Mitigation technologies for counteracting the UHI effects and for improving outdoor thermal comfort in mediterranean urban open spaces: a study of vegetation and cool materials effects on pedestrian comfort in Rome

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Abstract

The present study investigates the influence of building materials, traditional as well as innovative, and vegetated urban surfaces on the urban microclimate and on pedestrian outdoor thermal comfort in a typical Mediterranean city: Rome. It focuses the attention on selected mitigation technologies aiming to increase the albedo of cities: high reflective materials called *cool colored materials,* and the use of vegetative surfaces: *green roofs*, *green walls* and trees, with the main purpose to test, verify and quantify the overall microclimate mitigation and thermal performance of the aforementioned strategies, The study proposes and analyses, through CFD calculations (ENVImet v.4.0), five renovations scenarios: applying cool materials and vegetation on roofs, walls and pavements of the selected square. In order to support planning authorities and researches by going beyond the traditional way of urban heat island studies, the present study aims to highlight the multiple effects of cool colored materials on human comfort and to investigates which could be the best combination materials in terms of mitigation of ambient temperatures and pedestrian thermal stress. Therefore, air temperature as well as the physiologically equivalent temperature (PET) were applied to take into account the effect of the variations of urban materials on human comfort, the studies focuses the attention and draw its conclusions through the comparison of the Envimet thermal maps and the values of the different scenarios in terms of deltas variations. The results show the negative effect of cool colored materials on human thermal comfort when applied isolated to surfaces in direct contact with pedestrians, such as pavements and urban façades, nevertheless it underlines the benefit associated with a mixed combination of cool materials and trees, setting the path for further research in this direction.

Introduction

There is a strong public interest in creating liveable and comfortable urban open spaces, because of their role played as social aggregator and in supporting the urban metabolism (Martinelli et al., 2014). As heat stress is expected to occur more frequently, more intense and long-lasting in the Middle Europe in the 21st century (Meehl & Tebaldi, 2004), mitigation and adaptation strategies for the improvement of urban climate (Santamouris, 2014) are necessary to enhance health, comfort and to follow the latest communal agreements concerning climate change (Cop 21, 2015). With these regards, a resilient city is low risk to natural and man-made disasters, it reduces its vulnerability by building on its capacity to respond to climate change challenges, disasters and economic shocks (ICLEI,2013). Concerning the mitigation strategies two are the most important cooling measures: increase of vegetated surfaces and of urban albedo (Shashua-Bar & Hoffman, 2000). According to Akbari et al. (2001) most of the summer heat islands are created by the lack of vegetation and the high solar radiations absorptions at urban surfaces. Even though there are a solid body of researches that point out the mitigation effect that vegetation and cooling surfaces might have, (Akbari et al., 2001; Synnefa et al., 2008; Kolokotsa et al., 2013), there remain some unsolved issues that require further research. Especially concerning the reflective materials: whereas their use on roof has proved to an efficient technologies for the improvement of outdoor microclimate conditions as well as indoor, their use on grounds and buildings façades can be seen as contributing positively or negatively to pedestrian comfort and building energy balances (Erell, Boneh, Pearlmutter, & Bar-Kutiel, 2013). Therefore, the present study focuses on the materials' characteristics of the urban open spaces surfaces in terms of physical characteristics, such as albedo and permeability, and thermal characteristics, such as emissivity and thermal trasmittance, and compare variations the ambient temperatures and surface temperatures as well as on mean radiant temperature and Pet values. The study investigates the influence of building materials and vegetated surfaces on pedestrian outdoor comfort. In particular the main interest is to assess the multiple effects that cool materials might have on pedestrian comfort not only on the mitigation of UHI, in order to deepen the knowledge related to these advanced materials technologies and to understand the peculiar behaviour of innovative and vegetated surfaces depending on their different combinations and applications on the urban surfaces of the built environment.

1 Case study: Piazza San Silvestro, Rome (Italy)

1.1 Study area

The study analyses a specific urban square in the city of Rome: Piazza San Silvestro, selected for its morphological, typological and social features. Its relevance has been assessed by a recent requalification intervention (Portoghesi, 2011) and an interesting microclimatic study assessing the influence of daily shading pattern on human thermal comfort and attendance in the square (Martinelli, Lin, & Matzarakis, 2015). Even though the initial design proposed an integration of trees and green lawn as well as the insertion of a fountain in the elliptical square, the final construction didn't include those elements and proved to have no concerns for the microclimatic conditions and the thermal behaviour of the place (Martinelli et al., 2015). The surrounding buildings, representing the urban interface of the open space and its main interacting surfaces, are about 4-5 floor height, with a H/W ratio equal to 0.36. Thus, the square doesn't offer a natural or shaded environment during the hot season, especially during the summer when the low albedo and the high emissivity of the materials of pavements doesn't mitigate the heatwaves effects.

1.2 Methods

Five urban renovation scenarios are proposed, based on bioclimatic and energy efficiency criteria, with the specific aim to examine the isolated as well as the combined effects that vegetation and 'cool' materials have on the outdoor comfort, focusing on design aspects such as: position, distribution and ratio of different outdoor materials. The tools used in the simulation are the numerical microclimate model ENVI-met 4 and BIOmet (Huttner & Bruse, 2009*),* for assessing thermal comfort in terms of PET index. The methods used in this study consist of the following: (i) the selection and modelling of specific renovation interventions, (ii) the selection of specific cool materials already object of investigations in previous researches (Santamouris et al., 2011; Gobakis et al., 2015) as test reference, (iii) the evaluation stage. The square is near one of the main street of the historic centre (Via del Corso) close to relevant tourist attractions, shopping boulevards, offices and the related public transport hub, its relevance has been assessed by a recent requalification intervention (Portoghesi, 2011). The square is a quadrangular paved open space measuring approximately 80 x 60 m^2, the surrounding buildings are about 4-5 floor height, with a H/W ratio equal to 0.36. The roof average albedo is 0.40, the walls' albedo is 0.45 and the pavements measures about 0.30 whereas the Sky View Factor (SVF) is 0.7. Thus, it doesn't offer a natural or shaded environment during the hot season, especially during the summer when the low albedo and the high emissivity of the materials of pavements exacerbate the heatwaves effects. The simulations were carried out from the 21st of June 2015 at 6.00 a.m. to the 6.00 a.m. of the 22nd of June 2015 (24 hours), in order to stabilize the calculations and to analyze the nocturnal effects of the upgraded surfaces. For validating the accurancy of the model the weather data input (Tab.1) were selected from a near weather station (Ciampino) and from the *ItMeteoData Test Year Reference* Database (2013): wind speed measures 4.5 m/s with a direction of 225°, T air is equal to 292.75 K – 19.6 °C, specific humidity measures 11.5 g/kg, relative humidity is 83%. The first stage was the selection of the most interesting combinations in terms of vegetated and cool surfaces that could be applied in an historic urban square, the five mitigation scenarios were modelled according to three criteria: the selection of those combinations that maximize the cooling effect of singular materials, the combination of mixed materials (cool and green), the minimal intervention. The 1st scenario, '*total green scenario'*, aims to increase the green surfaces applied to the whole urban open space it includes *green roofs, green walls* and trees, the 2nd scenario, focuses on the minimal intervention and on the principal surfaces interacting with the pedestrian level: the urban pavement. It aims to analize the combined cooling effect of trees and cool pavements. The 3rd scenario aims to convert building roofs and façades into green surfaces while applying cool materials on the urban pavements, the 4th scenario called '*total cool colored'* aims to the upgrade of the surfaces albedo through the substitution of traditional roof, wall and pavement material with *cool colored* ones, lastly the 5th scenario on the other hand apply *cool colored coatings* on roofs and walls and increase the vegetated surfaces and trees on the urban pavements. The second stage was the selection of cool materials database: the asphalt (albedo=0.20) was renovated with a cool colored thin layer asphalt (a=0.45), the basalt pavement (a=0.22) with a white Portland cement coating mixed with dolomitic marbles (a=0.89), flint blocks with cool colored concrete tiles (a=0.65); for the walls façade, the entire surfaces of pastel plaster and bricks (a=0.30-0.45 ca.) have been renovated with a yellow cool coating with TiO_2 (a=0.73), finally for the roofs surfaces: concrete tiles (a=0.30) have been upgraded with cool dark colored concrete tiles (a=0.60), brick tiles (a=0.50) with cool red brick tiles (a=0.65). Regarding the cool materials' database they were selected from previous scientific studies (Santamouris et al. 2011), whereas regarding the trees and grass they were selected from the ENVImet default database (Table 1, Table 2).

Initial material	Initial albedo	Final upgraded material	Final albedo	Delta Upgrade
Pavements				
Asphalt	0.20	Cool colored thin layer asphalt	0.45	+ 0.25
Basalt	0.80	White Portland cement with dolomitc marbles plaster	0.89	+ 0.09
Flint blocks	0.40	Cool colored pigmented concrete tiles	0.65	+ 0.25
Walls				
Areated brick block with lime plaster	0.40	Yellow cool coating with TiO_2	0.73	+ 0.33
Roofs				
Ceramic gres tiles	0.45	Cool dark colored tiles	0.60	+ 0.20
Clay Brick tiles	0.40	Cool red brick tiles	0.65	+ 0.25

Table 1. Materials database

Name	Leaf Type	Albedo
Lemon Tree (Citrus x limon)	Decidous	0.40
Judas Tree (Cercis siliquastrum)	Decidous	0.70
Koelreuteria paniculata	Decidous	0.60
Grass (Luzerne)	Evergreen	0.20

Table 2. Trees and vegetated surfaces

The third stage was the modelling in ENVImet of the different configuration scenarios for the environmental upgrade of the urban historical square, during this phase some adjustments have been made in order to correct some limitations within the CFD software, exposed in the next paragraph.

1.3 Limitations of the ENVImet software

In order to understand the process supporting materials digital modelling, the microclimatic results and make valid comparisons among the different scenarios it is important to underline the limitations of the ENVImet software used in this study (ENVI-met v.4.0, summer 2016). ENVImet is a valid CFD software for the evaluation of thermal factors (air temperature, mean radiant temperature, etc), nevertheless some limitations related to the resolution of the space model and to the accurancy of some default materials have to be considered in order to put the results in proper perspective. First, regarding the model resolution, ENVImet allows a minimum grid cell dimension of 1m therefore it was impossible to model a thin green wall and green roof, thus the green wall and green roof tested in the study measure 1 mt in depth, resulting in a likely increased effects and values of the green surfaces to take into account. In addition, another relevant limitation linked to the material characterization of the surfaces concerns the 3d-mode, which represents the only way to apply and modify the materials of roofs and walls: the software doesn't support a detailed and easy application of the materials, thus for solving the problem it was modelled for walls and roofs only those materials most present to best approximate the real ante-operam condition. Therefore, since the majority of the walls characterising the urban square are in brick covered by light pastel colors of lime plaster, it has been selected a medium value plaster material (pastel yellow lime plaster, a= 0.45), and for the roofs there have been selected red clay tiles and (a=0.40) and ceramic gres tiles (a=0.45). Secondly, some of the materials contained in the default database need to be implemented or in some case corrected: for the basalt pavement used in this study the corresponding albedo presented in the default database has an albedo of 0.80 which is according to the scientific manual too high for a dark stone, thus all the deltas related to the pavement between the different scenarios and the default scenario with the default basalt stone need to be considered bigger than they appear. Thirdly, it is likely that the software can't calculate the heat release from walls at night which effects the air temperature at night, hence increasing the urban heat island intensity and the pedestrian thermal perception, and resulting in some computations stability problems.

2 Results and findings

In order to make comparison among the different scenarios, four main time steps were analysed: 8.00 a.m., 12.00 p.m., 6.00 p.m. and 12.00 a.m. CET, and four microclimatic parameters were taken into account for their influence on local microclimate and outdoor comfort: the air temperature (T_{air}), the surfaces temperature ($T_{surfaces}$), the mean radiant temperature (T_{mrt}) and finally the Physiologically Equivalent Temperature index (PET) (Höppe 1999; Matzarakis et al. 1999) in order to assess the outdoor pedestrian comfort. In the interest of underline the variations among the different scenarios, a specific point of the square was selected for its position and for the solar radiation hours to which it is exposed (equal to 9 hours of solar radiation during the day): point A (Fig. 1).

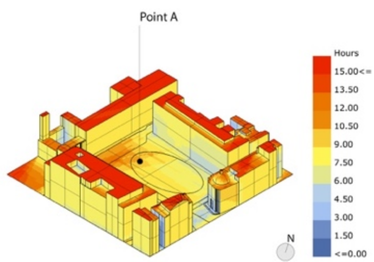


Figure 1. Point A, solar hour analysis calculated with Grasshopper software.

2.1 Observations

Concerning the air temperature values (T_{air}) the results at 12.00 a.m., described in Figure 2 (refer to the end of the document), show that the most efficient scenarios are the 1st (*total green*) and the 2nd(*cool pavement* + trees) in which the T_{air} values decrease between 0.6-1°C, whereas the others shows a decrease between 0.2-0.3°C. The deltas of the mitigation scenarios, in comparison with the initial condition, during the night time (12.00 p.m.) are moderate between -0.2-0.5°C. If we consider the $T_{surfaces}$ values (Fig.3), the 1st scenario (total green) shows a value of +23.7°C, the 2nd scenario (*cool pavement* + trees) shows a value of +23.1°C, the 3rd scenario (*green wall*, *green roof* and *cool pavement*) measures +25°C, the 4th (*total cool materials*) measures +25.5°C, finally the 5th scenario (cool roof, cool wall, trees) shows a value of +24.8°C whereas the initial condition measures +27.1°C. The most efficient solution is represented by the 2nd scenario that combines a *cool pavement* with trees, the data appears to suggest that the reflective capacities of the materials collaborates within the shading effect of the trees, as if the reflected ratio of solar radiation is captured and moderated by the shading influence of the tree itself. It is interesting to observe that the highest value among the renovation scenarios in terms of $T_{surfaces}$ is represented by the 5th solution (the mixed *cool colored scenario*+trees) that measures +24.8°C in comparison with the initial condition of +27.1°C. Regarding the mean radiant temperature values (T_{mrt}), as shown in Figure 4, the 1st scenario at 12.00 a.m. shows a value of +38.6°C, the 2nd shows a value of +30°C, the 3rd (*green roofs, green walls, cool pavements*) measures +61.4°C, the 4th (total *cool colored materials*) shows a T_{mrt} value of +64°C, and the 5th scenario (*cool roof*, *cool wall* and trees) shows a value of +39.5°C whereas the initial condition at 12.00 a.m. measures + 61.20°C. It appears that the most efficient scenarios are represented by the 2nd and the 1stscenarios measuring respectively + 30°C and +38.5°C at 12.00 a.m., whereas the 3rd and 4th scenarios show a worsening of the T_{mrt} with a delta of +0.20°C and +7.3°3 compared with the +61.2°C of the initial condition. This is a considerably interesting result since it shows the multiple effect that high reflective materials could have in an urban environment while considering the 'radiative landscape' (Rogora & Dessì, 2005) and the radiative exchanges between man and urban surfaces. Finally, a thermal comfort analysis was carried out to define environmental performance in terms of people wellbeing. Thermal comfort was considered in terms of PET index. The PET graphs (Fig.5) show an initial condition value of +36.4°C at 12.00 a.m., the 1st scenario (total green surfaces) measures +29.6°C, the 2nd scenario (cool pavement + trees) measures + 29.6°C and the 5th scenario (cool roof, cool wall, trees and grass) shows a value of +29.4°C, whereas the 3rd and 4th scenarios show a worsening of the PET value at 12.00 a.m. that measures respectively + 37.30°C and +40.32°C. During the night time the initial condition measures +14.4°C, the 1st scenario and the 2nd show increased value of +16.7°C and + 16.5°C respectively, whereas the 3rd, the 4th and the 5th solutions show values of +14.6°C, +14.2°C and 16.4°C. The PET increased values of those scenarios that present an upgrade in terms of trees is probably related to the high LAI index of the trees that decrease considerably the SFV thus limiting the dissipation of the heat stored during the day by the surfaces. It is important to observe that increasing the albedo without considering the principal radiative exchanges of a surfaces and its predominant behaviour in the urban open space may contribute to a decrease of the ambient air temperature as well as of the surfaces temperature, but on the other hand, it could increase considerably the mean radiant temperature values and worsen deeply the outdoor comfort for pedestrians. Therefore, the scenarios in which the principal upgrade was in terms of albedo of roofs, walls and pavements, show poor results in terms of comfort index. This situation occurs most likely because a *cool material* with a high reflective factor reflects most of the incoming radiation towards the surrounding environment, thus increasing the radiative landscape and creating a sort of 'glass effects' of the infrared radiation that eventually is absorbed by the human beings, as underlined in Erell et al. (2014) and Chatzidimitriou & Yannas (2015). Nevertheless, two interesting combined scenarios between natural and cool materials need further reflection: the 2nd scenario and the 5th scenario. Particularly the 2nd scenario, takes advantages from the reflective capacities of the innovative materials and the shading effect and evaporative cooling guarantee by the tree natural behaviour, hence it may represent a good basis for further applications. Figure 6 shows the changes in terms of materials, surfaces' area that undergone changes and configurations in 3d models, Table 3 shows the temperatures and Pet values variations of each scenario for the reference point A, whereas

Table 4 shows a graphic synthesis of the renovation scenarios, the materials upgrade in terms of albedo, and the resulting thermal values.

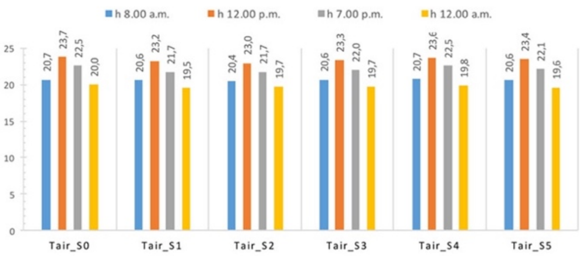


Figure 2. Air Temperature values

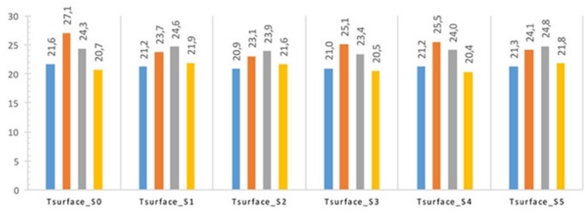


Figure 3. SurfaceTemperature values

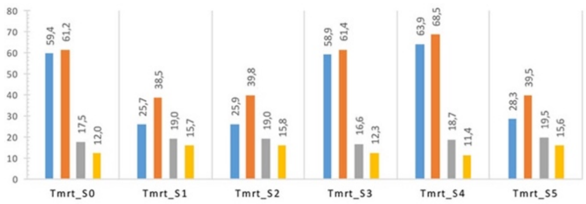


Figure 4. Mean RadiantTemperature values

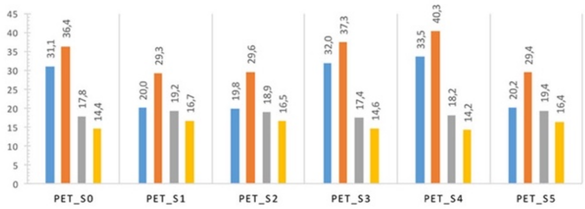


Figure 5. PET values

	T air (°C)				T surfaces (°C)				T mrt (°C)				PET (°C)			
	h8.00 a.m.	h12.00 p.m.	h7.00 p.m.	h12.00 a.m.	h8.00 a.m.	h12.00 p.m.	h7.00 p.m.	h12.00 a.m.	h8.00 a.m.	h12.00 p.m.	h7.00 p.m.	h12.00 a.m.	h8.00 a.m.	h12.00 p.m.	h7.00 p.m.	h12.00 a.m.
S 0	20.65	23.7	22.55	20	21.6	27.1	24.3	20.7	59.45	61.2	17.5	12	31.1	36.4	17.8	14.4
S 1	20.55	23.2	21.65	19.5	21.2	23.75	24.6	21.9	25.65	38.55	19	21.9	20	29.55	19.2	16.7
S 2	20.4	23	21.7	19.6	20.9	23.1	23.9	21.6	25.9	29.8	19	15.75	19.8	29.6	18.9	16.5
S 3	20.65	23.3	22	19.7	21	25	23.45	20.5	58.9	61.4	16.65	12.35	32	37.3	17.4	14.6
S 4	20.7	23.6	22.5	19.8	21.2	25.5	24	20.4	63.9	68.5	18.7	11.4	33.5	40.3	18.2	14.2
S 5	20.55	23.45	22.1	19.6	21.3	24.1	24.8	21.8	28.3	39.5	19.55	15.6	20.2	29.4	19.4	16.45

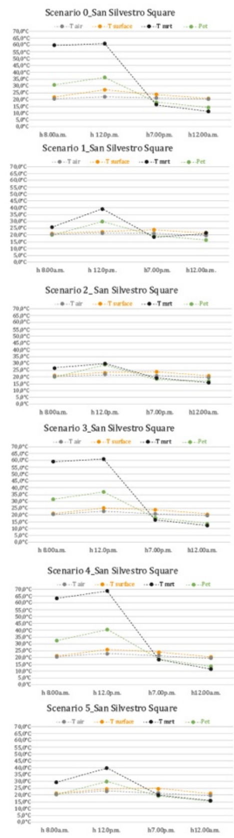


Table 3. Graphic representations of the variations among the different scenarios and the temperatures trends.

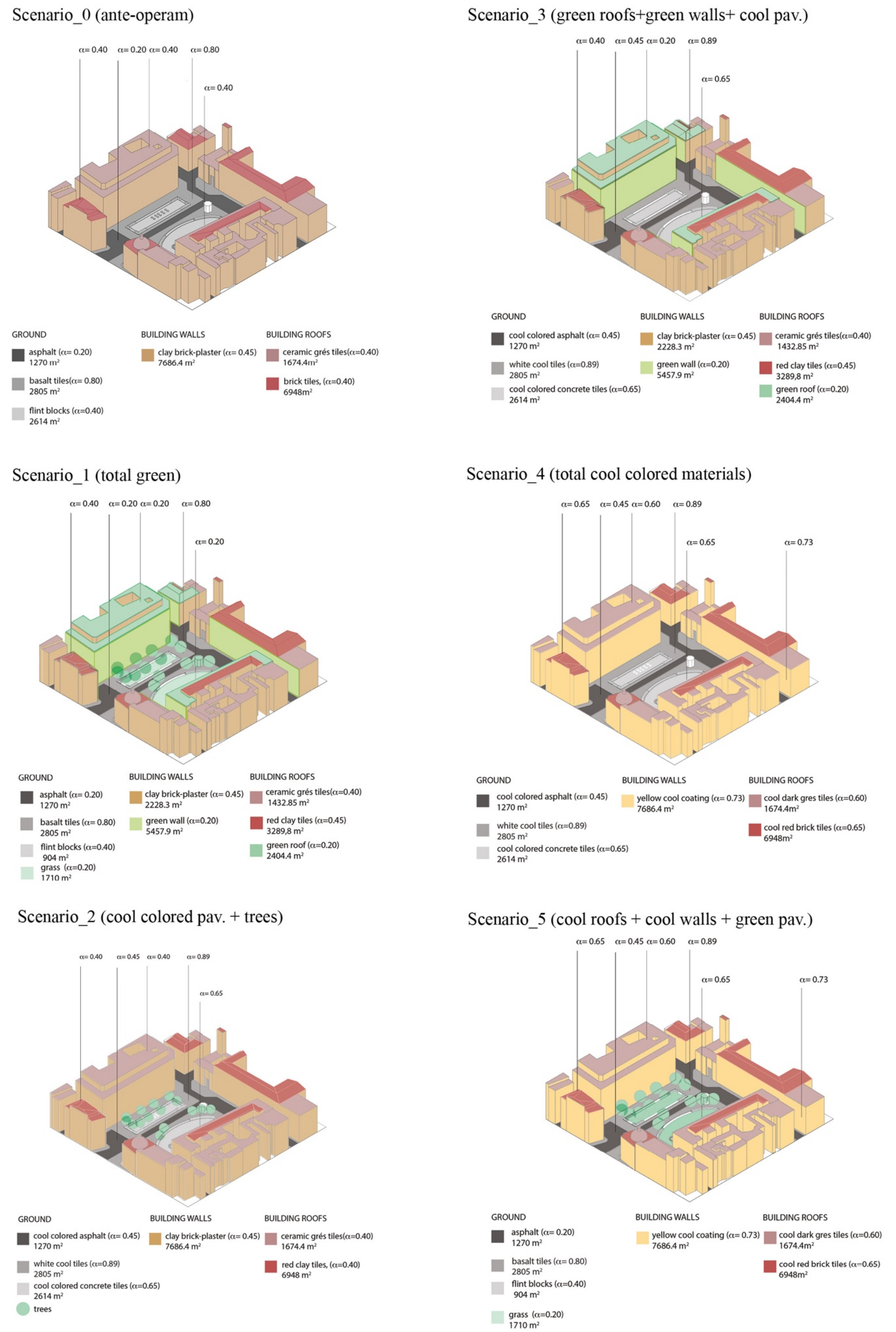
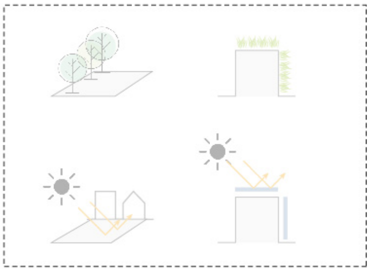


Figure 6. Ante-operam and renovation Scenarios models.

Table 4. Synthesis of the Ante-operam and Renovation Scenarios: percentages, actions, albedo variations, temperature trends.

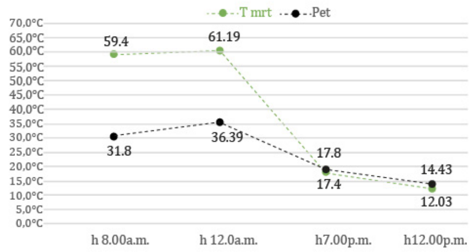
Actions & Strategies	Upgraded Factors	PET (Values for reference point A*)

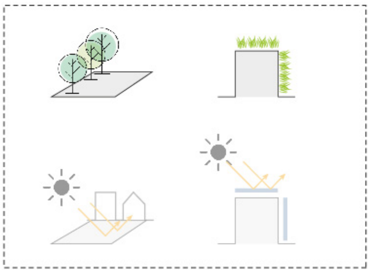


__Green Surfaces__
floral essences

__Pervious Surfaces__
Semipervious: 39%

__Albedo Values__
Values between 0.15-0.45

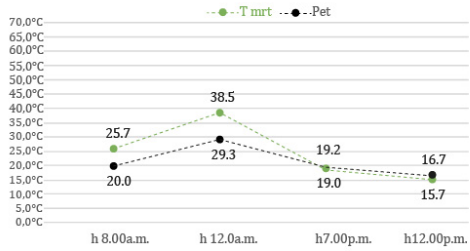


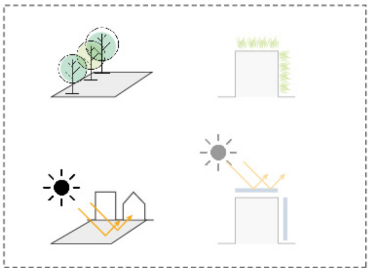


__Green Surfaces__
Decidous Trees (28 tot.), grass, green walls, green roofs

__Pervious Surfaces__
Semipervious:18%
Pervious: 34%

__Albedo values__
Values between 0.15-0.45

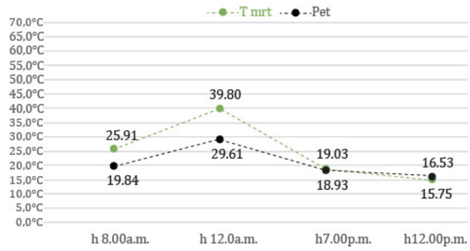


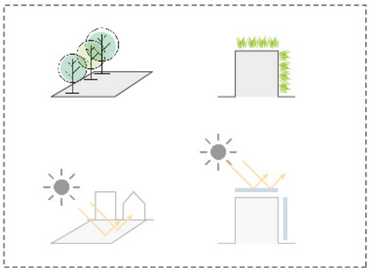


__Green Surfaces__
Decidous trees (n. 28 tot.)

__Pervious Surfaces__
Semipervious: 39%

__Albedo Values__
Values between 0.25-0.90

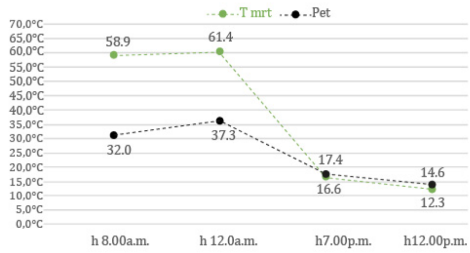


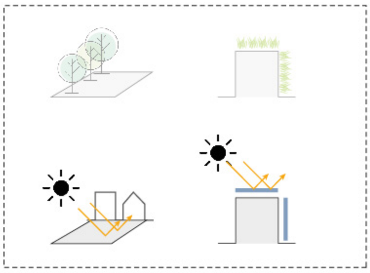


__Green Surfaces__
Decidous trees (n.28 tot.), green walls, green roofs

__Pervious Surfaces__
Semipervious: 39%

__Albedo Values__
Values between 0.25-0.90

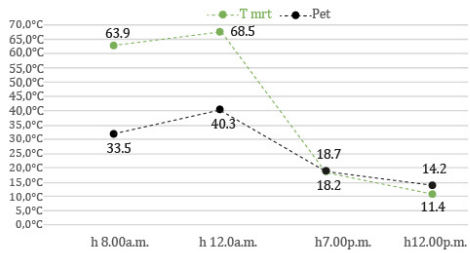


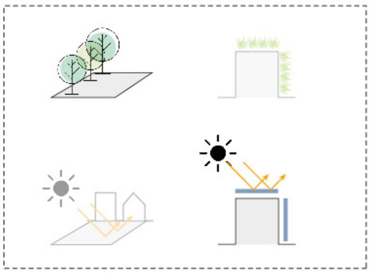


__Green Surfaces__
None

__Pervious Surfaces__
Semipervious: 39%

__Albedo Values__
Values between 0.25-0.90

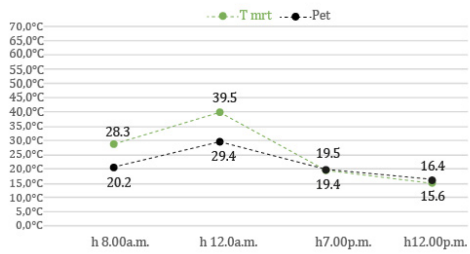




__Green Surfaces__
Decidous trees (n. 28 tot.), grass, green walls, green roofs

__Pervious Surfaces__
Semipervious:18%
Pervious: 34%

__Albedo Values__
Values between 0.65-0.90



3 Conclusions

Although use of high albedo materials for urban surfaces may reduce the air temperature and the surface temperature to which pedestrian are exposed, this reduction of the long-wave emission is offset by increased reflection of solar radiation. If applied on the roof surfaces it dissipates and reflects towards the sky sphere in a 'win—win situation' as stated by Erell (2014), whereas if applied on those urban surfaces that mostly interact with pedestrian, such as pavements and walls, it doesn't represent a good solution for outdoor wellbeing. Regarding the vegetation, further simulations are needed in order to assess the performance of different roof and wall technologies, since the cooling effect on the outdoor environment, as well as their performance on the indoor, vary considerably in green typology, location, orientation and building construction.

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