EVALUATING THE ENVIRONMENTAL PERFORMANCE OF INDOOR PLANTS IN BUILDINGS

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ABSTRACT

The effect of indoor plants on indoor environmental conditions is often underestimated or ignored while undertaking building simulation performance assessments. The literature suggests that regularly irrigated plants will evaporate and transpire, and as a result, they could alter the humidity, temperature and CO_2 concentration inside buildings. Indoor plants could in some cases also affect the amount of solar radiation falling on surfaces, but relevant shading calculations would require adequate geometrical definitions of the plants in relation to their position in building spaces. This paper explicates a methodology for representing indoor plants in whole building simulation. The current state-of-the-art in building simulation will have to accommodate new developments for modelling the heat and moisture fluxes from indoor plants and their growth mediums. Methods for achieving a representation of these fluxes in simulation programs are discussed and demonstrated by integrating a new model for indoor plants in the ESP-r simulation program.

INTRODUCTION

A number of authors have experimentally quantified the effect of indoor plants on indoor environmental conditions in buildings. Raza et al. (1995), for example, measured and verified the ability of certain succulent plants in removing CO_2 from indoor hospital spaces and from within an environmental chamber. Similarly, low light requiring plants were tested in chambers and it was found that they could remove significant quantities of formaldehyde, xylene and ammonia. (Wolverton and Wolverton, 1993).

Fjeld (2000) used questionnaires to assess the effect of plants on health and discomfort symptoms of workers in an office building and also of workers of the radiology department of a hospital building. The results showed that when plants were in the above building spaces the health and discomfort symptoms were reduced by approximately 25% (Fjield, 2000).

Mangone et al. (2014) took measurements of indoor conditions in an office building for a whole year. The authors used at the same time questionnaires for building occupants and they found that the presence of plants in the work environment had a definite positive effect on the thermal comfort of the participants, which indirectly could also result in energy savings and occupant productivity improvements.

A thorough summary of the benefits offered by indoor plants is given by Lohr (2010) who reports improvements on indoor air quality, health (e.g. lower stress levels), comfort and overall occupant productivity.

Raji et al. (2015) reviewed the impact of greening systems on buildings' environmental performance. Their review included previous field research studies that demonstrate the ability of indoor plants to purify the indoor air, for example by reducing indoor VOCs and CO_2 levels, which in turn could result in reducing the need for mechanical ventilation (Pennisi and van Iersel, 2012; Tarran et al., 2007).

Raji et al. (2015) also documented the limited number of previous studies that report the effect of indoor plants on indoor humidity levels. In particular, in a study by Lohr (1992) it was found that indoor plants in offices with limited ventilation could increase the humidity levels by about 15% while the humidity levels in well ventilated rooms with plants were not affected.

Stec et al. (2005) developed a detailed simulation model to analyse the energy performance of double skin facades with plants. The model was implemented by using SIMULINK (2015) and while focusing only on the double façade it was well-discretised and with all relevant heat and moisture balances clearly defined. The authors report difficulties for determining the properties of the plants while relationships that estimate the aerodynamic and stomatal resistances of plants (i.e. resistances that affect the evapotranspiration) were not discussed. The simulation results demonstrated that plants are more effective shading systems than intenal blinds due to the fact that they convert a significant part of the incident solar radiation into latent heat (Stec et al., 2005).

In addition, the relation between indoor plants and relative humidity levels has been studied in detail by researchers for greenhouses (Perdigones et al., 2008). A number of mathematical models for describing the energy and water vapour balances of greenhouses have been reported by several authors (Seginer and

Kantz, 1986; Yang et al., 1990; Papadakis et al., 1994; Wang and Boulard, 2000; Rondriguez et al., 2002; Dayan et al. 2004; Fahmy et al. 2012; Bouzo et al., 2006; Kindelan, 1980). These models vary from simple to detailed and the energy and moisture balances that they are using could, in many cases, be applicable to plants within usual indoor spaces. However, such models have not been integrated within whole building simulation programs in order to take into account of the variety of systems and conditions in buildings (e.g. natural ventilation) and to calculate the models' underlying state variables simultaneously with the rest of the heat and moisture balances that are applicable to typical buildings. This work aims to develop a model that accounts for heat and moisture fluxes from indoor plants and integrate it within the ESP-r finite volume whole building simulation program (2015). The main advantage of having the model in a building simulation program versus the previous decoupled approaches is that a user can evaluate the effect of plants in any building type and condition.

The next sections of the paper will describe the fundamental equations and parameters of the proposed model and the solution method that has been integrated within ESP-r and adds/removes the resulted heat and moisture fluxes to the zone's energy/moisture balance.

MODEL DEVELOPMENT

Indoor plants energy balance

A typical energy balance on a node representing indoor plants is described by equation 1. This equation is similar to an energy balance for the inside layer of an opaque surface but with the addition of the evapotranspiration term (and the exclusion of the conductive part to/from the outside surface layers):

$$\rho_{pl} \cdot C_{pl} \cdot \delta_{pl} \frac{dT_{pl}}{\Delta t} = h_{c_{pl}}(T_a - T_{pl}) + \alpha_{pl} Q_{inc} + \sum_{i=1}^{N} h_{r_{pl_{s_i}}}(T_{s_i} - T_{pl}) - Q_{LH} \quad (1)$$

For the above Equation 1, researchers have identified temperature dependent relationships for calculating the convective coefficient ($h_{c_{pl}}$) between canopies and air (Stec, 2005; Stanghellini, 1993). It is also well known that for Equation 1 the radiation heat transfer coefficient depends on the indoor surface temperatures (a non-linear dependence). Temperatures are state variables and therefore the calculation of temperature-dependent convective and radiative coefficients in a simulated thermal zone is done in ESP-r by using the temperatures from the previous time step while alternative options for using for example constant convective heat transfer coefficients could be a user's choice. This linearisation technique (i.e. evaluating coefficients one time-step in arrears) is well established and described in the literature (Beausoleil-Morrison, 2000; Clarke 2001). This is the approach that is also used in the new plants model for the convective heat transfer coefficient ($h_{c_{pl}}$) of equation 1. In our initial indoor plants model the convective heat transfer coefficient for the plants ($h_{c_{pl}}$) is taken as the average indoor convective heat transfer coefficient of all zone surfaces from the previous time step. However, the long wave radiation part of the energy balance in Equation 1 is currently a non-trivial task to implement for a plant's surface within a thermal zone. For this reason, the first version of the model presented in this paper assumes that the temperature of the plant and the temperature of the building surfaces are similar. The long wave radiation is therefore assumed to be negligible and the relevant term in equation 1 will be zero.

Formulating indoor plant energy balance for the integration with ESP-r

The implicit ($t + \Delta t$) and explicit (t) schemes of Equation 1 are combined to bring them to the Crank-Nicolson scheme that is used by default in ESP-r ($\xi = 0.5$ in Equation 2). It should be noted that as for all numerical solutions in ESP-r the user could also select an alternative fully implicit or explicit solution. The unknown future time step ($t + \Delta t$) terms are placed on the left side of the equation while the present time step (t) and all other known terms are placed on the right side. The final form that will be used as a basis for the plants' model integration is given in Equation 2:

$$\left(\rho_{pl} \cdot C_{pl} \cdot \delta_{pl} + \xi \cdot h_{c_{pl}} \cdot \Delta t\right) \cdot T_{pl}^{t+\Delta t} - \xi \cdot h_{c_{pl}} \cdot \Delta t \cdot T_a^{t+\Delta t} + \xi \cdot \Delta t \cdot Q_{LH}^{t+\Delta t} = \left(\rho_{pl} \cdot C_{pl} \cdot \delta_{pl} - (1-\xi) \cdot h_{c_{pl}} \cdot \Delta t\right) \cdot T_{pl}^{t} + (1-\xi) \cdot h_{c_{pl}} \cdot \Delta t \cdot T_a^{t} + (1-\xi) \cdot \alpha_{pl} \cdot \Delta t \cdot Q_{inc}^{t} + (1-\xi) \cdot \Delta t \cdot Q_{LH}^{t} + \xi \cdot \alpha_{pl} \cdot \Delta t \cdot Q_{inc}^{t+\Delta t} \quad (2)$$

As mentioned earlier, the above Equation 2 does not include the long wave radiation part of Equation 1. Equation 2 has three (3) unknown state variables on the left hand side (T_{pl} , T_a , Q_{LH}). We will show that the latent heat from evapotranspiration (Q_{LH}) is, with regard to equation 2, dependent on the zone air temperature (T_a) and zone relative humidity (ZRH), and we will use an assumption from the literature that it is independent of the plants' temperature (T_{pl}). This assumption could reduce the number of unknowns in Equation 2 and by employing iterative methods it is possible to derive a solution that alters accordingly the energy and moisture balance of a thermal zone in ESP-r. It is important at this stage to discuss how the evapotranspiration term in Equation 2 has been implemented in ESP-r.

Evapotranspiration flux

The Penman-Monteith single-source model (Equation 3) that combines energy and mass transfer has been used as basis to account for the evapotranspiration flux (Q_{LH}) (Monteith, 1981):

$$Q_{LH} = \lambda \cdot E = \frac{\Delta \cdot (R_n - G) + \rho_a \cdot C_a \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma \cdot \left(1 + \frac{r_s}{r_a}\right)} \quad (3)$$

The slope of the saturated vapour pressure - temperature curve (Δ) could be estimated with Equation 4 (Allen et al., 1998):

$$\Delta = \frac{4098 \left[0.6108 \cdot exp\left(\frac{17.27 \cdot T_a}{T_a + 237.3}\right)\right]}{(T_a + 237.3)^2} \quad (4)$$

Note that it is common to use air temperature (indoor air for our model) than plant temperature for calculating the slope (Δ). Knowledge of the future time step indoor air temperature is however an unknown state variable and an iteration technique will be employed for the purposes of solving Equation 2. This is explained in the next section of the paper.

The net radiation at the plant surface (R_n) is equal to the amount of radiation absorbed by the plant's surface plus the amount of long wave radiation that is emitted by the plants. We already mentioned that the first version of the model does not include the long wave radiation emitted by the plants and the net radiation R_n will therefore be equal to the absorbed by the plants short wave radiation. This is represented by the term ($\alpha_{pl} Q_{inc}$) in Equations 1 and 2. The amount of incident solar radiation on the plants (Q_{inc}) is also used within the main energy balance equation for the plants (Equation 2) and it is for the first version of the indoor plants model a user defined time step input. This has the disadvantage that the user should pre-calculate Q_{inc} with tools such as Radiance (2015) and then import the time-step values for the plants model in ESP-r (an interface has been developed for this purpose). It is expected that a future evolution of the indoor plants model will include a method that uses the existing solar distribution (insolation) routines of ESP-r at time step level in order to calculate Q_{inc} . On the other hand, a user-defined input for Q_{inc} could offer flexibility in accounting for other sources of radiation other than the sun (e.g. from artificial lights).

The heat flux to soil (G) in Equation 3 is also assumed to be zero and therefore the model is not appropriate for modelling plants that receive significant amounts of shortwave radiation and are based on large soil areas.

The saturation vapour pressure of air (e_s) and the vapour pressure of air (e_a) are taken as:

$$e_s = 0.6108 \cdot exp\left(\frac{17.27 \cdot T_a}{T_a + 237.3}\right) \quad (5)$$

$$e_a = ZRH \cdot e_s \quad (6)$$

The zone's air relative humidity (ZRH) is an unknown variable at future time step ($t + \Delta t$) and an iterative solution should also be employed in this case (as discussed in the next section).

The psychrometric constant (γ) in Equation 3 varies with altitude but the variations for the constant (γ) are not significant and for the first version of the indoor plants model in ESP-r it has been taken as 0.065 kPa/°C.

The most challenging to obtain variables of Equation 3 are the surface resistance (r_s) to water vapour at the evaporating surface (mostly plants and their stomatal in our case) and the aerodynamic resistance (r_a) to vapour transfer. The aerodynamic resistance (r_a) is derived by the following processed version of the semi-empirical equation from Thom and Oliver (1977):

$$r_a = \frac{665}{1 + 0.54 \cdot U_2} \quad (7)$$

The above equation is only applicable for low wind speeds (<1 m/s) that are predominant in indoor spaces. Alternative methods for deriving the aerodynamic resistance will need to be implemented in future developments of the indoor plants model in order to account for a wider variety of situations (e.g. higher indoor wind speeds). The indoor wind speed (U_2) in Equation 7 should be equivalent to a wind speed measured at 2m height. However, in the context of most buildings simulated by building simulation tools the indoor wind speed could be derived from the following three cases (based on the available air flow calculation options in ESP-r):

- as an average value per zone when scheduled mechanical air flow rates have been specified by the users. In this case, the scheduled volume flow rate values are divided by the zone's floor area to calculate the average time step velocity needed for Equation 7;
- As a calculated output from connections between nodes defined by a nodal air flow network simulation. Deriving the indoor air velocity for the purposes of using it in Equation 7 is not straightforward because the plants in the proposed model have currently an arbitrary position in the zone while an indoor air node for the air flow simulation is associated with several connections between flow components and flow rates. Our proposed model is currently using one time-step in arrears to calculate the average air velocity from all the connections associated with the indoor air flow node of the zone;
- As a precisely positioned output from the CFD solver of the building simulation tool. While significant advances have been reported and demonstrated with regard to coupling the CFD domain with the other domains (e.g. thermal) in building simulation (Negrao, 1996; Beausoleil-Morrison, 2000), such model configurations are

not common and were outside the scope of the indoor plants model presented in this paper.

The surface resistance (r_s) in Equation 3 has been reported to be directly related to the stomatal resistance of individual leaves. The following relationship was found to be appropriate for dense vegetated plants (Allen et al., 1998) and has been used for the indoor plants model of this paper:

$$r_s = \frac{r_l}{LAI} \tag{8}$$

The stomatal resistance of leaves (r_l) is a plant specific parameter and researchers have correlated it with environmental factors and water availability. In particular, a number of authors have simplified the calculation of stomatal resistance by accounting only for the effect of solar radiation, air temperature, air vapour pressure deficit and the water content of the soil (e.g. Jarvis, 1996; Gerosa et al., 2012). The stomatal resistance (r_l) calculation that we adopted in our model is therefore accounting for the above parameters and expressed as:

$$r_l = r_{lmin} \cdot \frac{f(Q_{rad})}{f(T_a) \cdot f(VPD) \cdot f(swc)} \tag{9}$$

The minimum stomatal resistance r_{lmin} is a crop specific property and it is a user input for our model. The effect of incident solar radiation (or could also be radiation from lights) $f(Q_{rad})$ on stomatal resistance has been confirmed in the literature, albeit not a clear consensus can be reached for the most appropriate relationship to be used for this parameter of Equation 9. A number of relationships that are often specific to the type of plant for a specific study have been used in the literature (e.g. Gerosa et al., 2012; Lhomme et al., 1998; Noilhan and Planton, 1989; Nagai, 2003). In our model, we have developed a flexible method that allows the user to decide the best relationship for estimating $f(Q_{rad})$. The user in ESP-r is currently given two choices but additional ones could be easily added in the future: to use either a linear or an exponential function that determines $f(Q_{rad})$ from the incident on plants solar radiation (Q_{inc}):

$$f(Q_{rad}) = \alpha \cdot (\alpha_{pl} \cdot Q_{inc}) + \beta$$
$$or \tag{10}$$
$$f(Q_{rad}) = \exp\big(a \cdot (\alpha_{pl} \cdot Q_{inc})\big) + \beta$$

Note that $f(Q_{rad})$ should always be ≥ 1.

The above approach has the benefit of allowing the user to input a relationship that is not restricted to the amount of incident solar radiation but it could for example be dependent on other parameters such as the Photosynthetically Active Radiation (PAR).

In general, there have been a large number of studies that have attempted to derive and verify functions that could be used in Equation 9. Given the wide options available for these functions our model is currently using relationships that have been reported and cited several times in the literature, however there is also an option for the user to specify an overall constant total stomatal resistance (r_l) value per time step.

The temperature function $f(T_a)$ and the vapour pressure deficit function $f(VPD)$ are taken in our model from Nagai (2003) as:

$$f(T_a) = 1 - 0.0016(298 - T_a)^2 \tag{11}$$

$$f(VPD) = 1 - 0.025\left(\frac{e_s - e_a}{100}\right) \tag{12}$$

The function for the dependence of stomatal resistance on water stress $f(swc)$ is taken from Noilhan and Planton (1989) as:

$$f(swc) = 1, \quad if\ w_2 > w_{cr}$$
$$f(swc) = \frac{w_{swc} - w_{cr}}{w_{cr} - w_{wilt}}, if\ w_{wilt} \leq w_{swc} \leq w_{cr} \tag{13}$$
$$f(swc) = 0, \quad if\ w_{swc} < w_{cr}$$

Where the critical value w_{cr}= 0.75 w_{sat} (Thomson et al., 1981).

The wilting (w_{wilt}) and saturated (w_{sat}) moisture contents of the soil are user inputs that are usually taken from soil texture classification tables. A typical values for w_{wilt} is 0.03 m^3 m^{-3} for sandy soils, while for clays it could be greater than 0.2 m^3 m^{-3}. However, the values for the saturated water content (w_{sat}) do not vary significanly and they can be for example 0.43 m^3 m^{-3} for sandy soils and 0.38 m^3 m^{-3} for clays.

One of the most challenging parts of the model development stage was to determine a method to calculate the water content of the soil (w_{swc}). Calculating the water content of the soil would require at least an additional soil node in the model where a water mass balance equation would have to be solved at every time step. The water balance should include the incoming water from irrigation, the water leaving from the soil node (e.g. via drain, evaporation and root uptake) and calculate at every time step the water retained in the soil node (i.e. the average water content of soil w_{swc}). Excellent papers are available in the literature that discuss larger scale modelling problems and include complex water balances in soils (e.g. Noilhan and Planton, 1989; Celia et al., 1990; Van Dam et al., 1997; Simunek et al., 2006). Given that soil in indoor spaces is often of a small volume it was deemed as it would not be within the scope of this study to explicitly define the soil and its properties only for estimating the stomatal resistance of indoor plants. The indoor plants model presented in this paper does however allow for a user-defined time step input of volumetric water content in soil (w_{swc}) in order to be able to solve Equation 13.

Finally, with regard to Equation 9 it should be noted that $f(T_a)$, $f(VPD)$ and $f(swc)$ take values between 0 and 1.

All variables of Equation 3 have now been defined and the next section presents the method of solution that couples the indoor plants energy balance (primarily defined by Equation 2) with the building zone energy balance within the ESP-r solver.

METHOD OF SOLUTION

Figure 1 summarises the overall implementation and integration of the indoor plants model in ESP-r. For each simulation time step ESP-r provides the present time step air temperature (T_a^t) and relative humidity (ZRH^t). An initial guessing of the future time step air temperature ($T_{a\_assumed}^{t+\Delta t}$) and relative humidity ($ZRH_{assumed}^{t+\Delta t}$) is then done. The model currently uses the future ambient air temperature as a basis for the initially guess but the specific logic could be altered and enriched with other parameters relatively easily.

The model continues with the calculation of the average indoor air velocity (U_2^t) in accordance with the earlier discussion for Equation 7 (using one time step in arrears) and uses it to calculate the aerodynamic resistance (r_a).

Plant-specific user inputs (LAI, $r_{lmin}, \alpha_{pl}, \alpha, \beta$) are then used in combination with the user-defined incident solar radiation and soil water content values in order to solve Equations 4 to 13 and calculate all the parameters needed for Equation 3. Once the latent heat flux for the future time step ($Q_{LH}^{t+\Delta t}$) is calculated (Equation 3) the model uses user inputs for the plants' thermal storage capacity (ρ_{pl}, C_{pl}, δ_{pl}) to solve Equation 2 for the plants' future time step temperature ($T_{pl}^{t+\Delta t}$).

The effect of the plants on indoor conditions is then accounted by introducing a new control law in ESP-r that, at every time step, alters the zone energy balance as follows:

- Deducts the amount of solar radiation absorbed by the plants' surface ($\alpha_{pl} \cdot Q_{inc}^{t+\Delta t}$) from the sum of direct and diffuse solar radiation entering the zone;
- Adds the calculated convection and latent heat fluxes to the zone air node balances. The latent heat flux ($Q_{LH}^{t+\Delta t}$) is taken from Equation 3 and the convective flux ($Q_{conv}^{t+\Delta t}$) from Equation 14 and by using the assumed value of the indoor air temperature ($T_{a\_assumed}^{t+\Delta t}$) as follows:

$$Q_{conv}^{t+\Delta t} = h_{c_{pl}}^t \left(T_{a\_assumed}^{t+\Delta t} - T_{pl}^{t+\Delta t}\right) \qquad (14)$$

ESP-r will then calculate the actual future time step zone air temperature and relative humidity (noted as "new" $T_a^{t+\Delta t}$ and $ZRH^{t+\Delta t}$ in Figure 1). As shown in Figure 1, a convergence check will then be done initially for the assumed indoor air temperature and afterwards for the assumed indoor air relative humidity. If convergence is achieved the simulation continues to the next time step. Otherwise, if the predicted and the assumed values do not converge, the initial assumptions for $T_{a\_assumed}^{t+\Delta t}$ and $ZRH_{assumed}^{t+\Delta t}$ are corrected and the iteration continues by returning to the point where Equations 4 to 13 are to be solved again with new assumptions (Figure 1).

CONCLUSION

A dynamic model that accounts for the effect of indoor plants on indoor air conditions has been developed and integrated within the ESP-r building simulation program. The model takes into account the amount of solar radiation absorbed by plants and alters the zone's energy and moisture balances by adding a convective and an evapotranspiration flux. The numerical solution and the underlying equations that have been used in the model were presented together with a brief discussion on the challenges for obtaining some of the required model parameters (e.g. basic soil properties).

The model presented here has certain limitations; the long wave radiation heat exchange between plants and indoor surfaces is not accounted for, it is not applicable for plants with roots in large soil areas (e.g. evaporation from soil is not included in it), and physiological growth of plants with time-varying LAI and canopy thickness has not yet been implemented. Future work will aim towards model validation and the quantification of the importance of some of the current model assumptions.

While in most cases the effect of indoor plants on indoor conditions is not necessarily significant, there had not been hitherto a model within whole building simulation programs that could simulate buildings with large vegetated surfaces. Such cases could become important for example when the vegetated surfaces have been positioned in a way which could affect comfort and/or thermal loads (for example, when they block solar radiation). The model of the present paper extends the state-of-the-art in using whole building simulation for evaluating the performance of indoor spaces with plants. Such spaces are nowadays common in certain building types (e.g. offices).

NOMENCLATURE

ρ_{pl} = density of plants (leaves/stems), kg m^{-3}
C_{pl} = specific heat of plants, J kg^{-1} $^oC^{-1}$
δ_{pl} = thickness of canopy, m
T_{pl} = Temperature of plant/canopy, ^{o}C
T_a = Temperature of indoor air, ^{o}C
T_{s_i} = Inside face temperature for surface i, ^{o}C
t = current time step
$t + \Delta t$ = future time step
$h_{c_{pl}}$ = convection coefficient (plants-air), W m^{-2} $^oC^{-1}$

α_{pl} = solar absorptance of plants, -
Q_{inc} = incident solar radiation on plants, W m^{-2}
N = number of indoor surfaces facing the plant, -
$h_{r_{pl_{s_i}}}$ = radiation heat transfer coefficient between plants and indoor surface i, W m^{-2} ^{o}C^{-1}
Q_{LH} = evapotranspiration (latent) heat flux, W m^{-2}
ξ = weighting between implicit and explicit forms of the energy balance, default: 0.5
λ = latent heat of vaporisation ≈ 2450·10^{3} J kg^{-1}
E = amount of evaporated water (flux), kg s^{-1} m^{-2}
Δ = slope saturation vapour pressure - temperature curve, kPa C^{-1}
R_n = net radiation at the plant surface, W m^{-2}
G = soil heat flux, assumed: 0 W m^{-2}
ρ_a = air density, kg/m^{3}
C_a = specific heat of dry air, J kg^{-1} ^{o}C^{-1}
e_s = saturation vapour pressure, kPa
e_a = vapour pressure of air, kPa
r_a = aerodynamic resistance, s m^{-1}
r_s = surface resistance (to flow of water vapour), s m^{-1}
γ = psychrometric constant: 0.065 kPa °C^{-1}
ZRH = zone indoor relative humidity (%)
U_2 = indoor wind speed, m s^{-1}
r_l = stomatal resistance of a leaf, s m^{-1}
LAI = Leaf Area Index, -
r_{lmin}= minimum stomatal resistance of plant, s m^{-1}
$f(Q_{rad})$ = function for the role of solar irradiance on stomatal resistance, -
$f(T_a)$ = function for the role of air temperature on stomatal resistance, -
$f(VPD)$ = function for the role of vapour pressure deficit on stomatal resistance, -
$f(swc)$ = function for the role of volumetric soil water content on stomatal resistance, -
α, β = function coefficients for estimating $f(Q_{rad})$,-
w_{sat} = saturated volumetric water content, m^{3} m^{-3}
w_{cr} = critical volumetric water content, m^{3} m^{-3}
w_{wilt} = wilting volumetric water content, m^{3} m^{-3}
w_{swc} = mean volumetric water content, m^{3} m^{-3}
T_{amb} = Ambient air temperature (weather file), ^{o}C
$T_{a\_assumed}$ = Temperature of indoor air assumed during the iteration process, ^{o}C
$ZRH_{assumed}$= Relative humidity of indoor air assumed during the iteration process, %
C = Constant used for the assumption of the future time step indoor air temperature (default 0.5K)
D = Constant used for the assumption of the future time step indoor relative humidity (default 5%)
ΔT_{conv} = Convergence criterion for temperature (default: 0.1K)
ΔZRH_{conv} = Convergence criterion for relative humidity (default: 1%)
Q_{conv} = convective heat flux (plants - air), W m^{-2}

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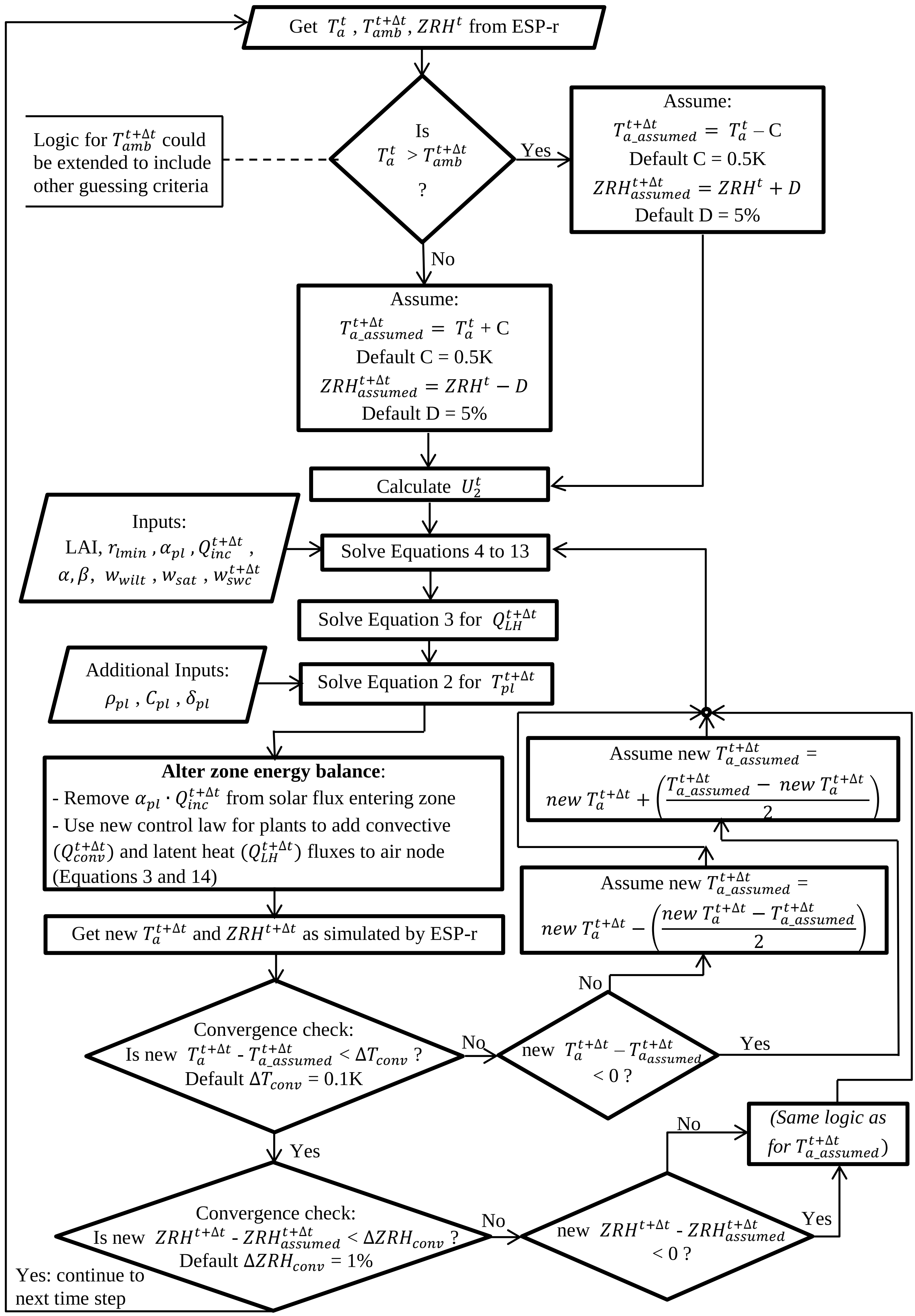

Figure 1 The solution method for the indoor plants model as implemented in ESP-r.