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Coupling a Building Energy Simulation Tool with a Microclimate Model to Assess the Impact of Cool Pavements on the Building's Energy Performance Application in a Dense Residential Area

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Abstract: Replacing conventional pavements with the corresponding high albedo ones constitutes a well-known technique to improve outdoor thermal environment of modern cites. Since most of the existing studies assess the impact of the high albedo pavements at the pedestrian's height and with respect to thermal comfort, this study aims to examine the effect of the application of highly reflective pavements on the heating and cooling energy needs of a building unit, located inside a dense urban area. Aiming at a higher accuracy of the energy performance simulations, an integrated computational method between ENVI-met model, Meteonorm weather data generator and Energy Plus software is established, to consider the site-specific microclimatic characteristics of the urban areas. The analysis is performed both for the design and the aged albedo values as significant changes may occur due to aging process. The analysis revealed that the application of cool materials on the ground surfaces only marginally affects the energy performance of the examined building unit, both for the design and the aged albedo value; changes on the annual heating and cooling energy demand, for both albedo scenarios did not exceed 1.5% revealing the limited potential of cool pavements regarding the improvement of the energy performance of urban building units.

Keywords: ENVI-met; microclimate analysis; coupling; cool pavements; energy performance simulations

1. Introduction

The increased rates of urbanization and industrialization of the 20th and 21st centuries have dramatically changed the land use and cover of modern cities, affecting the citizens' quality of life and lifestyle both in a positive and negative way [1]. Despite the multiple facilities offered in the citizens of large cities concerning health, education, technical knowledge, and comfort, major issues due to land modification and transformation have also arisen. One of the most important negative outcomes of the urbanization involves the urban warming and the higher ambient air temperature (Tair) values, reported inside the urban areas, compared to respective values in the nearby rural areas. The energetic basis and the formation of the latter differentiation, also described with the term 'Urban Heat Island' (UHI) phenomenon [2,3], is a very well documented phenomenon worldwide [4–8] since it affects multiple domains of the human life in large cities, including the degradation of the urban air quality [9,10], the poor outdoor thermal comfort of pedestrians [11–13] and the considerable energy penalty on the building sector. In fact, based on the existing evidence, the higher ambient Tair values lead to an increase of the buildings' cooling energy demand that generally outweighs the marginal reduction of heating needs [14–16], with the gap being even higher in the cooling dominated climates [17].

Given that in the future, even higher urban Tair values are to be expected due to the ongoing climate change, contributing to the already existing worrying microclimatic issues [18,19], a great number of scientific studies have assessed the effect of various strategies towards the improvement of the urban thermal environment [20,21]. To this aim, one of the most commonly examined mitigation and adaption strategies involves the application of materials presenting high albedo and high infrared emittance on the urban ground surfaces, also reported as 'cool materials' [22,23]. More precisely, the term 'albedo' describes the total reflectance of a specific surface, considering the hemispherical reflection of radiation, integrated over the solar spectrum, while both secular and diffuse reflection are included [24,25]. The term 'infrared emittance' designates the ability of the surface to emit energy away from itself compared with a blackbody operating at the same temperature [26]. According to Qin [23], the materials characterized as 'cool' ones, should absorb and store lower amounts of solar radiation, compared to conventional materials, so as to maintain reduced surface temperatures (Tsurf). As a result, the application of high albedo materials on the urban ground surfaces would lead to lower heat storage and lower surface temperatures and thus, to reduced sensible heat release towards the surrounding environment, compared to conventional products for the ground surfaces [26]. At this point, it is important to emphasize that:

- The increase of solar reflectance can be achieved through various techniques including: (a) the addition of light color aggregates [27], (b) the use of light colored paints that are highly reflective in the visible wavelengths [28,29], (c) the use of light-colored pigments on coatings so as to increase the solar reflectance in the near-infrared wavelengths [30,31] and (d) the creation of thermochromic coatings, that thermally respond to the conditions of the outside environment, changing reversibly their color as the outside Tair rises [32]. In the current study, existing experimental results of the second and the third category will be further used for the analysis (see Section 3: Materials and Methods)
- Cool materials, presenting high albedo values, can be also implemented in the components of the building envelope, involving roofs and vertical facades. Yet, the assessment of such applications is out of the scope of this study and only the high albedo pavements (i.e., applications on the urban ground surfaces) will be examined.

Table 1 summarizes the albedo values of common conventional and cool paving materials, reported in the existing literature. Regarding the conventional paving materials, the aged asphalt pavements (i.e., a few months after the first exposure) tend to have higher albedo than the newly cast, due to the aggregate exposure after the asphalt binder oxidation. On the other hand, the opposite trend is noticed for the conventional concrete paving materials, for which the albedo value after a few months of continuous use is reduced compared to the newly cast pavements, due to weathering and abrasion.

Table 1. Reported values of albedo for conventional and cool paving materials.

Material	Solar reflectance/albedo values	Ref.
New, black conventional asphalt	0.04–0.06	[24,33]
Aged conventional asphalt (after the first months of use: oxidization of the binder and the corresponding exposure of the aggregates)	0.10–0.15	[23,24,34]
New cast, conventional grey concrete pavements	0.25–0.50	[33,35,36]
Aged conventional grey pavements (after the first months of exposure: weathering and abrasion)	0.19–0.40	[37,38]
Cool white toping on asphalt	0.30–0.45	[24,39,40]
Cool yellow thin layer asphalt	0.35–0.44	[24,39]
Cool colored concrete pavements	0.45–0.70	[24]

As previously mentioned, various techniques have been used so as to achieve a high solar reflectance value; indicatively, for the asphalt pavements, a common method is the use of white or light-colored aggregates in the asphalt mix. Another method involves the addition of a thin cool-color topping over the existing pavement; existing experimental campaigns suggested an increase of the albedo by almost 30% when the cool aggregates have been used [27], whereas the cool toppings can lead to an increase of the albedo value by 0.35–0.40.

Aim of the Study

Up to the present time, the relevant scientific studies have primarily evaluated the cool pavements' effect with respect to the outdoor thermal comfort of pedestrians, using simulation means; the performed analysis involves the comparison of the obtained simulation results of the Tair at the human biometeorological height, (i.e., at 1.5 m from the ground level) along with other parameters affecting human thermal comfort, before and after the application of the high albedo materials [41–47]. On the other hand, only a small number of scientific studies have assessed the cool pavements' effect on reducing the Tair values at diverse vertical levels [48,49] or the way that their application influences the nearby buildings' energy demand [50]. Yet, based on the existing knowledge, microclimatic changes and the respective reduction of the ambient Tair due to cool pavements' applications, are expected to influence not only the pedestrians' thermal balance but also the energy performance of the buildings located inside the area under investigation [50–52].

In this context, the present paper aims to assist the existing gap and provide further insight on the effect of the lower Tair values due to the high albedo materials on the annual heating and cooling energy needs of a generic building unit, located inside a dense residential area of a Mediterranean city. In order to accurately evaluate the effect of microclimatic changes due to the cool pavements' applications on the building unit's energy demand, the applied building energy performance simulation (BEPS) tool is coupled with a microclimate model; in this way, a higher efficiency on the energy performance calculations is achieved since the impact of the local microclimatic conditions is accounted for [53–56]. Further details on the coupling approach are given in the following section.

Moreover, the parametric analysis is carried out both for the design and the aged albedo values; in fact, the materials' albedo is determined by the optical properties of the outer surface layer of the materials and thus, significant changes may occur over time [57]. Indicatively, Kyriakodis et al. [42] have found a reduction of almost 50% in the albedo of a cool yellow asphalt, applied in an urban area in Athens, Greece, after six months of continuous use as a result of atmospheric pollutants and particles issued by vehicles emissions but also due to dirt and rubber from the vehicles tires. Similarly, the analysis of onsite observations of Lontorfos et al. [58] revealed an important loss of the initial solar reflectivity of cool asphalts and pavements after 12 months of exposure, reaching 40% and 15% respectively, again as a consequence of dust and rubber deposition. A review of previous studies assessing the ageing and weathering of cool pavements' applications is given in [49]. Considering the albedo changes during the lifecycle of the ground surface materials is thus of crucial importance to achieve higher accuracy on the cool pavements' effect on the buildings' annual heating and cooling energy needs. The acquired knowledge, combined with the existing evidence on the cool materials' impact on outdoor thermal comfort, is expected to provide a holistic evaluation of their overall performance on the urban built environment. It is also important to mention that in this study, the analysis only focuses on the long-term performance of the optical properties of the ground surfaces materials, whereas the evaluation of the long-term mechanical properties such as linear and nonlinear viscoelastic are out in the scope of the study. Further details can be however found in [59].

The paper is organized in the following way: Section 2 provides a description of the case study area. In Section 3, the modeling approach and the one-way coupling procedure towards the assessment of the cool pavements' effect on a typical building unit's heating and cooling energy demand is described. Section 4 presents the energy performance simulation results of the examined building unit, before and after the application of high albedo materials on the ground surfaces, while in Section 5, the main conclusions are summarized and discussed.

2. Case Study Area

The study area is located in a high-density residential neighborhood of the city of Thessaloniki (40.65 °N, 22.9 °E), situated in the northern part of Greece and placed along the North-East coast of Thermaikos gulf. According to the Köppen Climate Classification the climate type of the city is "Csa" corresponding to hot-summer Mediterranean climate, characterized by generally hot, dry summers, mild, wet winters and evenly distributed rainfall throughout the year [60]. The site extends to 40,000 m^2 and contains six blocks of residential buildings, covering 33% of the ground surface of the study area (Figure 1a). The buildings are 7–8 stories high (i.e., 22.0–25.0 m), while there is a very limited number of detached houses, of 7.0–9.0 m height. Moreover, the sky view factor of the study area fluctuates between 0.20 and 0.50 and the pervious surface fraction is lower than 10%. Open spaces mainly involve street canyons and courtyards of irregular shape between building volumes. The main streets traversing the study area are (a) Papandreou and Voga canyons, having an N–S orientation and running along the western and eastern edge of the model domain respectively, (b) Kalliga street canyon, having a NW–SE orientation and (c) Pittakou canyon, the axis of which is East-West orientated. Moreover, the building unit the energy performance of which will be assessed, as a function of the cool pavements' application is located in the latter canyon (Figure 1b). Finally, vegetation consists of low deciduous trees and bushes placed on both sides along the main streets of the study area while there is only a limited number of tall mature trees inside Kalliga street canyon.

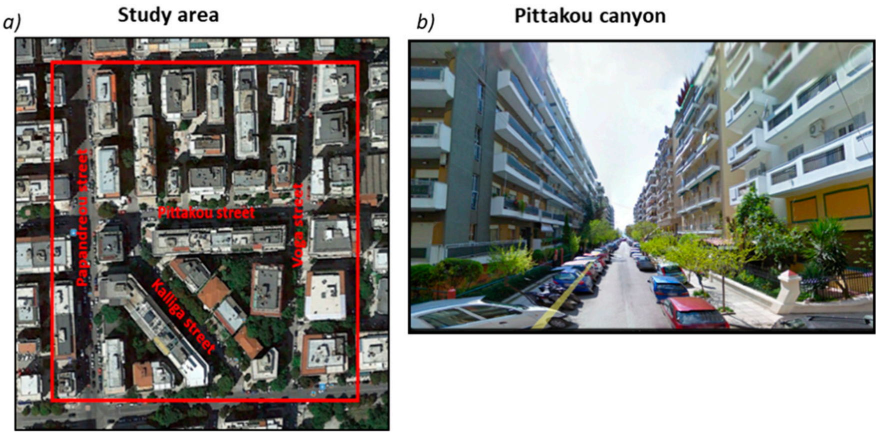

Figure 1. (**a**) Google earth image of the study area, indicating the main street canyons, (**b**) Street view of Pittakou street canyon in which the building unit, the energy performance of which will be assessed, is located.

3. Materials and Methods

As already mentioned in Section 1, the current paper describes a coupling method between a BEPS tool and a microclimate model to consider the impact of the site-specific microclimatic characteristics, as a result of the cool pavements' application, on the assessment of a building unit's energy performance. The key parameter for the establishment of the coupling procedure is the hourly weather dataset, introduced as a boundary condition in the BEPS tool and reflecting the typical meteorological characteristics of a specific location. According to the IEA Annex 53 [61], the weather dataset introduced in the BEPS models, comprising of 8760 hourly values of various climatic variables, will strongly influence heating and cooling loads calculations, systems' dimensioning, etc. To date, the existing dynamic BEPS tools use hourly weather data, the generation of which is generally based on the statistical processing of long-term climatic observations, that are mainly available from weather stations, located in the peripheral zones of the cities. However, the climatic records, observed in suburban and rural areas, cannot be considered as representative of the conditions occurring inside an dense urban area since the complex interactions between solar radiation, wind speed and the increased urban density are not accounted for [54,62].

To address this issue, a more sophisticated procedure for the generation of typical weather years for dynamic BEPS that do capture the particularities of the urban microclimate of the examined urban area, as a function of its morphological and geometrical characteristics (i.e., before and after the high albedo pavements 'application) is here implemented. The approach followed in the current research is based on the interconnection of (a) The ENVI-met v.4 microclimate model, (b) the Meteonorm weather data generator and (c) the dynamic BEPS tool Energy Plus (see Figure 2).

As a first step, a microclimate model of the study area, in which the examined building unit is located, is created in the ENVI-met model. Microclimate simulations are then performed for the case study area surrounding the examined building unit, for 12 representative days (one for each month), defined through a detailed statistical analysis of long-term climatic records. The microclimate simulations concern both the existing conditions, in which the ground surfaces are covered with conventional paving materials but also the high albedo pavements, both for the design and the aged albedo values. At a second step, the major microclimatic parameters, estimated in front of the examined building unit are extracted from the ENVI-met model and their average values are introduced in Meteonorm weather generator to stochastically create the site-specific, annual climatic datasets, henceforward entitled 'urban specific weather datasets' (USWDs). A total number of three USWDs is created: one for the current conditions and two for the scenarios of the cool pavements. The generated, hourly weather datasets, representative of the microclimatic conditions of the urban site (before and after the high albedo pavements applications) are then used as an input boundary condition for the building unit's dynamic energy performance simulations with the EnergyPlus model. The detailed procedure to create an USWD, reflecting the microclimatic conditions in the near vicinity of a building, is presented in detail in a previous scientific work of Tsoka et al. [63].

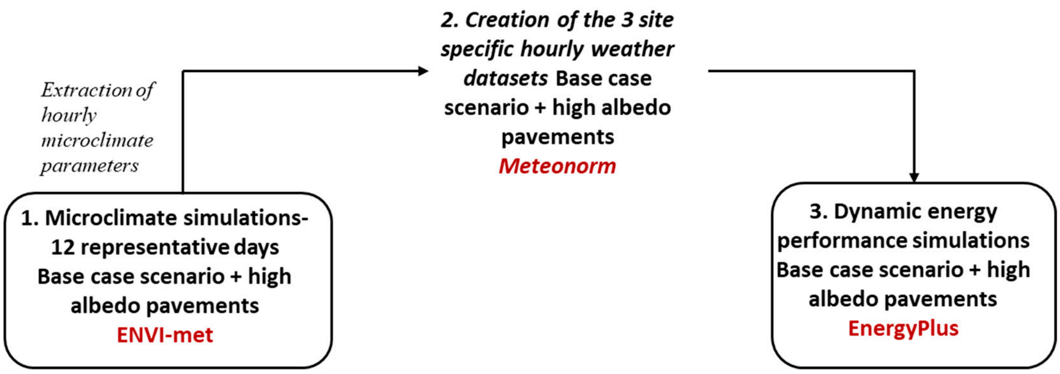

Figure 2. The implemented, one way coupling approach between the ENVI-met microclimate model and the EnergyPlus tool.

3.1. Modeling the Urban Microclimate of the Case Study Area in ENVI-met.v.4 and Extraction of the Microclimate Parameters

In the current study, microclimate simulations are conducted with the ENVI-met v.4 microclimate model. ENVI-met is based on the fundamental laws of fluid dynamics and thermodynamics and can simulate complex surface–vegetation–air interactions in the urban environment. The detailed characteristics of the model along with its structure and the mathematical equations governing the various sub-models (i.e., atmospheric, soil and vegetation sub-model) are provided in [64]. In order to assess the microclimatic conditions of the study area under different meteorological conditions and to acquire the necessary data for the creation of the USWDs, microclimate simulations are performed for 12 representative days, one for every month. The detailed procedure for the selection of the 12 representative days is given in [63]. The area input file of the case study area along with the position of the generic one-floor building unit, the energy performance of which will be assessed, are given in Figure 3a–c. The study area is modeled using a domain size of 135*135*20 grids (i.e., x-grids*y-grids*z-grids), corresponding to a grid size of 1.5 m*1.5 m* 3.0 m. Building floors have a height of 3.0 m height whereas, the height of the base floor was considered as 4.5 m high; seven nesting grids were also set around the model domain area and the total runtime for each representative day is 24 hours. Moreover, five receptor points, providing hourly simulation results from the ground level till the top of the domain, have been set in front the examined building unit, at a distance of 0.75 m from the building unit's façade (Figure 3d). The meteorological boundary conditions, including wind speed, wind direction, hourly values of Tair provided from the weather station of the Aristotle University in Thessaloniki and RH, used for the forcing along with the mean monthly value of soil temperature, have been from the weather station of the Aristotle University in Thessaloniki. Finally, the thermal properties of the various construction materials are based on the ISO standard 10456 [65]. The following scenarios are simulated.

1. BC-Base case scenario: Base case scenario, in which the urban ground surfaces are covered by conventional asphalt and concrete pavements, the albedo of which is set to 0.12 and 0.30 respectively. The adopted values are based on the existing literature (see Table 1)
2. Des.CM-Design cool materials scenario: the conventional asphalt and concrete pavements are replaced with the corresponding cool ones, having their design albedo values of 0.40 and 0.70 respectively. The considered design values of cool materials' albedo are the initial ones before any weathering phenomena whereas the adopted values are based on the existing literature (see Table 1). In the current research, changes on the albedo value are considered to be due to the overlaying of thin light-colored topping as an extra layer over the existing pavements.
3. Aged.CM-Aged cool materials scenario: the high albedo asphalt and pavements are considered to have lost their initial reflectivity by 40% and 15% respectively, due to the weathering and ageing process (values based on the observations of Lontorfos et al. [58]).

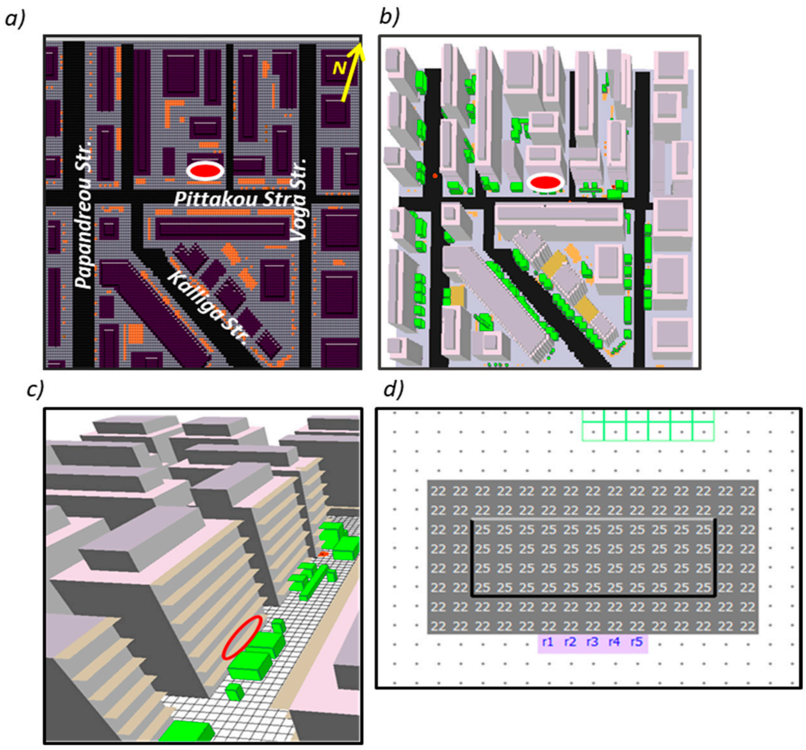

Figure 3. Position of the investigated one-floor building unit (**a**) at the plan of the area input model, (**b**,**c**) at the 3D model and (**d**) position of the receptor points in front of the investigated building façade.

A total of 36 microclimate simulations are conducted (i.e., for 12 representative days for each one of the three scenarios). It has to be emphasized that the meteorological boundary conditions for every representative day remain the same among the examined scenarios; microclimatic changes and modifications on the estimated energy demand of the building unit will be thus attributed only to the different reflectivity of the urban ground surfaces.

In order to assure the ENVI-met model's performance to accurately reproduce the diurnal variation of microclimatic variables, the simulated air temperature and relative humidity values for four representative days—one for each season of the year—were compared with the respective onsite measurements inside the case study area. The detailed validation procedure and the respective calculated quantitative metrics are described in [63]. The obtained errors were within the range of the existing values, already reported in the literature [66] and thus, microclimate simulations are conducted for all the rest of the representative days and for all three scenarios.

The last step of the microclimatic simulations involves the extraction of the necessary microclimate data. As previously mentioned, five receptor points, providing microclimatic values of all major microclimatic quantities have been placed at 0.75m away from the façade. The corresponding location of the receptor points in front of the investigated one-floor building unit façade is shown in Figure 3d. For this study, an intermediate building unit was considered (other apartments are located at its left and right side), while further geometrical details are given in the following section. For every representative day and for all three scenarios, microclimate values are extracted for the heights of 4.5 m and 7.5 m (i.e., bottom and top of the one-floor building level), from the five receptors and the obtained values are then averaged and used as input data for the Meteonorm weather generator to create the site-specific weather datasets. The created hourly climatic files, reflecting the microclimatic conditions occurring in front of the examined building unit before and after the cool materials' application, are then used for the dynamic energy performance simulations.

3.2. Development of the Thermal Model of the Examined Building Unit in the EnergyPlus Model and Dynamic Energy Performance Simulations Using the USWDs

The dynamic energy performance simulations towards the assessment of the building unit's energy demand with respect to cool pavements are performed with the EnergyPlus model [67], a tool that has been widely validated and applied all over the world for building energy analysis [68–71]. In EnergyPlus, the calculation of the thermal loads of buildings is based on the heat balance method, taking into account the heat fluxes on outdoor and indoor surfaces and also the transient heat conduction through the building elements [72]; further details on the model's structure and features are provided in [73–75]. The plan of the generic building unit and the respective 3D model, introduced in the EnergyPlus tool, are shown in Figure 4. The generic building unit is designed as a single thermal zone of a net floor area of 80 m^2. Only the main façade of the building unit is exposed to the exterior conditions, while the vertical façade, separating the apartment from the staircase, is exposed to an unconditioned thermal zone. Special care was paid on the geometry representation of the building unit in both models, so as to avoid inconsistencies. Finally, the construction period of all buildings of the study area is before 1980, prior to the implementation of the national thermal insulation regulation and thus no thermal protection is considered for the building components. The construction materials, mainly comprising of reinforced concrete and brick elements, along with the dimensions of the building components and the operational schedules have been selected according to the respective data of the Report for the recast of the Hellenic Thermal Regulation of the Energy Assessment of Buildings) [76,77]. It has to be emphasized that in all three simulation runs (i.e., for the three scenarios) the configuration of the building's geometry along with the modeling parameters and the operational schedules are the same; the parametric analysis and the different simulation results are attributed (a) on the use of the different hourly weather file (i.e., before and after the cool pavements' application) and (b) on the different site ground reflectance, defined as an input parameter in the EnergyPlus model, strongly affecting the radiative energy balance of the examined building unit's surfaces.

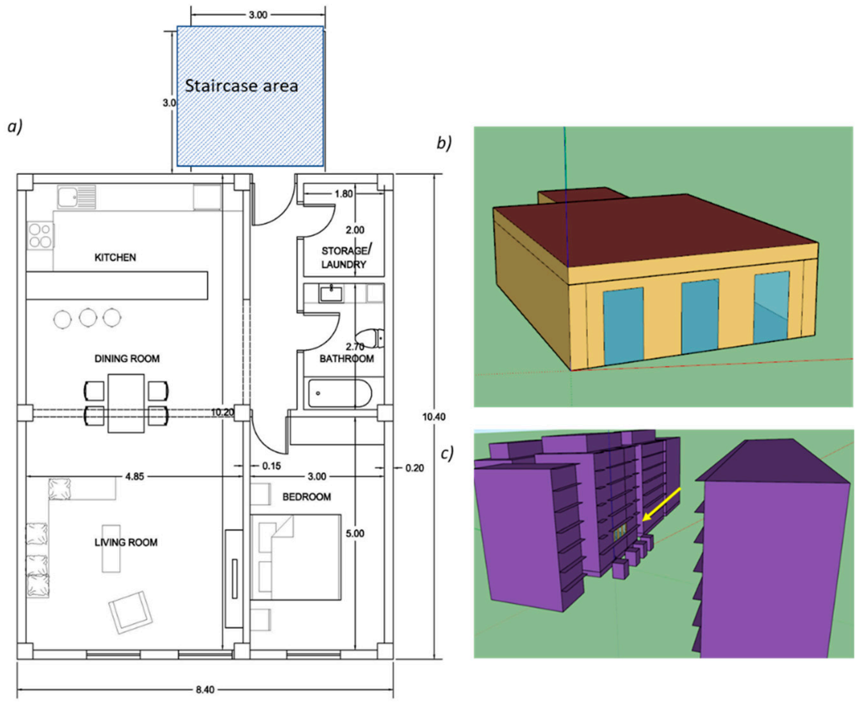

Figure 4. (**a**) Plan of the typical building unit, (**b**) the corresponding 3D model and (**c**) indication of the location of the investigated building unit in the building and the surrounding obstacles.

4. Results and Discussion

4.1. Effect of the High Albedo Materials on the Average Monthly Air Temperature

In this section, the results of the comparison of the monthly Tair values of the three generated USWDs are presented (i.e,. USWD$_{_BC}$, UDWS$_{_Des.CM}$, USWD$_{_Aged.CM}$). As previously mentioned, the created site-specific weather datasets, are based on the ENVI-met simulation results and reflect the microclimatic conditions in front of a one-floor building unit (i.e., heights between 4.5 m and 7.5 m from the ground level) of the case study area, before and after the implementation of high albedo pavements, while both the design and the aged albedo values were considered. The calculated hourly Tair values for the three examined scenarios were further processed and the estimated average monthly Tair values of the three USWDs along with the respective deviations are shown in Figure 5. The analysis of the Tair on a monthly basis throughout the year suggests a similar profile for all three USWDs with the BC scenario generally presenting higher Tair values. More precisely, comparing the base case scenario with the design cool pavements' application, suggested the highest differences in May and July. Still, the respective reductions are rather moderate and do not exceed 0.3 °C. During the winter period, the estimated differences are even smaller and they only range between 0.02 °C and 0.08 °C. The calculated reduction of the ambient Tair in front of the examined building unit is attributed to the lower amounts of sensible heat, being transmitted towards the surrounding air, as a consequence of the high albedo pavements, the higher solar radiation reflectance and the lower ground surface temperatures. Based on the ENVI-met simulation results, the sensible heat release from the asphalt surface towards the ambient air during July, was reduced by almost 35% for the 'design' albedo value of cool pavements compared to the base case scenario.

Still, what has to be emphasized is that in winter, the solar radiation intensity and the solar heights are considerably lower and thus, the effect of high albedo pavements on lowering the ambient Tair value is less significant. In addition, the results of previous studies conducted for the same study area, suggested that despite the substantial effect of the high albedo pavements on lowering the Tsurf [78], their effect on the reduction of the ambient air temperature is rather moderate even in summer, while their cooling potential is decreasing as the distance from the ground increases [49].

To continue, when the albedo degradation as a result of weathering and rubber/dust deposition is considered, the estimated reduction of the ambient Tair becomes of lower importance; peak differences are again noticed during summer, without however exceeding 0.2 °C. In other words, the estimated monthly Tair difference between the base case scenario and the cool pavements in June and July, is 60% and 35% lower when the aged albedo values are considered rather the design ones. This is due to the higher amounts of sensible heat, being henceforward released towards the air, as a consequence of the lower albedo and the consequent higher solar radiation absorption from the ground surface materials, compared to the Des.CM scenario.

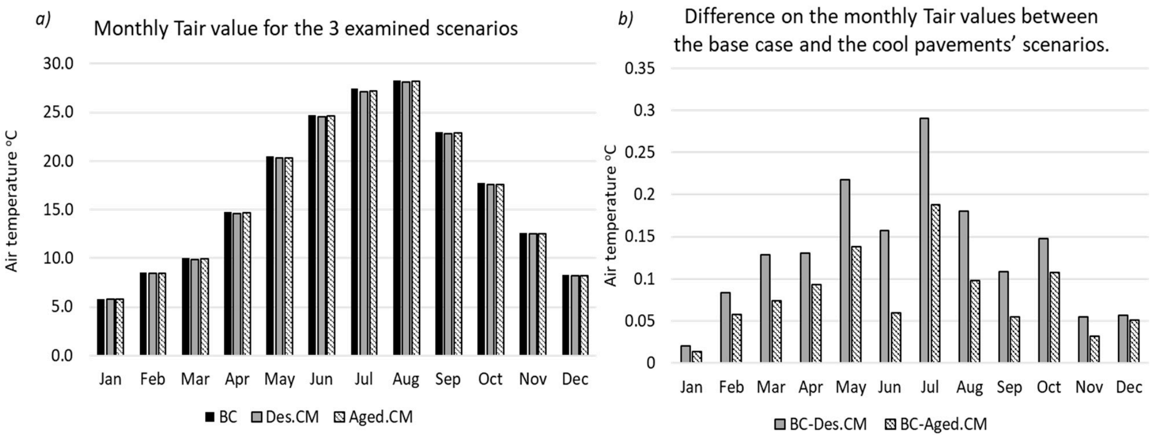

Figure 5. (**a**) Mean monthly values of Tair for the 3 USWDs, corresponding to the base case scenario and the cool pavements' applications and (**b**) the estimated differences on the monthly Tair values due to the cool pavements' applications, having the design or the aged albedo values.

The abovementioned results revealed the more prominent effect of cool pavements on lowering the ambient Tair values in front of the examined building unit during the spring and summer period. In order to further assess their cooling potential as a mitigation strategy, the daily maximum and the daily average Tair values during the summer month of July, have been calculated and the corresponding discrepancies between the base case and the cool pavements scenarios are shown in Figure 6.

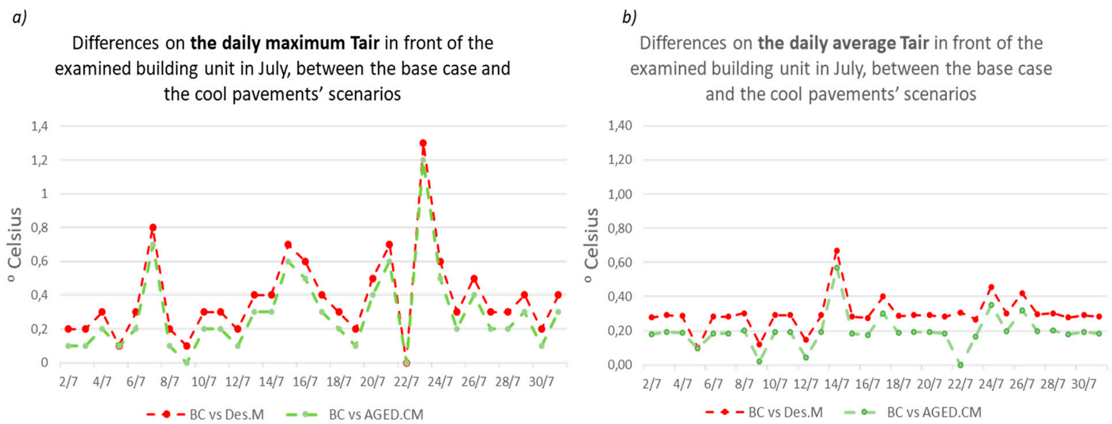

Figure 6. Evolution of the differences of (**a**) the daily maximum and (**b**) the daily average Tair in front of the examined building unit in July, between the base case and the cool pavements' scenarios.

It can be generally said that the high albedo pavements are more efficient in regulating the daily maximum rather than the daily average Tair values, estimated in front of the examined building unit. More precisely, during July, the reduction of the daily peak Tair values due to the application of the design cool pavements ranged between 0.05 °C and 1.3 °C; yet, for most of the days, the achieved reduction of the maximum daily Tair (mainly occurring around noon) did not exceed 0.8 °C. Furthermore, it can be seen that the effect of cool pavements was considerably reduced when the aged albedo values have been considered.

In terms of the estimated daily average Tair values, the application of the design cool pavements contributed in a rather moderate decrease of the ambient Tair, with the respective reductions not exceeding 0.63 °C. Again, the consideration of the aged albedo values led to even smaller changes on the average daily air temperature.

Finally, the generated, hourly weather datasets, representative of the microclimatic conditions, occurring in the near vicinity of the examined building unit, before and after the application of the high albedo pavements are used as input boundary condition for the building units' dynamic energy performance simulations with EnergyPlus. The dynamic energy performance simulation results are given in the following section.

4.2. Effect of the High Albedo Pavements on the Building Unit's Heating and Cooling Energy Needs

The simulation output of the annual heating and cooling energy needs of the investigated building unit, both for the existing conditions and after the application of the cool pavements is depicted in Figure 7, while the respective energy savings due to the high albedo materials are shown in Table 2. It can be generally said that the replacement of conventional asphalt and concrete paving materials with the corresponding high albedo ones only provide minor changes on the building unit's energy performance, even in the case of the design albedo values (i.e., when no albedo degradation is considered). More precisely, the estimated annual heating energy needs of the examined building unit, are marginally higher by 0.75% in the case of the design cool materials compared to the base case scenario. This is due to the slightly lower ambient Tair values, estimated inside the study area, after the cool pavements' application (see Section 4.1) which is not however counterbalanced by the small rise of solar gains (see Figure 8).

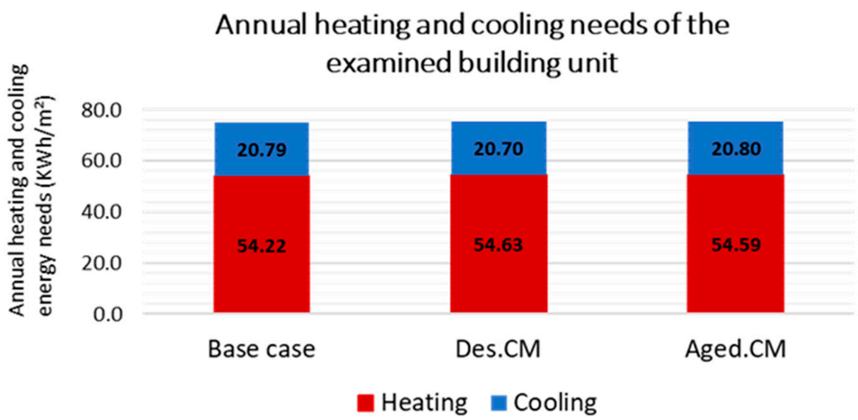

Figure 7. Estimated annual heating and cooling energy needs of the one-floor building unit for the 3 examined scenarios.

In fact, the application of high albedo pavements leads to an increase of the solar gains transmitted into the thermal zone of the building unit, due to the higher amounts of the reflected solar radiation towards the surrounding environment; the EnergyPlus model accounts both the direct and the reflected radiation from the exterior surfaces to calculate the amount of the solar radiation received by the window surface and the part of it being transmitted into the thermal zone and thus a moderate rise of solar gains is reported during the heating period, ranging between 1.0% and 10.0%. Moreover, when the aging scenario is considered, the additional solar gains due to the reflected solar radiation become of lower importance and their contribution on the energy balance of the building unit is rather negligible. Given thus the insignificant changes of the ambient Tair, estimated for the aged cool materials scenario along with the minor modifications on the solar gains, the estimated heating energy demand of the examined building unit strongly approximates the base case scenario with the difference not exceeding 0.7%.

Table 2. Percentage difference of the heating and cooling energy demand due to the cool pavements' application, both for the design and the aged albedo values, compared to the base case scenario.

Energy savings (percentage difference %)		
	Heating	**Cooling**
Des. Cool materials vs. Base case	0.8%	−0.5%
Aged Cool materials vs. Base case	0.7%	0.0%

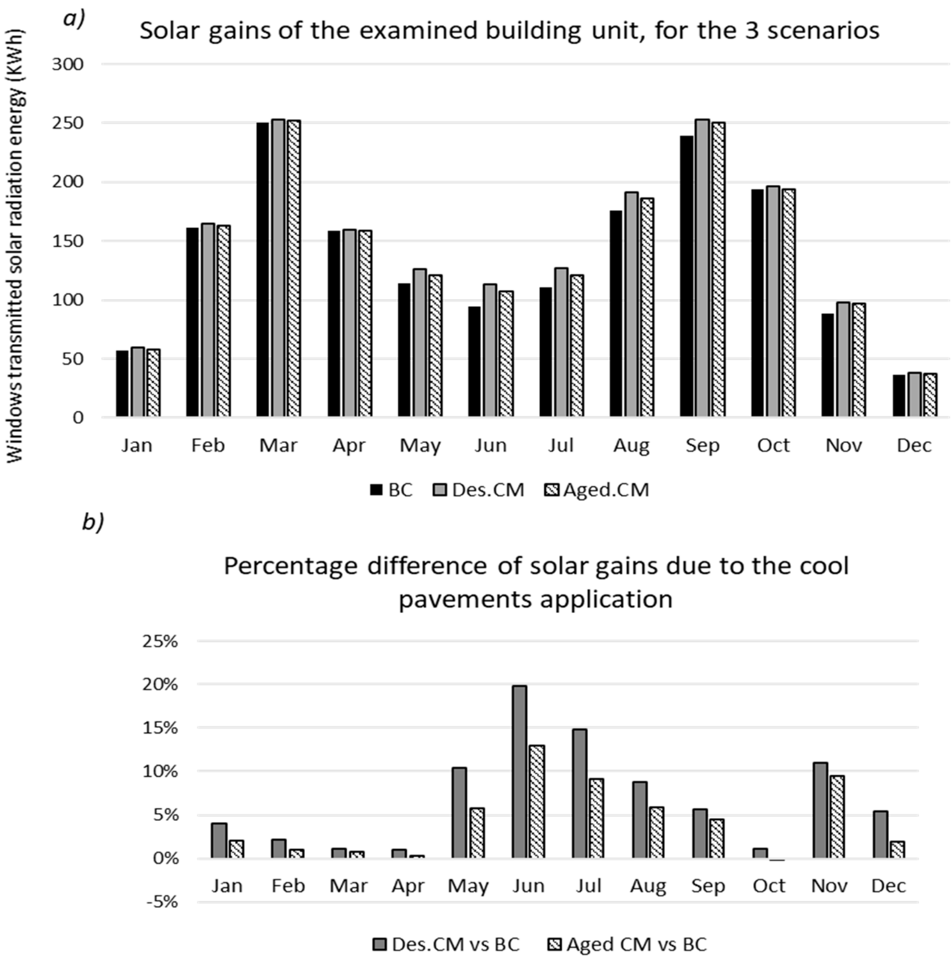

Figure 8. (**a**) Solar radiation energy transmitted into the thermal zone by the windows in the one-floor building unit and (**b**) percentage difference on the solar gains due to cool pavements application, compared to the base case scenario.

During the cooling period, the positive effect of the higher albedo values on the reduction of the ambient Tair values (see Section 4.2) is compromised by the important rise of the reflected solar radiation and the increase of the solar gains transmitted into the building unit's thermal zone. Indicatively, in July, the mean ambient Tair value in front of the building unit is reduced by 0.3 °C when the design albedo values are considered, a fact that could potentially lead to a reduction of the cooling energy needs; yet, the solar gains of the thermal zone were found higher by 20%, compared to the base case scenario. As a result, for this specific month, a rather negligible reduction of the cooling energy needs that did not exceed 3%, was noticed for the design albedo values of the cool pavements, whereas on an annual basis, the estimated decrease was only limited to 0.5% Finally, no changes on the estimated cooling energy demand of the building unit were noticed when the aged albedo values are considered.

Despite the less remarkable rise of solar gains, the achieved Tair reduction of the ambient air is of lower importance and thus, no modifications on the building unit's energy performance were noticed. Based on the abovementioned result, the potential of high albedo pavements on improving the energy performance of a building unit located in a dense urban area, was proven rather minor, while similar results were also reported in a previous scientific study of Santamouris et al. [50]. Moreover, considering that the cooling potential of cool materials decreases as the distance from the ground increases [49], rather negligible changes on the heating and cooling energy demand are expected for the building units, located on the upper floors (i.e., above the 1st floor level). Furthermore, given that the design albedo values may decrease within the first month of exposure due to dust, rubber deposition etc., the aged albedo values should be also considered so as to accurately evaluate the cool pavements' contribution on the microclimate's improvement and the buildings' energy demand during their whole lifecycle.

5. Conclusions

The use of high albedo materials on the urban areas consists a very common mitigation strategy towards the reduction of the urban warming and the improvement of the urban buildings' energy demand. The majority of the existing studies focus on applications of high albedo materials on the building roofs, whereas only a few have assessed the effect of highly reflective pavements on the buildings' energy performance. In fact, the latter applications have been mainly examined with respect to the urban microclimate and the pedestrian's thermal balance. However, the overall performance of high albedo pavements on the urban built environment should be assessed under a global perspective in which the achieved microclimatic improvements, the pedestrians' thermal balance, and the urban buildings' energy performance are accounted for. To address this issue, the current study describes a one-way coupling procedure between the ENVI-met model and the EnergyPlus tool towards the investigation of the effect of high albedo pavements on the energy demand of a generic building unit, located in a dense residential area of a Mediterranean city. Given that important albedo changes may occur over time, the analysis was conducted both for the initial, high albedo values and the aged ones.

The obtained simulation results suggested that the replacement of the conventional dark asphalt and concrete pavements with the corresponding, light-colored, high albedo ones, would lead to negligible changes on the annual heating and cooling energy demand of the examined building unit. Especially during the cooling period, the moderate reduction of the monthly Tair values, achieved due to the cool pavements' applications, is counterbalanced by the rise of the reflected solar radiation, finally leading to higher solar gains of the thermal zone. Furthermore, when the aged albedo values are accounted for, the cool pavements' implementation becomes even less effective in terms of the building unit's annual energy needs.

In other words, the results of the current study indicate that the unique application of the high albedo coatings on the urban ground surfaces is rather ineffective in terms of decreasing the buildings' annual cooling energy demand. The reason that the emphasis is mainly given on the summer period relies on the fact that in the Mediterranean countries such as Greece, the high urban temperatures have been proven to negatively affect the energy demand for cooling, while the energy demand for heating is only marginally reduced [18]. Considering the ongoing climate change, even higher air temperatures are to be expected, leading to a rise of the current cooling energy needs. Given that in the Mediterranean countries, the cooling energy requirements are primarily provided by air conditioners and heat pump systems [79], an important raise of the peak electricity demand will be thus expected, exacerbating from one hand, the use of fossil fuels to generate power and on the other hand, the greenhouse gas emissions. In light of the above and aiming on the resilience of modern cities, the application of cool coatings should be combined with other strategies such as urban vegetation, water elements etc. so as to reduce the ambient Tair values and regulate the summer energy penalty of the urban warming. In parallel, the acquired results highlighted the need for the industry and the academy to direct their efforts in the development of cool materials that will stand during their whole lifecycle without compromising their optical properties. Although cool coatings applications have been extensively examined through experimental campaigns, their actual durability on real roadways has been far rarely assessed. Further research should be thus needed on the durability of cool coatings and their sensitivity on weathering, soling, traffic loads etc.

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