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Assessing the effects of urban street trees on building cooling energy needs: The role of foliage density and planting pattern

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A R T I C L E I N F O

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Coupling ENVI-met and EnergyPlus

A B S T R A C T

This study presents an one-way coupling approach between the ENVI-met microclimate model and the EnergyPlus building energy simulation program, to assess the effect of the urban greenery on the improvement of the buildings' cooling energy needs, in a dense urban area in Thessaloniki, Greece. Three commonly encountered urban tree species with different foliage densities are analyzed, whereas 2 different planting patterns are also considered. The obtained results indicate that the potential of trees on cooling the ambient air temperature and regulating the buildings cooling energy needs is mainly attributed to the radiative shading and the respective reduction of the solar heat gains of the exposed building façades. Moreover, the reduction of the building's cooling energy demand due to the addition of trees is directly related to their foliage density and their planting pattern. The higher energy savings up to 54 % have been achieved when the trees formed a continuous shading canopy and for the Leaf Area Density of 2.5 m^2/m^3. Yet, the cooling potential of street trees has been found rather minor when they were not tall enough to shade the biggest part of the outer building façade.

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 (Akbari et al., 2016; Rizwan, Dennis, & Chunho, 2008). Despite the multiple facilities provided to the citizens of large cities concerning health, education, technical knowledge and comfort, major issues due to land modification and transformation have also arisen with the most important negative outcome involving the urban warming and the reduced quality of urban microclimatic conditions (Santamouris, 2007). Apart from the degradation of the urban air quality (Sarrat et al., 2006) and the sever deterioration of the outdoor thermal environment (Salata et al., 2017), the increased urban air temperatures also involve an important energy penalty for the building sector (Santamouris, 2014, 2015; Santamouris et al., 2015); the existing scientific results reveal a considerable increase of the cooling energy demand that noticeably outweighs the marginal reduction of heating needs (Fanchiotti, Carnielo, & Zinzi, 2012; Kolokotroni, Zhang, & Watkins, 2007; Street et al., 2013), with the gap being even higher in cooling dominated climates (Tsikaloudaki, Laskos, & Bikas, 2011).

In light of the above, the establishment of methods that would improve the urban microclimate and attenuate its energy penalty on the building sector is a challenging issue. To date, various strategies have been proposed towards this direction, with the addition of the urban greenery, either as a component of the building envelope or as a part of the urban landscape, being one of the most common and widely evaluated strategies (Bowler et al., 2010; Gago et al., 2013; Goussous, Siam, & Alzoubi, 2015; Hsieh et al., 2018; Tan et al., 2017; Tzoulas et al., 2007; Wang et al., 2014; Ziogou et al., 2018). Findings of relevant studies suggest that the counterbalancing role of vegetation on the buildings' cooling energy demand primarily relies on the following two parameters: (1) the shading of the buildings surfaces, leading to lower amounts of solar energy absorbed and stored by the building's envelope and transmitted though conduction into the buildings (Huang et al., 1987) and (2) the physical processes and the evapotranspiration of plants, resulting in the cooling of the surrounding air (Abhijith & Gokhale, 2015; Cohen, Potchter, & Schnell, 2014; Morakinyo et al., 2017; Wang et al., 2018; Zhang, Zhan, & Lan, 2018). To date, there is a considerable amount of studies, assessing the role of street trees and

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plants on the improvement of the outdoor thermal environment under hot summer conditions and the consequent reduction of the buildings' cooling energy needs, either by empirical or by simulation means (Ko, 2018). Findings of the recent literature review of Santamouris et al. suggested that the addition of street trees inside urban areas may lead to maximum Tair reduction ranging between 0.1 °C and 5.0 °C with a median maximum temperature drop close to 1.5 °C (Santamouris et al., 2017). The important contribution of street trees on the outdoor Tair cooling has been also indicated in another recent literature review of (Tsoka, Tsikaloudaki, and Theodosiou (2018); the summary of findings of previous simulation studies, suggested that the addition of trees and hedges in the urban canyons may result in a reduction of the peak ambient Tair, between 0.20 °C and 5.0 °C, with the respective median value being close to 1.0 °C. It has however to be emphasized that trees can also act as additional barriers, to wind flow, resulting in lower wind velocities and reduced heat removal from the urban surfaces through convection (Mochida et al., 2008; Tsoka, 2017); taking thus into consideration both the benefits and the penalties provided, the existing scientific evidence agree on the overall positive effect of trees, as long as they are strategically planted (Akbari, 2002; Ko, 2018)

In terms of the vegetation's positive effect on the buildings' energy needs, the results of a monitoring campaign of Parker et al. in Florida has suggested that planting trees and shrubs around a building can reduce the daily air-conditioning electricity use by 50 % as a result of the solar radiation interception and the evapotranspiration effect (Parker, 1983). Findings of a recent study of Morakinyo et al. also underlined the role of vegetation on the buildings indoor thermal environment and the consequent use of air-conditioning (Morakinyo, Balogun, & Adegun, 2013). The monitoring campaign, established in Akure City, Nigeria, involved the measurement of indoor and outdoor climatic parameters for two similar neighboring buildings, with the one being shaded by trees and the second being fully exposed to solar radiation; the analysis of the acquired records indicated maximum indoor-outdoor temperature differences of 5.4 °C and 2.4 °C for the unshaded and the tree-shaded building respectively. In the same context, the simulation results reported in the study of Chagolla et al. have highlighted the major contribution of trees on the reduction of the annual energy needs of a residential building in Mexico, reaching 76.6 %, compared to an identical, unshaded one (Chagolla et al., 2012). Similarly, Calcerano and Martinelli have numerically evaluated the effect of tree shading on the energy demand of two residential buildings, consisting of one and two floors, in Rome (Calcerano & Martinelli, 2016). Five different planting patterns and their shading effects have been examined and the obtained simulation results indicated a considerable reduction of the cooling energy demand, varying from 11.1 % to 44.4 % and from 12.8 % up to 48.5 % for the 1-floor and 2-floor building respectively, depending on the planting arrangement an the number of trees around the buildings.

Yet, evidence from the recent literature review of Ko (2018), summarizing the results of studies that assessed the trees' effect on the buildings cooling energy needs indicated wide variations on the reported energy savings, varying from 2.3 % to 90 %. Apart from the different climatic conditions, strongly affecting the outcome of the investigated studies, other parameters also influence the estimated energy savings (Hsieh et al., 2018), among which the most important involve:

- the plant's height and the crown geometry
- the planting pattern and the distance between trees and buildings
- the canopy characteristics (i.e. shape of the crown and Leaf Area Density (LAD) corresponding the portion of leaf surface in m^2 within a m^3 of air (Yang et al., 2012)
- the tree' species and its level of maturity

As emphasized by Hsieh et al. (2018), the first three of the above-mentioned parameters will have a strong impact on the shading effect, whereas the evapotranspiration will be mainly influenced by the tree species and its maturity level.

Up to the present time, even if the increase of the Green Coverage Ratio, the trees height and the planting configurations with respect to the buildings cooling energy needs have been thoroughly investigated (Aboelata & Sodoudi, 2020; Balogun, Morakinyo, & Adegun, 2014; Calcerano & Martinelli, 2016; Hsieh et al., 2018; Morakinyo et al., 2016; Shahidan et al., 2012; Zhao, Sailor, & Wentz, 2018), this is not the case for the canopy characteristics and the foliage density. In other words, even if there is a general, well established knowledge that the higher the density of the trees' foliage (i.e. the LAD value), the higher the achieved Tair cooling and the lower the solar gains (and thus the lower the cooling energy needs) (Hsieh et al., 2018; Wang & Akbari, 2016), there is a lack of scientific studies assessing the magnitude of the achieved cooling for different steps of LAD increase. Furthermore, the existing scientific studies examine the overall effect of vegetation on multi-storey buildings (Aboelata & Sodoudi, 2019; Morakinyo et al., 2016; Morille et al., 2016; Yang et al., 2012), without a distinct analysis of separate buildings floors. Especially in multi storey residential buildings in urban areas, the received amounts of solar radiation are expected to be considerably different, as the distance from the ground increases, affecting also their energy requirements.

In this context, the current study aims to assess via simulation means the role of different foliage densities, on the improvement of the energy performance of generic building units, located at different building floors of a multi-storey building in the center of the city of Thessaloniki, Greece. To this aim, 3 different LAD values, corresponding to commonly encountered urban trees species are considered, ranging from 1.5 m^2/m^3 to 2.5 m^2/m^3 and with a step of increase of 0.5 m^2/m^3. It has to be emphasized that in the existing bibliography, there are no specific LAD values, defining a strict categorization of trees in terms of their foliage density. Most studies mainly apply empirical onsite observations to define a tree type as 'porous', 'dense' or 'very dense' with regards to its LAD measurements. Still, a tree with a crown having a LAD value between 0.5 m^2/m^3 and 1.5 m^2/m^3 is generally considered as a sparse one, LAD values close to 2.0 m^2/m^3 would suggest moderately dense foliage, while trees with LAD values higher than 2.5 m^2/m^3 would be considered as dense ones (Liu, Zheng, & Zhao, 2018; Morakinyo et al., 2020; Tan, Lau, & Ng, 2016).

Following an integrated computational approach described in the following sections, the current study aims to provide answers to the following questions:

i what is the relationship between the tree's foliage density, expressed by the *LAD* value (leaf-area density with units of m^2 foliage area per m^3 canopy volume (Yang et al., 2019) and the temperature values of the air layer in front of the examined building units?
ii what is the influence of the arrangement of street trees on the improvement of the local microclimate with respect to air temperature values in the near vicinity of the examined building units?
iii what are the potential changes on the cooling energy needs of the 1st and 3rd floor building unit due to addition of street trees with respect to their LAD value and their planting pattern (i.e. planting distances)?

2. Methodology

In the current section, the implemented methodological framework is presented. The characteristics of the case study area, the onsite monitoring campaign and simulation scenarios are initially described. Secondly, the applied simulation tools along with the proposed one-way coupling methodology and the modeling procedure are presented.

2.1. Case study area

The study area (Fig. 1.i) in which the examined building units are located, is part of a high-density residential neighborhood of the city of

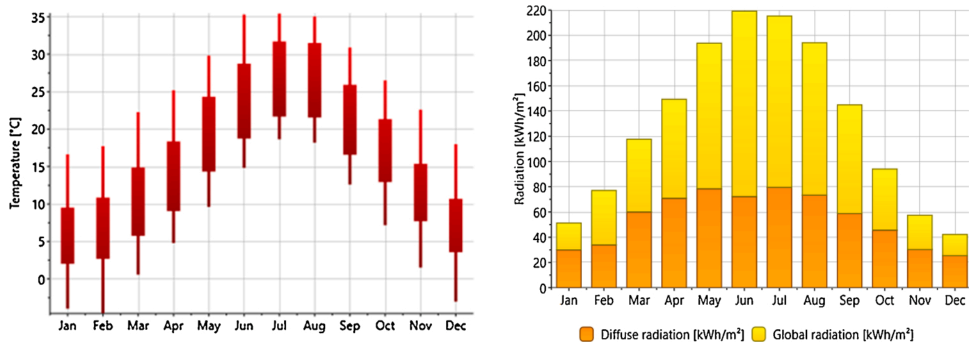


Fig. 1. Evolution of the monthly air temperatute and solar radiation values for the city of Thessaloniki, Greece (diagrams issued from Meteonorm.

Thessaloniki (40.65 °N, 22.9 °E), in the northern part of Greece. The climate of the city is Mediterranean, generally characterized by hot, dry summers, mild, wet winters and evenly distributed rainfall throughout the year. During the winter months, climatic records suggest average daily temperatures close to 6.5 °C, falling to 2.1 °C overnight; however, during the coldest winters, considerably lower Tair values can be noticed even below − 10 °C. During summer, the mean high and low Tair values are around 30.5 °C and 17.5 °C respectively, with the recorded maximum air temperatures of the last decades rarely exceeding 40 °C. Finally, July is the warmest month of the year with Tair averages of 26.7 °C (Kottek et al., 2006). The monthly air temperatute and solar radiation values for Thessaloniki, are depicted in Fig. 1.

The investigated site extends to 40 000 m^2 and contains 6 blocks of residential buildings, covering 35 % of the total ground surface of examined site. The buildings are 22.0–25.0 m high, mainly constructed during the period 1970–1980 and the sky view factor of the study area fluctuates between 0.20 and 0.50, whereas the pervious surface fraction is lower than 15 %. The main street canyon of the study area (i.e. Pittakou street canyon) where the 2 examined building units are located, is presented in Fig. 2a and b. Building envelope construction materials mainly comprise of cement and concrete elements, while the ground surfaces are dominated by impervious materials such as asphalt and concrete pavements and only a small part is covered by loamy soil and other permeable materials. A detailed description of the respective thermal and optical properties of the encountered materials is provided in the following sections.

2.2. Onsite measurements of air temperature and relative humidity

Onsite microclimatic measurements of air temperature and relative humidity have been performed for 15 consecutive hot summer days during July 2016 (with no extreme heat wave events) to acquire the necessary data for the assessment of the performance of the microclimate model. A high accuracy weatherproof Hobo-data logger for outdoor environment has been placed inside a suitable radiation shield and mounted on a tripod (Fig. 2c and d). It was then positioned in a 1st floor balcony in a building of Pittakou Street, at 4.5 m from the ground level. The reason that this specific position has been chosen is mainly attributed to the important duration of measurements, requiring thus a safe location of the equipment, away of potential damages by cars, pedestrians etc. According to the logger manufacturer, the accuracy of the air temperature sensor is ±0.21 °C for records varying from 0.0 °C to 50.0 °C while for the relative humidity sensor, the **accuracy is** ± 2.5 % for the corresponding measurements ranging between 10 % and 90 %. The height of the sensor above the balcony was 1.10 m. Special attention has been also paid so as to avoid potential boundary effects formed along the building walls; based on the recommendations provided by Niachou, Livada, and Santamouris (2008), the tripod was placed at a distance of 0.60 m from the exterior building façade. The sensor was recording air temperature and relative humidity at an interval of 1 h and measurements during all days were performed under clear-sky and low wind speed conditions while there were not any extreme heat-wave events.

2.3. Simulation tools

In this study, the outdoor microclimatic conditions of the investigated study area, both for the current conditions and for the vegetation scenarios are simulated with the ENVI-met v.4 model (Bruse & Fleer, 1998). It is a prognostic, three-dimensional, grid-based microclimate model, designed to simulate complex surface-vegetation-air interactions in the urban environment. Based on the fundamental laws of fluid dynamics and thermodynamics, it can simulate the diurnal cycle of major climatic variables, such as air and soil temperature and humidity, wind speed and direction, radiative fluxes etc., with a typical horizontal resolution from 0.5 m to 5.0 m and a time step of 1–5 seconds (Bruse & Fleer, 1998; Envi-met, 2020; Huttner, 2012), while the simulated time period usually varies between 24 h and 5 days (Simon, 2016). The model contains (a) the one-dimensional (1D) boundary model, used for the initialization of the simulation and the definition of the boundary model conditions, (b) the 3D core model, consisting of 3D cells that represent different elements, such as buildings, vegetation or atmosphere. The air temperature and humidity are estimated using the combined

Fig. 2. Google earth image of (a) the examined study area, (b) the examined street canyon and (c,d) radiation shield of the logger.

advection-diffusion equations, whereas wind field calculations include a full 3D CFD modeling, solving the nonhydrostatic three-dimensional Navier-Stokes equation and using the Boussinesq approximation. Concerning the calculation of the radiative fluxes, the model accounts for the shading by obstacles (buildings and vegetation) as well as for the shortwave and longwave radiation which is reflected by the various surfaces (Huttner, Bruse, & Dostal, 2008; Simon, 2016), (c) the soil model, which is connected to the underside of the 3D atmospheric model and (d) the vegetation model, including the simulation of the transpiration rates, the leaf temperatures of trees and the heat and vapor exchanges between the plants and the atmosphere. In fact, with the newly developed 'Albero' feature in the ENVI-met model, the accuracy of the simulations of the interactions between the vegetation elements and the surrounding atmosphere is considerably increased. Several scientific studies have also concluded that the model can accurately model the physiological and thermal performance of plants including transpiration rates the changes of leaf temperatures inside complex urban environments (Liu et al., 2018; Simon et al., 2018). A detailed overview of the model's characteristics along with its limitations is provided in a recent review of Tsoka, Tsikaloudaki et al. (2018).

The energy performance simulations and the assessment of the cooling energy needs of the examined are conducted with the EnergyPlus v.7 dynamic model, a structured, modular, open-source building energy performance simulation model, created by the United States Department of Energy (D.B. Crawley et al., 2001). Its official release dates back in 2001 and since then it has been widely validated and applied all over the world for building energy analysis (Coakley, Raftery, & Keane, 2014; Fumo, Mago, & Chamra, 2009; Griffith & Crawley, 2006; Loutzenhiser et al., 2007). 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 (Eskin & Türkmen, 2008); further details on the model's structure and features are provided in (D. Crawley et al., 2001; Documentation, 2007; Sousa, 2012). One of the main input boundary conditions of the EnergyPlus model is the hourly weather file, consisting of hourly values of all major climatic variables over a whole year. These weather files are generally based on the statistical analysis of long-term climatic records observed in meteorological weather stations in the peripheral zones of cities. As a result, the site-specific microclimatic conditions, as a function of the morphological and geometrical characteristics of the study area cannot be accounted for. To harness this limitation, in this study, the weather file for the energy performance simulations will be updated with the ENVI-met simulation output, both for the current conditions and the vegetation scenarios. The proposed modeling procedure is analysed in Section 2.5.

2.4. Simulation scenarios

Vegetation in the current conditions (i.e. base case scenario) mainly involve a few deciduous trees of the type of *Hibiscus Syriacys*, placed along the street canyons of the study area. The hibiscus tree in the base case scenario is rather short, with a height of 2.0–2.5 m and a crown diameter close to 1.0 m. Its shading effect is thus only limited to the ground surfaces, whereas the building's facades are not protected by its crown and foliage. Regarding the examined vegetation scenarios, 3 tree species of different LAD values, ranging from 1.5 m^2/m^3 to 2.5 m^2/m^3 and with a step of increase of 0.5 m^2/m^3 are assessed, with the respective values corresponding to sparse, moderate and dense crown. Given that the emphasis is here given on the effect of the foliage density on the Tair cooling and the building units' cooling energy needs, other major geometrical parameters remain the same in all cases. More precisely, in all 4 cases, the trees total height, crown diameter and lower crown height is considered 10.5 m, 3.5 m and 3.0 respectively, suggesting medium height trees with narrow crown (Morakinyo et al., 2020). The established scenarios of trees and their geometrical and foliage characteristics correspond to three commonly encountered vegetation types in urban areas of many European cities (Gillner et al., 2015; Kontogianni, 2017), while they rather tolerant to drought, associated with summertime heat wave conditions (De Jaegere, Hein, & Claessens, 2016): the *liriodendron tulipifera* (LS), the *aesculus hippocastanum* (AS) and the *tilia cordata* (TS).

For every one of the above-mentioned tree types, 2 planting patterns are examined:

- 1st planting pattern: trees arranged in uniform rows, creating a continuous shading canopy with no space between the crowns. This scenario would suggest a 60 % increase on the Green Coverage Ratio of the examined street canyon compared to base case.
- 2nd planting pattern: tree arranged in uniform rows with space of 9.0 m between them and grass covering the ground surface between trees, leading to a 30 % increase on the Green Coverage Ratio of the examined street canyon compared to the base case.

In both cases, trees are considered to be planted at a distance of 3.0 m from the buildings. The considered characteristics of the studied tree species are presented in Table 1, whereas Fig. 3 depicts the vertical distribution of the LAD profile of the 4 examined tree species and for the Hibiscus syriacus of the base case scenario, as accounted for the modeling of the plants.

2.5. Modeling procedure

In this study, the effect of street trees and their foliage characteristics on the cooling energy demand of generic urban building units is investigated. To increase the accuracy of the simulation results, an integrated simulation method between a microclimate model and a dynamic Building Energy Performance Simulation tool (BEPS) is adopted. In fact, when it comes to the modeling of trees, the existing dynamic BEPS models can sufficiently handle the induced shading effect on the ground and buildings' surfaces by the trees' foliage; yet, the important evapotranspiration effect and the latent heat release, cooling the ambient air cannot be handled (Morille et al., 2016). Given the significant impact of the local microclimatic conditions on the buildings cooling energy needs (Bouyer, Inard, & Musy, 2011; Santamouris et al., 2018; Yang et al., 2012; Zhang et al., 2018b), the establishment of more sophisticated, integrated approaches towards the assessment of the effect of street trees on the buildings' energy needs is of crucial importance. Similar coupling approaches between microclimate models and BEPS tools towards the investigation of the local microclimatic conditions on the building's energy performance have been also adopted by many previous studies (Aboelata & Sodoudi, 2019; Gobakis & Kolokotsa, 2017; Kolokotsa et al., 2016; Morakinyo et al., 2016; Santamouris et al., 2018).

2.5.1. Coupling approach between ENVI-met and energy plus

A one way-coupling simulation approach towards the assessment of the effect of street trees on the building's energy needs is here applied. More precisely, a one-way coupling procedure of the ENVI-met with the Energy Plus model is adopted, to provide to the latter tool, updated input climatic conditions that do reflect the particularities of the local microclimate, before and after the addition of green elements. The coupling procedure is based on the following steps:

- The 2 models of the study area are created in the 2 simulation tools i.e. the ENVI-met model and the Energy Plus, while special attention has been paid so as to achieve the correspondence of surfaces and a proper exchange of data between the 2 simulation tools.
- Microclimatic simulations for the case study area are conducted for the representative summer day, both for the current conditions and for the vegetation scenarios (1 (current)+2 × 3(2 planting patterns and 3 tree types).

Table 1
Examined vegetation scenarios and characteristics of the investigated trees (Gillner et al., 2015; Kontogianni, 2017).

	Tree Type	Symbol	Tree height* (m)	Lower crown height* (m)	Crown radius*(m)	LAD value (m^2/m^3)
Vegetation scenarios	1. *Liriodendron tulipifera*	LS	10.5	3.0	2.5	**1.5**
	2. *Aesculus hippocastanum*	AS				**2.0**
	3. *Tilia cordata*	TS				**2.5**
Base case-current conditions	Hibiscus Syriacus	HS	2.5	1.0	1.0	1.0
	Grass	GS	0.3	0.0	–	0.5

* values, corresponding to mature trees, based on relevant measurements that are reported in the existing literature (Gillner et al., 2015; Kontogianni, 2017).

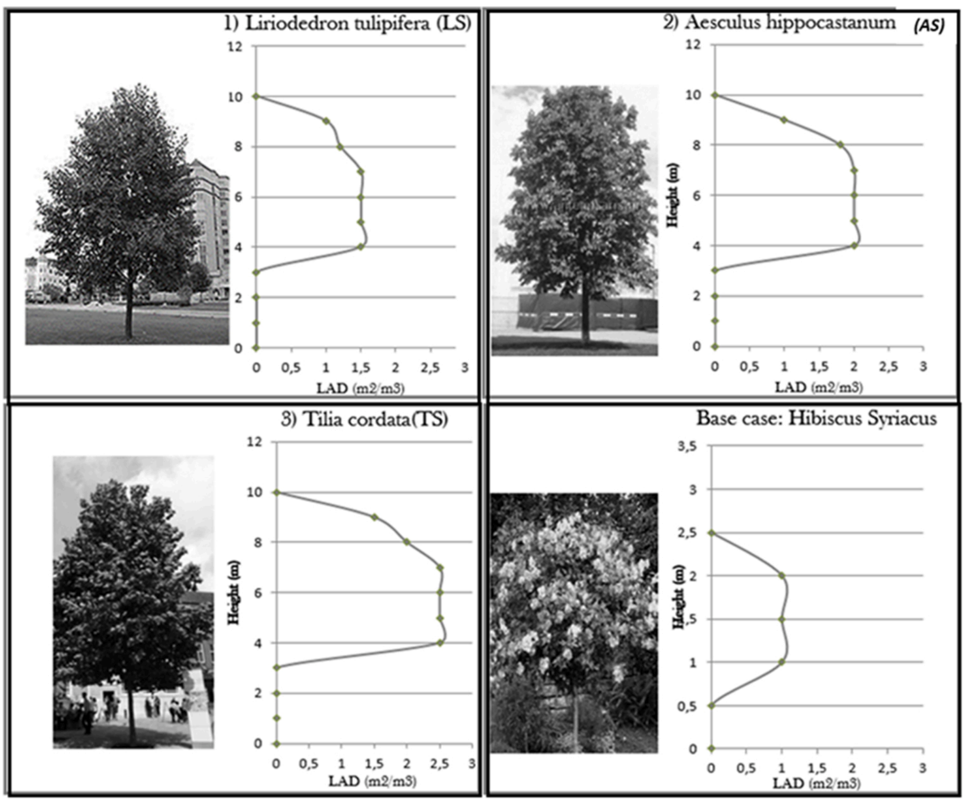


Fig. 3. Vertical distribution of the LAD profile of the 3 vegetation scenarios (LS, AS and TS) and for the Hibiscus Syriacus of the base case scenario. These LAD values have been considered for the modeling of the plants in the ENVI-met microclimate model.

- For each scenario (i.e. current conditions and vegetation scenarios), the estimated hourly values of air temperature, relative humidity, wind speed and wind direction on each outer cell of the examined building units are extracted from ENVI-met.
- For every examined scenario, the hourly weather file of the EnergyPlus model is updated with the hourly outputs of the respective ENVI-met simulations. i.e. air temperature, relative humidity, wind speed, wind direction.
- The building units' energy performance simulations are then performed via the Energy Plus model, using the updated weather files

The proposed computational approach is implemented for a representative summer day of July, the warmest month for the city of Thessaloniki. To this aim, the 22th of July 2016 is chosen, the definition of which has been based on a detailed statistical analysis of long-term climatic observations (see reference Tsoka et al. (2018) for the detailed methodology for the definition of the representative day)

2.5.2. ENVI-met microclimate simulations

At a first step, microclimate simulations both for the base case and the vegetation scenarios are performed for the selected, representative summer day. The required input parameters for the microclimate simulations with the ENVI-met model involve (a) the area input file, generated through a graphic interface and representing the geometrical characteristics of the study area and (b) the configuration file, containing the meteorological boundary conditions of the simulations. For the generation of the model's geometry and the representation of the case study area of 40 000 m^2 (i.e. 200m × 200m), a set of 134 × 134 grids has been adopted for the x and y axis with a resolution of 1.5 m; in the z axis, the number of cells was set to 20 with a 3.0 m resolution (i.e. equal to the average floor per height). Seven nesting grids have been also placed around the main domain area, to reduce the boundary effects and assure the numerical model's stability. The ground properties of the nesting grids are those of concrete pavements to approximate in a realistic way the surfaces on the boundaries of the study area. The geometry and the foliage characteristics of the modeled plants have been designed in the 'Albero' tool of the ENVI-met model, according to the respective characteristics depicted in Table 1 and Fig. 3. The considered thermal and optical properties of the building envelope and the ground surface materials are shown in Tables 2 and 3 respectively.

The plot and 3D area input files of the base case and the vegetation scenarios (for the two examined planting patterns) are shown in Fig. 4. The yellow dotted line and the yellow circle indicate the street canyon and the building in which the generic building units, the energy

Table 2
Thermal and optical properties of the building envelope materials according to values provided by (TEE, 2017).

	Plaster	Brick	Concrete	Roof Tiles (concrete)
Thickness (m)	0.02	0.19	0.20	0.03
Therm. conductivity (W/mK)	0.87	0.51	2.5	1.50
Density (kg/m^3)	1800	1500	2400	2100
Specific heat (J/kg.K)	1000	1000	1000	1000
Solar reflectance*	0.40	–	–	0.30
Emissivity*	0.90	–	–	0.90

* Solar reflectance and emissivity only refer to the outside layers of the building walls and roofs.

Table 3
The physical properties of the ground surface material (ISO, 2007a, 2007b).

	Asphalt	Concrete Tiles	Soil
Volumetric heat capacity Cp (J/m^{3}K)	2.1×10^6	2.1×10^6	3.0×10^6
Therm. conductivity (W/mK)	0.70	1.50	1.50
Water content at field capacity* (m^3 of water/m^3 of soil)	0.00	0.00	0.25**
Solar reflectance	0.12	0.30	0.20
Emissivity	0.90	0.90	0.95

performance of which will be assessed, are located. A total number of 7 ENVI-met simulations is performed – 1 for the current conditions and 6 for the vegetation scenarios (i.e. 2 spatial layouts and 3 examined tree types). The boundary conditions involving wind speed, wind direction, hourly values of Tair and RH, used for the forcing along with the mean monthly value of soil temperature were obtained from the meteorological station of the Aristotle University of Thessaloniki. A summary of the meteorological conditions in the model boundaries is provided in Table 4. Finally, in order to obtain the necessary microclimatic parameters for the coupling procedure, 5 receptor points have been placed in front of the façades of the building in which the investigated building units are located. The 'receptors' function in the ENVI-met model offers the possibility to acquire all major microclimatic variables at different heights, from the ground level till the top of the model domain. Following the recommendations of Yang et al. (2012) and Morakinyo et al. (2016), the five receptor points providing microclimatic values of air temperature, relative humidity, wind speed, shortwave radiation etc. were placed at 0.75 m away from the building façade (see Fig. 5).

2.5.3. Extraction of microclimate data and modification of the climatic files

The models of the study area have been generated in the 2 simulation tools i.e. the ENVI-met model and the Energy Plus, to achieve the correspondence of the surfaces and a proper exchange of data between them. In both tools, when creating the building volumes, the ground floors are considered to have a height of 4.5 m and the typical building floors has a height of 3.0 m. Moreover, for both building units, only the main façade is considered to be exposed to exterior conditions, while the ground surface, ceiling and the rest of the vertical facades are considered as adiabatic due to the same operational schedules and cooling setpoints between the apartments. Yet, the components of the building envelop in Energy Plus are considered as single entities, while a grid-based geometry is used at the ENVI-met model. To overcome this barrier, each façade of the examined building units is considered to consist of a number of cells, whereas data for these cells are provided by the receptor points (see Fig. 5). Thus, for the examined 1 st floor building unit, microclimate values for air temperature, relative humidity, wind speed and wind direction are extracted for the heights of 4.5 m and 7.5 m, from the five receptors. For the 3rd floor building unit the respective extraction is performed for the heights of 10.5 m and 13.5 m.

The obtained hourly values are then averaged (i.e. for the 1 st floor, average values for 4.5 m and 7.5 m and for the 3rd floor, average values for 10.5 m and 13.5 m) and the acquired averages are used to modify the existing weather file in the Energy Plus model. Through this approach,

Table 4
Meteorological input boundary conditions.

Input parameters	22th of July 2016
Mean wind speed at 10 m above ground	1.15 m/s
Prevailing wind direction	SW (225°)
Roughness length	0.1*
Air temperature forcing	Hourly data from meteo station
Relative humidity forcing	Hourly data from meteo station
Cloud coverage	No clouds
Specific humidity at 2500m	7g/kg*
Solar adjustment factor	1
Soil upper layer (0−20 cm) initial temperature	305 K
Soil upper layer (20−50 cm) initial temperature	304 K
Soil deeper layer (below 50 cm) initial temperature	293 K*
Soil upper layer (0−20 cm) moisture content*	50 %*
Soil upper layer (20−50 cm) moisture content*	60 %*
Soil upper layer (below 50 cm) initial moisture content*	60 %*

* ENVI-met default values.

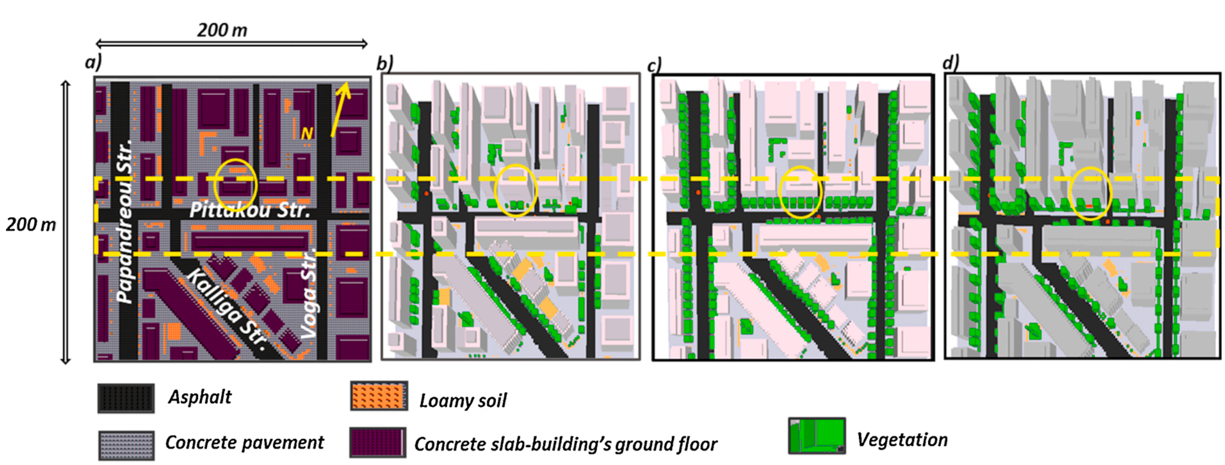


Fig. 4. (a) the plot and 3D area input files of (b) the basic configuration with low vegetation coverage (c) the vegetation scenario with continuous rows of trees (d) the vegetation scenario with discontinuous rows of trees. The yellow dotted line and circle show the studied street canyon and the location of the examined building units.

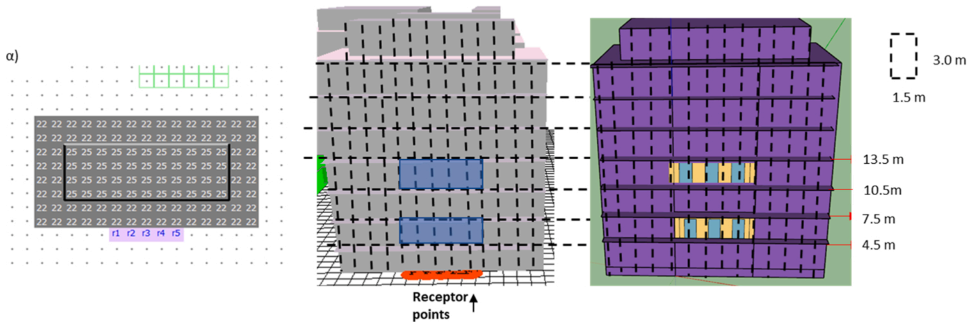


Fig. 5. (a) Location of the receptor points, in front of the examined building units, (b)Sketch of the grid representation in the ENVI-met model and location of the examined building units (in the blue rectangle) and (c) correspondence of the outer surface with the EnergyPlus model.

the microclimate data of the air layer around the examined building units, as a function of the trees species and their planting pattern can be now considered by the corresponding EnergyPlus model.

2.5.4. Building energy performance simulations with energy plus

As earlier mentioned, the cooling energy needs of a generic 1st and 3rd floor building units are simulated with the Energy Plus model. To initialize the Energy Plus simulations, the default Energy Plus weather (EPW) dataset for the city of Thessaloniki is modified with the acquired microclimate simulation results for the representative summer day, previously extracted from the ENVI-met model (as described in the previous steps). To assess the role of the street trees on the building units' cooling energy needs, a total number of 7 Energy Plus simulations is conducted for every building unit – 1 for the current conditions and 6 for the vegetation scenarios, following the coupling approach described in section 2.5.1. The flow of the conducted simulation runs is shown in Fig. 6.

It should be also noted that each simulation run is symbolized according to the tree type and the selected spatial configuration; for example, the simulation run '*LS*1' would correspond to the case that the trees of type *liriodendron tulipifera* are arranged in uniform rows so as to create a continuous shading canopy. Accordingly, the simulation run '*LS*2' would involve the planting of *liriodendron tulipifera* with a distance of 9.0 m between the crowns and grass covering the ground surface are between trees.

Regarding the characteristics of the investigated building units, the buildings of the examined case study area have been constructed during the decade 1970–1980, when no specific requirements for the thermal protection of the building envelopes were imposed. A non-insulated envelope is thus taken into consideration. Besides, according to the results of a previous statistical analysis of the building stock in Thessaloniki (Theodoridou, Papadopoulos, & Hegger, 2011), the average total floor area of a building unit constructed during the period 1970–1990 is close to 85 m^2-90 m^2. To this end, a generic building unit has been

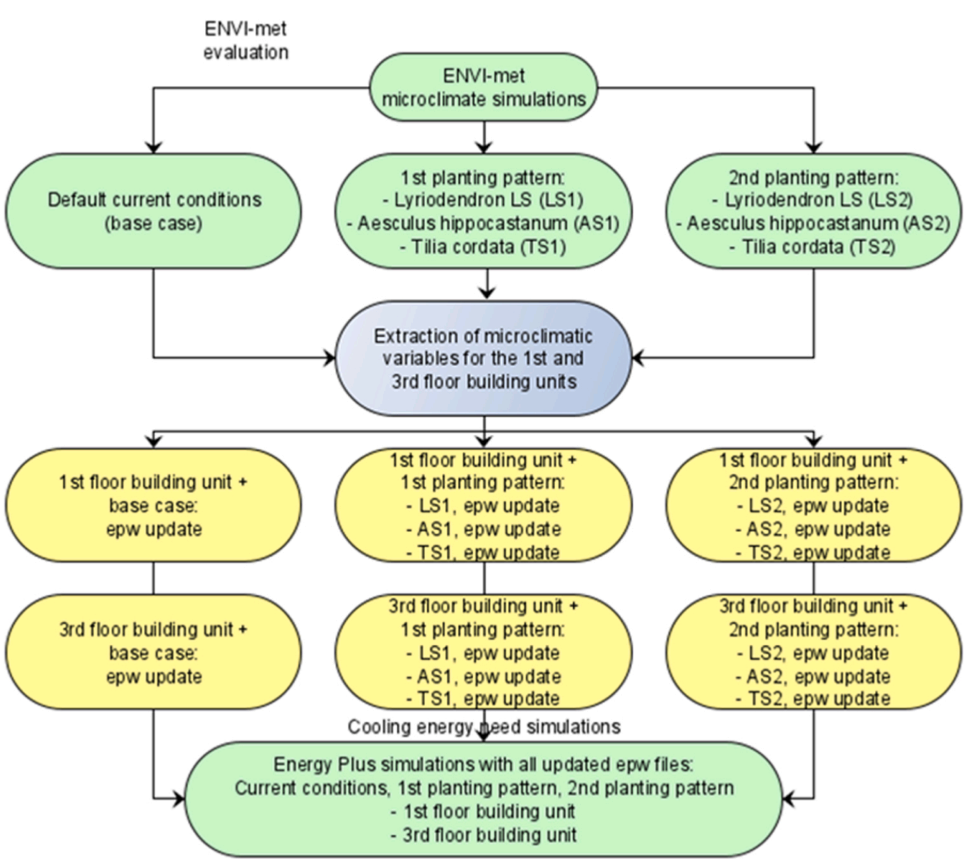


Fig. 6. Diagram presenting the performed simulation runs.

designed, consisting of a living room and a kitchen, a bedroom and a bathroom with a total floor area of 88.0 m^2 and a net floor area of 80 m^2.

The plan of the assumed building unit and the respective 3D model, introduced in the EnergyPlus tool, is presented in Fig. 7. The generic building units have other neighboring apartments on the same floor, while the staircase area is assumed to be an unconditioned thermal zone (no cooling setpoint is considered). The heat transfer between the examined thermal zone and the staircase area are thus taken into consideration during the energy performance simulations. The thermal and optical properties of the construction materials of the building units' envelope are the same with those considered at the ENVI-met simulations. Concerning the windows' thermal properties, double glazed, synthetic PVC windows are considered with the conductance of the synthetic frame equal to 2.8 W/m^2/K, according to values of the Technical Guides of the recast of the Hellenic Thermal Regulation of the Energy Assessment of Buildings (TOTEE20701-1/2017, 2017TOTEE1-1/, 2017TOTEE20701-1/2017, 2017). Finally, the operational schedules of the generic building units, involving occupancy, lighting, equipment, ventilation, heating and cooling setpoints along with the infiltration rates, unintentionally introduced from the outside environment into the thermal zone, are set according to the respective values of the above mentioned Technical Guides (TOTEE20701-1/2017, 2017TOTEE1-1/, 2017TOTEE20701-1/2017, 2017). All relevant parameters are given in Table 5. At this point, the following remarks should be done, in terms of the solar radiation and the respective shadowing calculations: in both EnergyPlus and ENVI-met, the 'ray--tracing' method is adopted. Yet, the calculation of the reflected solar radiation is conducted with higher precision in the Energy Plus model since all three patterns of reflection (beam to beam, beam to diffuse, and diffuse to diffuse) are considered (Yang et al., 2012).

Nevertheless, the Energy Plus provides a more simplified approach on the definition of the albedo of the ground surfaces since a homogenous ground albedo is generally assumed for the simulations. Moreover, trees in the Energy Plus are only treated as obstructions like adjacent buildings, characterized by a solar transmissivity that can be scheduled by the user, depending on the season.

Based on the above-mentioned remarks and in order to provide an accurate simulation of the solar gains the following approach is adopted:

Table 5
Input boundary conditions and operation schedules for the energy performance simulations.

Parameter	Unit	Value	Schedule type
Occupancy	Persons/ 100m^2	5	Fraction Schedule: During the whole year, 100 % of occupancy occurs from 00:00 to 07:00 a.m. and from 17:00 p.m. to 00:00. 50 % of occupancy occurs from 07:00 am to 17:00 p.m.
Air change/ ventilation	m^3/s/ person	0.042	Fraction Schedule: follows the occupancy schedule.
Night ventilation	ACH	3	Fraction Schedule: Performed during the cooling period and from 00:00 till 08:00 a.m., only if the indoor air temperature is higher than the outdoor air temperature by 1.0 °C.
Lighting	W/m^2	6.4	Fraction Schedule: During all months, from 00:00 till 08:00 a.m. :0, from 08:00 a.m. till 17:00 p.m., 0.3 and from 17:00 p.m. till 00:00, 0.75
Cooling setpoint	°C	26	Fraction Schedule: Cooling period: From 15/04 till 14/10
Heat gain from people	W/person	80	Fraction Schedule: follows the occupancy schedule
Heat gain from equipment	W/m^2	4.0	Fraction Schedule: follows the occupancy schedule
Infiltration rates	ACH	1	Fraction Schedule: During the whole year, 100 %

- the solar radiation gains, received by the facades of the building units and the corresponding shadowing effects of the neighboring obstacles are calculated by EnergyPlus; the surrounding obstructions of the building units (i.e. buildings and trees) are generated into the EnergyPlus geometric model following the geometrical characteristics, defined in the ENVI-met model (see Fig. 8). Regarding the modelling of plants, trees with a total height of 10.5 m, lower crown height of 3.0 m and crown diameter of 5.0 m are designed in the Energy Plus, in front of the examined building units and according to

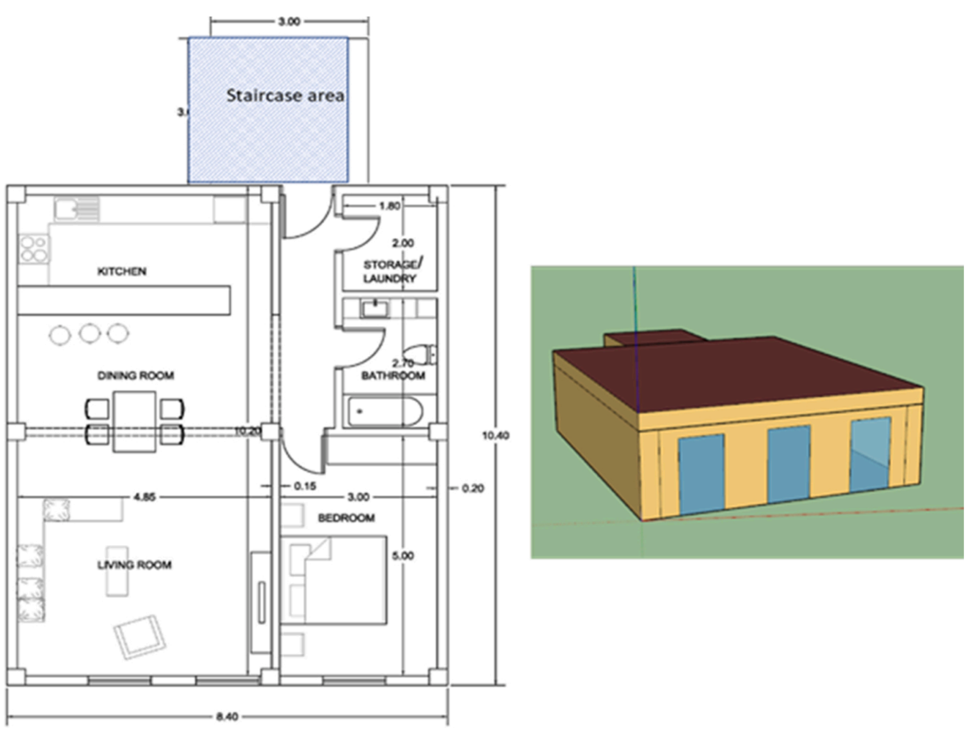


Fig. 7. Plan of the generic building unit and the corresponding 3D model.

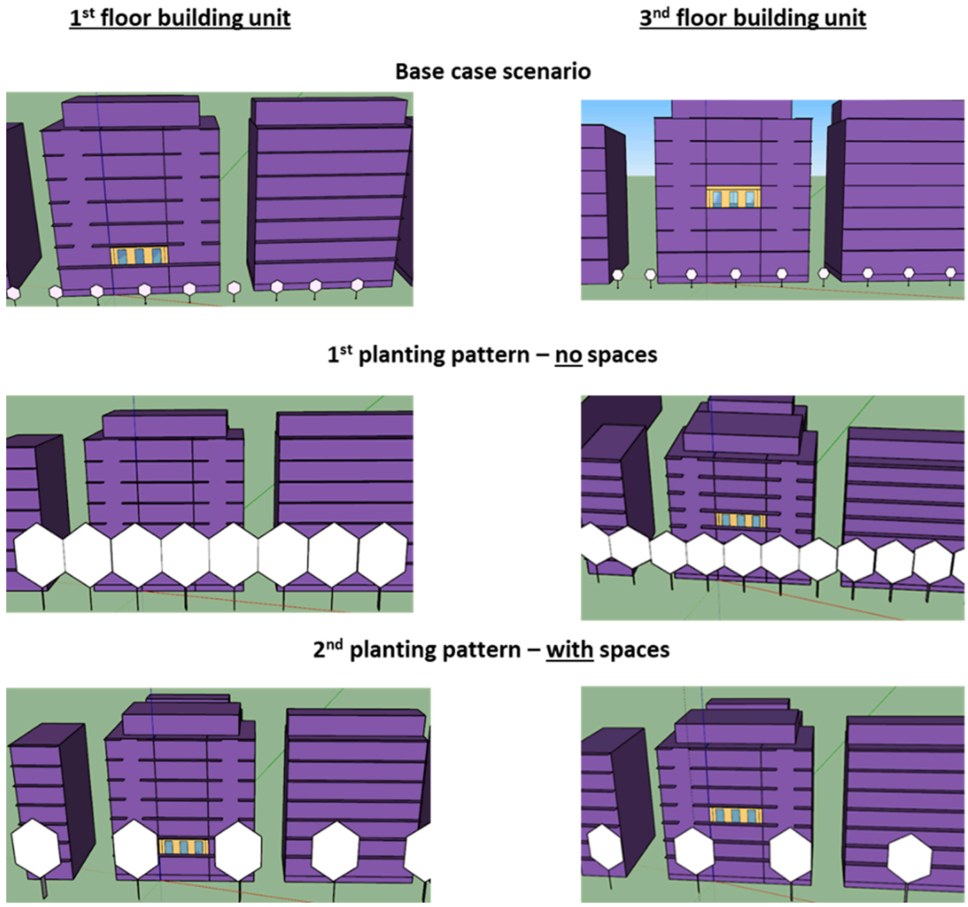


Fig. 8. Energy plus models of the investigated 1st and 3rd floor building units and the surrounding obstacles for the base case scenario and the 2 planting patterns.

the 2 investigated planting patterns. The geometric representation of the trees is simplified and relies on a two dimensional hexagonal surface as proposed by (Calcerano & Martinelli, 2016) and (Robitu et al., 2006).

- The accurate modelling of the trees' impact on the building units' cooling energy needs, imposes also the consideration of the different transmissivity of solar radiation through the crowns of each examined tree type. It is obvious that the higher the foliage density (in this study expressed by the LAD value) the higher the blocking of solar radiation rays. In this study, the definition of the transmissivity of the global radiation with respect to the examined tree species is based on relevant onsite monitoring campaigns and their respective results, reported in the literature. Based on the existing evidence provided by (Konarska et al., 2014; March & Skeen, 1976; Takács et al., 2016) the solar transmissivity of the global radiation of the *Liriodendron (LS),* the *Aesculous hippocastanum (AS)* and the *tilia cordata (TS)* during summer conditions is set to 11 %, 9.4 % and 8 %.
- The average ground albedo is defined according to the respective in the ENVI-met model. Given that the asphalt, the concrete pavements and the soil have an albedo of 0. 12, 0.30 and 0.20 respectively, an average ground reflectance of 0.25 is set in the Energy Plus model for the base case scenario. (according to the corresponding area of the ground, covered by asphalt, concrete pavement and soil); the respective ground reflectance for the 1st and 2nd scenarios of trees' planting pattern is set equal to 0.23 and 0.22 respectively.

Finally, a simplified approach has been here applied for the definition of the convective heat transfer coefficients of the building units' surface thermal exchange and the equation developed by McAdams has been used (McAdams, 1954)

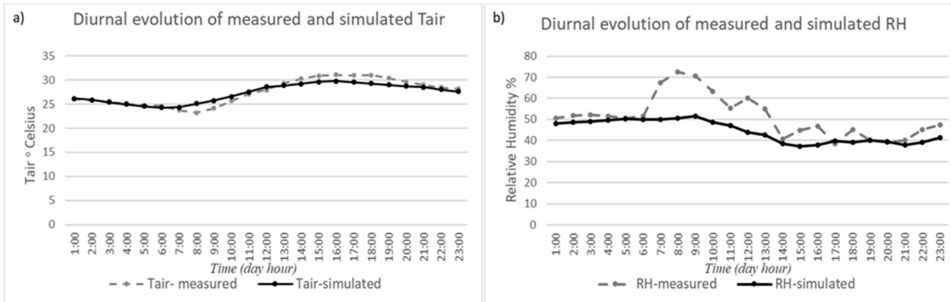
$$hc = 5.7 + 3.8\mathrm{Vz}$$

Where V_z is the wind velocity in m/s, as defined in the modified. epw weather file.

3. Results and discussion

3.1. Evaluation of the ENVI-met model

The evaluation of the performance of the ENVI-met microclimate model is conducted using the onsite measurement results of Tair and RH, for the selected simulation day. The hourly climatic records have been compared with the corresponding modelled values and their diurnal evolution for the 22th of July 2016 is shown in Fig. 9. The ENVI-met model generally underestimates the daytime air temperature and overestimates part of night time and morning values, confirming a trend that has been already reported in previous studies (Tsoka, Tsikaloudaki et al., 2018). The absolute maximum and minimum difference between the observed and the simulated hourly Tair is equal to 1.80 °C and 0.03 °C respectively. To assess the model's performance, the Root Mean Square Error (eq.1), the Mean Absolute Error (eq.2) and the Index of Agreement (eq.3) have been selected and the estimated values were then compared with the respective ones reported in the literature. As it can be seen in Fig. 9a, considering the Tair values, the estimated MAE, RMSE and IA are equal to 0,82 °C, 1.02 °C and 0.9.We consider the error as acceptable, as it is within the range of corresponding reported values,. More precisely, in the recent literature review of (Tsoka, Tsikaloudaki et al., 2018) a meta-analysis of the results of 48 ENVI-met studies, assessing the ability of the model to accurately simulate the diurnal profile of Tair has been conducted. As the authors mention, the reported MAE values



RMSE=1.02 °C
MAE= 0.82 °C
IA= 0.94

RMSE=10.2%
MAE= 7.7%
IA= 0.97

Fig. 9. Diurnal evolution of the recorded and the simulated Tair and RH values during the representative summer day (values corresponding at the first floor building level) and the corresponding quantitative metrics.

range between 0.27 °C and 3.67 °C with a median value of 1.34 °C, while for the RMSE and IA, the respective reported errors are between 0.52 °C–4.30 °C and 0.4 – 0.8. Based on the above-mentioned remarks, it can be said that the ENVI-met model can accurately simulate the diurnal Tair values.

$$\text{RMSE} = \left[N^{-1} \sum_{i=1}^{N} (Pi - Oi^2 \right] ½ \tag{1}$$

$$\text{MAE} = N^{-1} \sum_{i=1}^{N} |Pi - Oi| \tag{2}$$

$$\text{IA} = 1 - \left[\sum_{i=1}^{N} (Pi - Oi)^2 / \sum_{i=1}^{N} \left(\left|Pi - \overline{O}\right| + \left|Oi - \overline{O}\right| \right)^2 \right] \tag{3}$$

At this point it is important to mention that the parameters that contribute to the error involve (a) potential inaccuracies on the determination of the model geometry, (b) the input boundary conditions for air temperature, issued from a meteorological station outside the study area, neglecting thus the higher air temperature inside the urban district (c) the neglect of the heat release from air conditioners, transportation and other human activities, during the microclimate simulation and (d) the fact that the multiple reflections of solar radiation within the canyon are not handled by the model (only the first surface reflection is considered during the simulation).

Regarding the parameter of relative humidity, the model tends to underestimate the diurnal RH values with maximum and minimum deviations reaching 18 % and 0.5 %. The reported high difference between the observed and the simulated RH relies to the fact that the study area is strongly influenced by the sea breeze effect, a phenomenon that is not handled by the model. It has to be emphasized that, in the existing literature, studies assessing the ENVI-met model' s performance towards the accurate estimation of the RH are far fewer compared to those, assessing the parameter of air temperature. Yet, the estimated statistical difference metrics for the RH (Fig. 9b) are within the range of the existing relevant evidence and they are thus considered as acceptable; based on the meta-analysis study of Tsoka, Tsikaloudaki et al. (2018) the reported RMSE and MAE range between 2.04 %–10.20 % and 2.50 %–7.78 % respectively, whereas higher errors were found in coastal areas where the prominent sea breeze effect cannot be handled by the ENVI-met model.

As previously mentioned, the HOBO data logger has been located at the first-floor building level. Unfortunately, due to limitation of resources, a measuring campaign at multiple heights from the ground level (i.e. from the ground till the roof top) or at different horizontal spots (i.e. exposed or covered from solar radiation) could not have been conducted. Undoubtedly, multiple measuring spots would have contributed to a more thorough evaluation of the model and thus, to an even more accurate representation of the case study area and its microclimatic conditions. Still, following the existing literature practices from the one hand, and assuring the model's performance at the 1 st floor level via the above-mentioned process on the other hand, permits us to considered that for the purposes of the present study, the ENVI-met model can sufficiently and accurately reproduce the microclimatic parameters within the model domain. At the next step and after assuring the ENVI-met model's performance for the base case scenario, further microclimate simulations for the established vegetation scenarios are conducted and the obtained simulation results are described in the next sections.

3.2. Impact of street trees on the outdoor air temperature

The estimated hourly Tair reduction, occurring in front of the examined 1st and 3rd floor generic building units as a result of the different examined vegetation scenarios is given in Fig. 10. Each pair of diagrams (i.e. i and ii) depicts the predicted diurnal Tair decrease in front of the 2 building units for a specific LAD value; in each diagram, the continuous curve corresponds to the obtained simulation results for the first planting pattern (i.e. continuous canopy), whereas the dotted curve reflects the simulation results for the second spatial configuration. In the base case scenario and during the simulation day, the external façades of the 2 examined building units (facing South) are not sheltered by the neighboring buildings or vegetation and thus, they continuously receive solar radiation from the early morning till the afternoon. In the current conditions, the modeled Tair outside the examined 1st and 3rd floor building unit fluctuates between 24.2 °C–30.0 °C and 24.1 °C–29.7 °C respectively, with the peak daily Tair values being observed at 15:00 p.m.

- *Regarding the 1 st floor building unit*

When trees are planted according to the 1st planting pattern (i.e. continuous shading canopy) the whole façade of the examined, 1st floor building unit is shielded by the tree's foliage; lower amounts of solar radiation are thus absorbed and stored by the exterior façade and consequently, the convective heat transfer towards the surrounding air is also reduced. Apart from the reduction of the solar gains, the Tair drop is also attributed to the increase of the latent heat release through the evapotranspiration of plants. The simulation results suggested that the higher the foliage density, the lower the solar gains and the higher the increase of the relative humidity of the ambient air. As depicted in Fig. 11a the relative humidity of the air layer in front of the 1st floor building unit increased by 1.5 %–4 % and by 2 %–7 % compared to the current conditions, due to the vegetation scenarios *LS1* and *TS1* with peak differences being noticed in the morning. Similar magnitudes of RH changes as a result of street trees planting have been also reported by Morakinyo & Lam (2016).

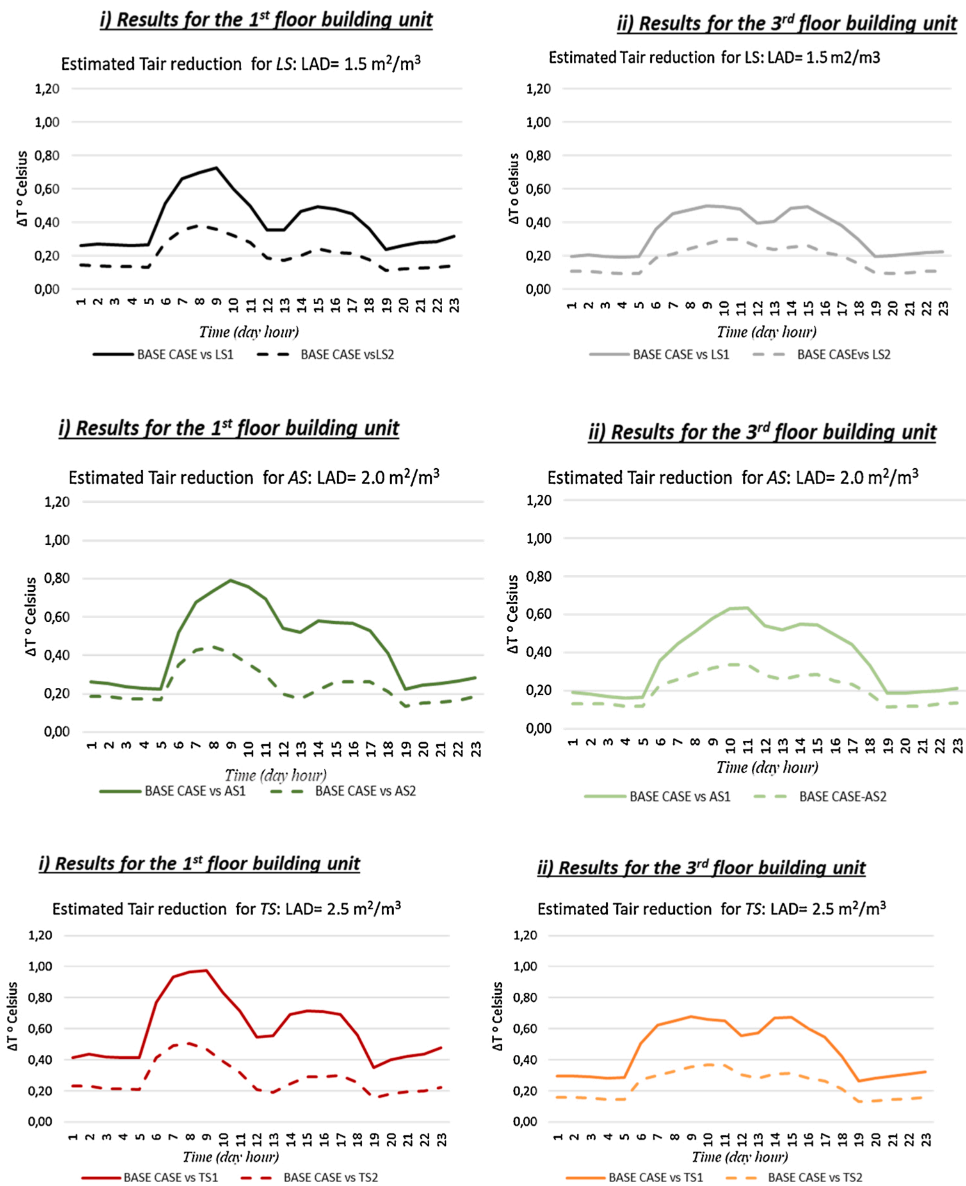


Fig. 10. Estimated Tair reduction, occurring in front of the examined 1st and 3rd floor building units, for different LAD values and for the 2 investigated planting patterns.

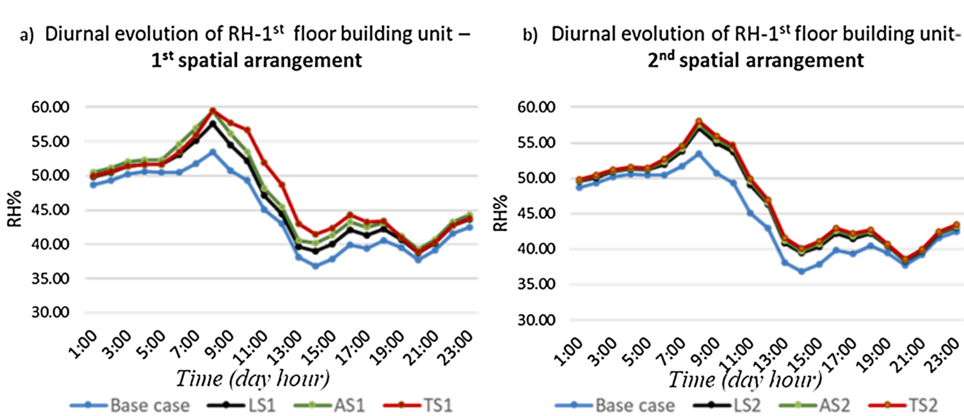


Fig. 11. Increase of RH by trees in comparison to the base case scenario.

Planting *Lyriodendron* trees with a LAD of 1.5 m^2/m^3 in uniform rows inside the street canyon (i.e. scen. *LS1*) led to an average daily Tair reduction in front of the building unit's exterior facade of 0.40 °C, compared to the base case scenario. The peak daily Tair decrease of 0.73 °C was noticed at 9:00 a.m. Under the same planting pattern, the use of trees of *Aesculous hippocastanum* type, having a LAD of 2.0 m^2/m^3 (i.e. scen. *AS1*) has only led to a marginally higher average daily Tair decrease reaching 0.45 °C. In parallel, planting *Tilia cordata* trees, of LAD = 2.5 m^2/m^3 in a continuous shading canopy (scen. *TS1*) resulted in a higher reduction of the Tair in front of the examined building unit, with a daily average and peak decrease of 0.60 °C and 1.0 °C respectively, compared to the current conditions. It is also worth mentioning that, for the first planting pattern (i.e. 60 % rise of the GCR), increasing the LAD value from 1.5 m^2/m^3 to 2.5 m^2/m^3 would only contribute to a further reduction of the daily average and maximum Tair by 0.20 °C and 0.30 °C. respectively. In other words, planting trees with LAD values higher than 1.5 m^2/m^3 would finally result in rather moderate further microclimatic improvements in terms of Tair values. This is mainly attributed to the fact the solar radiation gains of the examined street canyon's surfaces and the consequent sensible heat transfer to the air have been substantially reduced even for the vegetation scenario of 1.5 m^2/m^3; a minor further decrease is thus achieved when more dense tree types are considered.

To continue, when the second planting pattern is considered, the cooling potential of trees is strongly reduced, regardless of the LAD value. Adding trees with a LAD of 1.5 m^2/m^3 in uniform rows with space of 9.0 m between the crowns (i.e. scen. *LS2*) has only led to a small average daily Tair reduction of 0.20 °C in front of the building unit's exterior facade, 50 % lower of the respective reduction for the scenario *LS*1. Similarly, for the scenarios *AS2* and *TS2 (*LAD of 2.0 m^2/m^3 and 2.5 m^2/m^3 respectively) the higher foliage density of the modeled trees did not result in any further Tair reduction. This is mainly due to the higher solar gains, being henceforward received by the façade of the building unit compared to the 1st planting pattern (**see** Table 6**)** but also to the lower amounts of latent heat release towards the atmosphere. The increase of the RH of the air layer near the examined building unit presents a rather uniform profile, regardless of the LAD value (Fig. 11b) with the peak differences not exceeding 5 %. The acquired findings are in line with the results of the study of Wang and Akbari (2016), assessing the cooling potential of various steet trees in an urban area of Melbourn and under different planting patterns (i.e. with and without space between the crown).

Moreover, the magnitude of the estimated Tair cooling due to the higher presence of trees generally agree with relevant findings in the existing literature. Indicatively, Chen et al. have found that doubling the vegetation coverage in an urban area of Melbourne, Australia, can contribute to a reduction of the average summer daily maximum temperature by 0.3 °C (Chen et al., 2013). In the same vein, Ng et al. suggested that covering 33 % of the total surface of a high rise area in Hong Kong with tall trees of 20 m height and a peak LAD value of 1.1 m^2/m^3 would lead to a maximum Tair decrease by 1 °C at the pedestrians' height (Ng et al., 2012), whereas similar Tair reductions have been also mentioned in (Tsilini et al., 2015) and (Santamouris, 2015).

- *Regarding the 3*rd *floor building unit*

The obtained simulation results indicated that the cooling effect of the trees has been considerably decreased at the level of the 3rd floor building unit and for all the examined vegetation scenarios. This is due to the minor shadowing of the façade, provided by the plants since the upper part of the crown only reaches the lower part of the examined apartment (i.e. 10.5 from the ground level); only a minor reduction of the incoming solar gains is thus achieved, compared to the base case scenario. The lower air temperature of the air layer near the examined, 3rd floor building unit is thus primarily attributed to the evaporative cooling from the breathing of plants and secondly to the reduction of solar heat gains. The addition of *Lyriodendron* trees with a LAD of 1.5 m^2/m^3 in uniform rows (i.e. scen. *LS1*) led to an average daily Tair drop of 0.30 °C, compared to the base case scenario. Yet, the achieved Tair reduction is 18 % lower than the corresponding cooling for the 1st floor building unit. Again, the use of trees of *Aesculous hippocastanum* type, having a LAD of 2.0 m^2/m^3 has only led to a marginally higher average daily Tair decrease reaching 0.37 °C. The higher Tair reduction has been again found for the *Tilia cordata* tree type; planting the respective trees in continuous row with no spaces between them resulted in a average and maximum daily reduction of the Tair of 0.45 °C and 0.68 °C respectively, compared to the current conditions. Still, the cooling potential of trees at the 3rd floor level was 20 % lower compared to the 1st floor apartment. Finally, planting trees with spaces between the crowns resulted in a significant attenuation of the trees' cooling potential regardless of the foliage density. In fact, the peak daily Tair reduction, estimated near the 3rd floor building unit's exterior façade was 0.30 °C, 0.34 °C and 0.37 °C for the scenarios *LS2, AS2* and *TS2* respectively, 50 % lower of the Tair reduction achieved when the respective species have been planted according to the 1st planting pattern.

3.3. Energy performance simulation results

At a next step, the sensible cooling energy needs of the 2 examined building units during the representative summer day are evaluated. The estimated sensible cooling energy demand (for a cooling setpoint of 26 °C) of the examined 1st and 3rd floor apartments, both for the base case and the different vegetation scenarios are provided in Figs. 12 and 13 respectively. The daily sensible cooling energy needs and the solar radiation gains along with the percent reduction for each vegetation scenario for the 1st and 3rd floor building unit are depicted in Tables 6 and 7 correspondingly. The obtained results indicate that the addition of street trees and the combined effect of shadow and the lower convective heat transfer led to a decrease of the sensible cooling energy demand for both the examined building units. Yet, the estimated cooling potential considerably differs as the distance from the ground increases. In parallel, the higher the foliage density, the higher the solar radiation blockage and the lower the solar heat gains of the thermal zone.

Planting trees with a LAD value of 1.5 m^2/m^3 and 2.0 m^2/m^3 according to the first planting arrangement (i.e. *LS1* and *AS1*), contributed to a major decrease of the solar heat gains of the 1st floor apartment by

Table 6
Daily sensible cooling energy needs and solar radiation gains for the **1st floor building unit**, for the reference and the examined vegetation scenarios.

Sum- Zone daily sensible cooling energy needs (KWh/day)							
	BC	*LS1*	*AS1*	*TS1*	*LS2*	*AS2*	*TS2*
	19.28	11.71	10.64	8.81	16.92	16.22	15.88
Reduction compared to BC		**−39.25 %**	**−44.83 %**	**−54.34 %**	**−12.25 %**	**−15.86 %**	**−17.64 %**
Sum- Daily solar radiation gains (KWh/day)							
	BC	*LS1*	*AS1*	*TS1*	*LS2*	*AS2*	*TS2*
	5.25	1.82	1.75	1.70	4.33	4.28	4.25
Reduction compared to BC		**−65 %**	**−67 %**	**−68 %**	**−18 %**	**−18 %**	**−19 %**

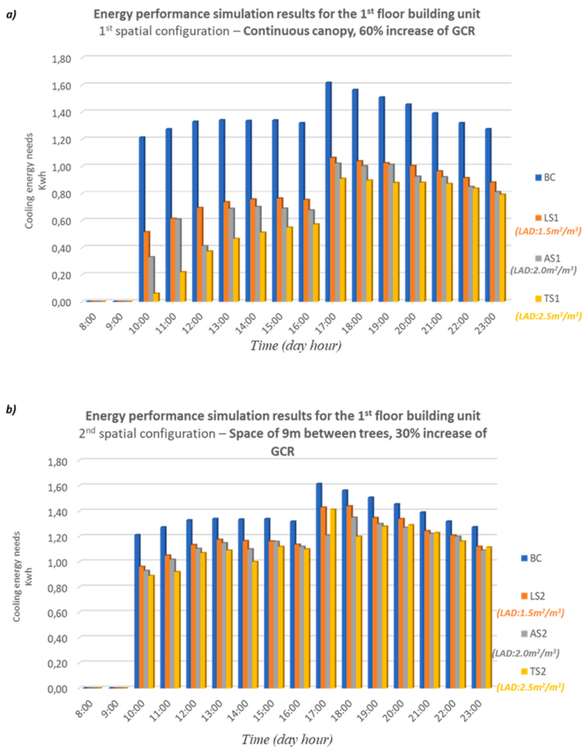


Fig. 12. Evolution of the hourly sensible cooling energy needs of the examined 1st floor building units, for the base case and the different vegetation scenarios for (a) the first and (b) the second simulated planting pattern.

Fig. 13. Evolution of the hourly sensible cooling energy needs of the examined 1st floor building units, for the base case and the different vegetation scenarios for (a) the first and (b) the second simulated planting pattern.

Table 7
Daily sensible cooling energy needs and solar radiation gains for the **3rd floor building unit**, for the reference and the examined vegetation scenarios.

Sum- Zone daily sensible cooling energy needs (KWh/day)							
	BC	*LS1*	*AS1*	*TS1*	*LS2*	*AS2*	*TS2*
	18.98	16.50	16.41	16.17	17.31	17.14	17.04
Reduction compared to BC		−13 %	−14 %	−15 %	−9 %	−10 %	−10 %
Sum- Daily solar radiation gains (KWh/day)							
	BC	*LS1*	*AS1*	*TS1*	*LS2*	*AS2*	*TS2*
	6.04	5.08	5.08	5.08	5.41	5.40	5.38
Reduction compared to BC		−16 %	−16 %	−16 %	−11 %	−11 %	−11 %

65 % and 67 % correspondingly. The lower amounts of the transmitted solar heat energy along the lower ambient Tair values (see section 3.2) resulted in substantial daily energy savings reaching 39.3 % and 44.83 % compared to the base case scenario. The higher energy savings of 54.34 % have been found for the scenario with the higher foliage density (i.e.TS1). Yet, it can be said that the application of very dense trees instead of moderately dense tree species does not seem to provide any further substantial changes on the building unit's energy needs. In fact, increasing the LAD value from 1.5 m^2/m^3 to 2.0 m^2/m^3 and 2.5 m^2/m^3 has led to a moderate further reduction of 5 % and 15 % respectively for the building unit's cooling energy needs. This ismainly attributed to the fact that the solar radiation gains of the building unit's façade and the sensible heat transfer to the indoor thermal zone have been substantially reduced even for the vegetation scenario of 1.5 m^2/m^3; a small further decrease is thus achieved when higher LAD values are modeled. To continue, the estimated energy savings of the 1st floor building unit have been considerably lower when the second planting pattern of trees and a 30 % increase of the GCR considered. Given the space of 9.0 m between the trees crown, the façade of the 1st floor building unit is not sufficiently protected by the trees' foliage and thus, a small reduction of the solar heat gains by 18 %–19 % has been found. Moreover, the foliage density did not seem to play now an important role on the building unit's energy performance. Given the minor shading effect of the 2nd configuration of trees and the lower achieved Tair cooling due to the evapotranspiration (see section 3.2) the predicted energy savings fluctuated between 2.36 kW h/day and 3.4 kW h/day for the *LS2* and *TS2* scenarios respectively. Finally, the cooling energy needs of the 3rd floor building unit were not significantly altered after the addition of street trees, compared to the base case scenario.

The planting scenarios LS1, AS1 and TS1 led to moderate cooling energy savings by 13 %, 14 % and 15 % respectively whereas for the second planting pattern, the maximum energy reduction of 10 % was estimated for the TS2 scenario. The reason of the lower energy savings for the 3rd floor apartment mainly relies on the height of the modeled trees (i.e. 10.5 m) that impedes the façade shadowing and the reduction of the solar radiation transmitted into the examined thermal zone; for both planting patterns and regardless of the foliage density, the addition of street trees only resulted in a minor reduction of the solar heat gains of the 3rd floor apartment, fluctuating between 0.66KWh/day and 0.96KWh/day

It is also important to mention, that in this study, our emphasis is given on the energy performance of a non-insulated building unit with respect to the vegetation's presence. This building unit is considered representative of the existing residential building stock in Greece, generally characterized by low energy performance levels and high annual energy demand for heating and cooling purposes (Theodoridou, Papadopoulos, & Hegger, 2011). Besides, based on the existing scientific evidence, the consideration of a contemporary, thermally insulated, and airtight envelope would have led to different results regarding the cooling energy needs. As mentioned in a recent study of Toparlar, Blocken, Maiheu, and van Heijst (2018) the addition of a thin layer of insulation in an existing 1970–1990 construction in Belgium could reduce its cooling energy demand. Yet, a further increase of the insulation levels along with a decrease of the infiltration rates has led to decreased heat losses due to ventilation during the summer period. Comparing thus to a non-insulated case, an airtight insulated building could potentially present higher cooling needs due to lower infiltration rates and the lower heat removal. A sensitivity analysis would be thus necessary to define the optimum insulation levels so as to achieve high energy performance during cooling period. In our case, this analysis rests out of the scope of the present study, presenting however an important perspective for future work.

4. Main conclusions and future perspectives

The current paper presented an one-way coupling procedure between the ENVI-met microclimate model and the Energy Plus simulation tool, to assess the role of street trees on the reduction of the cooling energy needs of generic building units inside a dense urban area. Three tree species with different foliage densities and planted at 2 different planting patterns have been investigated. The obtained results suggested that:

- the cooling potential of trees is mainly attributed to the radiative shading and the respective reduction of the solar heat gains of the exposed façades of the examined building units.
- when trees are planted in a continuous row, the GCR of the study area has been increased by 60 %. Under this assumption, increasing the LAD value from $1.5\,m^2/m^3$ to $2.5\,m^2/m^3$ may contribute to a further average daily Tair reduction in front of the 1st and 3rd floor building unit by 0.22 °C and 0.15 °C respectively.
- the potential of the urban street trees to regulate the building's cooling energy demand is directly related to their foliage density and their planting pattern; for the 1st floor examined building unit, the higher energy savings, up to 54 % have been achieved when the trees formed a continuous shading canopy, whereas the higher the LAD value, the higher the reduction of the estimated cooling energy needs.
- the energy saving potential of the examined trees has been proven rather moderate for the 3rd floor apartment compared with the 1st floor one. This is because the modeled trees were not tall enough to shade the biggest part of the external wall and thus, the solar radiation transmitted inside the thermal zone was not substantially reduced.

The findings of the present study revealed the substantial effect of vegetation on the improvement of the outdoor thermal environment and the reduction of the buildings cooling energy needs. Yet, the performed analysis is not exhaustive and further research and combination with other studies is necessary so as to obtain a global perspective on the topic. Irrigation issues, water content, soil thickness and plants health have not been treated in this study. Moreover, a further sensitivity analysis examining multiple plants' height, shape and planting patterns would provide significant insight on the suitable vegetation arrangements, depending on the characteristics of the study area. Another interesting perspective of the study would be also the detailed estimation of the near wall phenomena occurring near the examined building units' facades after the addition of street trees and how the pollutants concentrations are affected by the decelerated flow near the building walls.

Finally, it is important to highlight that the application of a coupling approach between ENVI-met and Energy Plus towards the evaluation of urban greenery on the buildings energy demand is undoubtedly a helpful method for engineers, architects and urban planners, provided that the limitations and features of both models are accounted for by the user during the interpretation of the simulation outcome. In this paper, uncertainties regarding the reliability of both models (ENVI-met and EnergyPlus), along with their inputs and parameters and their co-simulation process have been pointed out. For instance, potential inaccuracies on the representation of the case study area in the ENVI-met model may occur since sloped or non-flat surfaces are not easily described, while special care should be always paid on both tools to avoid inconsistencies and support the exchange of data between them.

Furthermore, regarding the inputs of the ENVI-met model in this study, we did not use as input measured values of global horizontal radiation; instead, the radiation values were directly simulated by neglecting the influence of cloudiness. Secondly, the optical properties of the building and ground surfaces introduced in the ENVI-met model such as albedo and emissivity, were not measured on site but were chosen thanks to a literature review, while ageing phenomena and change over time were not considered. Regarding the dynamic energy performance simulations with the EnergyPlus, many input parameters used in this paper were not measured or tested on site, as for example the infiltration rate or the occupancy profiles. These data were provided again by technical guides and literature review. It is also important to mention that Energy Plus provides also a more simplified approach on the definition of the albedo of the ground surfaces since a homogenous ground albedo is generally assumed for the simulations. This assumption and the long wave radiation exchange need to be improved in the future.

Finally, in this study, co-simulation between ENVI-met and Energy Plus is based on an one-way coupling procedure, performed for a limited time period. A strong coupling (i.e. urban microclimate model and energy performance simulation tools running at the same time till convergence is achieved so as to go through the next time step simulation) could increase accuracy, but in this study, this was hard to achieve. The main limitation is due to the high precision of ENVI-met describing explicitly the study area, leading thus to high computational cost and the need to simulate only short study periods (Lauzet et al., 2019). Still, in spite of the above mentioned limitations, coupling microclimate models with dynamic energy performance simulation tools is an up to date solution so as to accurately evaluate the role of urban climate on the buildings energy needs, from the one hand and to propose suitable strategies for further improvement, on the other hand.

Declaration of Competing Interest

The authors report no declarations of interest.

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