Improving School Transition Spaces Microclimate to Make Them Liveable in Warm Climates

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Abstract: The so-called urban heat islands (UHI) is a thermal phenomenon characterized by higher air temperatures in the urban area than in rural surroundings. Vernacular passive strategies such as courtyards are proved to be useful to generate specific microclimates, especially in the warmer regions of the Earth. Courtyards increase the porosity of the cities, understanding porosity as building voids. Accordingly, their study will be fundamental in reducing the UHI effect by generating urban cooling microislands. This paper aims to analyze two passive strategies capable of modifying the thermal effect of radiation inside the courtyard of two school buildings: albedo and vegetation. In this regard, two case studies were assessed, both of them located in the city of Seville. Results show that the temperature in these spaces can vary up to 7 °C depending on the albedo, which confirms the importance of detecting an optimal albedo factor. In addition, data showed a significant increase in the thermal delta (TD), courtyard versus outdoor temperature, after the installation of a vegetal facade. Accordingly, both strategies will be fundamental in locations affected by climate change, especially considering that they are not only effective cooling strategies but also relatively easy to implement in the building’s refurbishment process.

Keywords: albedo; building envelope; coating materials; vegetation; courtyard; urban heat island; climate change

1. Introduction

Global average temperatures have increased over the last decades and their effects are worrying for today’s population. This rise in average temperatures is speeding up even more in large cities with the so-called urban heat island (UHI) effect influencing the daily life of these cities [1]. This thermal phenomenon implies that, while in rural areas the temperature decreases during the night, in the cities this cooling does not occur, producing an overheating of the urban downtown. UHI is more noticeable in hot periods when materials with high thermal capacity act as urban heat sinks during the night. Furthermore, in addition to the thermal accumulation produced by the materials, the massive construction of the ground in the big cities prevents adequate ventilation that helps to reduce this effect. This singularity, related to urban density, has been confirmed by numerous studies at different latitudes, with a value reaching up to 12 °C between rural and urban areas [2,3]. The main difference between the two areas is the presence of hard materials, which are thermally absorbent compared to the nature that invades the rest of the spaces. Therefore, the increase in the presence of vegetation can help to balance this aspect.

Increasingly prevalent summer heatwaves are detrimental to people’s comfort and impair their abilities and health [4]. These heat waves are causing even higher overheating in large cities due
to the UHI effect. In the city centers, the UHI in the summer is caused by the absorption of the high solar radiation by the urban surfaces [5]. Therefore, the comfort of the inhabitants of large cities is compromised and, hence, mechanical cooling of homes and workplaces is generally used, modifying the air quality and contributing to the city overheating [6]. Overheating is directly related to health. Heat absorption by the human body can lead to serious health problems in populations at risk. Reducing warming, especially in large cities, is a real and current problem. Therefore, making cities cooler seems to be of vital importance for public health [7]. Passive strategies such as courtyards have been incorporated by traditional architecture helping to temper the buildings overheating [8].

Not only their geometry but also the building envelope, especially cladding materials used in facades and outdoor pavements, are elements involving a great impact on the microclimatic conditions of the building’s environment. This influence is especially relevant in semi-outdoor or transition spaces such as inner courtyards since their specific microclimates are less dependent on climatic phenomena such as wind speed and direction and other associated thermal convection flows. Courtyards are essential for the proper balance of city porosity, understanding porosity as building voids, so their treatment and study will be fundamental in reducing the UHI effect of cities. The percentage of urban areas assigned to these spaces is significant in Mediterranean cities, so variations in their cladding materials can widely modify the overheating of these spaces [9]. Courtyards not only generate a specific microclimate but also are in direct contact with the building’s internal rooms, contributing to the comfort of these indoor spaces and reducing the use of mechanical cooling systems, a fundamental aspect in the increase of temperature and air quality in cities [10].

The albedo is defined as the measure of the diffuse reflection of solar radiation out of the total solar radiation that is reflected by the surface of a particular material. The albedo value ranges from 0 to 1, being 0 the value for a material surface that absorbs all the radiation it receives, and 1 for a material surface that does not absorb any radiation but reflects 100% of it [7]. The materials used as the coating surfaces have an important role in the reduction of the thermal gains and the overheating of the cities. In this way, it is possible to achieve a thermal balance in a specific urban environment, reducing the absorbed solar radiation [11]. The use of materials characterized by a remarkably high reflectance reduces the solar radiation absorbed to a greater extent than conventional materials, being useful to reduce the temperature of certain spaces in cities, and therefore, reducing the UHI effect [12]. Different studies carried out on albedo deal with their ability in terms of air and surface thermal managing, but hardly anyone takes into account the users’ thermal comfort perspective [13]. In courtyards, a specific microclimate is generated, with a thermal reduction compared to the outdoor temperature [14]. The analysis of the influence of albedo and vegetation as passive strategies in these spaces can help to clarify their relevance in buildings and cities [15,16].

Additionally, the impact of vegetation on the courtyard microclimate is another important cooling strategy to counterbalance global radiation and high air temperature [17]. The tempering effect of vegetation is due to the evapotranspiration physical phenomenon, the blockage of solar radiation, and the reflection of the solar radiation due to its higher albedo compared to other materials [5]. The vegetation performs two particular functions in these systems: (a) intercepting sunlight before the building gets warm, which is an energy-saving instrument that controls solar radiation in the summer and avoids overheating and temperature fluctuations inside the buildings. Additionally, (b) decreasing wind speed [18]. The cool surfaces provided by the leaves can be effective in reducing the energy used for cooling and heating [19]. The vegetation acts as a cooling element due to evapotranspiration [20], a process based on the evaporation of water in the vegetation and surrounding soil [21].

This paper aims to shed light on the urban overheating phenomenon by analyzing thermal conditions in courtyards. The study focuses on the building envelope, analyzing the microclimatic impact of the coating materials. To this end, the effect of albedo and vegetation, and the resulted thermal differences within two case studies located in the city of Seville have been considered. The microclimatic evaluation has been performed through two different experimental setups applied in two free-running school buildings. Assessment of the thermal parameters in the outdoor environment
and the courtyards, and building data related to the geometry, orientation and solar direct radiation would be previously studied to evaluate the courtyards’ thermal tempering potential. Although the results obtained in this study are limited to the geometry of transitional spaces such as courtyards under climatic and radiation conditions defined by a precise location, the proposed method has several advantages: it is simple, fast and can be easily implemented in microclimate assessments of outdoor and semi-outdoor spaces. Furthermore, the main novelty of the study is to determine the influence of building envelope surface materials in these semi-outdoor spaces quantifying their impact as passive strategies through full-scale experiments.

2. Materials and Methods

A methodological model to determine the influence of the different parameters on the courtyard microclimate was applied (Figure 1). Firstly, a detailed description of the selected case studies and a climate analysis of their location to determine the more suitable periods for field monitoring campaigns were achieved. Secondly, studies of sunlight conditions and radiation were performed. Afterwards, a field monitoring campaign with the previous and later state, after the application of the experiments, for both case studies was carried out. Additionally, finally, the experiments results were analyzed.

![Figure 1. Overview of the methodological assessment.](image)

2.1. Case Studies, Location and Climate Description

In this research, two case studies located in the south of Spain were analyzed, specifically, two free-running school buildings in the city of Seville (Seville, Spain, 37° 22′ 58″ N 5° 58′ 23″ W, 16 m. a.s.l.). This city is characterized by a warm climate, with high temperatures in summer. The Spanish building regulation, CTE [22], which categorizes the country’s climate zoning, references Seville as a B4 climate zone, which indicates a winter with mild temperatures and very hot summers (the highest summer severity). According to Köppen’s classification, the city is located in a Csa category area, characterized by hot summers, with a dry and warm climate [23]. The hottest months of the year are characterized by low rainfall. The courtyards selected as case studies have different geometric characteristics, but share orientation and have been monitored under the same climatic conditions over a minimum period of two weeks. The geometry of the courtyard is a fundamental aspect to take into account in the study in addition to the climatic characteristics defined by the location. Previous studies confirm the importance of the relationship between the height (H) and width (W) of the courtyard, known as the aspect ratio (AR) [24] (Equation (1)). Aspect ratios of both courtyards are calculated.
aspect ratio (AR) [24] (Equation (1)). Aspect ratios of both courtyards are described in Table 1. AR (I and II) are defined, one for each of the two main dimensions of the courtyard.

$$AR = \frac{W}{H}$$  \hspace{1cm} (1)

| Case Study | City   | Climate Zoning [22] | Surface (m²) | Dimensions (m) | Height (m) | AR I | AR II |
|------------|--------|---------------------|--------------|----------------|------------|------|-------|
| Case 1     | Seville| B4                  | 152.2        | 8.6            | 17.7       | 7    | 0.81  | 0.40  |
| Case 2     | Seville| B4                  | 35.9         | 5.2            | 6.9        | 5    | 0.96  | 0.72  |

Both case studies are located in primary schools and used to be considered as secondary areas. Currently, due to the Covid-19 pandemic, not only the importance of classrooms’ natural ventilation (to avoid aerosol transmission) has been enhanced but also the importance of using outdoor spaces as teaching spaces has been highlighted.

Case Study 1. The first case study is a public school building located in a district in the north of the city. It has a central courtyard on the upper floors where the study is held. The courtyard is in direct contact with the nearby rooms. All of them are classrooms. The courtyard’s pavement is coated with a black waterproofing material (Figure 2).

![Figure 2. Case study 1: Courtyard overview.](image)

Case Study 2. The second case study is a school building located in the eastern part of the city, recently refurbished. The building includes a central courtyard with square proportions (Figure 3).

![Figure 3. Case study 2: Courtyard overviews.](image)

The following table summarizes the main climatic and geometric characteristics of the case studies analyzed in this study (Table 1). A representation of the geometry of the courtyards is shown in Figure 4 to better compare their proportions.
2.2. Field Measurement Methodology

Different field monitoring campaigns have been carried out in both case studies when the buildings were unoccupied to avoid the interference of the users’ load [25]. The minimum period for each monitoring campaign was two weeks. Temperature measurements were taken simultaneously inside the courtyards and on the roof of the buildings. The field monitoring campaigns have been carried out during the warm season to evaluate the influence of the courtyard’s tempering effect related to the UHI effect. Measurements have been made using a PCE-FWS-20 (Table 2) portable weather station located on the roof of the buildings, in an open area without any walls or buildings that could affect the measurement of the outside temperature that surrounds the building. This temperature has been compared with the meteorological data provided by the Spanish Agency of Meteorology (AEMET) [26]. The outdoor temperature data differ a few degrees in both measurements; this is because the AEMET data are measured at the airport of Seville, located in the outskirts of the city, thus, avoiding the UHI effect inside the city.

| Sensor                  | Variable       | Accuracy  | Range          | Resolution |
|-------------------------|----------------|-----------|----------------|------------|
| Data logger TESTO 174(H/T) | Dry bulb Temp. | ±0.5 °C   | −20 to +70 °C  | 0.1 °C     |
|                         | RH             | ±0.1%     | 0–100%         | 2%         |
| PCE Instruments PCE-FWS 20 | Dry bulb Temp. | ±0.1 °C   | −40 to +65 °C  | 0.1 °C     |
|                         | RH             | ±5%       | 12–99%         | 1%         |
|                         | Wind           | ±1 m/s    | 0–180 km/h     | -          |

Data obtained inside the courtyards have been recorded by TESTO 174 H and TESTO 174 T (Table 2) data loggers that have been placed 10 cm apart from the walls, located at different heights to check the temperature stratification inside the courtyard. The data loggers have been protected from direct sun radiation by applying a ventilated shield made with insulation material, which also protected them from the radiation from the building envelope. In Figures 5 and 6, the data loggers’ position is displayed.
2.3. Solar Study and Site Radiation

A solar study of both case studies was carried out to detect the optimum facades of the courtyard to adequately plan the field monitoring campaigns (Figure 7).

Additionally, the solar radiation distribution of the planning area was calculated in order to evaluate the potential efficiency of any intervention in pavements and facades. Autodesk Revit software [27] that belongs to the BIM environment was used to determine solar radiation distribution during the hottest day of each monitoring campaign. Figure 8 displays the distribution of the total...
accumulated insolation in case study 1 during one monitoring week, from 9th September to 16th September. In parallel, Figure 9 exposes the distribution in case study 2, from 24th September to 1st October. The maximum and minimum cumulative insolation values for both case studies are shown in Table 3. These values represent the radiation accumulated by the courtyard facades depending on their orientation. Note that in the present research, the solar radiation study was limited to the courtyard unit inside the buildings.

![Figure 8. Case study 1: Cumulative insolation from 9th September to 16th September.](image)

![Figure 9. Case study 2: Cumulative insolation from 24th September to 1st October.](image)

| Case Study | Maximum Cumulative Insolation | Minimum Cumulative Insolation |
|------------|-------------------------------|-------------------------------|
| Case 1     | 28 kWh/m²                     | 4 kWh/m²                      |
| Case 2     | 33 kWh/m²                     | 4 kWh/m²                      |

The results of the analysis, in terms of accumulated energy of a surface (kWh/m²), include direct radiation, diffuse radiation, radiation reflected from the ground, shading of surrounding objects, the portion of the sky “visible” by the surface and the angle of incidence between the sun and the face being analyzed [27]. As observed in Table 3, the accumulated solar radiation data for the two case studies analyzed revealed similar maximum and minimum values. This is explained by the similarity in orientation and AR values of both courtyards, despite corresponding to different sizes.

2.4. Experiments

As part of the research, the materials of the courtyards’ envelope, facades and pavement were changed during the field monitoring campaigns: in case study 1, a change in the albedo of the pavement, with a specific color modification (Experiment 1) and in case study 2, the incorporation of vegetation inside the courtyard consisting of the installation of a vegetal façade (Experiment 2).

Experiment 1. Taking into account previous research [16], in which a study was conducted to see the effects on the microclimate of the albedo in a courtyard, the pavement was covered with two
sheets, one white (albedo 0.91) and one black (albedo 0.37). This showed the influence of surface color on indoor and outdoor thermal comfort in public and urban spaces, such as courtyards. Based on this methodology, a similar experiment was carried out in case study 1. The main goal was to study the impact of the albedo on the courtyard microclimate in a warm climate area such as Seville. Due to the current condition of the courtyard pavement (a black waterproofing membrane), another sheet with a higher reflection coefficient was used to study its impact, and to analyze its possible use as a cooling strategy, thus improving the courtyard thermodynamic performance and the comfort of the surrounding classrooms.

To carry out this experiment, air and surface temperature data loggers and a thermal imaging infrared camera were used. The sheet used in the experiment was a 2.00 m × 7.50 m waterproof polymer roofing SIKA ® (SIKA, Baar, Switzerland) membrane (Figure 10). Based on the solar study, this sheet was placed in the area that receives the highest direct solar radiation during the students’ time at the school (from 9:00 a.m. to 5:00 p.m.). The sheet used is Sarnafil TS 77-18 (SIKA, Baar, Switzerland) (waterproof membrane for roofing purposes), it has a CIGS (Copper Indium Gallium Selenide) reflectance of 95%, a solar reflectance of 0.90, an initial emittance of 0.85 and a solar reflectance index of 112. A TESTO 885 thermal camera (TESTO, Lenzkirch, Germany) and a TESTO 435 surface temperature sensor (TESTO, Lenzkirch, Germany) were used to check the surface temperature of the courtyard.

![Figure 10. Case study 1: Waterproof polymer roofing SIKA ® membrane placement.](image)

Experiment 2. Knowing the significance of vegetation as a key strategy in minimizing urban overheating, the second study consists of a modification of one of the facades’ surface coating of the courtyard in case study 2. For this purpose, a plant layer with drip irrigation was installed on the facade with the highest direct radiation from the sun as shown below (Figure 11). The vegetal system used was an optimal passive facade solution consisting of an industrialized and sustainable system that puts together different plants in the same module to be part of the constructive elements in the building’s facade. The vegetal facade was defined by several 100 cm × 100 cm modules (39.4 inches × 39.4 inches). Each module was constituted by several elements that are available in the market and do not require advanced technology: galvanized welded mesh and a plastic cell (replaceable by a metal box) with a substrate for the development of plants. The system includes a galvanized steel structure as a support frame.
3. Results and Discussion

Results of the two UHI mitigating strategies were analyzed below according to the methodology used; first, results corresponding to the field monitoring campaigns are presented, establishing the previous thermal behavior of the selected courtyards. Then, the results after the implementation of the strategies described in the experiments and the potential improvement of the thermal behavior were analyzed.

3.1. Analysis of Previous Thermal Behaviour before Strategies Implementation

The thermal tempering performance of the courtyard in case 1 was not particularly relevant (see Figure 12). The microclimatic analysis carried out shows a thermal delta (TD; Equation (2)), up to 4–6 °C for an outdoor temperature range between 25 and 30 °C.

\[
TD = \text{Outdoor Temperature} - \text{Courtyard Temperature}, \tag{2}
\]

Data loggers placed inside the courtyard show an average TD up to 2 °C. The limited thermal behavior improvement of the courtyard is due to two fundamental aspects: on the one hand, the courtyard geometry, since it has a low AR, which does not allow great stratification and compromises the thermal behavior. On the other hand, the black pavement finishing material, capable of absorbing a great amount of solar radiation, and turning it into overheating. However, the same low AR allows the courtyard to be properly ventilated at night, greatly reducing daytime overheating.

The courtyard thermal behavior in case 2 was better than in the previous case study, tempering better the outdoor temperatures, and achieving a TD up to 4 °C at the time of the maximum daily temperature (Figure 13). For a courtyard with an AR lower than 1, this is an adequate TD [3]. In this case, to be able to carry out the subsequent comparison, the results show the values measured on the south-west and south-east facing facades, with hardly any difference between the two. The low depth of the courtyard implies that there is hardly any thermal stratification inside, as in case study 1. In this case, the pavement was white gravel (albedo range close to 0.7), a less absorbent material than in case study 1.
The previous TD of 4 °C measured in the first stage (displayed in Figure 16) increased up to 11 °C with the installation of the vegetal façade, comparing a day with similar outdoor temperatures. While both facades presented no thermal difference before, after the adoption of the vegetation strategy, a difference up to 2 °C at some hours of the day is observed, despite the proximity between the facades (Figure 15). Moreover, the main objective being the thermal tempering of the microclimate generated by the courtyard is noticeable. In case study 2, a vegetal facade was implemented in the south-west wall, being the facade that receives more hours of direct solar radiation. When the vegetal facade was installed, it substantially improved the TD regarding the outdoor temperature. While both facades presented no thermal difference before, after the adoption of the vegetation strategy, a difference up to 2 °C at some hours of the day is observed, despite the proximity between the facades (Figure 15). Moreover, the main objective being the thermal tempering of the microclimate generated by the courtyard is noticeable. The previous TD of 4 °C measured in the first stage (displayed in Figure 16) increased up to 11 °C with the installation of the vegetal façade, comparing a day with similar outdoor temperatures.

3.2. Comparison of Thermal Mitigation Strategies Effectiveness

In case study 1, the results show (Figure 14a) how the impact of texture and color of the pavement is fundamental to the thermal behavior of a space such as a courtyard. While the surface temperature of the original black pavement sheet was 70 °C, the surface temperature of the new white sheet was 50 °C, i.e., about 20 °C difference between the surface temperatures of the two materials. A second thermal image was taken when the new sheet was lifted and removed to see the effects that it had on the existing pavement. It can be seen that a lot of heat is stored on the back of the sheet, but it did not reach the temperatures of the current pavement (Figure 14b). Finally, when the sheet was fully removed and another thermal picture was taken, the thermal footprint was visible while the floor temperature is recovered (Figure 14c).

Figure 13. Previous thermal behavior (02–09 October) of case study 2.

Figure 14. Case study 1: (a) thermographic image of albedo modification, (b) partial removal of the new sheet and (c) total removal of the new sheet.
In the present research, the addition of the vegetal facade and water ponds largely determined their climatic behavior. Previous studies have observed differences between the outdoor and courtyard temperatures up to 15.8 °C when vegetation and water ponds are used in the courtyards [16]. In the case of public buildings that are intended to be thermally refurbished to promote sustainable performances as free-running buildings, this study shows that courtyards offered a great opportunity and are relatively easy to execute, by changing some of the finishing materials. Moreover, improving the microclimate in these types of spaces in schools offers the possibility to use them as teaching spaces and subsequently improves natural ventilation possibilities of the adjacent classrooms, a fundamental issue currently, due to the Covid-19 pandemic.

Specifically, it is possible to lower the surface temperature of a pavement by several tens of degrees by modifying the albedo range. It is also feasible to increase above 10 °C the courtyard TD concerning the outdoor temperature by introducing vegetation into the courtyard using low-maintenance vegetal facade adapted to the local climate. Furthermore, these strategies can help to reduce the increase of temperatures in cities and improve thermal comfort in adjacent-to-the-courtyard rooms within free-running buildings.

All things considered, the obtained data show a significant transformation of the original microclimate for both case studies, which implies the main contribution of this paper that is to highlight the potential of using an experimental method, based on the evaluation of possible modifications of the coating materials, for a more comprehensive assessment of courtyards’ microclimatic performance.
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