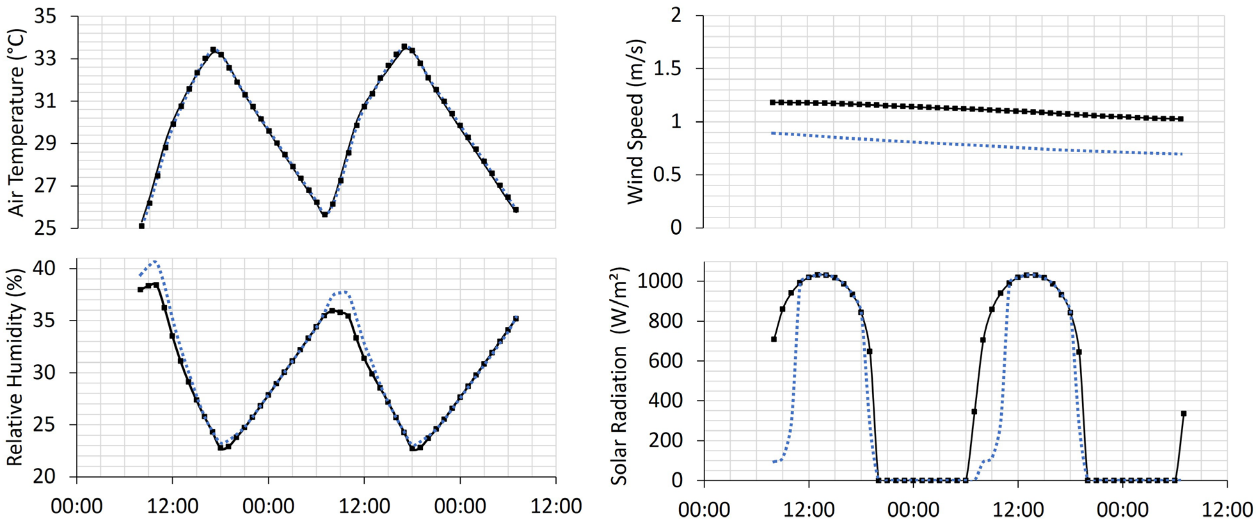

Figure 8. Climatic parameters of the initial situation (in black) and the mitigation scenario (in blue) simulated at measuring point n° 1, compiled by the authors.

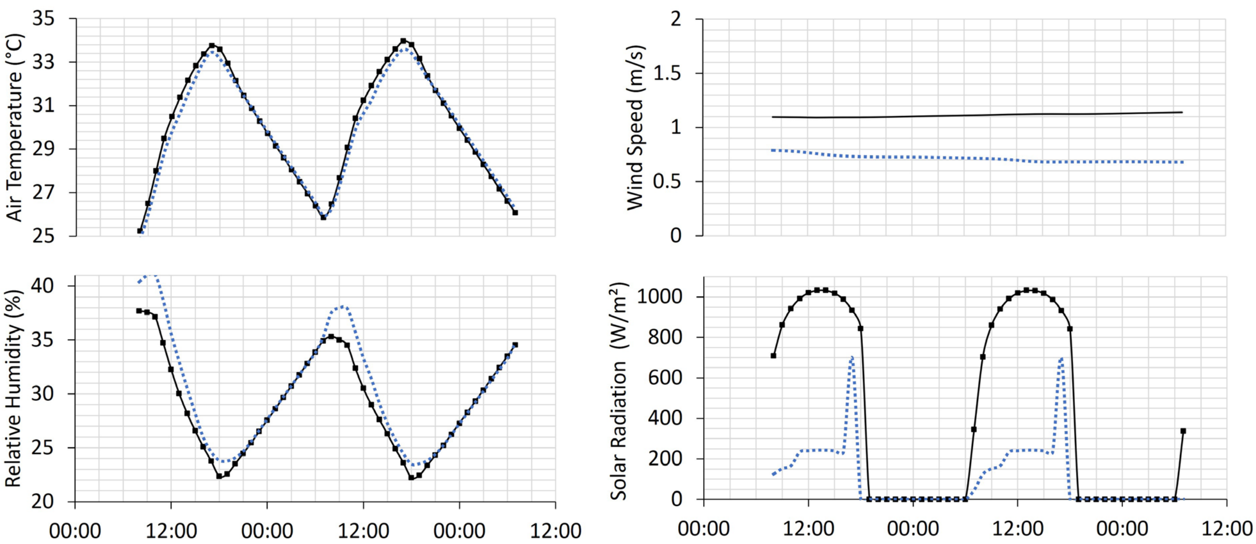

Figure 9. Climatic parameters of the initial situation (in black) and the mitigation scenario (in blue) simulated at measuring point n° 2, compiled by the authors.

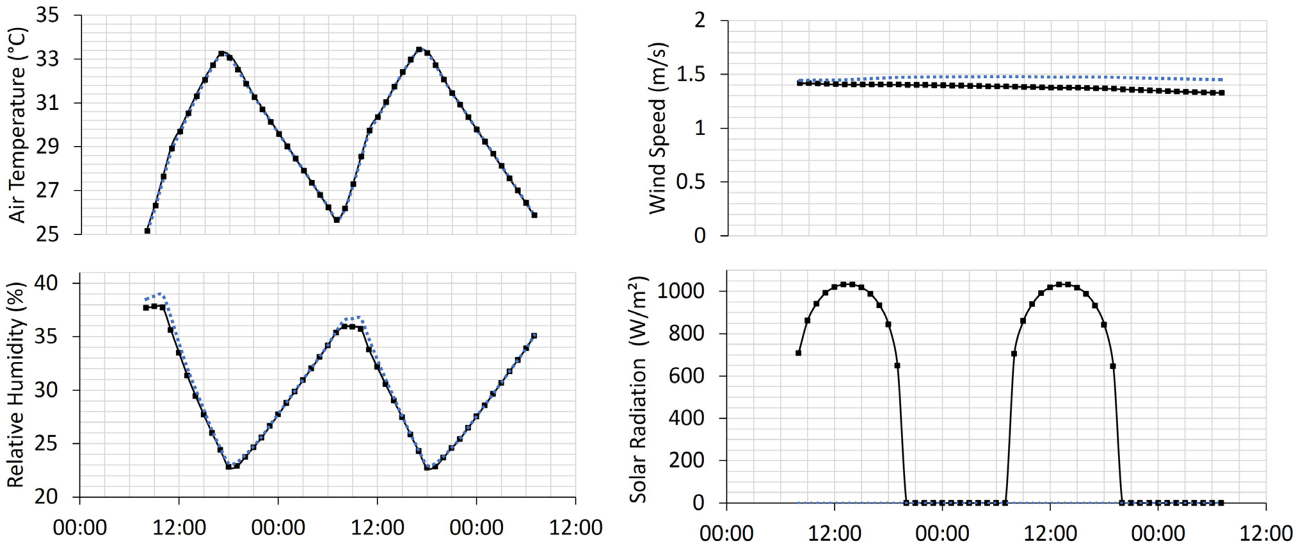

Figure 10. Climatic parameters of the initial situation (in black) and the mitigation scenario (in blue) simulated at measuring point n° 3, compiled by the authors.

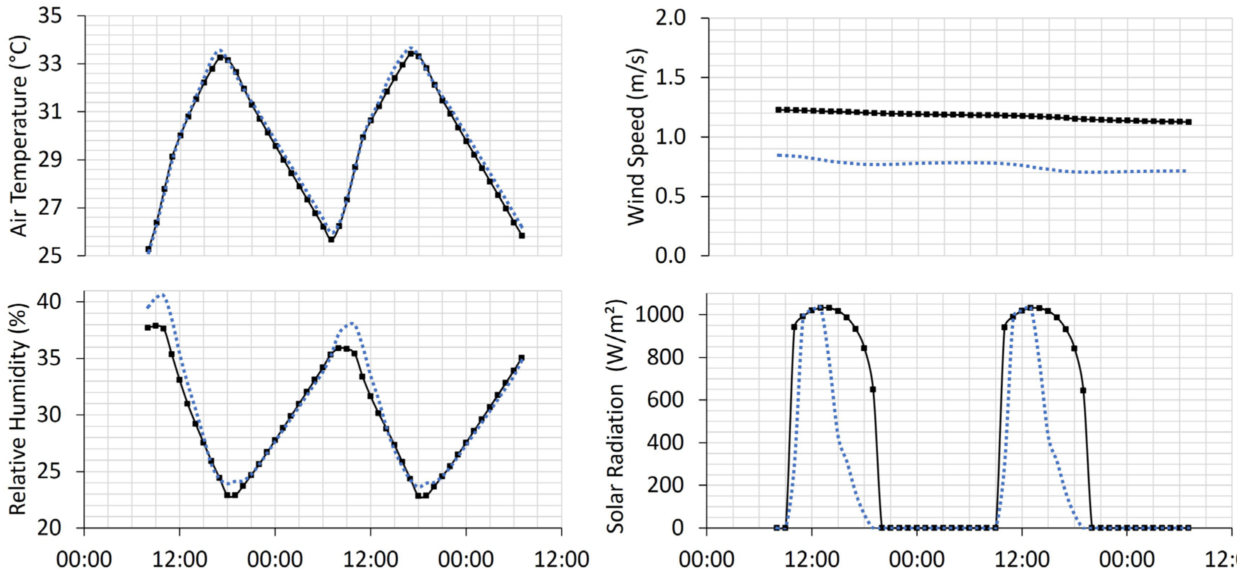

Figure 11. Climatic parameters of the initial situation (in black) and the mitigation scenario (in blue) simulated at measuring point n° 4, compiled by the authors.

3.2. Impact on Thermal Comfort: Evaluation of the Mitigation Scenario

PMV is the thermal comfort index that has been chosen to evaluate the impact of the mitigation scenario. The objectives are (i) to evaluate if the solutions implemented in the mitigation scenario improve thermal comfort, and (ii) to identify which ones are the most effective.

First, as shown in Figure 12, except for the first measuring point, the mitigation scenario has a significative impact on the PMV. For both scenarios, the curve follows the same pattern: the PMV increases from 9 h to 16–17 h and then decreases from 16–17 h to 9 h. It must be highlighted that the PMV is always positive, which means that thermal sensation changes from slightly warm (+1) to extremely hot (+5). From 9 h to 20 h, the PMV of the mitigation scenario is lower than that of the initial situation, and thus is associated with an improvement in thermal comfort. From 20 h to 9 h, the PMV of the mitigation scenario is higher than that of the initial situation, which induces higher thermal sensations and therefore a decrease in thermal comfort. In the peaks of intensity of the curve, when thermal comfort reaches very critical levels, the mitigation scenario manages to lower the PMV by up to 2 points (see the third measuring point in Figure 9).

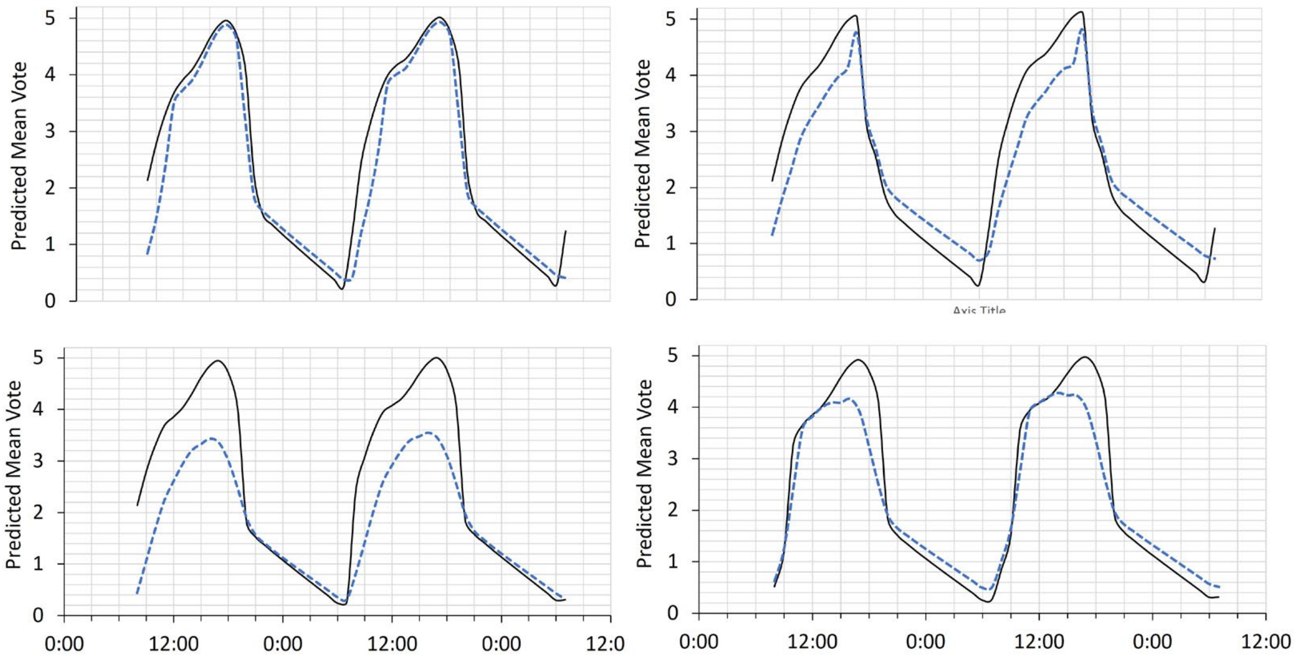

Figure 12. The simulated PMV of the initial situation (in black) and the mitigation scenario, compiled by the authors.

Therefore, in general, the mitigation scenario provides better thermal conditions in Matadero Madrid for three reasons: (i) improvements in thermal comfort are quantitatively much more important than negative effects, (ii) the initial situation creates very inequal sensations throughout the day, whereas the mitigation scenario enables us to smooth the curve, and (iii) improvements occur in strategic periods of time, i.e., in rush hours, stemming approximately from 16 h to 21 h, and thus permit us to improve thermal comfort when it is most needed.

Then, the second objective is to identify which of the solutions implemented to improve Matadero Madrid's outside thermal comfort are the most effective. Table 3 presents the solutions which have been implemented at each measuring point are presented. By relating the solutions (Table 3) to their impact on thermal comfort (Figure 12), it is possible to deduce the effect of specific solutions.

Table 3. The solutions implemented in the mitigation scenario, compiled by the authors.

Position	1	2	3	4
Green resting area	✓	✓		
Tree canopy		✓		✓
Fabric canopy			✓	

First, it is shown that the green resting area, even when combined with another solution (tree canopy), does not have any significant effect on outdoor thermal comfort. Then, the tree and fabric canopy permit us to significantly improve thermal comfort during rush hours by decreasing thermal discomfort by about 1 and 1.5 units, respectively. These results highlight the importance of direct solar radiation in thermal comfort sensations and thus the necessity of including shadowing assets in plans aimed at improving thermal comfort in situations of heat stress. Furthermore, it demonstrates that the characteristics of the shadow is also a key factor: sparse trees (the second measuring point) are less effective than lines of tree (the fourth measuring point), which themselves are less effective than a wide fabric canopy (the third measuring point).

4. Discussion

The purpose of this paper was to explore the impacts on thermal comfort of solutions that comply with current legal, administrative, and cultural limitations of Matadero Madrid. In this sense, the simulated scenario acknowledges the cultural center's activities, respects urbanism coherency and legal restrictions, and is not esthetically invasive. However, even if this scenario combining a fabric canopy, tree canopy, and green area significantly improves thermal comfort, it does not enable us to reach an optimal level of the PMV. Thus, this section focuses on discussing the pros and cons of the three different implemented solutions, analyzing their advantages and disadvantages, and exploring ways of improving the presented scenario.

Two of the implemented solutions—the fabric and tree canopies—are aimed at providing shade to visitors of Matadero Madrid during daylight hours. The analysis of their impact on thermal comfort showed that these shadowing assets are key to reducing heat stress. With regard to the quantitative results, the fabric canopy seems to be a more effective alternative. This is due to the fact that the opaque fabric manages to totally block the sun, while the tree canopy achieves different levels of shading depending on the density of the foliage cover. The tree canopy could provide at least the same level of improvement in thermal comfort as the fabric canopy if we increased the number of trees per m^2 [50]. However, the implementation of a dense tree canopy has not been proposed in this study because it would induce important modifications of the environment. In this sense, it must be outlined that the industrial fabric was selected because its easy removal allows for the organization of events such as concerts or open-air cinemas.

The last of the implemented solutions—the green resting area—does not have noticeable effects on thermal comfort. However, several authors outline the relevance of associating it with a tree canopy to create green shaded areas for leisure and relaxation [51–53]. In that sense, the numerous additional benefits that these two NBSs could provide must be highlighted. They enable cities to globally enhance their resilience and the quality-of-life of citizens by improving many indicators related to human health and well-being, water quality and regulation, carbon sequestration, and biodiversity [54]. Furthermore, as NBSs involve living organisms that grow and evolve, these benefits tend to increase throughout their lifetime. On the contrary, the fabric canopy is a manufactured product which has a limited time of use and must be changed periodically. In this sense, its integration within the mitigation scenario has an impact in term of costs and GHG emissions, from production and maintenance to disposal.

The results show that the current limitations of Matadero Madrid make it complicated, if not impossible, to design a scenario that enables us to reach an acceptable level of outdoor thermal comfort. To consider the implementation of more meaningful interventions, some of these limitations should be omitted. This would enable us to identify which restrictions could be adapted to be more permissive and unlock the adaptation potential of Matadero Madrid. In this context, it would be interesting to explore scenarios including more invasive NBSs, such as a green roof or living wall, whose positive effects on outdoor thermal comfort, notably by reducing temperatures at the street level, have been widely demonstrated [55–57]. These NBSs would also improve indoor thermal comfort as they act as isolating layers on façades and roofs [58].

Another relevant aspect to explore is the evolution of Matadero Madrid in terms of activities and purpose. Thus, in addition to mitigation solutions implemented to "reduce greenhouse gas emissions and concentrations in the atmosphere", the scenario could consider the integration of adaptation measures to "prevent and minimize damages and to take advantage of opportunities created by such change" [59]. Concretely, the methods of adapting the use of the outdoor space during extreme heat periods could include the relocation of Matadero Madrid's activities to indoor spaces, where thermal comfort is easiest to control, or the concentration of outdoor mitigation solutions in specific areas to create pedestrian paths with acceptable levels of thermal comfort [60].

Finally, a special emphasis must be placed on the fact that this paper only considers the current climate context, while it is known that in the years to come, the climate change phenomenon will lead to a drastic increase in temperatures and in the frequency of extreme climatic events such as heat waves in the Iberian Peninsula [61], which would exacerbate UHI negative effects on human health in summer [62]. In Madrid, the climate in 2050 is predicted to resemble Marrakech's climate today [63]. This critical situation highlights the necessity of being ambitious when it comes to investigating and proposing mitigation and adaptation strategies to improve thermal comfort during extreme heat periods.

5. Conclusions

The objective of this paper was to investigate the potential of different solutions to diminish UHI effects and improve outdoor thermal comfort in Matadero Madrid in summer. This article began with the presentation of Matadero Madrid, an explanation of its significance as a case study, and a description of the methodology which followed in the article. Once the framework was set and the methodology presented, the simulation results of the scenario combining a fabric canopy, tree canopy, and green area were studied first considering the impact on climatic parameters then on thermal comfort. Through the implementation of the scenario, the results show that it has an impact on direct solar radiation and wind speed but does not affect air temperature and relative humidity. Moreover, the thermal comfort impact assessment shows that the scenario provides better but not optimal thermal sensations. Indeed, from 12 h to 18 h, thermal comfort still reaches values between 3 and 4 (Figure 12), associated with hot and very hot thermal sensations.

This paper's discussion outlined that further research should focus on designing more ambitious scenarios. First, in terms of implemented solutions, research should consider more invasive NBSs which could modify distinctive architectural elements of Matadero Madrid. This ambit of research would be particularly valuable as it would help identify legal and administrative constraints that currently restrain transformative projects aimed at improving cities' resilience in Spain. Then, in terms of strategies, future studies should integrate adaptation actions that question the way in which citizens should live in the city, when outdoor climate conditions result in risks to human comfort and health. Furthermore, these ambitious scenarios should consider the evolution of the climate not only to provide results for current contexts and for the years and decades to come, but also to find solutions applicable and effective in the medium term. Finally, even if UHI is a local phenomenon, wider scales and scopes must be considered to understand its multiple causes and consequences. In that sense, thermal exchanges between Matadero Madrid and its neighborhoods should be considered to determinate if local actuations could have an impact on a larger zone or if this type of scenario is relevant only as part of a wider urbanistic plan at the city scale. Moreover, in addition to impacts on thermal comfort, other kinds of benefits which have an influence on citizens' overall comfort, e.g., psychological well-being and air quality, and the city's sustainability, e.g., biodiversity and water flow regulation, and that could provide the integration of Nature-Based Solutions in Matadero Madrid should be considered.

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