The effect of the orientation and proportion of a plant-covered wall layer on the thermal performance of a building zone

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ABSTRACT

The aim of the present work is to analyse thoroughly the influence of the orientation and proportion (covering percentage) of plant-covered wall sections on the thermal behaviour of typical buildings in the Greek region during the summer period. As to the effect of construction parameters, the layer position of masonry/insulation has been also considered. The investigation has been carried out using a thermal-network model that adequately simulates the building zone under assumption; its validation was based on experimental results from a recently reported study. The model makes provision for several heat-flow paths in order to take into account the leaf cover on the external wall surface, heat transfer through the surfaces that constitute the building envelope, and natural ventilation. The influence of orientation and covering percentage of plant foliage for walls with different configurations was studied using representative outdoor environmental data for the zone location at a specific time period.

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1. Introduction

The appropriate use of vegetation on the built environment can adequately adjust the urban microclimate and improve the thermal behaviour of building envelopes. Plant-covering of building surfaces is one common way to provide a beneficial cooling effect within the building zone. Plants absorb a considerable quantity of solar radiation for their growth and biological functions, such as photosynthesis, respiration, transpiration and foliage evaporation. These issues are thoroughly discussed by Krushe et al. [1]. In addition, the plant-covered layer is functioning as a solar barrier that reduces the absorption of solar energy all through the day period due to the reflective properties of plants. The absorption coefficient value for a plant-covered wall surface is estimated to be about one third of that for a conventional surface. The emerged peak temperatures and variations are essentially lower, while the unwanted heat flow from the outdoor to the indoor environment is reduced. Besides the achievement and preservation of thermal comfort conditions within buildings, plant-covered surfaces reduce air movement phenomena (wind effect) and are beneficial to the controlling of the humidity within the building zone [2–4].

The scale of the influence of plant-covered surfaces depends on several parameters. First of all, factors such as the covering percentage, density and width of plant foliage that covers building surfaces have an important bearing and their extent defines the effectiveness of plant cover. In [5–7] the impact of the above factors is examined for different environmental conditions and constraints. Secondly, the solar absorption coefficient of exposed surfaces (exterior coating) delineates the amount of solar energy that is absorbed by the thermal mass of building envelopes. As it is pointed out in [8] the colour of the external surface has a decisive effect on the temperature profiles at each characteristic section of the structure; as the lightness/darkness of a surface increases, the indoor temperature field decreases/increases and vice versa. Moreover, the impact of the plant foliage also depends on the orientation of the plant-covered wall layer. In [9] the dynamic thermal response of wall configurations with different orientations is examined thoroughly by employing a thermal-network model. Finally, the contribution of thermal insulation is critical even when a plant-covered layer is considered. As it was reported by Asan [10,11], shell surfaces that lack thermal protection can not prevent overheating phenomena due to extensive sunshine during the hot periods of the year. The geometrical and thermo-physical properties of building materials, as well as the relative position or allocation of insulation on masonry (wall configuration) have a very profound effect on the zone's thermal behaviour. An excellent overview of computational methods that takes into account the impact of thermal mass on the indoor conditions is given in [12]. The importance of plant-covered surfaces is central in warm climates and primarily in urban areas, since external horizontal and
vertical surfaces exposed to solar radiation are subjected to wide daily and annual temperature variations; this applies to the mild climate conditions of the Mediterranean area [13,14].

In this study the thermal performance of a building zone is assessed by taking into account the orientation and proportion of a plant-covered layer to the total wall area. For all examined wall orientations, which correspond to each compass point, the covering percentage of plant foliage sections varies from 0% to 100%. The investigation is carried out during the cooling period for a presumed passive or active building sited in the northern Greek region. Various wall configurations are examined with the insulation positioned as one layer in different allocations. The modeling of the thermal zone is based on a lumped capacitance thermal-network model in which thermal resistances and capacitances are linked to each other via a number of nodes. This thermal-network has several heat-flow paths in order to take into account the leaf cover on the outer wall surface, heat propagation through the multi-layered configurations and natural ventilation. The mathematical solution of the lumped model is accomplished in discrete time steps by the nodal method. This approach allows the evaluation of the building’s thermal response by considering and adjusting the parameters of multi-flow paths in an efficient way. The accuracy of the presented circuit modeling has been validated using actual conditions from earlier experimental and computer simulation studies.

The assumed environmental data correspond to precise environment spatial and time conditions. Results from the transient thermal analysis are focused on the developed temperature variations and peaks on both the interior and exterior wall surfaces of the investigated passive building zone. As is shown here, the incorporation of plant-covered wall sections is very important towards achieving a desirable indoor environment. Simulations have revealed that climbers can provide an important cooling potential regarding the daily temperature reduction of peak temperatures. The influence of the leaf layer is strongly correlated with the proportion of the effective area that plant foliage covers and its orientation. Additionally, the type of wall configuration modifies the developed temperature field within the building zone. Finally, the conclusions regarding the function of the cooling system have shown that the appropriate use of a green layer on a wall surface can essentially reduce the daily energy requirements of the active thermal zone. The scale of this effect depends on the orientation of the leaf cover layer, besides the allocation of masonry and insulation.

2. Overview of the impact of plant-covered layers

The adoption of plant-covered surfaces is aesthetically and ecologically appropriate as an adequate architectural feature that promotes passive building design. Their use leads to an energy conscious design approach that prevents heavily populated urban areas from changing to a deteriorated natural environment. As mentioned by Hien et al. [7], the greening of buildings, and especially the use of plant-covered surfaces (vertical or horizontal), leads to the accomplishment of the fundamental principles of sustainable construction. From this point of view, this aspect is critical in order to fulfill the forthcoming mandatory European Directives [15].

The contribution of vegetation and strategic landscaping to the thermal performance of building envelopes, for various climatic conditions, has been investigated thoroughly in several studies. As it was pointed-out by Meier [16], the appropriate placement of vegetation, nearby a building or landscaping can beneficially improve the thermal comfort within the indoor environment, in addition to the reduction of cooling energy demands. The cautious use of vegetation has long been renowned as a means to diminish the needless solar energy absorbed by the building envelope in a straightforward and low-cost way. As an outcome it has been shown that the external vegetation layer leads to lower temperatures on the building surfaces. The measured lower temperatures on the building surfaces reveal a positive adjustment of the building micro-climate [2–4].

As to the direct influence of landscaping, several experimental and computer-simulation studies have investigated the temperature reductions at characteristic points of the building envelope and energy saving within buildings. In [2], it has been shown how the greening of buildings via a planted roof functions positively, by reducing the indoor temperature fluctuations and by increasing the thermal capacity of the horizontal slabs. The consideration of this scheme can have an essential bearing when designing passive buildings in urban or rural places. Recently, the present authors have presented the effects of plant foliage that covers wall sections via an experimental setup [17]; results have pointed out the effectiveness of wall plantation, when compared with bare wall sections that are exposed directly to solar radiation, for buildings in densely populated urban areas in the Mediterranean region, during the cooling period. In another study, McPherson et al. [18] simulated the energy savings due to landscaping by employing the MICROPAS computer simulation model; it was revealed that irradiance and wind reduction have an essential impact on residential building energy behaviour. In [19] Holm adopted a dynamic computer model, DEROB, which simulates the thermal influence of deciduous evergreen vegetation cover on external walls. Simulation results of the indoor air temperature were validated and calibrated against actual field temperature measurements, using an experimental setup, during the summer period. It was reported that there exists a strong correlation between the measured and the calculated temperatures with the validated leaf cover model. The cooling/heating advance effect of a leaf-covered wall against a bare wall was examined for various combinations of building configurations of a similar design, climate patterns and orientations, for summer and winter design days.

In view of the fact that the present work analyses the influence of a green wall on the thermal performance of a building, it is useful to depict the current state of green wall technology and clarify some typical green wall systems. A green wall, also commonly referred to as a vertical garden, is a descriptive term that is used to refer to all forms of vegetated wall surfaces. The concept of green walls is an ancient one, with examples in architectural history reaching back to the Babylonians with the famous Hanging Gardens of Babylon. Nowadays, green wall technologies can be divided into two major categories: (i) Green facades and (ii) Living walls. These categories of green walls are illustrated in Fig. 1 and described below.

2.1. Green facades

Green facades are a type of green wall system in which climbing plants or cascading groundcover are trained to cover specially designed supporting structures. Green facades are mainly rooted at the base of these structures, in the ground, in intermediate planters or even on rooftops. Green facades can be anchored to existing walls or built as free-standing structures, such as fences or columns. Self-clinging climbing plants have commonly been used to create green walls, since their sucker root structure enables them to attach directly to a wall, covering entire surfaces (Fig. 1a). However, these aggressive plants can damage unsuitable walls and/or cause difficulties when the time comes for building maintenance and plant removal. Lately, technological innovations have resulted in the development of new trellises, rigid panels and cable systems to...
support vines, while keeping them away from walls and other building surfaces. Two green facade systems are frequently used.

(i) **Modular trellis panels** are made from a welded steel wire that supports plants with both a face grid and a panel depth (Fig. 1b). This system is intended to seize a green facade off the wall surface so that plant materials do not attach to the building envelope. Furthermore, the above design scheme provides a restricted growing environment for plant foliage, with multiple supports that permits the maintenance and integrity of the building membrane. The panels that form the grid can be stacked and joined to cover large areas, or formed to create shapes and curves. In addition, because the panels are rigid, they can span between structures and can also be used for free-standing green walls.

(ii) **Cable and wire-rope net systems** use either high-tensile steel cables and/or a wire-net (Fig. 1c). Cables are employed on green facades that are designed to support faster growing climbing plants with a denser foliage. On the other hand, wire-nets are often used to support slower growing plants that require the added support these systems provide at nearer intervals. Wire-nets are more flexible and provide a greater degree of design applications than cables. Thus, various sizes and patterns can be accommodated as flexible vertical and horizontal wire-ropes are connected through cross clamps.

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**Fig. 1.** Representative green wall systems: (i) Green facades; (ii) Living walls.
2.2. Living walls

Living wall systems are composed of pre-vegetated panels, vertical modules or planted blankets that are fixed vertically to a structural wall or frame. These panels can be made of various types of material, and support a great variety of plant species. Due to the diversity and density of plant life, living walls normally require more intensive maintenance and protection than green facades. There are various forms of living walls, with the main differences occurring between interior and exterior designs. As shown in Fig. 1d–g, the most familiar living wall systems are: (i) Modular walls; (ii) Vegetated mat or ‘Mur vegetal’ walls; (iii) Biofiltration ‘active’ walls; (iv) Landscape walls.

3. Thermal analysis

The investigation of a building zone that includes a leaf-covered wall, with a simulation model, is a quite complicated process. This is because the proportion of plant-covered sections in a wall surface, its orientation and the building construction configurations of the envelope, affect the thermal analysis in a different way. Also, during the simulation period the transient thermal analysis is influenced by a number of design factors that simultaneously modify the thermal response of the building zone. The precise description and modeling of the building, as well as the exactness of the assumed environmental conditions, are decisive for the reliability of outcomes. In the following sections the above issues are discussed in detail.

3.1. Building zone description

The present analysis is concerned with a building zone located in the Greek region and more precisely in the urban environment of Thessaloniki. As shown in Fig. 2 the single-storey thermal zone is a vacant square space 10 m × 10 m, with its height at 3 m (cubical shape of the building shell with an aspect ratio, B.A.R. = 1). Thus, the floor area and the zone volume are \( A_s = 100 \text{ m}^2 \) and \( V_A = 300 \text{ m}^3 \), respectively. Each one of the walls is facing each compass direction. In addition, the floor is in contact with the earth-soil and the flat surface of the ceiling is opposed to the sky. In order to obtain results that assess precisely the effect of the orientation and proportion of a green layer on the thermal behaviour of an analysed building zone, the morphology of the surrounding terrain is neglected. The natural obstacles or buildings in the nearby surrounding environment, which could cause a reduction of the amount of solar radiation that reaches the building envelope, are not considered. As a result, the reference building is assumed to be located into an open space city-urban tissue, and the vertical and horizontal surfaces of the building zone are exposed directly to the outdoor environmental conditions.

The aim of this study is to evaluate the influence of the orientation and covering percentage of plant-covered sections of wall surfaces. Climbing plant foliage (Parthenocissus tricuspidata) is of defined width (25 cm) and density (thick foliage that forbids the penetration of direct solar radiation towards the exterior wall surface). For all analysed wall orientations, which match to each compass point (north, east, south and west), the covering percentage of the leaf-cover layer varies progressively from 0% (bare wall: plant free) to 100% (totally plant-covered wall: full coverage). The impact of the orientation of a leaf cover layer on the thermal reduction effect of a building shell depends on the overall intensity of solar radiation. With reference to the construction details of the building, the analysed building zone comprises vertical masonry walls and horizontal reinforced concrete slabs with insulation, while glazing surface elements are assumed to be negligible (windowless building zone). The geometrical and thermo-physical properties of the construction materials are based on international values that comply with the actual state in the Greek area. This is in view of the fact that the mandatory compliance with European policies and directives has forced several industrial units of the construction sector to fulfill specific regulations (national codes and legislative framework) and demands (product innovation and certifications). As a consequence, some sustainable development issues have been adopted in Greece’s construction industry, which modify the conventional and well-established technology and methods of production [21].

The walls of the building are presumed to consist of a similar common multi-layer wall structure, comprising masonry (\( M \), 20 cm as one brick layer or 2 × 10 cm as two brick layers) and insulation (\( I \), 5 cm as one layer). Additionally, a typical plaster (\( P \), 2.5 cm as one layer) is placed at both exterior and interior wall surface coatings, while the value of its outdoor absorption coefficient is \( a_s = 0.50 \). Consequently, the total thickness of the wall structure is constant.

![Fig. 2. Schematic representation of the analysed building zone.](image-url)
with its value at 30 cm. The wall configurations are investigated with the insulation placed as one layer in different allocations: (a) on the outer surface of the masonry—this wall configuration is denoted as P-IM-P (4 layers); (b) on the inner surface of the masonry, P-MI-P (4 layers) or (c) the mid-centre of the masonry, P-MI-M-P (5 layers).

The studied bare or plant-covered wall elements are illustrated in Fig. 3a and b, respectively. Their characteristic sections are respectively:

- **Bare wall sections exposed directly to solar radiation** (Fig. 3a)
  (a) Outdoor environment (ambient-air) o
  (b) Exterior surface (outer boundary) se
  (c) Interior surface (inner boundary) si
  (d) Indoor environment of building zone in

- **Wall sections incorporating a leaf cover** (Fig. 3b)
  (a) Outdoor environment (ambient-air) o
  (b) Within the plant foliage gr
  (c) Exterior surface (outer boundary) se
  (d) Interior surface (inner boundary) si
  (e) Indoor environment of building zone in

The slabs of the building envelope consist of a typical multi-layer structure, comprising constantly concrete (C, 15 cm as one layer) and insulation (I, 5 cm as one layer). On the inner surface of the floor, a granite layer (5 cm as one layer) is presumed that covers its surface. The entire thickness of the floor slabs is 25 cm. These slabs are analysed with the insulation placed as one layer on the exterior surface of concrete (in contact with the ground). On the outer surface of the ceiling, which is exposed directly to the atmosphere, a tile layer (2.5 cm as one layer) is employed and covers up the surface of the ceiling, which is exposed directly to the atmosphere, 30 cm as one layer. On the inner surface of the floor, the rotational velocity is \( \omega = 2 \cdot \pi \cdot f \), with \( f \) the radial frequency \( (f = 1/86,400 \text{ s}) \). As shown in Table 2, for the summer season over the last 5 years (2004–2008), the outdoor temperatures averagely vary within \( T_{o,\text{min}} = 20.8^\circ \text{C} \) to \( T_{o,\text{max}} = 31.5^\circ \text{C} \) [22]. Additionally, the recorded value of \( T_{o,\text{mean}} \) is 26.15 \(^\circ\text{C}\), whereas the temperature range and amplitude of the periodic heat wave are 10.7 \(^\circ\text{C}\) and 5.35 \(^\circ\text{C}\), respectively. Outdoor temperature variations are considered to have a steady periodic pattern with an equivalent diurnal average over a period of several days.

The sol-air temperatures \( T_{s,a,\text{mean}} \) are also specified in Fig. 4a. This daily-periodic forcing function, that includes the effect of solar radiation, simulates precisely the outdoor conditions that affect each subdivision of the building envelope. For the external surfaces of the building zone, apart from the floor surface, the non-sinusoidal periodical forcing functions \( T_{s,a} \) are defined by [10,11]:

\[
T_{s,a}(t) = T_o + \frac{a_s \cdot Q_{sol}}{h_e} - \frac{\varepsilon \cdot \sigma \cdot (T_o^4 - T_{surr}^4)}{h_e}
\]

\( h_e \) represents the exterior surface heat transfer coefficient and \( a_s \) the solar radiation absorptivity of the exposed to the environment surface. The later is taken to be even for the surfaces of the zone, with its value set at \( a_s = 0.50 \). For the case of a wall that consists of a green layer, the outdoor absorption coefficient corresponds to the related properties of the leaf cover. The first term in Eq. (2) represents the convection and radiation heat transfer to each surface, when the average surrounding surface and sky temperature is equal to the ambient-air temperature, \( T_{surr} = T_o \). The last term represents

![Fig. 3. Typical sections of (a) a bare wall element and (b) a plant-covered wall element.](image-url)
the temperature correction for the radiation heat transfer when 
\[ T_{\text{surr}} \neq T_{o} \]; it ranges from about zero for vertical wall surfaces to 4°C for horizontal roof surfaces facing the sky, due to the low effective sky temperature [23].

The graphs in Fig. 4b illustrate the deviation of incident solar radiation \( Q_{\text{sol}} \) per hour, for the summer period. These values correspond to regular days with no clouds and for various surface orientations. The value of the solar reflectance of the ground is assumed 0.20.

As to the effect of wind, the air velocity and direction of the prevailing warm (day period) or cool (night period) winds that blow in the assumed area are given in Table 3 [17]; all year round southern breezes come from the sea. In summer, sea breezes are increased and are an asset in achieving thermal comfort. However, as is clear from the mean monthly wind speed values, severe winds do not blow very often during the cooling period, while low daily wind speed values are apparent. For approximately 49% of the days there is no wind airflow at all, on an annual basis. In this study the influence of wind speed and direction on the investigated building is assumed to be negligible. Hence, the heat transfer process for the investigated building facade, due to funnelling cooling southern breezes through the leaf canopy (air movement), is ignored.

Furthermore, the analysed region is characterized by a high relative humidity with an annual average of 68% which, except in July and August, even reaches 100% for short periods. The minimum and maximum average relative humidity values are recorded in July (56%) and June (64%), respectively. The average value of relative humidity during the entire cooling period is 59%. Relative humidity data are presented in Table 3 [17].

### 3.3. Thermal-network modelling

In the present work, the modelling of the thermal zone employs a one-dimensional circuit model in which thermal resistances and capacitances are connected to each other via a number of nodes. The circuit is derived by consideration of the well-known analogies between the thermal and electrical laws. Node voltages and branch currents correspond to temperatures and heat flows, respectively. This modelling allows the interpretation and formation of the governing equations on the basis of a “physical circuit analogue” that combines the topological and algebraic data of the problem under study [24]. In the present formulation, instead of setting up the model state-equations and solving the corresponding differential equations numerically by an integration technique (e.g. 4th order Runge–Kutta method), a transient nodal solution is employed which allows the adjustment of the various parameters in discrete time steps, \( \Delta t \).

The modelling of the circuit capacitors (heat-storage elements) is accomplished by introducing appropriate resistances in series with time-varying voltage sources; thus, the effect of capacitor charging or discharging is modelled by adjusting iteratively their corresponding voltage sources. In this way, at each discrete step during the solution, the resulting thermo-electrical network is solely resistive with fixed or time-varying voltage and/or current sources. Its iterative nodal solution provides the heat flows (branch currents) in the various heat-flow paths and the temperatures (node voltages) at all the nodes of the thermal multi-node model under consideration. The advantage of this approach lies in its flexibility in the modelling of non-linear components, as it allows the controlling of the model parameters

<table>
<thead>
<tr>
<th>Period</th>
<th>Year of records</th>
<th>Minimum temperature values</th>
<th>Maximum temperature values</th>
<th>Mean temperature values</th>
</tr>
</thead>
<tbody>
<tr>
<td>June</td>
<td>2004</td>
<td>18.10</td>
<td>29.80</td>
<td>23.70</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>20.00</td>
<td>30.50</td>
<td>25.10</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>20.80</td>
<td>31.70</td>
<td>26.10</td>
</tr>
<tr>
<td></td>
<td>2007</td>
<td>19.10</td>
<td>29.30</td>
<td>24.00</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>18.30</td>
<td>28.90</td>
<td>23.30</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>22.30</td>
<td>33.30</td>
<td>27.80</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>21.90</td>
<td>32.20</td>
<td>26.80</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>22.10</td>
<td>32.80</td>
<td>27.30</td>
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<td></td>
<td>2008</td>
<td>21.30</td>
<td>32.00</td>
<td>26.50</td>
</tr>
<tr>
<td>August</td>
<td>2004</td>
<td>22.50</td>
<td>33.20</td>
<td>27.60</td>
</tr>
<tr>
<td></td>
<td>2005</td>
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<td>30.90</td>
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<td></td>
<td>2004–2008</td>
<td>20.80</td>
<td>31.50</td>
<td>26.15</td>
</tr>
</tbody>
</table>

**Table 2** Average temperature values during the summer season, over the last five years (2004–2008).

<table>
<thead>
<tr>
<th>Period</th>
<th>Wind direction</th>
<th>Relative humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean monthly wind speed (m/s)</td>
<td>Prevailing wind direction</td>
<td>Absolute minimum value (%)</td>
</tr>
<tr>
<td>June</td>
<td>2.0</td>
<td>South</td>
</tr>
<tr>
<td>July</td>
<td>2.1</td>
<td>South</td>
</tr>
<tr>
<td>August</td>
<td>2.0</td>
<td>South</td>
</tr>
<tr>
<td>Entire summer period</td>
<td>2.0</td>
<td>South</td>
</tr>
</tbody>
</table>

**Table 3** Average wind speed/direction and relative humidity values during the summer season.
during the model solution. This is very advantageous especially when dealing with applications involving electromechanical systems for controlling temperature/humidity [24].

A general outline of heat propagation through the assumed building envelope is given in Fig. 5. The employed lumped capacitance thermal-network model makes provision for several heat-flow paths (Figs. 6 and 7), under detailed forcing functions that define the environmental conditions, in order to simulate: (a) the combined processes of conduction, convection and radiation through the building envelope (walls and slabs); (b) the process of heat storage within the thermal mass; (c) the heat transfer mechanisms through the foliage canopy of the green wall; and (d) the rate of air-changes due to ventilation within the passive building zone [24,25]. Accordingly, the model consists of eight central heat-flow paths that correspond to the four walls, the plant-covered wall, the two slabs and the zone ventilation (air recycling). However, when the percentage of the effective wall area that plant foliage cover is 0% (lower limit: plant free) or 100% (upper limit: full coverage), the model consists of seven heat-flow paths. Along the structural paths, transient conduction, convection and radiation are modelled one-dimensionally, while transverse heat-flows are assumed negligible. Moreover, heat-flow mechanisms on a wall with climbing plants. In order to take into account the plant-covered canopy, the presented PCW-model accommodates the transitional structural component among the outdoor and indoor environment by including two major model-subdivisions: the wall model (WM-model) and the canopy model (CM-model).

3.3.1. WM-model

The WM-model consists of a distinct number of n-layers that correspond to the materials that comprise the wall configuration. As shown in Fig. 6b, each layer i (subscript i denotes the type of material, i = 1 to n) consists of a discrete set of n_i-sections, by using the multi-node representation described earlier. Hence, each section comprises three nodes in series; thus, a typical section includes two thermal resistances R_i and a single lumped thermal capacitance C_i at the mid-node (RCR-sections). The above elements characterize the thermal resistance and capacity of the structural materials that form each layer-section, respectively. Thus, the present modelling takes into account: (a) the propagation of heat, due to conduction, through the building envelope and (b) the heat stored within the thermal mass of building materials (volumetric heat capacity). Their values are determined on the basis of their geometrical and thermo-physical properties:

\[ R_i = \frac{d_i/(2 \cdot m_i)}{k_i \cdot A} \]  \hspace{1cm} (4)

\[ C_i = \rho_i \cdot c_i \cdot (d_i/m_i) \cdot A \]  \hspace{1cm} (5)

where A, d_i, \rho_i, c_i correspond to the wall area and thickness of the material layer i, respectively. Additionally, \(k_i, \rho_i\) and \(c_i\) correspond to the thermal conductivity, density and specific heat. In order to ensure an accurate solution the number of sections, i.e., number of nodes in the x axes, of the multi-layered WM-model must be sufficient; this number depends on the properties of the material [24]. It is essential
to point out that the task of a thermal capacitance is similar to the function of a current source. Thus, the charge or discharge of a thermal capacitance corresponds to a negative or positive non-linear heat flow, respectively.

3.3.2. CM-model
The heat propagation through a plant-covered canopy is a complicated and multifaceted procedure. In order for the CM-model solution to take realistically into account the thermal response of the green layer, the findings of previously conducted experimental and simulation studies have been used for the modelling of the conditions within the canopy [5,17,19]. The CM-model incorporates an outer surface with an absorption band similar to a complete leaf cover. In this way, the outer surface of the leaf cover acts as an optical filter that adjusts the proportion of penetrated solar energy, as well as the fraction of reflected and absorbed
radiation. It appears that only the 12.8% of the entire incident solar energy is transmitted through the outer surface of leaves, while the reflected and absorbed percentages of energy are 15.6% and 71.6%, respectively. The equivalent percentage transmitted through two consecutive surfaces of leaves is about 5%. As was revealed in [19], minor differences in spectral optical properties tend to diminish with increasing the leaf cover thickness; at a thickness beyond 20 cm, the green layer tends to have the same optical and thermal properties. The above issue of energy balance of a leaf cover layer is highly complex and variable [1,19,27].

Also, a critical objective of the CM-model is to handle and adjust accurately the process of natural ventilation through the plant foliage. The current modelling aims to implement the actual rate of air changes, between the green layer and the outdoor environment, by taking into account the exact spatial conditions that appear at each time point of the analysis. As a consequence, the ventilation rate for the simulations is estimated on the basis of the specific model conditions, which are correlated with the outcomes of available measurements. The CM-model assumes multiple ventilated air spaces; each air space corresponds to a 5 cm width of the green layer and consequently the model incorporates five air spaces. The varying rate of air changes at each air space is assumed to decrease from the outer to the inner boundary of the canopy. The deeper air space sections of the foliage canopy function similarly to an insulation material, since they form an almost motionless film of air (negligible air flow). This thermal insulating layer diminishes the thermal transaction from the building wall elements to the external air. Overall, the whole plant-covered canopy can be adequately modelled on the basis of an equivalent thermal conductance factor. From a previous study [17] it was estimated that the thermal conductance of a 25 cm plant foliage width is almost 2 W/m²·K; this is approximately equivalent to the effect of double-glazing or a static air space of 7.5 cm thickness. Additionally, the modelling of the canopy takes into account the thermal mass of the plant foliage covering the wall; this comprises plant leaves, branches, roots, water etc. [19]. For each air space section of the canopy the thermal mass is assumed approximately constant.

The CM-model of a ventilated air space is illustrated in Fig. 6c. This comprises two thermal resistances $R_i$ in series and a lumped thermal capacitance $C_i$ in the mid-node (RCR-section). In the mid-node of each RCR-section, a branch that incorporates a resistance $R_v$ in series with a voltage source $T_o$ is connected. This simulates the exchanges of air between the air space and the ambient-air, due to natural ventilation. To the same mid-node coincides a branch that consists of a current source $Q_s$. This source defines the usual rate of energy absorbed daily by plant foliage, for its growth and biological functions during the cooling period, such as photosynthesis, respiration, transpiration and evaporation [1,19,27]. Therefore, approximately 80–90% of the short-wave radiation that affects the plant-covered wall surface is absorbed through the plants for their growth and biological functions, while only 15% is reflected. This is due to the: (a) photosynthesis, during which about 682 kcal are required for the production of each particle of glucose; (b) evaporation, during which about 530 kcal are used for each litre of water; and (c) transpiration and respiration [1,28]. The last issue refers to the biological function of the plants around the region of the roots, which is designated as ‘root breathing’. This helps so that, even during the frosty period, the roots and the soil temperature are higher compared to that of the external environment. Evidently, the last issue is not taken into account for the calculations of the simulation model during the summer season.

It is important to make clear that when the percentage of the green foliage is less than 100%, for a wall surface with a specific orientation, the thermal model incorporates two discrete heat-flow paths that correspond to the part of the bare wall and the part of the plant-covered wall, respectively.

- For the part of the bare wall, the canopy model (CM) is ignored and the modelling of the heat-flow path is based solely on the wall model (WM). As to the effect of the outdoor environment, an appropriate forcing function $T_{in}$ (voltage source), which takes into account the combined influence of ambient-air temperature and solar radiation, is employed. The fraction of solar radiation absorbed by the wall surface depends on the outdoor absorption coefficient of the wall’s exterior surface ($\alpha_s = 0.50$). This forcing function is correlated with the heat-flow path via the exterior heat transfer resistance $R_{se}$.
- On the other hand, for the part of the plant-covered wall, the PCW-model is considered for the simulations. As to the effect of the external conditions, the forcing function is defined by $T_o$ (voltage source) and $Q_{in}$ (current source). Both source branches act directly to the exterior surface of the green layer.
As shown in Fig. 7, all heat-flow paths that form the thermal-network model end to the indoor air node. The temperature of this node $T_{in}$ represents the temperature of the mixed interior air. A branch with a thermal capacitance $C_{th}$ that defines the stored heat within the air volume of the zone also coincides to the air node. The influence of the thermal mass of the furniture and indoor equipment is neglected. Moreover, the rate of air changes due to natural ventilation between the indoor and outdoor environment is taken into account via a compound branch that includes a resistance $R_{v}$ in series with a voltage source $V_{s}$. The values of the resistive elements $R_{v}$ are determined by [24,25]:

$$R_{v} = \frac{1}{V_{2} \cdot \rho_{a} \cdot C_{p, a} \cdot \alpha_{c}}$$  \hspace{1cm} (6)

where $V_{2}$ is the zone volume and $\alpha_{c}$ is the rate of air changes per second. In this study the rate of air changes, in an hourly base, is taken constant, $ACH = 1$ ($\alpha_{c} = 1/3600$). Each heat-flow path is connected to the indoor air node through the interior heat transfer resistances $R_{si}$. Their values are defined by:

$$R_{si} = \frac{1}{h_{i} \cdot A}$$  \hspace{1cm} (7)

where $h_{i}$ delineates the interior surface heat transfer coefficient, due to combined convection and radiation.

The validation of the PCW-model was performed using recently reported actual field measurements, taken from an experimental setup [17]. By taking into consideration the exact environmental conditions and parameters of the building design assumed by the experimental setup, the PCW-model simulation results were found to be sufficiently close to those obtained experimentally. Thus, the sensitivity of the PCW-model to microclimate (temperature variations) has been shown to be acceptable and simulation results have not shown a significant phase-hysteresis compared to the calibrated stationary method.

Generally, the modelling of building envelopes by taking into account the familiar analogies between the thermal and electrical laws is a well-known and established practice. In several studies, thermal circuit models were employed in order to analyse the dynamic thermal characteristics of buildings surfaces, the thermal behaviour of naturally ventilated buildings and the thermal performance of active controlled environments that implement complex components. The obtained results were thoroughly validated against field measurements or other comparable analysis approaches. The accuracy of a thermal-network model depends determinedly on the number of sections that comprise the structural heat flow paths and the time step for the simulations. Moreover, the rational modelling of the heat transfer mechanisms, as well as the consideration of the exact outdoor/indoor conditions, defines the precision of the transient thermal analysis. It is essential to mention that the current modelling approach has been proved to be an accurate and rigorous technique that can also take into account the non-linear relations, by adjusting progressively the non-linear parameters at each discrete time step [8,9,24–26,29].

4. Results and discussion

The use of a leaf cover introduces a flexible and dynamic self-regulating thermal control scheme capable of providing short and long term reactions to the environment. As already mentioned, the aim of the present study has been to assess the thermal performance of a building zone, during the cooling period, by taking into account the orientation and proportion of a green layer to the whole wall area. For all examined wall orientations, which correspond to each compass point, the covering percentage of plant foliage sections varies from 0% to 100%. In addition, various wall configurations are examined with the insulation positioned as one layer in different allocations. The most important results obtained from this study are:

- The peak temperatures on the exterior $T_{se,max}$ and interior $T_{si,max}$ surface of a bare wall (plant foliage covering percentage 0%) and a plant-covered wall (plant foliage covering percentage 100%). The above are examined with respect to the orientation and type of the wall configuration.
- The reduction of the developed daily peak temperatures (cooling effect) on the exterior and interior surface of the examined wall ($\Delta T_{se}$, $\Delta T_{si}$).
- The minimum $T_{min,min}$ and maximum $T_{min,max}$ daily temperatures within the building zone, as a function of the leaf covering percentage, orientation and type of wall configuration.
- The daily energy requirements of an active building zone, as a function of the leaf covering proportion (plant covering percentages 0% and 100%), orientation and type of wall formation.

4.1. Daily peak temperature variations on the exterior surface

The determined peak temperatures on the exterior surface $T_{se,max}$ of a bare wall (plant foliage covering percentage 0%) and a plant-covered wall (plant foliage covering percentage 100%) are illustrated in Fig. 8a–d. These graphs correspond to specific choices of construction and design parameters.

Regarding the bare north-oriented wall in Fig. 8a, the most severe temperature conditions appear when placing the insulation on the exterior surface of masonry (configuration P-IM-P). Hence, the peak temperature reaches up to 34.85 °C. For the placement of insulation in the mid-centre of masonry the maximum temperature is approximately 34 °C (configuration P-MIM-P). When the insulation is located on the interior surface of masonry the corresponding peak temperature is 33.69 °C (configuration P-MI-P). On the other hand, for a plant-covered north-oriented wall, peak temperatures are slightly lower compared with the temperatures on the bare wall. The value of the temperature difference among the bare and plant-covered sections is on average 1.73 °C.

As to the east wall that is directly exposed to the solar radiation, as shown in Fig. 8b the most undesirable temperature conditions are attained when the insulation is placed on the exterior surface of masonry. Thus, the peak temperature reaches up to 47.10 °C. When the insulation is placed between the two layers of masonry, the maximum temperature is about 43.09 °C, whereas when the insulation is on the interior surface of masonry the resultant peak temperature is 43.15 °C. For the east-oriented wall that incorporates a leaf cover the determined peak temperatures are considerably lower when compared to the temperatures on the bare wall. On average, the value of the temperature difference between the bare and plant-covered parts is 10.53 °C.

As shown in Fig. 8c, the most extreme temperature conditions for a bare wall with south orientation are emerged for the position of insulation on the exterior surface of masonry. Its corresponding peak value is 41.40 °C. When the insulation is placed in the centre of masonry the maximum temperature is 39.11 °C. For the case of the insulation placement on the interior surface of masonry the matching peak temperature is 38.85 °C. As expected, for a south-oriented plant-covered wall, peak temperatures are lower in comparison to the temperatures on the bare wall. The temperature difference between the bare and plant-covered wall sections is on average 6.46 °C.
For an uncovered to the sun west wall, as shown in Fig. 8d, the most undesirable temperature conditions are obtained for the configuration denoted as P-IM-P. Hence, the peak temperature reaches up to 53.45°C. For the configuration P-MIM-P the maximum temperature is about 49.76°C and for the configuration P-MI-P the consequential peak temperature is 49.11°C. For the case of a west-oriented wall that incorporates a green foliage layer the determined peak temperatures are considerably lower than those appearing on the bare wall surface. On average, the temperature difference between the bare and plant-covered wall parts is 16.85°C.

From the above results it becomes obvious that the effect of plant foliage on the daily peak temperature of the exterior wall surface is more significant for east- or west-oriented wall surfaces. Hence, due to the considerable impact of solar radiation, it seems that the lack of green layer leads to severe temperature peaks and unnecessary heat flows through the external surfaces with the above-mentioned orientations. On the subject of temperature differences between the east- and west-oriented surfaces, it is revealed that the west wall causes more unfavourable peak temperature values. This conclusion can be supported by the graphs in Fig. 4a that illustrate the daily fluctuations of sol-air temperatures $T_{sa}$ for all involved wall orientations; hence, the peak $T_{sa}$ values for the west wall are more severe compared to the east wall. On the other hand, for north- or south-oriented wall surfaces the influence of vegetation is less significant. In this case, the temperature peaks for the uncovered walls are lower. In addition, the graphs point out that the maximum values of peak temperatures on the exterior surface of the wall appear for the placement of insulation on the external surface of masonry. This is valid for both the bare and plant-covered wall sections. Therefore, $T_{se, max, IM} > T_{se, max, MIM} > T_{se, max, MI}$.

The extracted results have also revealed that the absence of plant foliage permits the rapid heating of the wall surfaces during the day. The maximum temperatures on the exterior surface of a bare wall are notably higher than those of the outdoor environment, $T_{se, max} > T_{o, max}$. Also, the temperature difference $T_{se, max} - T_{o, max}$ is on average 10.79°C, reaching up to 19.27°C for the case of the west-oriented wall. During the night period the exposed wall surfaces are cooled, on average, to 1.5°C below the ambient-air temperature. Similarly, for the plant-covered wall the peak temperatures on the exterior surface are again higher compared to those of the ambient-air, $T_{se, max} > T_{o, max}$. However, the temperature differences $T_{se, max} - T_{o, max}$ for the covered wall are significantly lower compared with those of the exposed wall. The temperature variation $T_{se, max} - T_{o, max}$ is on average 1.90°C, reaching up to 2.42°C for the case of the west-oriented wall. These outcomes clearly illustrate the crucial influence of plant foliage that absorbs a large amount of solar energy. Their use reduces essentially the quantity of the propagated heat flows that causes unwanted maximum temperature peaks and extensive temperature variations on the exterior surface of the wall, mostly when incident solar radiation has its maximum intensity. It should be also noted that due to the growth and biological functions of the plants, the emerged temperatures within the green canopy are lower compared to the temperatures of the ambient-air and the exterior surface, on a regular daily basis (day and night period). On average the difference is 1°C. Thus, $T_{gr, max} < T_{o, max} < T_{se, max}$. During the daytime outdoor air temperatures on the interior surface of the foliage are generally lower than those on the exterior surface of the foliage, and during the night temperatures on average decrease as heat flows from the interior to the exterior surface, due to the stored heat within the thermal mass of the building elements (thermal capacity).

### 4.2. Daily peak temperature variations on the interior surface

The assessed peak temperatures on the interior wall surface $T_{si, max}$ of an exposed and a covered wall are shown in Fig. 9a–d. These graphs correspond to walls having different orientations and configurations.
For the case of a north-oriented bare wall (Fig. 9a) the most severe temperature conditions on the interior surface are emerged when placing the insulation on the internal surface of masonry (configuration P-MI-P). The peak temperature reaches up to 28.59 °C while for the placement of insulation in the mid-centre of masonry the maximum temperature is about 28.12 °C (configuration P-MIM-P). When the insulation is located on the external surface of masonry the resultant peak temperature is 27.67 °C (configuration P-IM-P). For a plant-covered wall, peak temperatures are to some extent lower compared with the temperatures on the bare wall. The temperature difference between the bare and plant-covered wall sections is on average 0.65 °C.

Referring to an east wall that is directly exposed to the environment (Fig. 9b), the most undesirable temperature conditions on the interior surface are obtained when placing the insulation on the inner side of masonry. In this case, the peak temperature reaches up to 28.80 °C; when the insulation is placed between the two layers of masonry the maximum peak temperature is 28.31 °C and when the insulation is on the outer side of masonry, the estimated peak temperature is 27.87 °C. For a wall incorporating a leaf cover, the determined peak temperatures are significantly lower in comparison to the temperatures on the bare wall. On average, the value of the temperature difference between the bare and plant-covered parts is 2.04 °C.

As to the most intense temperature, as illustrated in Fig. 9c this appears on the interior surface for a bare wall with south orientation when the insulation is on the internal surface of masonry. Its corresponding peak value is 28.71 °C. When the insulation is placed in the centre of masonry the maximum temperature is 28.23 °C, and when the insulation is on the external surface of masonry the corresponding peak temperature is 27.77 °C. For a plant-covered wall, peak temperatures are lower than those on the bare wall. The temperature variation between the bare and plant-covered sections is on average 1.06 °C.

As illustrated in Fig. 9d, for an uncovered west wall the worst temperature conditions on the interior surface are attained for the configuration designated as P-MI-P where the peak temperature reaches up to 28.92 °C. For the configuration P-MIM-P the maximum temperature is approximately 28.48 °C, whereas for the configuration P-IM-P the corresponding peak temperature is 27.96 °C. For a plant-covered wall the assessed peak temperatures are considerably lower when compared to the temperatures on the bare section. On average, the temperature variation between the bare and plant-covered sections is 3.27 °C.

From all graphs it is evident that the influence of vegetation causes a decrease of the developed temperatures on the interior wall surface. For bare and plant-covered north-oriented wall configurations the temperature difference among the temperature peaks is very low, reaching up to 0.69 °C (configuration P-MI-P). On the other hand, for west-oriented walls the decrease is more pronounced, reaching up to 3.50 °C (configuration P-MIM-P). For east- and south-oriented walls, the temperature decrease reaches up to 2.23 °C (configuration P-MI-P) and 1.15 °C (configuration P-MI-P), respectively. As to the effect of the wall configuration, the PCW-model has shown that the temperature variations on the interior wall surface are low; for the assumed wall configurations, these variations are 0.95 °C and 0.80 °C for the bare and green sections, respectively. In most cases, the lower temperatures appear for the placement of insulation on the external surface of masonry (configuration P-IM-P). This is the case for both the bare and plant-covered wall surfaces. Therefore, \( T_{\text{II, max, MI}} > T_{\text{II, max, MIM}} > T_{\text{II, max, IM}} \).

4.3. Cooling effect on the exterior and interior wall surfaces

As presented earlier, the graphs in Figs. 8 and 9 reveal that the maximum temperature peaks on both the exterior and the interior surface for a bare wall are higher compared to those of a green wall. Accordingly, the temperature field and the temperature deviations
within the building envelope are improved during the warm cooling period; that is, plant foliage has a positive impact on overheating. The graphs in Figs. 10 and 11 illustrate the reduction of the developed daily peak temperatures (cooling effect) on the exterior and interior surface, respectively, for the analysed walls ($\Delta T_{se,\text{wall}}$, $\Delta T_{in,\text{wall}}$), due to vegetation.

Temperature reductions of the maximum values on the exterior surface of the assumed walls, due to a complete leaf cover of the wall (covering percentage 100%), are shown in Fig. 10. Overall, these values vary from 1.62 °C to 19.01 °C. It is clear that the cooling effect mainly depends on the orientation of the incorporated green layer. Therefore, for a similar type of wall configuration the reduction of the peak temperatures varies extensively. Similar experimental or simulation studies conducted in the past have also extracted analogous outcomes [4,5,16–19]. However, due to dissimilar conditions such as (a) the location and climate conditions, (b) the exact outdoor conditions and constraints in a specific location, (c) the type, density and distance of wall vegetation, (d) the orientation of the examined covered wall, (e) the building design attributes, (f) the mass type, configuration and characteristics of the building elements, (g) the developed indoor conditions due to the absence or involvement of a heating, ventilating and air-conditioning unit, and (h) the employed experimental or simulation setup, procedures and assumptions, it is very unsafe to compare results directly. As already mentioned, the cooling effect is less dependent on the wall configuration than on the wall orientation. Hence, for each compass point the reduction of the peak temperatures due to the wall configuration is less significant.

Corresponding results for the interior surface of the assumed walls, due to a complete leaf cover of the wall (covering percentage 100%), are given in Fig. 11. In general, temperature reductions of the maximum values vary from 0.58 °C to 3.50 °C. Primarily, the cooling effect depends on the orientation of the integrated green layer. Accordingly, the reduction of the maximum temperature values vary broadly, but the impact of wall configurations is less important compared to the influence of the green layer orientation.

It is less clear whether the effect of a green layer on a north- or south-oriented wall is less significant compared to an east- or west-oriented wall. This appears to be true, since the north and south wall surfaces receive a reduced amount of solar radiation compared to the east and west wall surfaces during the summer period in the Greek region. The above condition is addressed by the graphs in Fig. 4b, which outline the daily variations of solar energy $Q_{sol}$ for all analysed wall orientations. Accordingly, for opaque or transparent south surfaces (walls or glazing openings), the solar heat flow is large for winter and supplements heat losses, while for summer the heat flow is relatively small and restricts the undesirable heat gain [29].

4.4. Temperature variations within the building zone

The graphs in Fig. 12a–h provide the minimum and maximum indoor temperature fluctuations $T_{in,\text{min}}$ and $T_{in,\text{max}}$ for building zones that incorporate a wall with a variable surface proportion of plant foliage. These graphs depict the developed indoor temperature limits for an assortment of possible design parameters by employing the PCW-model.

It can be seen that the increase of the plant foliage percentage causes an almost linear decrease of the indoor minimum temperature values $T_{in,\text{min}}$. For a building zone that employs a north- or south-oriented green layer, the decrease of the $T_{in,\text{min}}$, as a function of the covering percentage is slight. Thus, for a building with a leaf cover on the north surface the overall diminution of the indoor temperature values (due to the increase of the cover percentage from 0% to 100%) is approximately 0.10 °C, 0.12 °C and 0.13 °C, for the configurations P-IM-P, P-MIM-P and P-MI-P, respectively. The corresponding temperature variations for a leaf cover wall surface on the south are 0.20 °C, 0.25 °C and 0.26 °C. For building zones that comprise an east- or west-oriented green layer the decrease of the $T_{in,\text{min}}$ as a function of the covering percentage is more considerable. For buildings with a leaf cover on the east surface, the decreases of indoor temperatures are about 0.42 °C, 0.49 °C and 0.53 °C for the configurations P-IM-P, P-MIM-P and P-MI-P, respectively. The corresponding temperature variations for a leaf cover on the west surface are 0.66 °C, 0.82 °C and 0.83 °C.

For all the analysed wall configurations, indoor maximum temperature values $T_{in,\text{max}}$ decline, as the percentage of plant foliage rises from 0% to 100%. This decrease is approximately linear. For a building zone that includes a north- or south-oriented plant-covered canopy, the decrease of $T_{in,\text{max}}$, with the covering percentage is slight. More specifically, for buildings with a leaf cover on the north surface the decreases of indoor temperatures (as a result of the increase of the cover percentage from 0% to 100%) are 0.22 °C, 0.26 °C and 0.28 °C for P-IM-P, P-MIM-P and P-MI-P wall configurations, respectively. The equivalent temperature deviations for a south wall are 0.38 °C, 0.46 °C and 0.49 °C. Also, for a building zone with vegetation at the east or west facade the decrease of $T_{in,\text{max}}$ is quite wide. Therefore, for buildings with a leaf cover on the east surface the decreases of indoor temperatures are 0.83 °C, 0.96 °C and 1.04 °C for P-IM-P, P-MIM-P and P-MI-P wall configurations, respectively. The corresponding temperature differences for a west wall are 1.27 °C, 1.56 °C and 1.57 °C.

As to the effect of the wall configuration, the graphs in Fig. 12a–h show that there exists an immense importance; these graphs clearly point out that the most desirable indoor temperatures of the building zone (low temperature values) appear for the placement of insulation on the external surface of masonry (configuration P-IM-P). In general, for the minimum and maximum indoor temperature values $T_{in,\text{MI}}>T_{in,MIM}>T_{in,MI}$ always prevails.
The comparison among the maximum temperatures on the interior surfaces of a building zone without a leaf cover (covering percentage 0%) and the achieved indoor temperature has shown that: (a) for a north or south surface the temperatures on the interior surface of the wall are mainly lower than the temperatures that appear in the indoor space of the building, i.e. $T_{in,\text{min}} > T_{in,\text{max}}$; and (b) for an east or west surface the temperatures on the interior surface of the wall are always higher than the temperatures that appear in the indoor space of the building.

Fig. 12. Variation of the minimum $T_{in,\text{min}}$ and maximum $T_{in,\text{max}}$ daily temperatures within the building zone vs. leaf covering percentage, orientation and type of wall configuration.
appear in the indoor space of the building, i.e. $T_{\text{in, max}} < T_{\text{sl, max}}$. This is true since the impact of solar radiation is more influential for east or west surfaces. On the contrary, for north or south surfaces the effect of sunshine is less significant. As the percentage of the green layer increases from 0% to 100% the above considerations are modified. For a covering percentage of 50% the earlier conducted comparison has shown that $T_{\text{in, max}} > T_{\text{sl, max}}$ without regard to the orientation of the plant-covered wall ($T_{\text{sl, max}}$ refers to the interior surface that incorporates the green layer). Thus, it seems that the absence of the green layer leads to severe temperature peaks and unnecessary heat flows through the building envelope. Since in the present study all surfaces of the presumed building zone are exposed to adverse environmental conditions, the beneficial effect of plant foliage seems mild. Thus, the employment of a leaf-covered wall reduces considerably the temperatures on the interior surface of the wall, which are even lower than the temperatures that appear in the indoor space of the building.

It is noted that during the present thermal analysis, the mean daytime indoor temperature for the bare building zone (covering percentage 0%) has been well above the mean outdoor dry-bulb temperature (26.15 °C); this is well above the acceptable comfort zone. Also, during most of the night period, the indoor temperatures lead to unwanted thermal comfort conditions. For a building zone having a plant-covered wall with a covering percentage of 100% the PCW-model has shown that the mean daytime indoor temperatures are slightly above or almost equal to the mean outdoor dry-bulb temperatures. This temperature value fulfils in a better way the thermal comfort requirements of the building under study. As expected, this is also valid during the night period. Consequently, the leaf cover produces a cooling effect within the passive building zone during the period of the analysis. The extent of this indoor cooling effect is variable, since it depends on the orientation and type of the wall configuration. For east or west plant-covered wall surfaces the cooling effect is more pronounced compared to north or south wall surfaces that include a green layer. In the present study, for a building zone that has a west-oriented leaf canopy (covering percentage 50%) and for a wall type P-MIM-P, the indoor temperature range is shown to be reduced from 27.2–28.1 °C without leaf cover to 26.7–27.4 °C with leaf cover, for a regular outdoor range of 20.8–31.5 °C. The above results of the PCW-model are in agreement with those of Holm [19].

### 4.5. Energy requirements of an active building zone

In this section, the thermal performance of an active building zone is analysed for the cooling period. The thermal analysis aims to evaluate the energy requirements of this zone. The presumed thermal zone is similar to the passive zone that was previously examined, while an appropriate cooling unit is considered (cooling supply). The air-conditioning unit is assumed to operate during the day from 08:00 to 20:00 (schedule period) and it is controlled by a switching device, the thermostat. For the remaining hours of the day the unit is inactive. Consequently, the thermal-network model incorporates an additional heat-flow path that takes into account the function of the cooling unit [24]. The above heat-flow path coincides with the indoor air-node of the thermal zone. As for the ventilation control of the building’s internal space a constant rate of air changes is considered ($ACH = 1$). The daily energy demands (cooling loads) of the thermal zone are shown in Fig. 13a–d. These graphs correspond to specific choices of construction and design parameters. Furthermore, the energy consumption was determined for a cooling system having a temperature in the thermostat of 20 °C.

Regarding a thermal zone that does not incorporate a green layer (plant foliage covering percentage 0%, for all surfaces that comprise the building zone) the most severe cooling loads appear when placing the insulation on the exterior surface of masonry
(configuration P-IM-P). Thus, the daily energy requirements reach up to 39.75 kWh. However, it is useful to point out that the P-IM-P configuration stores a large amount of energy, preventing large temperature swings on the indoor space of the building. The stored heat is progressively released to the interior of the building and a steadier overall environment is attained during the entire day period. For the placement of insulation in the mid-centre of masonry (configuration P-MI-M-P) the cooling loads are significantly lower. Thus, the energy requirements of the AC unit do not exceed 30.13 kWh; whereas for the P-MI-P configuration, since the heat stored in the construction mass is considerably lower, the indoor temperatures are sensitive to the outdoor temperature fluctuations and the forced conditions. Consequently: (a) the indoor temperature variations are higher compared to the P-IM-P configuration, for the non-scheduled period during the day; and (b) the energy consumption is lower compared to the P-IM-P configuration, for the scheduled period. The above outcomes for the bare thermal zone (Fig. 13) appear to be in agreement with the results of previously conducted studies [24,25,29].

For the case of a thermal zone that consists of a plant-covered wall (plant foliage covering 100%, for a wall with a specific orientation), the cooling loads are higher when the insulation is located on the exterior surface of masonry. Moreover, the placement of insulation in the mid-centre of masonry or on the interior surface of masonry leads to lower energy requirements. The above conclusions refer to all analysed orientations of thermal zones that incorporate a wall with a leaf cover. Furthermore, the cooling loads show important deviations for thermal zones that have a plant-covered wall with a dissimilar orientation. As is shown in Fig. 13a, the use of a green layer on a north-oriented wall causes an insignificant decrease of the thermal zone energy demands. More specifically, the energy requirements of the thermal zone are reduced by approximately 4.65%. On the other hand, as is shown in Fig. 13b, the energy consumption is reduced considerably for a thermal zone that incorporates an east-oriented plant-covered wall. Thus, the cooling loads are reduced by 18.17%, on average. Additionally, the energy saving for employing a leaf cover layer on a south-oriented wall is less significant compared to an east wall (Fig. 13c). For this case, the energy requirements of the thermal zone are lower by 7.60%. Finally, it has been shown that the greening of a west-oriented wall has a very profound effect on the thermal behaviour of a building zone (Fig. 13d). In fact, this influence is more valuable compared to the earlier cases. Therefore, the decrease of the cooling loads is about 20.08%.

5. Conclusions

In this study the thermal behaviour of a building zone that incorporates a plant-covered wall was investigated by employing a thermal-network model (PCW-model). More specifically the influence of wall orientation, percentage of wall plant foliage, and the type of wall configuration has been examined. The employed model allows the inclusion of several heat-flow paths for simulating the combined mechanisms of conduction, convection and radiation through the building envelope (VM-model) as well as through the foliage canopy (CM-model). The model solution was performed iteratively in discrete time steps by the nodal approach. Its validation was based on previously reported experimental results that have been shown to be in close agreement. The presented study has been carried out for a presumed building situated in the northern Greek region during the cooling period. Results, when the conditions and limitations allowed, were found to be in rational compliance with former experimental and computer simulation studies. The main conclusions drawn from this study are summarized as follows:

1. Temperature differences between the exterior and interior surfaces of plant-covered walls are essentially reduced when compared with the conventional bare walls. Consequently, the temperature variations within the building zone that include a plant-covered wall lead to superior thermal comfort conditions.
2. As the covering percentage of the plant foliage is increased their positive effect is also increased. The influence of a green layer on the wall surface is more pronounced for east- or west-oriented surfaces.
3. The placement of insulation on the exterior surface of masonry leads to lower temperature variations. Again, the cooling effect on the exterior and interior surfaces of a plant-covered wall is more profound.
4. The use of vegetation on poorly orientated walls can compensate their poor passive design or reduce efficiently the need for cooling loads (AC unit).
5. The adequate incorporation of a plant-covered wall in a building envelope is shown to be gainful from an energy conservation point of view, while it improves and regulates adequately the microclimate around the built environment to a considerable level by neutralizing the solar impact.

Overall, the adoption of plant-covered wall designs appears to be suitable for buildings located in the northern Greek region during the cooling period. Such designs can be considered as an asset that upgrades the indoor and outdoor thermal conditions and adds to the visual appearance of the building envelope.

References