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The adaptation of the "porous residential building model" to hot dry climates: The case study of a residential block in Athens, Greece.

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ABSTRACT: The "porous residential building" model has been proposed as a method of improving natural ventilation and reducing the cooling load in new buildings designed in dense cities located in hot humid climates. Conversely, in hot dry climates such a method would only introduce hot dry air indoors, producing discomfort. This research aims to investigate the adaptation of the porous residential building model to a hot dry climate, introduced as a retrofit method to improve the comfort conditions experienced in the introduced voids. A typical residential block located at the centre of Athens is selected and examined using the ENVI-met microclimatic software in order to assess the model's impact on the building's cooling load and the PET thermal index experienced inside the introduced voids. This research concludes that the conversion of the case study's corridors, into shaded outdoors spaces incorporating dense vegetated walls, constitutes an effective adaptation process of the proposed model. Keywords: porous, residential, hot dry climate, evaporative cooling, void, ENVI-met, PET index.

1. INTRODUCTION

The porous residential building model has been proposed as a way of improving natural ventilation and reducing the cooling load in new buildings designed for dense cities in hot humid climates. If the model were transferred to hot dry climates, however, one would anticipate that natural ventilation would introduce hot dry air indoors producing discomfort during the summer period. Moreover, in dense cities the performance of most natural ventilation techniques is reduced due to the significant decrease of wind speed caused by street urban canyons [1]. The aim of this paper is to investigate an adaptation of the porous residential building model for Athens, Greece, introduced as a retrofit method to improve living conditions in the existing building stock that overcomes these difficulties.

2. BACKGROUND

Athens is the fast-growing and high-density capital city of Greece. The Athenian climate is classified as Mediterranean [2] experiencing mild winters and hot dry summers [3]. During the summer period, on which this paper focuses, the air's quality is determined by a number of polluting episodes,

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during all seasons, lasting from two to seven days each, during which stagnant air conditions coupled with calms or light winds result in poor vertical air mixing and excessive atmospheric concentration of pollutants. These episodes have negative effects on the population's health [4].
The hot dry summers are also exacerbated by the urban heat island effect [3]. The effect is more intense in Athens due to a number of factors related to Athenian urban design such as abundance of narrow streets and lack of green spaces [5]. The resulting microclimatic conditions lead to high temperatures by day, and reduce the ability of the environment to act as a heat sink and to allow night ventilation, as the wind's velocity is dramatically reduced between buildings [6]. As a result of the increased urbanization, anthropogenic heat, topography, geographic location and urban design of Athens, frequent occurrence of high air temperature is observed, specifically in July and August.
A number of researchers have investigated the role of evaporative cooling in hot dry climates, through the use of vegetation to deliver a “cooling effect” reducing building energy consumption, improving air quality, and socially upgrading urban neighborhoods, with results that point toward its positive effect [7, 8, 9, 10]. Alexandri and Jones [11] discussed the microclimatic effect of covering the building fabric with vegetation for various climates and street canyon geometries. The research verified that there is great potential for reducing air temperature inside an urban canyon once vegetation is installed on building roofs and walls, which could decrease the building cooling load by 66%. In their Athenian case study, a canyon air temperature drop of 1^{o}C to 4.5^{o}C was observed when walls were covered with vegetation and of 2^{o}C to 6.5^{o}C when roofs were also covered. Overall, the research concludes that all air and surface temperatures decreased when walls and roofs were covered with vegetation as a result of the “*evaporative heat transfer on the green roof acts constantly as a heat sink and the radiative energy absorbed by a green roof is smaller than that absorbed by a concrete roof*” which led to the air masses entering the canyon being cooler from the vegetated roofs [11]. Moreover, the research showed that during hot periods, the efficiency of such method depends more on the density and geometry of vegetation, if the wind speed is limited. In conclusion, it is suggested that the implementation of vegetation as a method for mitigating heat stress observed in urban centers located in hot dry climates, is efficient even if the elements are of small scale, their efficiency depending on the design, type and strategic installation of vegetation.
The porous building model originates with the “space block design method” introduced by Dr. Kojima [12]. The design proposes the formation of a modular space block, such as a 2.5m cube, used either as a closed or open space which, when repeated and combined in different ways, creates a building form yielding various relations between indoors and outdoors. Murakami [13] used this space block design method and enhanced the research by using feedback from CFD analysis on its ventilation performance, whilst studying different space block sizes and configurations. They assumed that the model contains a number of additional features which enhance natural ventilation including a double skin roof, a PMV control

system and a radiation panel cooling system. Hirano's study [14] using the space block design method shared the same goals but incorporated a hybrid ventilation system, which controlled the openings and air conditioning operation according to external temperature. It examined two types of residential building models differentiated by their void ratios of 0% and 50%. The void ratio represents the percentage of the total space occupied by voids with the 0% void ratio representing a building without voids. Moreover, Hirano invented a separate type titled the "component scale void" model, which refers to double skin roofs and walls. Murakami's research concluded that "ventilation using various building and air conditioning devices, such as introducing natural ventilation, solar shading, a PMV control system, and radiation panel cooling reduces CO2 emissions at the running stage by 30%". Hirano's research concluded that the porous morphology can improve the performance of natural ventilation and diminish the building's cooling load. A void ratio of 50% can achieve four times larger air change per hour (ACH) rate and 30% faster wind speed than the 0% void ratio, as well as reduce the cooling load by 20% without compromising the indoor comfort level. In addition, it is shown that the third type, the component scale voids, can reduce the cooling load by reducing the cooling needs that arise from all except for the internal heat gains by 40% as it provides shading to the fabric.

3. RESEARCH AIMS AND METHODS

This research aims at emulating the porous residential building model by converting parts of the existing building into voids and experimenting with various void ratios and configurations. The adaptation scenarios concentrate on assisting the porous model with additional evaporative cooling through the use of vegetation elements, and are assessed by examining their impact on the building cooling load and PET thermal index experienced inside the introduced voids. A residential block in the center of Athens, adhering to the attributes of a typical Athenian residential block as described by Papamanolis [15], was selected and modeled. The selected case study was a newly built 7-storey building with pilotis located in the municipality of Athens (Fig. 1).

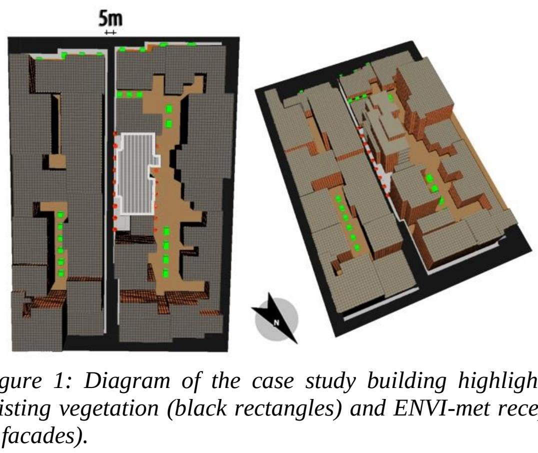

Figure 1: Diagram of the case study building highlighted in white, also showing existing vegetation (black rectangles) and ENVI-met receptors (white circles in front of facades).

Research tools: ENVI-met was used to assess the impact of the adaptation scenarios on the air temperature of the introduced voids. ENVI-met is a 3D computer model which simulates the microscale thermal processes taking place inside urban areas. It divides space into three-dimensional cells and bases its calculations on data describing a given environment's vegetation, urban and building geometry, materials and weather conditions. ENVI-met calculates the vegetation's physiological activities "at a leaf scale base and under the influence of varying environmental conditions" using the A-gs model [16]. This gives a more detailed calculation of the stomata's conductance by calculating both the different influencing factors and the synergistic effects between the various stimuli [17]. ENVI-met produces results based on the laws of thermo-dynamics and fluid dynamics in order to simulate the environmental microclimatic conditions, such as the heat exchanges taking place on the ground surface and building elements as well as air flow and turbulence [16]. Its advantage lies in its capacity to produce detailed spatial and temporal results by combining the effects deriving from the calculation of evapotranspiration, airflow and solar radiation. Version 4.0, gives the user the ability to design complex buildings and calculate the façade's temperature and wall energy balance based on an advanced 3-node transient state model [18]. ENVI-met's limitations include inability to model water turbulent mixing with simulation of water bodies. Moreover, ENVI-met allows, in each grid cell, vegetation to be installed in only one position along the length of the vertical axis, and that position is either the ground level or the top of a building. As a result, a number of design proposals incorporating a different configuration of vegetated semi-open spaces could not be examined. Additionally, this led to the modelling of trees in the form of vertical stacks of continuous vegetation piercing through semi open spaces consisting of two dimensional walking decks. Vegetated walls were modelled in the same fashion. Overall, we can keep in mind that in a real life situation a small number of additional parameters that cannot be accounted for in this research have an impact on the simulated environment.
Independent software, LEONARDO, was employed for the visualization of ENVI-met's outputs in the form of spatial variation maps of the four basic environmental parameters affecting thermal comfort outdoors being air temperature, relative humidity, mean radiant temperature (MRT) and wind speed. In order to acquire a more holistic understanding of the simulated phenomena, six receptors per level were placed in front of each free façade recording the state of the atmosphere and two inside each void. Results on these parameters were extracted manually by inspection from these maps for each of the simulated dates and hours, and then organized manually into tables. Subsequently, this research employed the PET index in order to assess the comfort conditions observed inside the voids. This index was selected as it is believed to incorporate most of the variables and thermophysiological processes defining comfort in comparison to other indices, and seems to currently be in more general use in investigating comfort outdoors. RayMan 1.2 developed by Matzarakis [19] to calculate the PET index was employed. The results from the LEONARDO tables were then fed into RayMan 1.2

manually in order to give a final output on the thermal comfort experienced in the introduced voids (Fig. 2).

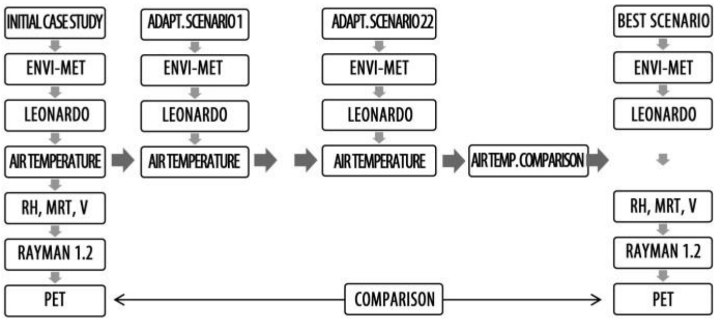

Figure 2: Research methodology

Design of Adaptation scenarios: The case study was modeled as a composition of brick walls and concrete slabs. Three separate designs depicting different ways of introducing voids inside the residential block were examined. All designs incorporate shading. The first design proposed the conversion of parts of each floor's apartments into semi open spaces; the second proposed the conversion of the block's corridors into outdoors spaces divided by semitransparent walking decks; the third pro-posed a combination of the first two design proposals. In each of the designs, different methods of introducing vegetation and water elements were examined. These methods allowed experimentation with the type and con-figuration of vegetation, yet they are guided by design restrictions set by ENVI-met. The methods included the introduction of vegetation in the form of vegetated walls, water in the form of ground pools, and vegetation in the form of trees. Overall, 22 different scenarios were examined. Each scenario was tested for three different leaf area densities (LAD) varying from light to dense using an optimum value for root area density (RAD).

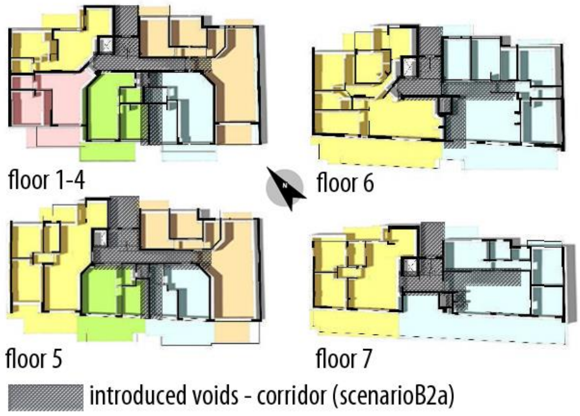

Figure 3: Adaptation Scenario B2a - diagram showing the different apartments per floor and the introduced voids replacing the public corridor and part of the apartment rooms.

Research Methodology: An initial selection of the most promising scenario was made for further analysis. Air temperature was employed for the selection, in advance of calculating the PET index. Results for all four basic parameters affecting thermal comfort were extracted for this scenario and inserted into the tables for Rayman 1.2. This avoided the need to calculate PET indices for all 22 scenarios, which would not have been feasible considering the time needed for the manual extraction of this data for Rayman 1.2. This decision route assumes air temperature to be the most dominant out of the four parameters. This assumption was based on the following facts. First, by sampling through the case study's results, we observed that the variation of relative humidity does not vary enough to be able to significantly affect thermal comfort. The wind speed recorded inside the voids and in front of the facades was not expected to vary significantly from the initial input fed to ENVI-met which was 0.1m/s. Additionally, both solar geometry and ENVI-met's figures for the solar exposure demonstrated that the walking decks dividing the voids, keep the voids shaded during most of day.
Consequently, the variation of MRT was expected to be limited in most cases. Although it is recognized that radiant temperature and air movement can be significant influences on comfort [20], given the aforementioned conditions, it was decided to use air temperature in selecting the scenario with the greatest potential for improving thermal comfort inside the voids. The research focused on the period between 09:00 and 15:00 in order to evaluate the capacity of the adaptation scenarios to block solar radiation and cool the air inside the voids during the hours of maximum global radiation of the summer's hottest day. Figure 2 illustrates this methodology.

4. FINDINGS AND DISCUSSION

Scenario B2a (Fig. 3), introducing vegetated walls with dense foliage in the communal corridors and shading through the use of semi-transparent decks, appeared to result in the lowest air temperature in most of the examined months and hours (Fig. 4). In this scenario, the building has been divided into two separate volumes, composed of identical materials and communicating through an outdoors seven storey corridor divided by heat protected glass walking decks. We also observed that amongst all cases, B2a was in the top four successful scenarios based on PET comparison (Fig. 4).

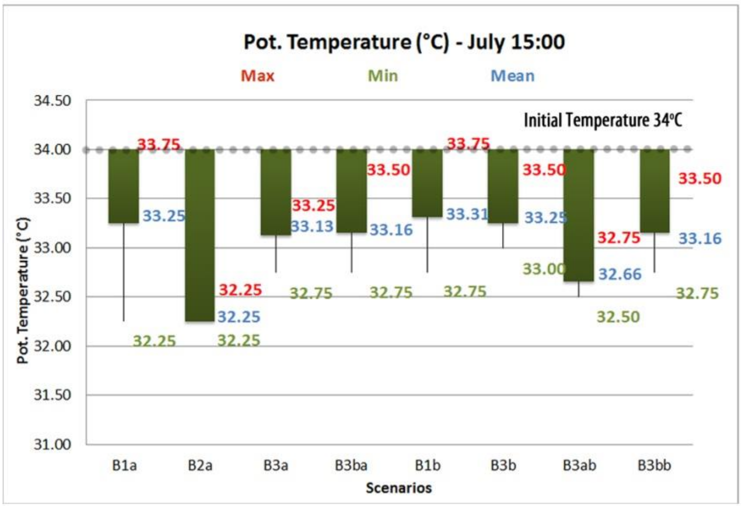

Figure 4: Air temperature inside the introduced voids, July, 15:00 – Comparison of different adaptation scenarios

PET calculation: In June, scenario B2a's Relative Humidity levels ranged between 45% and 61% in the voids, with small variation recorded between levels. Similarly, in July, values ranged between 39% and 60% and in August between 37% and 55%. Higher values were recorded toward the NE part of the corridor for all months. This is related to the fact that the SW part of the corridor was more exposed to solar radiation and had recorded airflows of greater speed. B2a's MRT in the introduced voids was at 48^{o}C at 09:00, 50^{o}C at 12:00 and between 51^{o}C and 52^{o}C at 15:00 in July. It must be noted that, unlike the case study, B2a presented very low MRT variation if any from level to level. The diurnal variation coincided with the facades' solar exposure; shaded surfaces present a lower MRT than the exposed. In order to explain the variation patterns observed between scenario B2a and the reference study, we need to consider that MRT is influenced by the direct, reflected and diffused solar radiation as well as by the surface temperature of the urban fabric's materials [21].

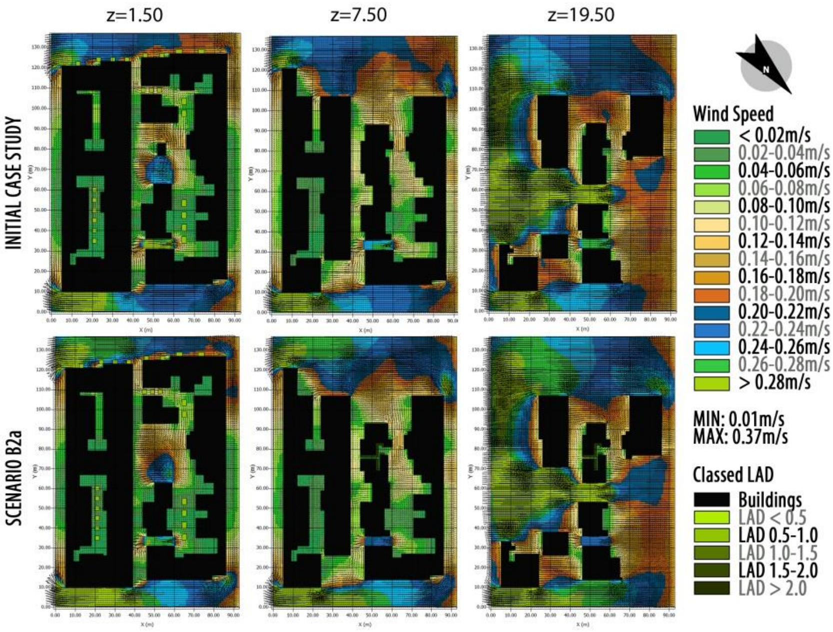

Figure 5: Wind Flow and Speed, July, 15:00 – Comparison of reference study (top) and adaptation scenario B2a (bottom)

The extent to which thermal comfort is affected by the urban fabric MRT in open spaces where the recorded air temperature is already high, is the subject of debate between Landsberg and Givoni, with the latter saying that it is negligible [22, 23]. In B2a, the corridor allowed for air flow between the new volumes and a certain amount of radiation reaching the lower levels of the building. Overall, this scenario allowed for a change in form which could explain the difference in MRT recorded in front of the facades. The wind velocity in scenario B2a ranged according to level in July at 09:00 between 0.01m/s and 0.13m/s at the SW part of the corridor and between 0.01m/s and 0.06m/s at the NE, at 12:00 between 0.05m/s and 0.16 m/s at SW and between 0.04m/s and 0.08m/s at NE and at 15:00 between 0.06m/s and 0.11m/s at SW and between 0.03m/s and 0.08m/s at NE (Fig. 5). The highest of these values were recorded on the top floors where the building is exposed to an almost unobstructed air field. Also, the existence of the pilotis led to the creation of fast air currents on the ground floor. According to the literature review, the wind speed was expected to reduce inside the street urban canyon and increase among the pilotis and the courtyard formed in the center of the urban block. The results of this research verified this, adding the fact that wind speed reached its maximum value at the top floor.

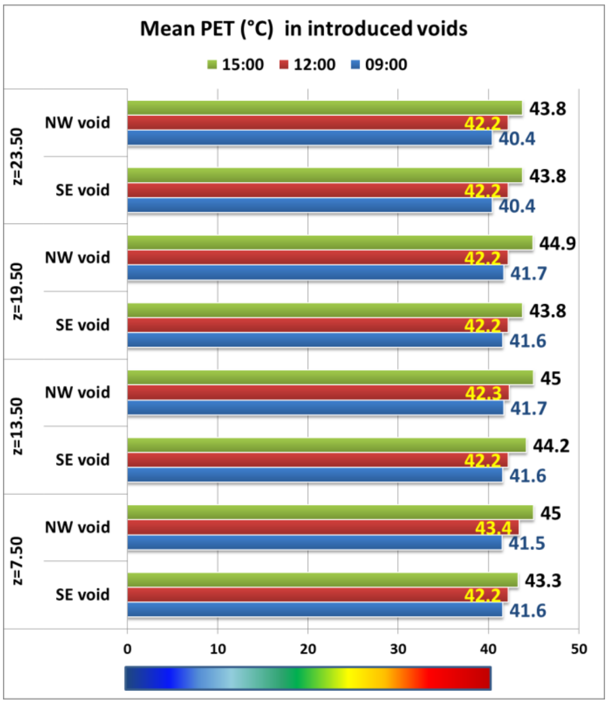

Figure 6: Mean PET index in the introduced voids of scenario B2a, July, 15:00.

In scenario B2a, PET values inside the voids ranged between 40.4°C and 41.7°C at 9:00, 42.2°C and 43.4°C at 12:00, and between 43.3°C and 45°C at 15:00 with small variation between levels not exceeding a difference of 1.7°C PET (Fig.6). Considering Amelung's conclusions [24] regarding PET comfort range being established between 18°C and 30°C, we can conclude that B2a didn't place the voids inside the neutral or moderate heat stress zone.

In scenario B2a, air and surface temperatures decreased in comparison to the reference case. Surface tempera-tures in B2a were between 50.3°C and 51.3°C at 9:00, 52.1°C at 12:00 and between 53.2°C and 53.4°C at 15:00with higher values observed at lower levels. The mean surface temperature difference reached a maximum value of 6.95°C at 12:00 (Fig.7). Surface temperatures at the NW façade also decreased in comparison to the reference case with the mean surface temperature difference reaching a maximum value of 6.8°C at 15:00 (Fig.7). Overall, we observed that B2a managed to keep the building facades from noting a dramatic diurnal increase in surface temperature.

The mean air temperatures inside the SE street canyon and NW courtyard, as recorded by the receptors installed

in front of the case study's facades, also decreased in scenario B2a when compared to the reference case. In scenario B2a, the mean air temperature was at 29.65°C inside the SE street canyon and 29.8°C in the NW courtyard at 9:00, 331.3°C in both areas at 12:00, and 32.65°C in both areas at 15:00. In the reference case, a maximum variation of +0.50°C was observed from the top of the building toward the ground level for both areas at 12:00. The same variation appeared at 15:00 for the NW courtyard, while the SE street canyon presented a top to bottom variation of +1.0^{o}C.

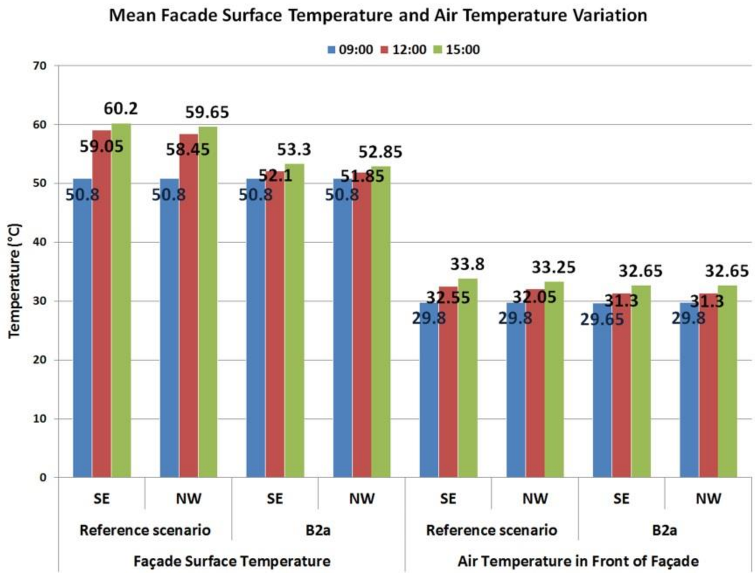

Figure 7: Mean Façade Surface Temperature and Mean Air Temperature in front of the building's facades as recorded by the receptors installed in front of the facades. July, 15:00.

Scenario B2a presented smaller variation from top to bottom that did not exceed a value of +0.3^{o}C in both areas at 15:00. To summarize, we observed that scenario B2a managed to keep both the SE street canyon and NW courtyard cooler than the reference case and at smaller temperature variation from level to level, with the mean air temperature difference reaching at 12:00 a maximum value of 1.25^{o}C for the SE street canyon and 0.75^{o}C for the NW courtyard (Fig.7).
In a simplified steady-state analysis in which internal thermal gains are not taken in consideration, any heat gains or losses (qE) from the building's fabric of an average U-value U, at an indoors temperature Tin and an outdoors temperature Tout are given by the relationship:

$q_E = U(T_{out} - T_{in})$ (9)

Using this relationship (9), the impact of scenario B2a on the reference case's cooling load was assessed for three different values of indoor air temperature (23^{o}C, 25^{o}C and 27^{o}C). Although the U-value changes when vegetation is installed on the building's fabric, leading to further cooling load reductions, this was not taken into consideration in this assessment as the aim of this research was to directly compare the impact of scenario B2a on the reference case's cooling load, without the influence of the fabric's changes. Using mean air temperature of the SE street canyon as the outdoors temperature, the cooling load decreased by 2.21% to 5.36% at 09:00, by 13.09% to 22.52% at 12:00 and by 14.35% to 22.79% at 15:00 according to different values of indoor air temperature used. When the NW courtyard mean air temperature was used, the cooling load decreased by 8.29% to 14.85% at 12:00 and by 7.80% to 12.80% at 15:00 with no change observed at 09:00. Using the SE part of the introduced corridor's mean air temperature, the cooling load decreased by 13.09% to 22.52% at 12:00 and by 13.89% to 22.06% at 15:00 with no change observed at 09:00, while when the NW part, the cooling load decreased by 1.84% to 4.46% at 09:00, by 8.29% to 14.85% at 12:00 and by 9.27% to 15.20% at 15:00. Overall, the percentages became greater when a higher indoor air temperature was used. It is worth noting that results based on an indoor air temperature of 27^{o}C are of particular importance when considering that Greek regulations set a limit cooling at 26^{o}C [25].

5. CONCLUSIONS

The research has found that the conversion of parts of residential blocks into semi open spaces incorporating green walls can improve the PET thermal index inside the newly created voids and decrease the cooling load of the reference case building.

Scenarios in which the reference case's public corridors were converted into open spaces with vegetated walls, led to decreased surface temperatures and street canyon air temperatures in comparison to the reference case as well as other adaptation scenarios introducing semi open spaces at the perimeter of the building. In particular, scenario B2a, showed a maximum surface temperature drop of 6.95^{o}C in the SE façade and 6.8^{o}C in the NW façade managing to keep the building facades from noting a dramatic diurnal increase. The same scenario also led to a maximum air temperature drop of 1.25^{o}C in the SE street canyon and 0.75^{o}C in the NW courtyard. According to the research results, scenario B2a was effective in achieving this through a combination of shading and evapotranspiration, yet it did not create comfort conditions that can described as thermally neutral inside the voids. However, when taking into account the resulting drop in air and surface temperatures, we can conclude that, overall, it improved the comfort conditions experienced in the building's surrounding environment. This was reflected on the reduction of the building's cooling load which reached a maximum of 22.52% at 15:00.

These positive results indicate that the porous residential building model can be adapted to residential buildings located in a hot dry climate. It also shows that architectural design can be a powerful tool in the quest of creating energy efficient buildings. The assessed model could also indirectly tackle other issues present in the Athenian urban environment, such as the lack of green spaces in the center of Athens.

It is important to keep in mind that this research has worked with the assumption that the vegetation is maintained in the best condition possible through time based on ENVI-met's inability to account for changes that might affect its condition, such as changes in watering schedules.

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