

Assessing and upgrading urban thermal resilience of a Spanish MoMo neighbourhood over the span of 1960–2080

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ABSTRACT

We are currently witnessing an unprecedentedly fast change in environmental parameters for which most cities worldwide are not well prepared. One of the most characteristic urban fabrics of many European cities is the residential neighbourhood typology built in the second half of the 20th century and influenced by the Modern Movement. This study aims to develop an assessment-and-upgrading methodology of the urban microclimatic resilience of these residential neighbourhoods, using a case study for the application considering past, present, and future climatic contexts. ENVI-met software is used to examine the original layout of the case study, its evolution up to the present time and the proposal for its adaptation to the worst climatic forecasts for the end of the century, suggesting solutions to enhance thermal comfort. The results show a significant reduction in extreme warm conditions of up to 6.3 °C in UTCI in the worst-case scenario at the century's end, proving the importance of passive strategies in achieving improved urban resilience in warm cities. The methodology applied in this study can serve as a starting point for a broader analysis to be applied to different urban typologies other than the residential one and in different climatic contexts.

1. Introduction

Global climate change (CC) is a pressing reality transforming the way people live in cities [1,2]. Despite the population being accustomed to annual seasonal weather changes, the extended duration and extremely high temperatures of summer periods in recent years, and the increasing number of heatwaves, have become major issues in many regions [3]. According to the IPCC's Sixth Assessment Report, a mean increase in global temperature between 1.1 and 5.7 °C by the year 2100 is projected [4]. Different technical reports on various emissions scenarios have been drawn up to reflect the best, medium, and worst CO₂ emissions expectations [5]. These studies are used to consider the possible future climatic conditions and to simulate possible situations. Recent studies have developed new approaches to statistically elaborate a prediction of future climate scenarios and, therefore, hourly data files. Some have used machine learning [6], while others still use morphing methods [7]. Machine learning methods, although may provide a deeper analysis, are still based on the IPCC emission scenarios, and the methodology and results are still in their early stages. Therefore, the future climate files

based on transformations or morphing using the IPCC's scenarios are still the most contrasted and accepted method to consider future climate conditions. The most pessimistic among the IPCC scenarios, RCP8.5, envisions a severe average increase of up to 5.7 °C. While this phenomenon will be global, the Mediterranean basin is expected to be particularly affected by extremely hot temperatures [8,9].

Cities on the European continent will be especially affected due to anthropogenic factors resulting from population concentration and current lifestyles. These extremely hot temperatures, which will affect people for long periods, pose an important health risk [10,11]. Furthermore, the energy consumption of HVAC systems needed to face these extreme temperatures has also become a public concern in the current inflationary period and energy crisis [12]. These issues should be addressed well in advance by policymakers, with the assistance of technical specialists such as architects, urban planners, and engineers.

A common feature of current European cities is the prevalence of low-income housing developments built between 1950 and 1980, in response to the exodus to cities after the end of World War II [13]. These developments were influenced by the Modern Movement (MoMo) in architecture, which emphasized standardization and modern industrial

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Nomenclature and abbreviations

AT	Air temperature
CFD	Computational fluid dynamics
CC	Climate change
HVAC	Heat, ventilation and air conditioned
IWEC	International Weather for Energy Calculation
MRT	Mean radiant temperature
MoMo	Modern Movement
RD	Representative Day
RH	Relative humidity
SC	Scenario
SVF	Sky view factor
UHI	Urban heat island
UN	United Nations
UTCI	Urban thermal climate index
WF	Weather file
WS	Wind speed

solutions [14,15]. Today, the presence of these neighbourhood typologies across Europe is significant. As a result, there is a considerable number of low-income districts where people with low economic resources have to face the coming climate threats [16]. Most of these families live in outdated constructions, many of them without HVAC systems or income problems to cope with their use, also known as fuel poverty [17]. Previous works have addressed this issue [18,19], their results evidencing the need to develop further studies to improve the built and urban environment [20], mostly in these especially vulnerable areas.

Originally designed with health, climate, and energy considerations in mind [21,22], many MoMo neighbourhoods have been modified to accommodate contemporary lifestyles [23]. However, these modifications often lack comprehensive technical criteria. These dwellings were originally designed with minimum space standards, creating small apartments with multiple bedrooms but prioritizing large outdoor public open spaces [15]. In Mediterranean cultures, particularly in southern regions, these public spaces play a crucial role in social life [24] and their design and comfort are significant in improving the quality of life of citizens. Nevertheless, their importance is often overlooked and the literature on the urban climate of MoMo neighbourhoods is scarce [25,26]. This raises questions about their current climatic performance and potential adaptations to future weather extremes.

In cities that are becoming increasingly dense and populated, achieving more thermally comfortable public spaces is a growing challenge. This densification, due largely to rural migration since the mid-20th century, is a trend that is still observed [27]. According to the latest UN report, 68% of the global population will reside in cities by 2025 [28]. This population concentration exacerbates phenomena such as urban heat islands (UHIs), which are intensified with population density and environmental transformation [29,30]. The more inhabitants, the greater the human activity and the more significant the environmental transformation [31]. These transformations also affect materials, which are denser, more impervious, and display higher thermal inertia [32]. Their composition and urban prevalence have a direct impact on the intensity of the UHI phenomenon [33,34], and in turn on the local microclimate. However, many urban interventions overlook these considerations, failing to improve local-scale microclimate and outdoor thermal comfort for pedestrians [35].

Several thermal comfort indexes are used to analyse outdoor human comfort, considering various meteorological phenomena and physiological responses [36–38]. However, these indexes differ in their parameter consideration [39–41] and application scales [42,43]. This study, based on the Universal Thermal Climate Index (UTCI), offers a

holistic approach to human thermal comfort variables. The UTCI takes into consideration air temperature (AT), relative humidity (RH), wind speed (WS), and mean radiant temperature (MRT), as well as human metabolic activity, thermoregulatory responses, and clothing levels. Given its global applicability, it can be used for comparative studies across different regions [44]. Furthermore, the scientific rigour and accuracy of this index have been extensively validated through on-site measurements in previous studies [45].

Given the complexity and numerous parameters involved, computational simulation tools have become instrumental in evaluating urban microclimate and thermal comfort. Despite requiring substantial computational resources and calculation time [46,47], these tools provide valuable insight into urban environmental performance, enabling the study of various configurations to identify the optimal solution for each context. Among the microclimate simulation tools available, the most widely utilized is ENVI-met [47,48]. Extensively validated by the scientific community [49–51], this tool allows to design 3D microclimate models to simulate surface-plant-air interactions in urban environments with a resolution of 0.5–10 m [48]. It provides detailed microclimate data of outdoor environments, including key climatic parameters and material responses. The results are then used to calculate thermal comfort indices, offering valuable insight into pedestrian thermal perception. ENVI-met is a powerful tool capable of simulating complex environments [52], so that several parameters and different scenarios applied to a case study can be appraised and compared. This is particularly useful in assessing the climatic resilience of a study area and upgrading its climate.

Urban thermal comfort is significantly influenced by city complexity, potentially generating microclimates on the local and microlocal urban scales [53]. Understanding urban microclimate is crucial for addressing urban overheating and its impact on the UHI effect. Previous research has explored the relationship between urban fabric and microclimate, manifesting the effect of different urban canyon shapes on local microclimate [54,55]. Many of these studies focus specifically on the reduction of the Sky View Factor (SVF) [56,57], an effect closely tied to stakeholder decisions and urban policies [35,54]. The influence of urban materials and surfaces on small-scale overheating has also been studied [33,58]. Studies have proved that the use of alternative materials can provide passive cooling to the urban microclimate thanks to their properties, such as albedo, which affects the capacity to reflect solar radiation and is related to material colour and texture [34,59]. In this regard, cooling pavements, characterised by a high solar reflectance and high infrared emittance [60] are considered effective in mitigating the effects of UHI [46]. Given their construction characteristics and exposure to sunlight, they can significantly reduce surface temperatures, as shown by previous studies [58,61]. Other researchers have addressed the ability to affect the microclimate based on some other parameters such as density, specific heat, or emissivity [62,63].

In order to reach a sustainable level of climatic resilience in existing urban areas, complex adaptation strategies are needed to prevent excessive overheating. Evaluation and quantifying the cooling potential of various urban mitigation strategies is becoming a crucial issue in the current literature [64,65]. Some studies have focused on different types of urban cooling strategies, exposing novel methodologies for numerical evaluation [66,67] where the most effective cooling strategies have been combined and evaluated on a large scale. This research has obtained a temperature decrease of up to 4 °C and the beneficial effects of these passive cooling methods on the local and regional cooling energy consumption were evaluated by coupling results.

Following the thesis of previous studies, there is evidence of the high influence of urban morphology and geometry on microclimate [68]. However, these parameters are not easy to change when working on existing built environments. Other researchers [65,68] have developed in-depth reviews focused on urban interventions, in which numerous methodologies, strategies, and combinations of actions are confronted and the cooling mitigation results are compared. Some of these recent

studies [69,70] have addressed the complexity of urban interventions, combining many possible strategies. Their conclusions show how a combination of cooling pavements, greenery/trees, shading elements, and evaporative/water systems is the most effective technique for enhancing comfort in urban environments, reducing air temperature by up to 4–6 °C, with an average decrease of around 4 °C [71]. In terms of thermal comfort [68], the decrease reached around 13 equivalent degrees. Several research [64,68] highlight that the most influential single strategy is the water-based. Other research has focused on the use of horizontal and vertical greenery, combining possibilities of green walls and innovative greenery by simulating them in ENVI-met software [72]. The conclusions in the literature coincide at the same point, the water-based solutions combined with greenery, solar control, and cooling pavement strategies give the most effective results, regardless of whether the study was monitored from real case studies or simulated combining various possibilities.

However, in the current drought situation, solutions based on water or water-demanded may not be the most indicated. In this sense, other studies have analysed the single effect of cooling pavements for smaller scales [73,74]. They found a 10 °C decrease in surface pavement temperature, but no significant decreases in AT were found only by the action of pavements. Other research has also evidenced that paving techniques alone have no great potential to reduce air temperature or thermal perception [59,64]. Therefore, to improve the cooling pavement results, other authors [75,76] have identified the use of grass and grass-paved, while others have focused on the use of artificial pervious pavements, which has also been found to improve comfort, particularly during wet periods or when irrigated [75].

Finally, other investigations concluded that the optimal combination for improving thermal comfort was not the same for the AT decrease [70]. The study highlights the importance of reducing the MRT when working on urban comfort, making solar control strategies crucial. Considering all the previous research, the remaining and most effective possibilities would be to block solar radiation, add some natural and self-maintenance vegetation, and use cooling and green pavement materials. Although these strategies have been shown for their mentioned daytime benefits, other studies [77] have reported no beneficial or slightly detrimental effects at night due to increased relative humidity and hindered ventilation. Therefore, solar protection and vegetation must be controlled and carefully studied to avoid detrimental effects at night. These conclusions from the existing literature must be considered when improving thermal comfort in the built environment.

This study presents a novel methodology for evaluating thermal comfort in existing neighbourhoods, addressing a gap in previous research, which often relied on non-real or artificially modified scenarios [64]. The analysis encompasses 60 years of historical evolution and urban changes in a case study neighbourhood, representative of many similar areas across Europe, and projects its future microclimatic performance. By comparing past, present, and future urban conditions

within their specific climatic contexts, the study informs the development of passive cooling adaptation measures to mitigate the effects of climate change and enhance thermal comfort. This research also provides recommendations for sustainable interventions in low-income urban areas influenced by Modern Movement (MoMo) architecture, prevalent in many European cities.

2. Materials and methods

This paper is structured into three main sections. The first provides a summary of the general methodology, introduces the application of a case study, outlines the scenarios analysed, and describes the simulation boundary conditions and settings. The second one presents the key results and refines the improvement proposals based on a cross-analysis of these and a previous iteration of different pavement combinations in ENVI-met in order to obtain the best UTCI results, considering the worst-case climate projections for 2080. Finally, the third section, which offers a summary of the main conclusions and findings of the study, outlines potential ways for future research.

2.1. Methodology outline

The methodology followed in this research is summarized in Fig. 1. A case study is selected based on its representativeness of the archetypical MoMo urban intervention, located in a climate under CC risk. The temporal frame of the simulation is selected, and weather simulation data are obtained for analysis. The ENVI-met software was selected for the study and the models are built based on documentation and onsite surveys. Onsite measurements and recorded data are used to calibrate the models. The results of each of the five proposed scenarios are analysed in terms of thermal comfort and its related parameters. An iterative process is performed in ENVI-met to select the optimal mitigation strategies for application in the proposal scenarios in order to improve thermal comfort under CC projections.

The initial data used for this research, as well as several onsite surveys and measurement campaigns, were obtained from diverse sources, shown in Table 1.

2.2. Case study

This research takes an existing urban development as a case study to apply the methodology. Despite the use of a specific district, it is structured and exposed in a way that enables its replication for any other district or urban typology that has suffered transformations in a warm region.

The case study neighbourhood is *Virgen del Carmen Group*, in the city of Valencia, one of the major cities in Spain, located on the east coast of the Iberian Peninsula (Fig. 2a). This determines a warm climate highly influenced by the Mediterranean Sea. During the last summer, 2023, the

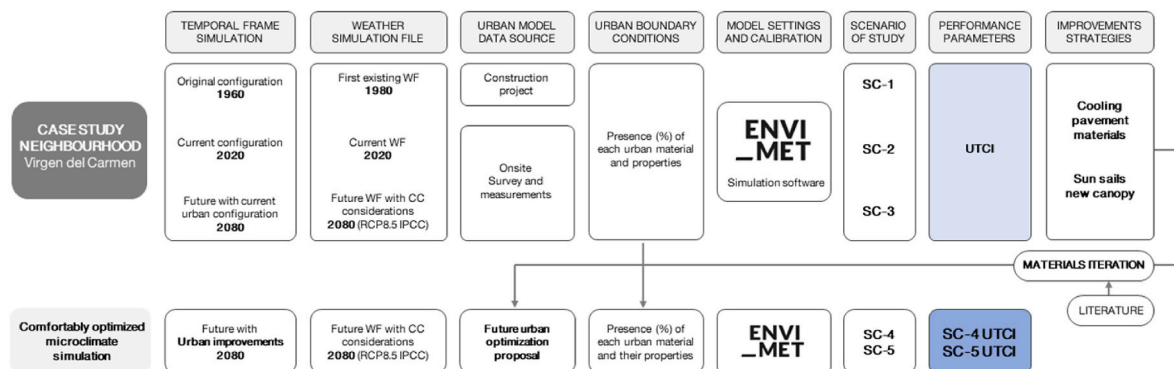


Fig. 1. Methodology workflow.

Table 1
Research data and study.

Data	Scenario	Source	Temporal frame	Description
Geometrical case study data used in simulation model	SC-1	Original construction project [78]	1960	Plans and drawings from the original project Confirmation of buildings' footprint, urban pavements and other elements survey Changes as part of the study conclusions
	SC-2/3	Cadastral plans and onsite survey	2020	
	SC-4	Research conclusions	2080	
	SC-5			
Material properties		Onsite survey and literature [33,79,80]	–	To be taken into account in the microclimatic simulation
Climatic data	SC-1	First IWECC weather file existing from DATSAV3 [81]	1980	First climatic data available in the repository of EPW files
	SC-2	SC-1 weather file morphed with CCWorldWeatherGen 1.9 (Based on HadCM3 [82] and IPCC reports [83])	2020	SC-1 weather file morphed to SC-2 climate
	SC-3/4/5	Idem	2080	SC-1 weather file morphed to SC-3/4 climate
	Model calibration	On-site monitoring campaign	2020	Data used for model calibration

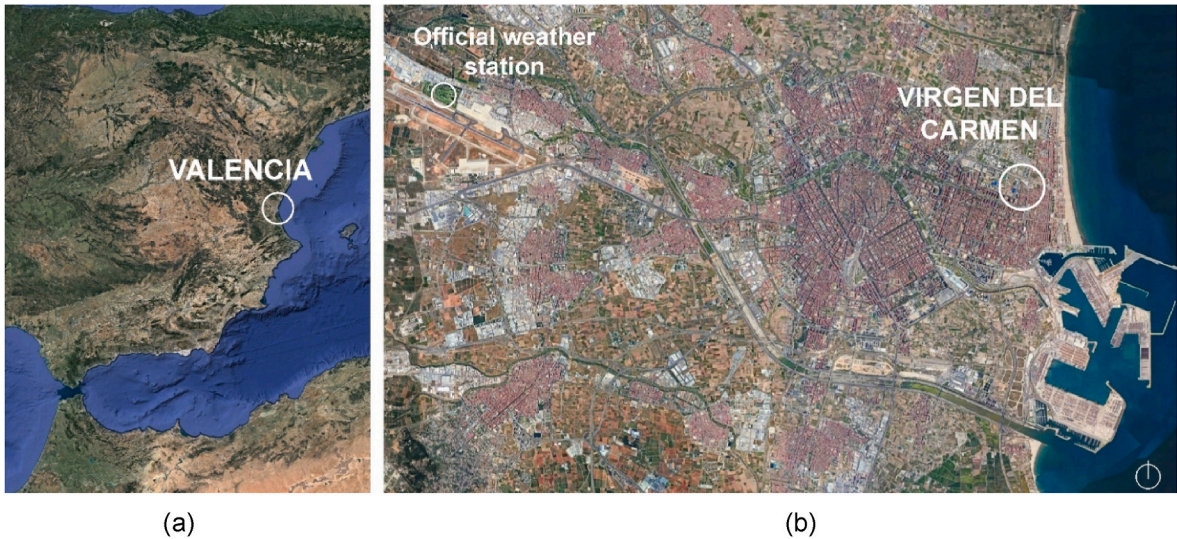


Fig. 2. Location of Valencia (a) and the case study neighbourhood (b).

city experienced its highest temperatures on record, reaching a maximum of 46.8 °C as documented at Valencia Airport Station [84] (Fig. 2b). The case study selected is just 1 km away from the sea.

According to the most recent updates and adaptations [85] of the original Köppen-Geiger climatic classification [86,87], Valencia’s urban area is catalogued as *BSh* climate, with moderate winters, warm and

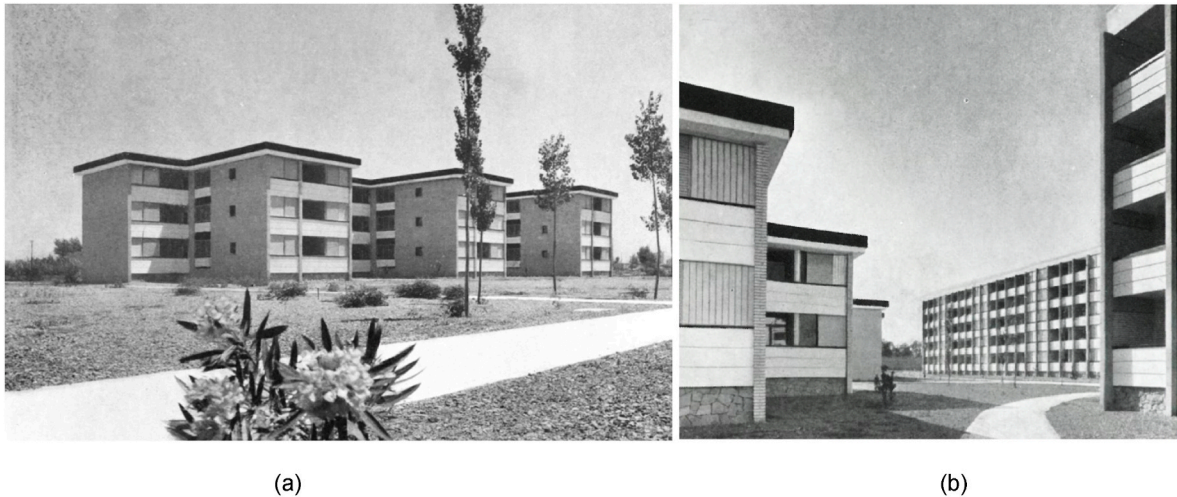


Fig. 3. (a) Public space aspect with the original MoMo urban configuration. Large open areas of sandy terrain, little vegetation, and isolated buildings. (b) Image of the space on between the buildings [78].

humid summers, and few annual precipitations.

The urban district of *Virgen del Carmen* was built in 1962 and contains 614 dwellings that were promoted under the National Houses Plan [88,89]. These dwellings featured highly cost-effective construction techniques utilizing new prefabrication and standardization methods such as prefabricated concrete panels [78]. Furthermore, minimum qualities, sizes, and distributions were required by regulations, while designers also prioritized avant-garde healthy design and comfort facility services [90]. Originally, this neighbourhood was built in a suburban area. Its architectural configuration was conceived under the MoMo guidelines, with a novel urban fabric (Fig. 3a and b). The buildings were designed in two typologies [78]: linear buildings and tower buildings. Nowadays, the case study area is part of the consolidated city. The public space of the case study has evolved in response to

significant changes in the surrounding urban context. These transformations have led to major changes in the urban configuration and its microclimate performance. These different layouts are considered case study scenarios (SC) in this work, contrasting and analysing their individual microclimate performances.

2.3. Comparison of study scenarios. Temporal frames and urban changes

This research aims to compare the microclimate performance of certain configurations of the same MoMo neighbourhood under diverse historic climate conditions. Three initial scenarios (SC) are therefore considered (Fig. 1).

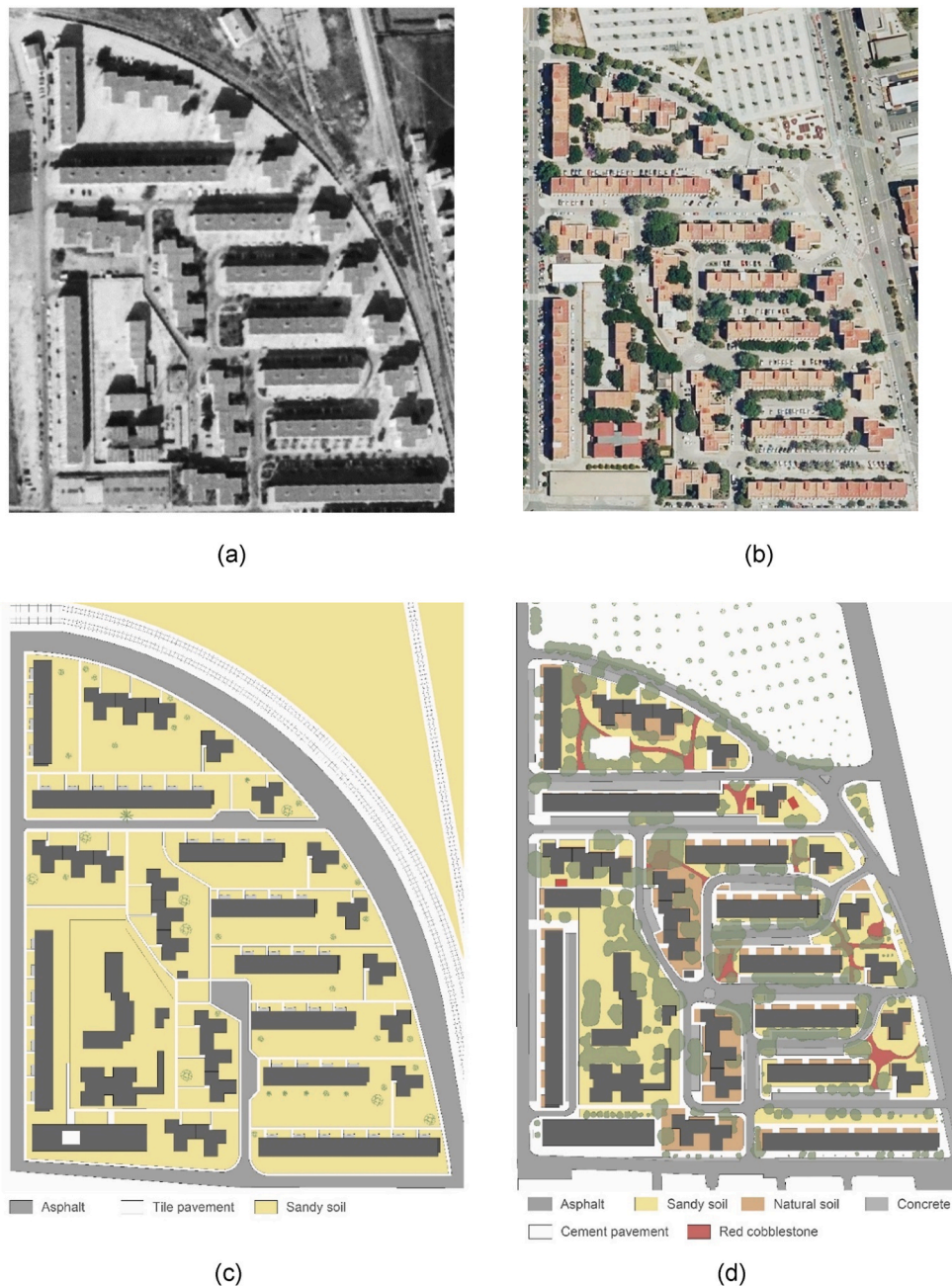


Fig. 4. Diverse urban area case study status. (a): First known aerial image, taken in 1980 with the urban configuration still very similar to original one [92]. (b): Current satellite image taken by PNOA [93]. (c): Architectural plan of SC-1 in 1960, original configuration with the project just ended. (d): Architectural plan of SC-2 and SC-3, current urban configuration in 2020.

- SC-1 (1960s): This scenario represents the original urban configuration of the case study when the construction was completed. In this SC-1 urban configuration, the MoMo values were perfectly recognizable. The buildings were isolated into two large open blocks of buildings, and the roads for traffic were shifted outwards. This was a vast area with sandy soil with narrow transversal walkways that connected the buildings (Fig. 3b). The public areas were large esplanades of terrain with almost no vegetation, apart from a few small trees and bushes dotted throughout (Fig. 3a). As a result, these arid areas had no solar protection or spaces to shelter on warm days (Fig. 4a). An SC-1 plan is shown in Fig. 4c.
- SC-2 (2020s): This scenario shows the state of the neighbourhood in 2023. Over the last sixty years, major changes to the case study area have modified its configuration. Several urban refurbishment projects were developed by the authorities to improve and update the urban spaces of the neighbourhood. As a result, the two large blocks originally built have been divided into several smaller blocks separated by numerous asphalt roads. New walkways were created, blocks and buildings are now surrounded by large surfaces of cement paving. Furthermore, new internal walkways were added with cobblestone pavements and several green areas next to the buildings. This resulted in a vast surface of hard impervious materials. However, a major gardening project was carried out, adding many trees and bushes to create a sizeable green canopy (Fig. 4b). The building balconies have also been modified, enclosing them with glazing so that the windows are located on the outer façade plane. In spite of this, the percentage of glazing area has not been modified substantially. The current configuration of SC-2 is shown in Fig. 4d.
- SC-3 (2080s): In this case, the research considers the same urban configuration seen in SC-2 (Fig. 4b and d), facing a more extreme climate by considering the effects of CC sixty years into the future. To this end, the worst scenario of the IPCC climate change report (IPCC scenario RCP8.5) has been considered [91]. This allows an evaluation of the performance of the neighbourhood's present urban configuration under the worst future climatic projections.
- SC-4 and SC-5 (2080s) Improvement proposal: Based on the results obtained from the analysis of previous scenarios and the existing literature, a fourth and fifth scenarios are proposed. Both represent a future 2080 scenario considering the same worst CC weather projection. The future proposal has been divided into two scenarios (4 and 5) as SC-4 interventions will focus solely on pavements while SC-5 will add shading elements. All the interventions are based on the use of cost-effective materials, which have been previously tested by other studies to be beneficial for microclimate and have low maintenance necessities.

2.4. Boundary conditions and ENVI-met simulation model setup

2.4.1. Simulation weather data

The weather data for the simulations has been obtained from the EnergyPlus database [94], in EPW format, which contains hourly data on typical climatic parameters for the entire year. This database has recorded climatic data from a local official meteorological station during the last years. In the case of Valencia, an IWEC file (International Weather for Energy Calculation), derived from up to 18 years of DAT-SAV3 [81] hourly weather data originally archived at the National Climatic Data Centre, is used. The information in the file contains data from 1980 to 1990. This is the earliest weather data information found. However, according to the literature and historical temperature registers [81], the local climate barely changed in the twenty years from 1960 to 1980. Therefore, it was considered that the 1980s weather file (WF) can be used to represent the 1960 summer weather conditions in SC-1. The Climate Change World Weather Generator (CCWorldWeatherGen 1.9) open-access tool was used to establish the weather information for the present and future scenarios. This software, previously used by numerous studies [95,96], considers the HadCM3 [82] global

climate model based on the RCP8.5 scenario [97]. It was used to morph the original file into the weather of 2020 and 2080, following the climate change predictions presented by the IPCC [83]. These expected CC scenarios are established by the major global authority and are officially recognised for all administrations while they have already been used in previous research [97].

The present study considers the RCP8.5 scenario [97], the most unfavourable. Although it could be difficult to predict the exact climate situation in 2080, the chosen scenario provides contrasted data on the worst expected situation. Therefore, any future improvement from this perspective will improve the results of this study, increasing the utility of its results.

In order to simulate representative warm conditions, the summer months of the weather file were analysed using Ladybug Tools [98,99] to find the most representative day [100]. We call a representative day (RD) a 24-h dataset from the weather file that is characterized by the least differences of maximum and minimum temperatures to the mean values of these maximum and minimum temperatures in the summer period considered: that is, the day whose sum of square differences between maximum and minimum temperatures and its mean values is the smallest of the period. Another restriction is applied, taking only sunny days, given that temperature and radiation are the two parameters most affecting thermal comfort. In mathematical notation, the (RD) is defined as follows:

$$RD = \text{Min} (A_i)$$

being

$$A_i = \left[(T_{i,max} - \overline{T_{max}})^2 + (T_{i,min} - \overline{T_{min}})^2 \right], i = 1N \quad (N = \text{number of days}),$$

Where $T_{i,max}$ and $T_{i,min}$ represents the minimum and maximum temperatures each day and $\overline{T_{max}}$ and $\overline{T_{min}}$ represent the mean maximum and minimum temperatures of the period.

This procedure is based on previous research applied to find the RD based on one parameter (pollution) [100] but simplified in order to account for the extreme values.

The original weather file data for July 17th was used in SC-1, the morphed 2020 file was used in SC-2 and the morphed 2080 file was used in SC-3, SC-4 and SC-5. Air temperature (AT) and relative humidity (RH) for July 17, 1980, 2020, and 2080 are shown in Fig. 5. These climatic data are used to establish the climatic boundary conditions in the ENVI-met software, entered in "simple forcing" mode, which according to the software developers [52] allows a better model calibration and avoids some detected model's instabilities when using the full forcing mode. The AT and HR have been hourly set, while wind and radiation have been calibrated according to monitored data.

2.4.2. Urban model materials

The study area has undergone several modifications as part of a long-term evolution which has changed the original shape of the urban

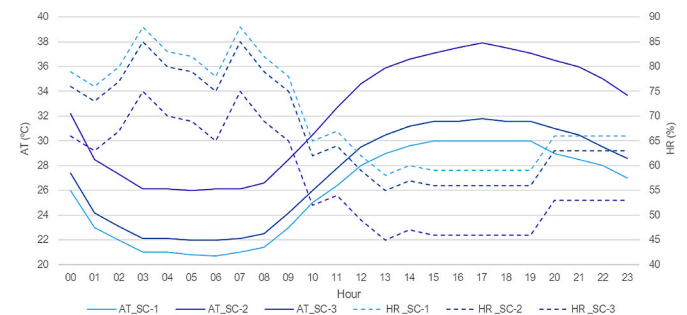


Fig. 5. AT (°C) and RH (%) for July 17, 1980, 2020, and 2080, the three temporal studied periods.

district. In the building's original state, its footprint accounted for 16% of the total urban area, while the rest of the urban area is 79,700 m². The proportion of each surface material in the urban area has been measured. The observed materials are shown in Table 2 and Table 3 for each individual SC studied. The properties of each material are collected in Appendix A. 1, Table A. T. 1.

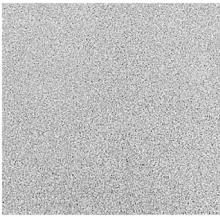
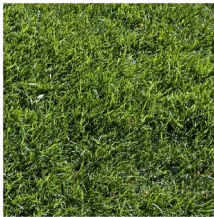
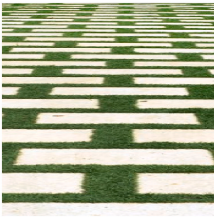
- SC-1: The neighbourhood had a large percentage of soft and pervious sandy terrain, representing 66% of the total surface area of public space. In contrast, as only 1% of the surface was covered by a green

canopy, most of the area was subject to direct solar radiation (Fig. 4c).

- SC-2 and SC-3: Following the transformation process, pavements were modified adding new hard and impervious materials. Currently, 78% of the surface is occupied by hard pavements in materials such as asphalt, cement, and other impervious surface materials. However, thanks to the gardening project, a new large green canopy of deciduous trees covers a surface of up to 11% (measured in the summer session) of the total area (Fig. 4d).

In addition to the pavement materials, the façade materials and

Table 2
Urban development pavement materials.

Pavement materials identification			
Asphalt	Tile Pavement	Sandy Soil	Natural Soil
P01	P02	P03	P04
			
Concrete	Cement Pavement	Red Cobblestone	Clear permeable asphalt
P05	P06	P07	P08
			
Clear walkway pavement	Grass	Paved grass	Textile shade
P09	P10	P11	S01
			

^aThe 2080's proposed textile shade is not a pavement, but was included to show its properties as part of the SC-5 model.

Table 3
Materials % presence per each scenario.

Pav. material	Asphalt	Tile Pavem.	Sandy Soil	Natur. Soil	Concr.	Cement Pavem.	Red Cobbl.	Clear perm. asphalt	Clear walkway pav.	Grass	Paved grass
ID	P01	P02	P03	P04	P05	P06	P07	P08	P09	P10	P11
SC-1	17%	5%	78%	–	0%	0%	0%	–	–	–	–
SC-2/3	30%	–	20%	6%	6%	35%	2%	–	–	–	–
SC-4/5	–	–	19%	–	–	–	–	26%	29%	7%	19%
Surface covering summary						Shadow covering summary					
Scenario	Impervious		Pervious		Green cover		Shade sail cover		Total shadowed area		
SC-1	22%		78%		1%		–		1%		
SC-2/3	74%		26%		13%		–		13%		
SC-4	29%		71%		13%		–		13%		
SC-5	29%		71%		13%		6%		20%		

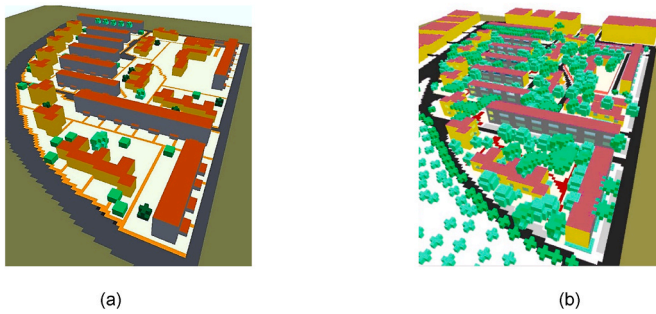


Fig. 6. Case study area 3D models. (a): ENVI-met model for SC-1. (b): ENVI-met model for SC-2/3.

properties have been compiled according to the onsite survey and the literature. These material properties are required in order to generate the different simulation models. All the ENVI-met material properties were assigned for each of the materials present in each SC as shown in Appendix A. 1, Table A. T. 2.

2.4.3. ENVI-met simulation model set-up

The urban models were built in SketchUp and exported to ENVI-met (Fig. 6a and b). The model size, location, simulation date, and other general parameters were established in the software. In this case, the same settings are used for all the simulations to enable comparison of the same case study but considering changes in urban contexts and climate conditions. The models use a grid where every cell has a size of $2 \times 2 \times 3$ m. This is fixed for all models to balance accuracy and simulation time [46]. Geographical and geometrical settings are expressed in Table 4. The models represent the case study neighbourhood and its immediate urban environment. The materials used for pavements (Table 2) and buildings (Appendix A.1 Table A.T.1) were created in the software with the material properties shown in Appendix A.1 Table A.T.2. Finally, trees and grasses are selected from the default library, choosing the options that better fit with the observed species.

The definitions of all the boundary conditions for the simulations are obtained from diverse sources as shown in Table 5. This allows it to obtain a complete definition of the model and its replicability. Finally, the validation and accuracy of the model were tested with calibration. To this end, onsite monitored data were acquired throughout the district and the measured data were compared with the simulated data. The comparison allows the calibration of the model by some adjustments and a resulting error assessment [112]. Further information about the

Table 4
Simulation model definition.

Field to be compiled	Values and data
Name of location	Valencia, Spain
Latitude	39.47
Longitude	-0.38
Size of grid (m): dx/dy/dz	2/2/3
Model dimensions: x/y/z	214/252/20
Telescoping factor	0%
Rotation out of grid north	18°
Level above the sea	4 m
Nr of nesting grid	5

Table 5

General settings assigned in simple forcing mode in ENVI-met.

Field to be compiled	Values and data	Source/Description
Start date	July 16, 1960_2020_2080	–
Start time	18:00	–
Simulation time	30 h	–
Humidity in 2500 m	4.5 g/kg	[46]
Windspeed (average)	3.53 m/s	Calculated based on official data [101]
Wind direction (average)	17.80° (0° = North)	Calculated based on official data [101]
Roughness Length	0.10	[102]
Building initial T°/Keep constant	27.0 °C/No	Buildings performing in free-running system
Plant settings and calendar	01SMDS; 020039; 01SLSS; 020080; 01PLDM; 010020	ENVI-met database
Timing section	By default	ENVI-met default
Soil humidity	By default	ENVI-met default
Soil temperature at: 0–20/20–50/50–200/<200 cm	20.0/19.0/17.0/15.0 °C	[103]
Radiation settings	Solar Adjustment Factor = 0.91	Adjusted according to official 17th July data [101]

calibration process can be found in Appendix A. 2.

2.5. Performance parameters

This research aims to analyse the suitability of the outdoor space existing in MoMo developments throughout history and under future climate change projections. In order to assess this suitability, focusing on the users of these spaces, thermal comfort is evaluated, using the UTCI. This index is analysed in the different scenarios at different points during the day, selecting the maximum and minimum temperature hours (6:00 and 16:00) and 2 h of busy use of the street (12:00 and 22:00). Heat maps and variation maps are shown and used in combination with the urban configuration to select several points of study. An in-depth analysis is carried out for each of these points, including UTCI and the main climatic parameters affecting it: AT, RH, MRT, and pavement surface temperature PST. The detailed analysis and the existing literature are used to draw up a project proposal to transform the area and improve future conditions.

3. Results and discussion

3.1. Analysis of SC-1, SC-2 and SC-3

This section shows the simulation results of thermal comfort of the three scenarios representing the original configuration and weather conditions (SC-1), the current scenario (SC-2) and the future projections (SC-3). Fig. 7 shows the UTCI simulated at the selected hours.

At 6:00 h, results for SC-1 and SC-2 are similar, ranging between 18.5 and 22 °C at all points of the selected area. However, in 2080 (SC-3), the UTCI increases significantly, reaching – and at times exceeding – 22 to 25.5 °C. The same tendency can be observed at 12:00 h, although in this case, the results for SC-1 and SC-2 are between 32 and 39 °C, while SC-3 is above 40 °C at all points. At 22:00 h, the difference in results between the three scenarios is greater, with higher temperatures for the UTCI observed in all cases: SC-1 results are mostly in the range of 22–25.5 °C; while those for SC-2 are 25.5–29 °C, and 32.5–36 °C for SC-3.

For a visual representation of the differences between scenarios in the area, Fig. 8 shows the variation in UTCI between SC-1 and SC-2 at the



Fig. 7. UTCI maps for the scenarios SC-1, SC-2 and SC-3 at different hours of July 17th.

selected hours. According to this, while at 6:00 h and 22:00 h SC-1 displays better results for UTCI (positive values indicate that UTCI in SC-2 is higher than UTCI in SC-1), at 12:00 and 16:00 h the results in SC-2 are better than those in SC-1 at many points, providing lower UTCI values due to the presence of vegetation. The vegetation provides shade to the area, reducing MRT and improving thermal comfort during the day. The shade provided by new buildings is causing the same effect. In contrast, during the night, areas with vegetation cover present a slightly worse performance than open areas given that vegetation blocks the

nocturnal radiation to the sky and hinders night-time ventilation.

The differences between SC-2 and SC-3 are shown in Fig. 9. In this case, climate change projections produce such a high increase in temperatures that UTCI results in the area are always higher in SC-3 than in SC-2, an increase in a range of between 2 and 7 °C, the highest difference observed at 22:00 h in the southwest section of the area studied. Some areas also display notably greater differences depending on the materials: pavements made of asphalt reach much higher UTCI levels in the future scenario than pavements with soil or concrete in the hours when

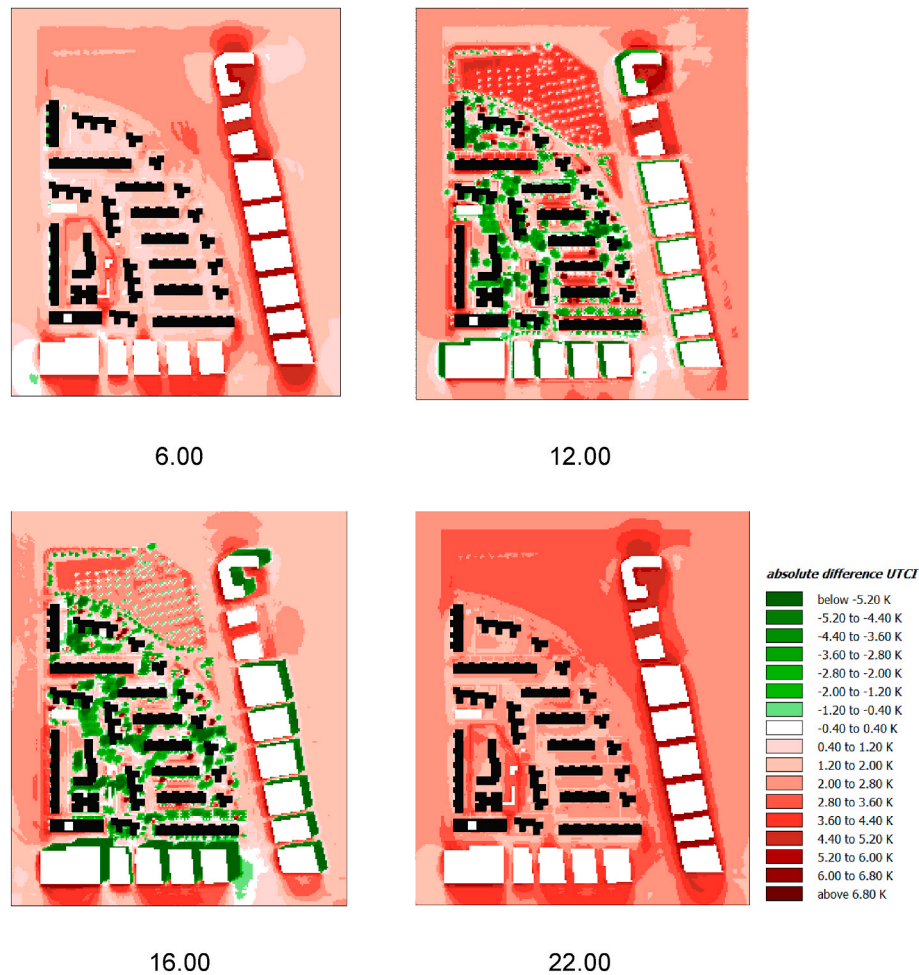


Fig. 8. UTCI difference between SC-1 and SC-2 (SC-2 - SC-1).

they receive direct solar radiation.

The most relevant climatic parameters considered for the UTCI simulation have also been obtained graphically in the three scenarios for the four selected times, directly related to the UTCI results shown in Fig. 7. These results, due to the document length, are shown in Appendix A3: The AT in Figure A.F.2, the MRT in Figure A.F.3, and the RH in Figure A.F.4.

3.1.1. UTCI parameter analysis at different points

For a more in-depth analysis of the different variables that influence UTCI results, five points in the area have been selected and their parameters are analysed for the entire selected day. These selected points are shown in Fig. 10 and their main characteristics are described in Appendix A.4. The selection of these points is based on their relevance to this analysis: Point 1 corresponds to an area used as a neighbourhood square where people usually gather; Points 2 and 4 are soil areas where vegetation has been included in SC-2. Points 3 and 5 are selected at different parts of the characteristic spaces in between the longitudinal buildings of this development.

The hourly UTCI results for each point in the three scenarios

analysed are shown in Fig. 11. These show the progressive increases in hourly UTCI in the individual scenarios in areas with no shade (P3 and P5). In contrast, points where shade has been incorporated present lower UTCI results in SC-2 and SC-3 in the central hours of the day than in SC-1 (P2 and P4), although SC-3 is always higher than SC-2. During central hours SC-2 shows a decrease of up to 5 °C compared to SC-1 due to the shadow effect. In the afternoon, P1 receives shade in SC-2 and SC-3, and in this case the values for SC-2 are lower than those for SC-1 (−5 °C) but not for SC-3. In general, the addition of shade by increasing vegetation in SC-2 and SC-3 provides better results during daylight hours than in SC-1. During the night, the tendency is the same in all points, increasing UTCI values for the three SCs.

To understand these results an in-depth analysis is carried out on the parameters that affect UTCI such as air temperature, mean radiant temperature, wind speed and relative humidity. The following sections show the main results of these variables for the points selected:

In relation to air temperature (Fig. 12), no major variations are observed between the different points within any of the scenarios (variations of 2 °C maximum between locations), although significant temperature variations are found between different scenarios. Night-

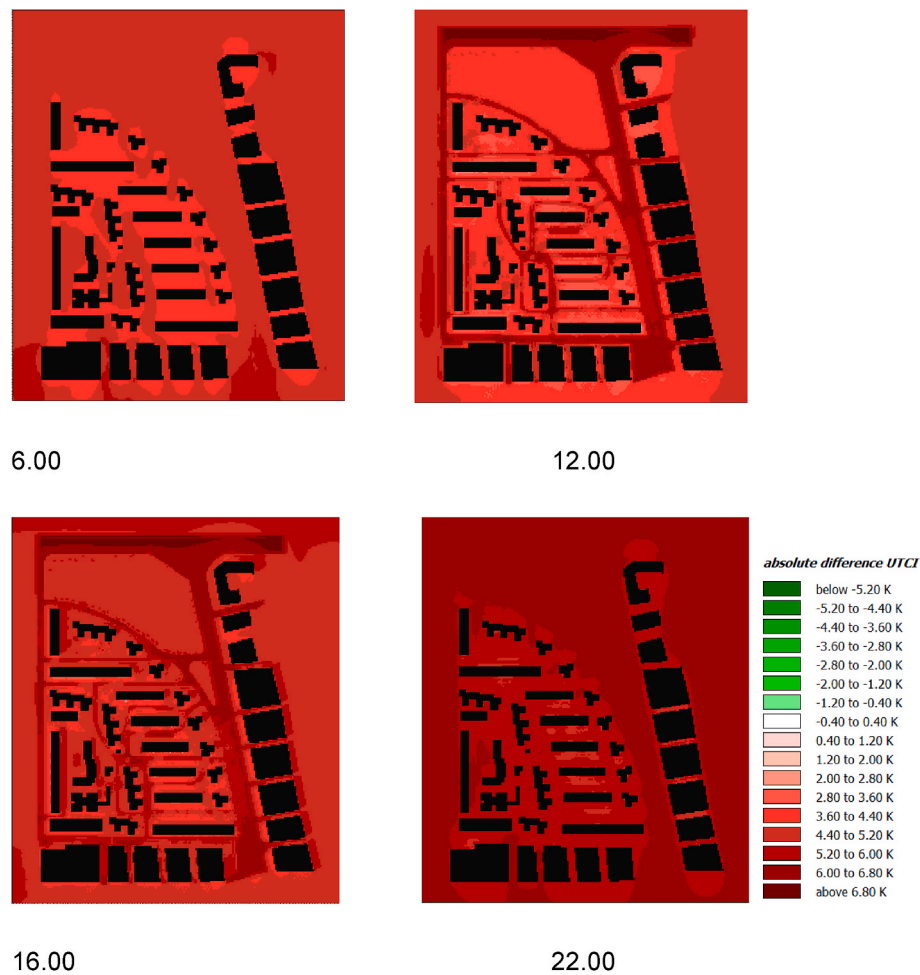


Fig. 9. UTCI difference between SC-2 and SC-3 (SC-3 - SC-2).



Fig. 10. Location of the points analysed.

time temperatures are higher in SC-2, than in SC-1. During the day, both years are quite similar, although the temperatures for SC-2 are more homogeneous than for SC-1. In SC-3, air temperatures are higher during all the hours of the day and reach extreme values of close to 37.5 °C during the day; during the night they do not fall below 26 °C (what is known as tropical nights).

Relative humidity (Fig. 13) does not vary significantly between the different points in any scenarios either (around 10% maximum). However, there are important differences between 1980, 2020 and 2080. Relative humidity in future projections is also lowered: from values between 45 and 75% in SC-1 to values ranging between 40 and 60% in 2080. Previous research showed that high relative humidity levels can worsen the thermal comfort of users [76].

Wind speed is another parameter that influences thermal comfort [104]. However, in all scenarios, the vegetation and built environment of the area hinder the wind flow in the different locations, reaching less than 1 m/s. It is therefore not considered a significant variable in the case study. In contrast, in this calculation, MRT is the parameter that most affects thermal comfort in outdoor environments, as already seen in previous research [105]. MRT considers the surface temperature of the materials surrounding every point, as well as the solar radiation received. It is therefore greatly affected by the shading and thermal characteristics of the materials in each location. Fig. 14 shows a comparison of all points in the different scenarios, representing MRT and the floor surface temperature: P3 and P5 are points without any shading at all in the SC. They show that surface temperature and MRT increase in successive scenarios, from a maximum of around 35 °C in SC-1 to more than 40 °C in SC-2 and SC-3. However, surface temperature in P3 is

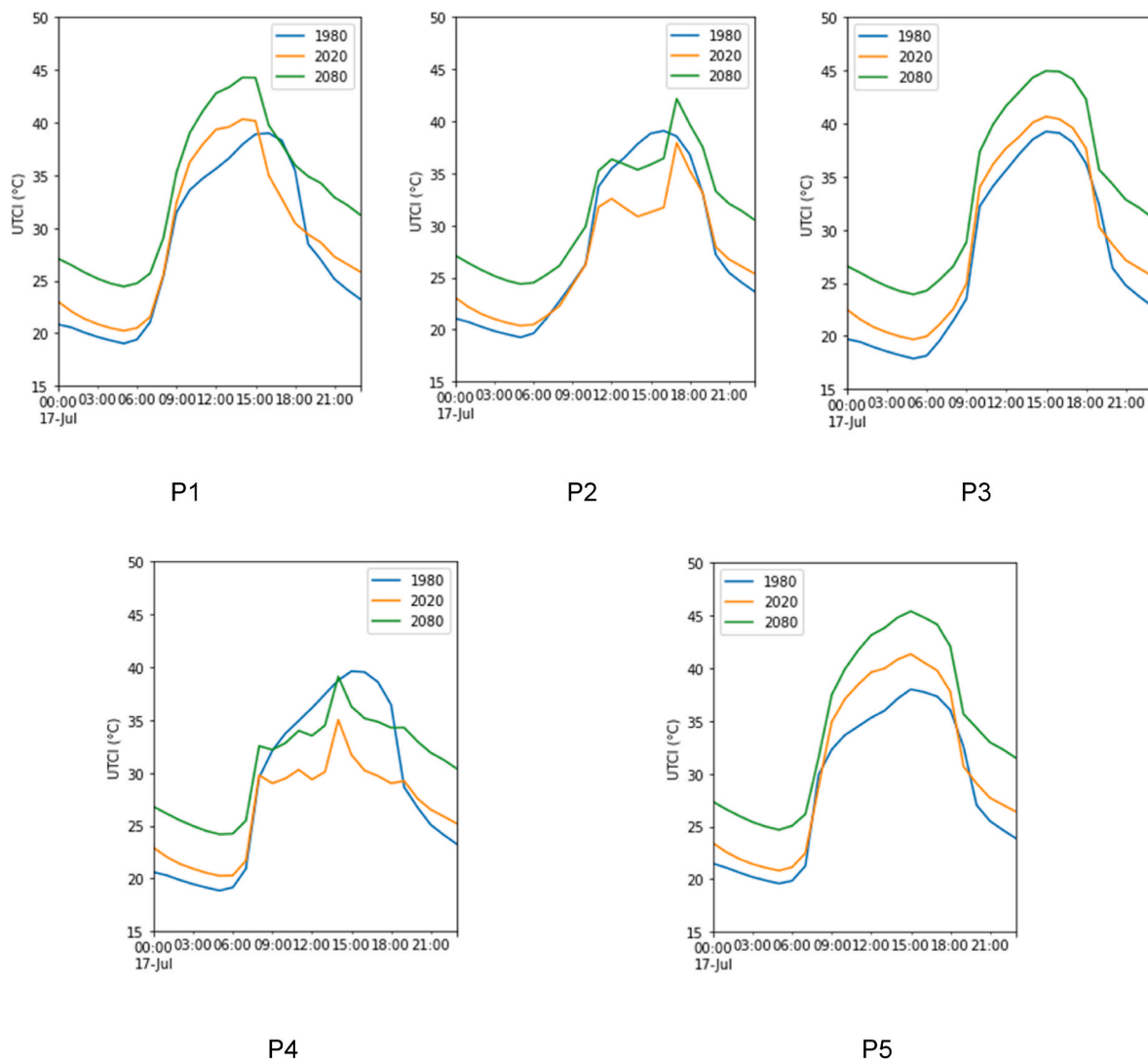


Fig. 11. Hourly UTCI results in the selected points at scenarios SC-1 (1980), SC-2 (2020) and SC-3 (2080).

lower in CS2 and SC-3 than in P5, as the new material used in P5, grey concrete, has a low albedo. This material also results in a higher MRT in P5 than in P3. In shaded points (P2 and P3), maximum surface temperature and MRT are higher in SC-1 than in the others. This explains why in shaded points, the UTCI for SC-2 is lower than in SC-1 despite the increased air temperature produced by CC. The reduction in MRT produced by shading can be of up to 40 °C.

Considering the effects of shading and materials on the evolution of the performance in the different scenarios, the next section proposes the urban renewal of the area through the incorporation of these mitigation strategies.

3.2. Proposal scenarios and urban mitigation strategies

The existing literature has identified several passive cooling strategies exposed previously. Although the water base solutions have been proved as the most efficient, the use of water strategies has been dismissed due to current and forecast drought conditions. Similarly, increasing the number of trees for shading is also problematic as the nighttime UCTI and MRT analysis has indicated. Therefore, based on the analysed performance of original, present, and future scenarios, this study proposes an urban renewal to mitigate the worst future climate change projections based on the implementation of new cooling pavement materials, grass solutions and the use of textile shading in the form

of awnings.

To obtain the materials best suited to these specific conditions, a preliminary iteration simulation for material performance was conducted using ENVI-met. Ten different material types were chosen based on previous research, each of these, with three variations in albedo and porosity. Simulations were performed for all thirty materials for a 24-h period in the future climatic conditions and the same ENVI-met parameters already shown. In order to analyse the behaviour of these materials under different boundary conditions, they were simulated with fractions directly irradiated, under the shade of a solid-building, shade from trees, and shade from a textile. Finally, the UTCI results and some of its parameters were analysed for each material at different points during the day, choosing the optimal and incorporating it into the improvement proposal scenario (Table 2 and Fig. 17).

Additionally, in terms of proposing an urban intervention, several aspects have to be considered along with the cooling capacity. On the one hand, it is crucial to consider the effects that these materials will have on the warmth, aesthetics, and welcoming nature of public spaces. The significance of these spaces as gathering points and hubs for social interactions within societies has been previously discussed. Urban reform is proposed with careful design considerations to create more liveable spaces, prioritizing pedestrians, and returning to the original MoMo values. Thus, the materials selected also exhibit suitable and aesthetic finishes to generate inviting and cooler spaces than the current

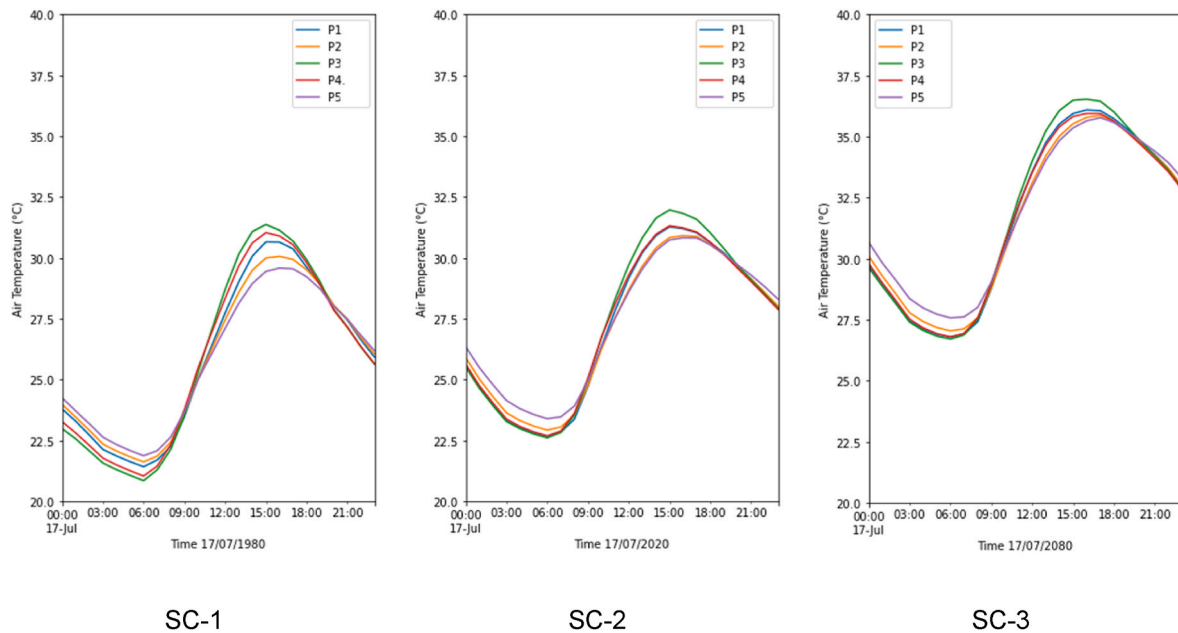


Fig. 12. Hourly air temperature results at the selected points in the simulated scenarios.

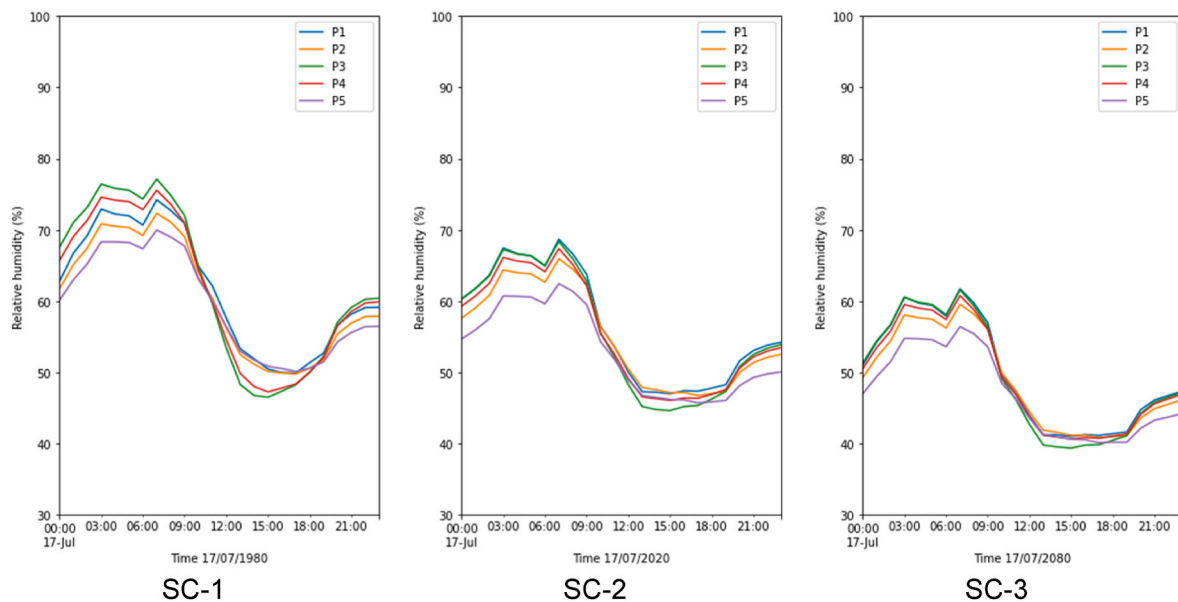


Fig. 13. Hourly relative humidity results at the selected points in the simulated scenarios.

ones.

On the other hand, another crucial aspect of such interventions is to consider, in addition to their effectiveness, the costs and long-term maintenance of the materials employed. Previous studies [73,106] have demonstrated, and this research corroborates, that the most effective and sustainable materials in terms of their cooling properties are light-coloured pavements with medium albedo, porous materials, grass or paved grass solutions and solar control strategies. However, while higher-albedo materials reduce temperature and radiation absorbed by pavements, they also have adverse effects on overall comfort due to their high reflectivity. Regarding the costs and associated maintenance of these new materials, a previous study [107] found that these materials may initially incur somewhat higher costs compared to traditional urban materials. Nonetheless, the study illustrated how the direct and indirect benefits of their cooling capacity offset this slight

initial cost over the long term, which also was confirmed by other studies [108,109]. The cooling effects of this urban reform will not only enhance user comfort, already yielding a direct positive impact, but will also lead to a marginal reduction in the cooling energy demand of adjacent buildings [107], resulting in indirect energy and economic savings for society. The same study further demonstrated that these materials did not differ significantly from traditional ones in composition and original life. However, due to their exposure to lower temperatures owing to their properties, their lifespan is further extended [110]. Building upon these studies, material selection was made as described below, always to achieve a beneficial balance in terms of their capacity to improve the microclimate, generate more pleasant spaces, and ensure their long lifespan with minimal or negligible maintenance.

The mitigation strategies are divided into two scenarios.

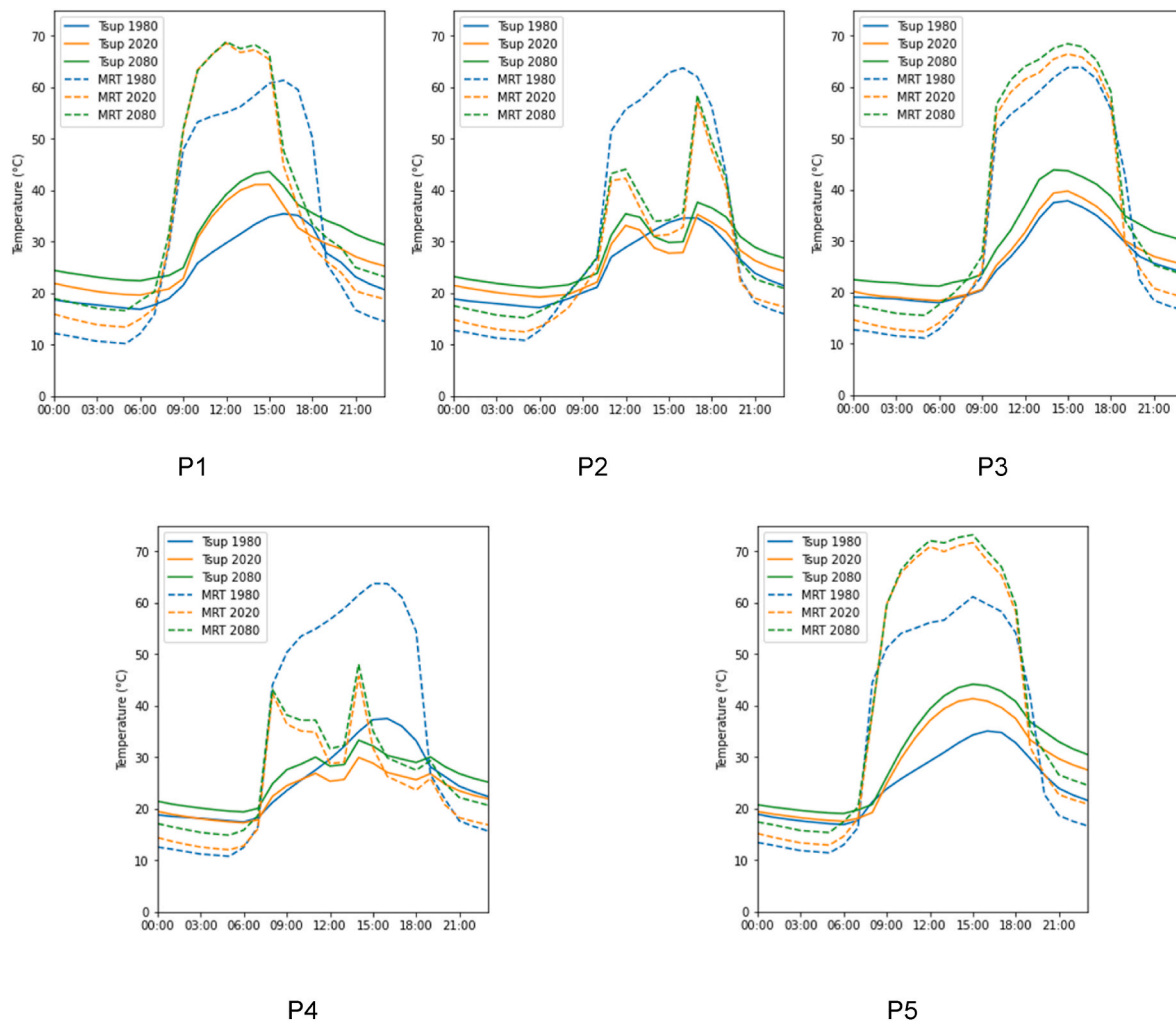


Fig. 14. Hourly surface temperature and MRT results in the selected points at scenarios SC-1 (1980), SC-2 (2020) and SC-3 (2080).

- SC-4 Proposal:

Fig. 8 shows that SC-2 improved the diurnal thermal perception of SC-1 in many areas, mostly due to the new shaded area. However, in many others, the performance is poorer due mainly to the use of new heavy, impervious, and low-albedo materials. Therefore, the SC-4 proposal (Fig. 15a and c) returns to the original concept of the MoMo neighbourhood. In the areas between blocks, roads are eliminated almost completely, and the public spaces are re-established for pedestrians. The MoMo open spaces are recovered but adapting to the future extreme climatic conditions. New materials are used for pavements and soils. The remaining asphalt is replaced with a clear permeable asphalt (P08 in Table 2 and Appendix A. 1, A. T. 2). The pavement of the walkways is changed to a new clear stone paving (P09 in Table 2) with a medium albedo and a lower thermal inertia than the previous cement pavement (Appendix A. 1, A. T. 2). Furthermore, a new walkway material, paved grass (P11 in Table 2), is added to create a walkable pavement that combines clear porous cement and small cavities of grass. This material, based on resistance grass species, has a higher albedo than regular grass, reflects more radiation, allows direct heat transmission to the soil, and is a rigid pavement that produces evapotranspiration, therefore helping to reduce temperatures (Appendix A. 1, A. T. 2). In addition, previous natural soil areas and other new ones are transformed into wild grass zones (P10 in Table 2), providing green soils that improve comfort. Finally, the original sandy soil (P03 in Table 2) is maintained but adapted to the new urban configuration. When

considering soil characteristics, SC-4 returns to the percentage of pervious surfaces observed in SC-1 (71%), while 45% of the total is natural or semi-natural soil (Table 3). Furthermore, the albedo of all new pavements has increased or maintained (Appendix A. 1, A. T. 2).

- SC-5 Proposal:

As solar direct radiation is one of the top factors worsening thermal comfort, scenario SC-5 incorporates new textile shading elements (S01 in Table 2) in the form of freestanding awnings (Fig. 15b and d) into the previous SC-4 design. The advantage of this kind of shading element is that it can be removed in the cold season and enables the creation of new covered areas without increasing RH. In the proposal, the awnings are placed at different heights, creating a non-uniform surface that does not obstruct ventilation. Considering the total shaded areas of public space (plants and awnings), up to 20% of the area of SC-5 is covered, increasing 7% from the original shaded area in SC-2 and SC-3 (3).

3.3. Proposal scenario results and analysis

The calculated UTCI result maps for the SC-3, SC-4 and SC-5 are shown in Appendix A.3, in Figure A.F.5. Additionally, the most relevant UTCI related parameters have also been obtained and shown in maps in Appendix A.3. Specifically, the AT in Figure A.F.6. and the MRT in Figure A.F.7. Furthermore, the differences between the UTCI in the various scenarios are shown ahead. Fig. 16 shows the UTCI difference

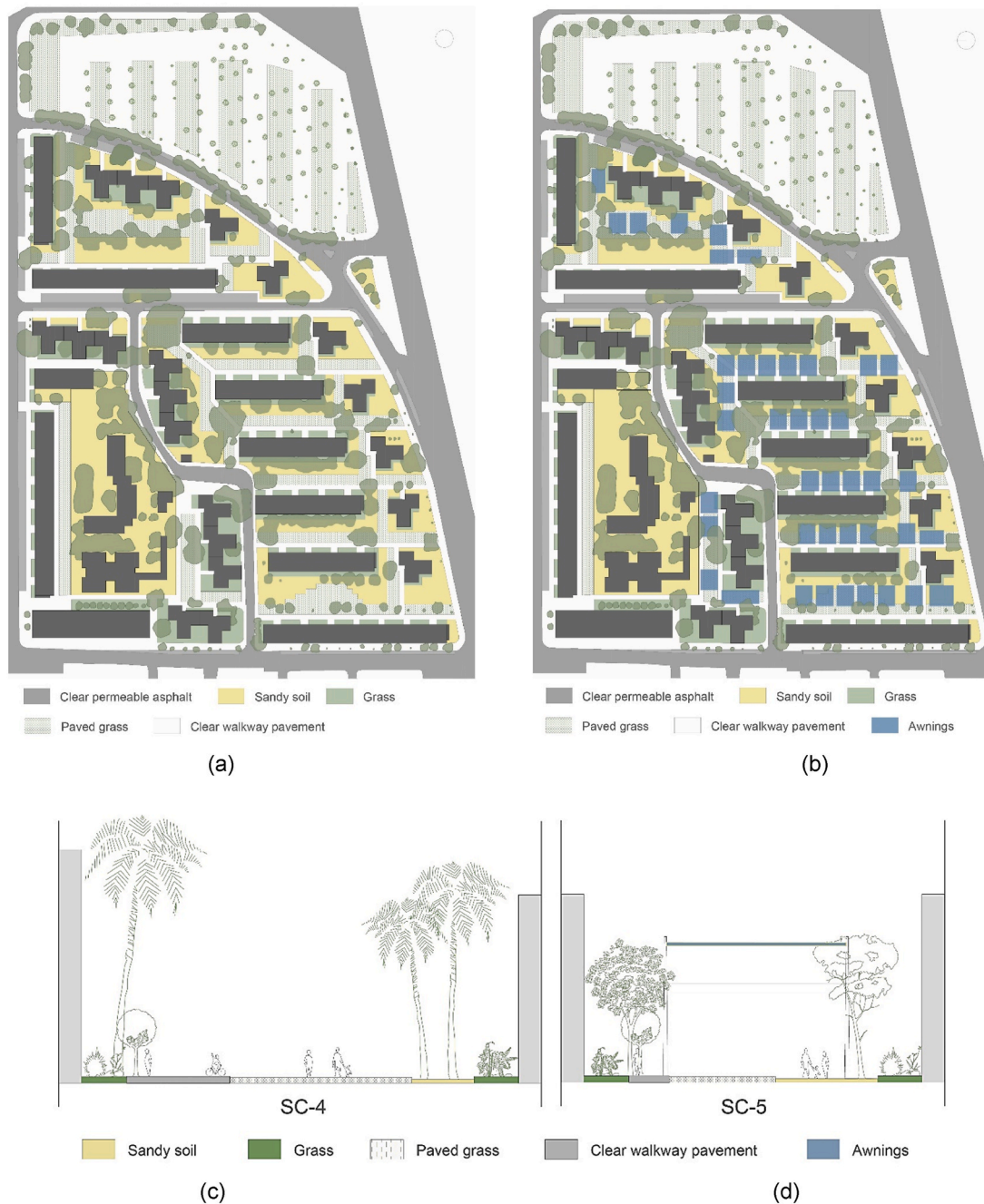


Fig. 15. (a - c) SC-4. (b - d) SC-5, new urban configuration proposals.

between SC-3 and SC-4 at different times of day. In general, better performance was observed at all hours in all areas where the materials had been replaced. The most notable improvement in UTCI values (up to 4.3 °C) occurs at noon, in the streets between the longitudinal blocks, where the asphalt road has been replaced with natural materials and paved grass. The reduction of UTCI in the north area outside the blocks is also worth noting, given that it is not shaded, so all improvement is the exclusive result of the change of material. During night-time the UTCI reduction in the area is lower, around 1 °C, but still noticeable.

Fig. 17 shows the UTCI difference results between SC-3 and SC-5, where the introduction of additional shading using awnings has been considered, in addition to the previous strategy regarding materials. In this case, the UTCI reduction at noon is even higher, reaching 6.4 °C, where the shading is installed. However, during the night (6:00 and 22:00 h), the areas under the shading provide a higher UTCI value than

the SC-3 with no shading installed (around 2.4 °C higher). This effect is the result of the shading blocking the night radiation to the sky of the pavement, preventing it from cooling down during the night. Although the surfaces are protected during the day, they also reach high temperatures and need to release radiation to the sky at night to reduce their surface temperature. As this is not possible, the UTCI under the awnings is higher during the night.

3.4. Discussion overview

3.4.1. Regarding the urban evolution of the case study and future projections

When comparing the first three scenarios, two distinct diagnostics emerge. From SC-1 to SC-2 there is a slight increase in temperatures due to the onset of climate change, although the differences are minimal. In

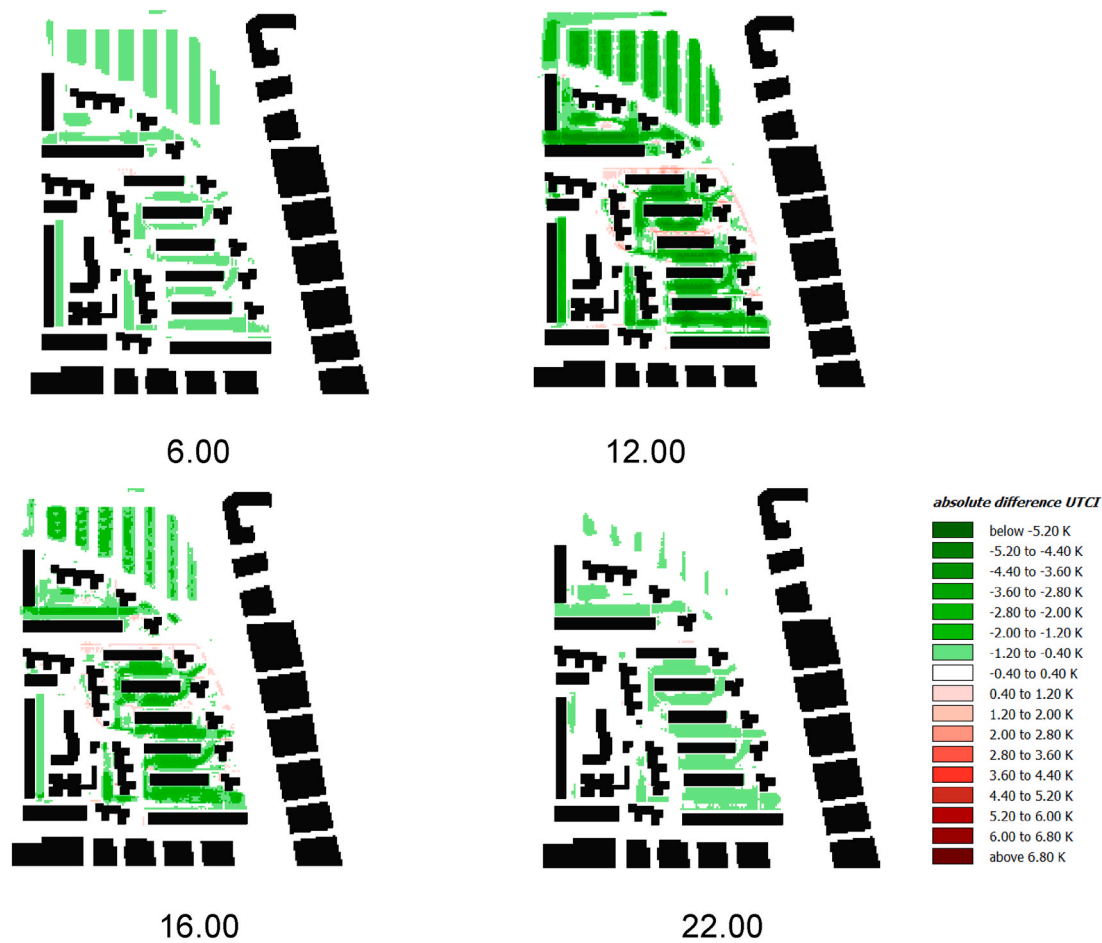


Fig. 16. UTCI difference between SC-3 and SC-4 (SC-4 – SC-3).

addition, the significant urban changes carried out have resulted in a noticeable improvement in comfort in the inner part of the neighbourhood, primarily due to the addition of a large green canopy from the SC-1 status, as previous studies confirmed [72,77]. Outside the shade of the trees, however, there is a slight general decline in comfort. This is attributed to the use of new heavy and dark urban pavements [58], such as conventional asphalts, concrete, and cement. This loss of comfort is more pronounced at night when the new materials release the heat absorbed during the day.

In contrast, a temperature increase of up to 7 °C is seen in SC-3 compared to SC-1, reflecting the worst possible climate change scenario for 2080 [83]. As a result, the comfort level for SC-3 has uniformly deteriorated compared to SC-1. Following such a significant temperature increase, the presence of vegetation alone is insufficient to improve the area's comfort. As the results of this research have shown, the case study area lacks the resilience needed to withstand the worst possible future climatic scenario.

3.4.2. Regarding the mitigation proposals

SC-4 focuses on pavement intervention. When analysing the literature on this subject, the use of cooling pavement is a feasible cost-effective solution for improving thermal comfort [73]. This intervention is affordable, requires low maintenance, and uses few resources [107]. Previous studies have reported a reduction of surface temperature of around 10 °C [74], while the maximum decrease in air temperature was between 1 and 2 °C [64], in line with the maximum decrease of 1.1 °C seen in this research. However, UTCI reduction is more significant, as these references also showed. SC-4 configuration has achieved a decrease of 4.3 °C in UTCI, aligned with previous research [77],

which obtained a maximum reduction even higher of 6 °C UTCI. This difference between air temperature and thermal comfort is because cooling pavement primarily affects radiation, thereby reducing MRT, which significantly influences pedestrians' thermal perception and UTCI equivalent temperatures. Additionally, the use of green permeable pavements in SC-4 also contributes to mitigating heat, as indicated Wollschläger et al. [76], who found a variation of up to 10 °C in terms of comfort in a small city scale. Moreover, the use of porous and low inertia materials enables heat transfer to the soil and exchange of humidity, thereby releasing absorbed heat quicker. Artificial porous materials or green natural soils such as grass or paved grass exhibit excellent thermal behaviour throughout the day, while leaf evapotranspiration aids in reducing air temperature. This behaviour coincides with previous research [75].

While cooling pavements have been shown to improve comfort in urban environments under extreme climate conditions, their effectiveness is often enhanced when used in conjunction with other strategies [59]. The use of pavement alone is supplemented with another passive cooling action in SC-5, introducing a new shade canopy using free-standing awnings as solar radiation filters. These cost-effective elements require easy installation and low maintenance and can be removed at the end of the warm season. They provide shade without adding humidity to the air, and their area of action, forms, and height can be designed as needed. Previous research has demonstrated that awnings can be crucial for blocking direct sun radiation, significantly reducing the mean radiant temperature (MRT) and improving comfort [71], which can be more important than AT when studying the thermal perception of pedestrians as highlighted [70]. Other studies have shown how these devices can complement other systems to reduce temperature

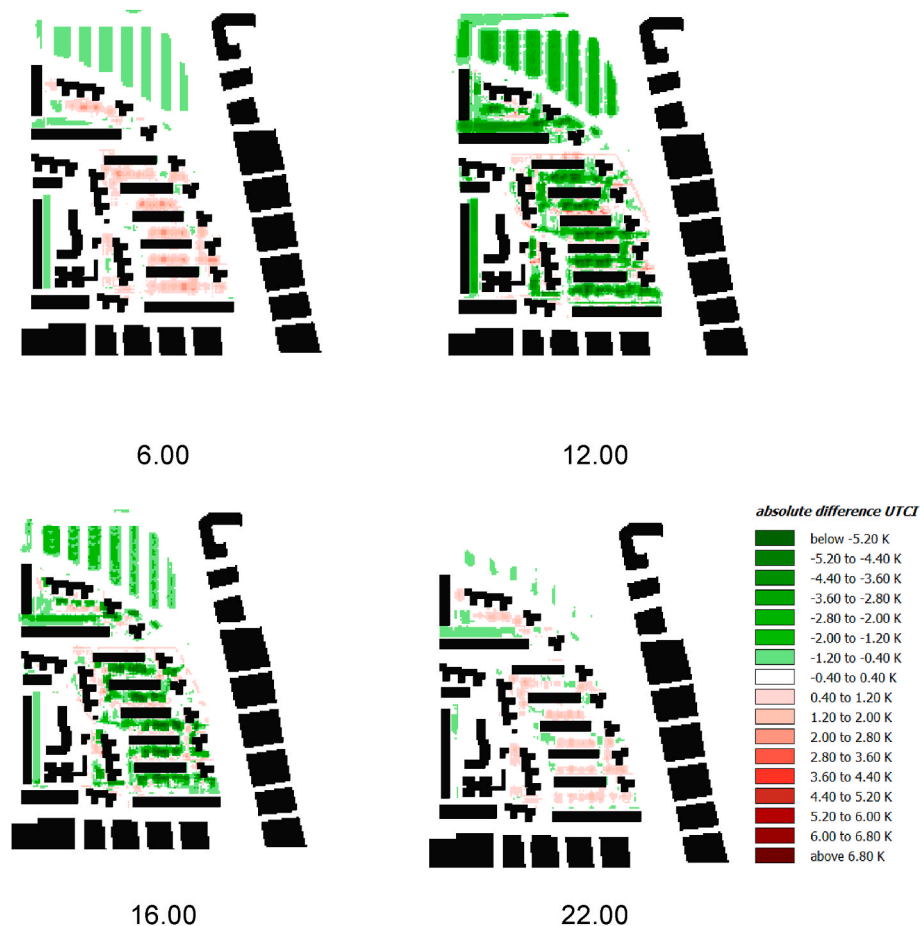


Fig. 17. UTCI difference between SC-3 and SC-5 (SC-5 - SC-3).

[64]. In this study, SC-5, which added this new shade, reduced the maximum UTCI by 3.5 °C compared to SC-4. This represents a reduction of 6.3 °C compared to the original urban configuration in SC-3, strengthening the cooling potential of these passive strategies. It is aligned with other previous studies with similar strategies in different scenarios [69,77], where the maximum UTCI reduction was around 7 °C. For the improved SC-5, the thermal perception during the central hour of the day has been lowered by one level on the UTCI scale perception. After implementing the strategies, SC-5 has several areas under 'strong heat stress' (32–38 °C) instead of 'very strong heat stress' (38–46 °C). Although the thermal perception is still not comfortable, the improvement in thermal perception is notable. These results confirm previous studies by other researchers, who pointed these strategies as the most effective in reducing heat without water consumption [68,69,71].

Nevertheless, the use of shading devices such as awnings produces a detrimental effect at night, which was also observed by a previous study [77]. As observed in Fig. 17, areas under the canopy experience slight nocturnal overheating. This is due to the blockage these surfaces create, preventing the radiation released by hot pavements from reaching the sky, as demonstrated in previous research [71]. The awnings also hinder nocturnal ventilation, trapping heat and humidity. This overheating increases thermal perception by up to 2 °C compared to the original configuration in SC-3. Therefore, an optimal solution could involve the use of the SC-5 configuration during the day to block solar radiation and reverting to SC-4 status during the evening and night to facilitate heat release and ventilation. However, this presents two challenges. Firstly, the use of mobile and mechanized structures such as urban awnings, which would allow for an adaptive and responsive urban cooling system, is not currently widespread. Secondly, computational fluid dynamic

(CFD) microclimate simulation software like ENVI-met does not support dynamic simulation when the model changes during the simulation time. This requires further research by technicians and programmers, as adapting the urban environment throughout the day will be crucial for achieving more resilient urban environments. This adaptability could lead to even better results than those presented in this study, with greater mitigation of high temperatures if the environment is optimized.

Additionally, non-climatic factors have been thoroughly considered in both improvement proposals. Revitalisation efforts adhere to the original MoMo space [20], yielding more liveable and pleasant environments for residents, thus providing an additional indirect benefit. Additionally, material selection has been guided by criteria such as affordability, low maintenance requirements, and long service life. Importantly, the mitigation strategies also contribute to reducing summer cooling energy demand. Although more research is needed to quantify the precise influence of the outdoors on the indoors, this relationship has already been shown [33,111]. This effect manifests itself in a reduction in electricity consumption for households, which, particularly in low-income districts, helps alleviate the prevalent issue of fuel poverty [12]. Therefore, the implementation of outdoor passive cooling strategies not only addresses comfort improvement challenges but also promotes broader social well-being and sustainability.

3.4.3. Study limitations and further research

Despite the promising results of this study, it is also necessary to consider some limitations. The assessment is carried out in a MoMo district, a very spread urban typology, but also particular and different from others. Thus, the methodology is exposed to allow its reproduction in further research analysing other kinds of urban fabric. This work uses the worst scenario of the IPCC scenarios of CC for future projections,

representing the most extreme conditions. Further approaches could include more favourable future conditions or more analytical methods to obtain climate files that can capture the dynamic changes in climate; however, better future climatic conditions will entail more notable mitigation results. Moreover, although the simulation day was chosen by a statistical analysis to be the most representative of summer, it should be borne in mind that simulations are made for a single day, so that further analysis could expand the results over other seasons and weather times. This constraint was imposed by the limitations of the ENVI-met simulation tool, which does not allow for dynamics simulations or the variation of daytime and nighttime conditions of shading elements in the model. It could be of great interest for further research since this dynamic and responsive design and subsequent simulation will also increase comfort with equivalent temperature reduction. Furthermore, a deep analysis of the cost and life cycle of specific materials chosen for these kinds of urban interventions is important and could be the object of a future investigation. Finally, further research could explore the quantification of the effectiveness of urban mitigation techniques in reducing indoor cooling demand, particularly in low-income neighbourhoods. The combined results of such approaches remain largely unexplored.

4. Conclusions

This study analyses the urban adaptation of a Spanish MoMo neighbourhood, examining its progression from its original construction to the present conditions and future projections. Considering the findings, mitigation strategies consisting of the use of cooling pavements and shading devices are proposed. It has been found that, although in its current condition the neighbourhood partially mitigates the current increase in temperatures compared to the original configuration, this is not sufficient for future projections considering the worst CC scenario. However, this urban layout, with a wide ratio of public space (84%) to built-up area (16%), archetypical for many other developments from MoMo, allows the implementation of strategies to improve the adaptation to extreme heat. This will be of great significance for the future resilience of these low-income housing developments.

According to the results, the strategy of using cooling pavements allowed a UTCI reduction of up to 4.3 °C under CC meteorological end-of-century projections, while this improvement increased to 6.3 °C when also including shading strategies. However, during the night, the use of shading devices hampers the potential release of heat to the sky and from the wind, worsening UTCI by up to 2 °C. Therefore, this study proposes the use of adaptive shading systems that can be retracted during the night. The simulation results of this final proposal have not been provided given the limitations of the simulation tool, which should be addressed in future research.

The methodology followed in this study, both in terms of analysing climate adaptation over time and iterating combinations of possible passive solutions, can be applied to many urban developments from the same period and style, but also to new and existing developments given the cost-effectiveness of the strategies used, affordable to stakeholders and policymakers. Moreover, the previous iteration made with a range of materials and properties, all obtained from the literature, have provided the optimized materials applied to this specific environment and climate conditions.

The findings of this research make it clear that mitigation strategies are vital for enhancing outdoor thermal comfort under current climate conditions, and their importance will only increase in light of future climate projections.

Disclosure statement

The authors declare no conflict of interest.

CRedit authorship contribution statement

Javier Sola-Caraballo: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Investigation, Formal analysis, Data curation. **Victoria Patricia Lopez-Cabeza:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Data curation. **Jorge Roa-Fernández:** Visualization, Investigation, Funding acquisition, Formal analysis. **Carlos Rivera-Gomez:** Formal analysis, Conceptualization, Funding acquisition, Investigation, Methodology, Supervision, Writing – review & editing. **Carmen Galan-Marin:** Writing – review & editing, Supervision, Resources, Conceptualization, Funding acquisition, Investigation, Methodology, Project administration.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.buildenv.2024.111485>.

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