SRC and its applications to building thermal control

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Abstract

Energy-efficient building design requires, the use of advanced thermal simulation programs and respective complex building models, for the estimation of the annual building energy demand. This complexity, limits the use of such models in model-based building climate control design, mainly because it entails additional difficulty in finding appropriate controllers. To meet the above requirements, a novice climate control method is introduced, which is based on SRC (a building thermal simulation program, which is complex enough for the initial building design phase and at the same time, simple enough for model-based climate control design tasks). In the suggested method, the problem of finding energy-efficient operation schedules of building devices, is formulated as a convex optimization problem and solved using a finite number of iterations, until a certain comfort criterion is met. The method is tested on a two zone building with external and internal openings, where the advantages of inter-zone air mixing and coupled building model thermal dynamics, are taken into account. The obtained operation schedules, when applied to the passive (openings) and active (HVAC) devices of the test building, exhibited higher energy savings than the schedules provided by a rule-based controller, while conforming to the same thermal comfort requirements.

Keywords - Energy-efficient, model-based thermal control, Coupled building dynamics, Inter-zone air mixing.

1. Introduction

Building models are generally abstract mathematical tools of varying complexity used to describe and predict building's thermal behavior as accurately as possible [8]. Coupled with the existing building models are model-based thermal control methods which have captured building's research community interest, as they lead to substantial energy savings compared with traditional rule based thermal control techniques. These control methods can be classified with respect to their dependence on the model's mathematical structure. Structure-independent methods (characterized also as "black box" methods), treat the building model as a black box [7], whereas structure-dependent methods (such as model predictive control methods (MPC) [5], [6], [2]) use model's mathematical structure to derive the controller's output. Structure-dependent methods are characterized as "white box" methods, since the model parameter values (not estimates) are used directly in their control schemes. Apart from completely structure-(independent or dependent) schemes, methods which update the controller output using parameter values from different models as the building state evolves in time, have been also developed, introducing the concept of co-simulation [9].

The proposed method is a structure-dependent method which rely on SRC, a building simulation program [4], in order to define a time and temperature dependent building model. The method can be described by an iteration scheme which uses SRC's model parameters in order to define and solve a convex optimization problem at every step. The solution of this convex problem, essentially defines the operation schedules of openings and HVAC devices of building spaces, which achieve thermal comfort with low energy consumption. The technique is an extension of the method of [4] in order to include HVAC devices. The characteristic, which differentiates this method from other MPC methods, is the fact that the control decisions are taken after the model's state trajectory has been completed and not during model's state evolution.

The paper is structured as follows: an upper level view of SRC in section 2 is followed by a detailed description of the steps of the proposed algorithm in section 3. The method is applied on a two-zone test building and compared with a rule-based controller in section 4. The paper resumes with the results of the comparison and final conclusions in sections 5 and 6.

2. SRC

System of **R**esistances and **C**apacitances (SRC) [3], is a program which performs thermal and energy building simulations by forming and solving two coupled systems of ODEs, one describing the thermal energy transfers and one modeling the humidity mass flows, among building elements, with boundary conditions the outside air/ground temperatures and humidity ratios respectively. SRC relies on the electrical analogy [1] to represent any building using a network of interconnected resistances (R) and capacitors (C) (RC network) as illustrated in figure 1. SRC uses the above representation in order to form:

- A time dependent resistance matrix [R(t)], containing the building's thermal resistances, due to material boundaries or convection phenomena, populated according to resistance interconnections.

- A capacitance diagonal matrix [C], containing the thermal capacitors modeling the temporal thermal storage of the building elements.

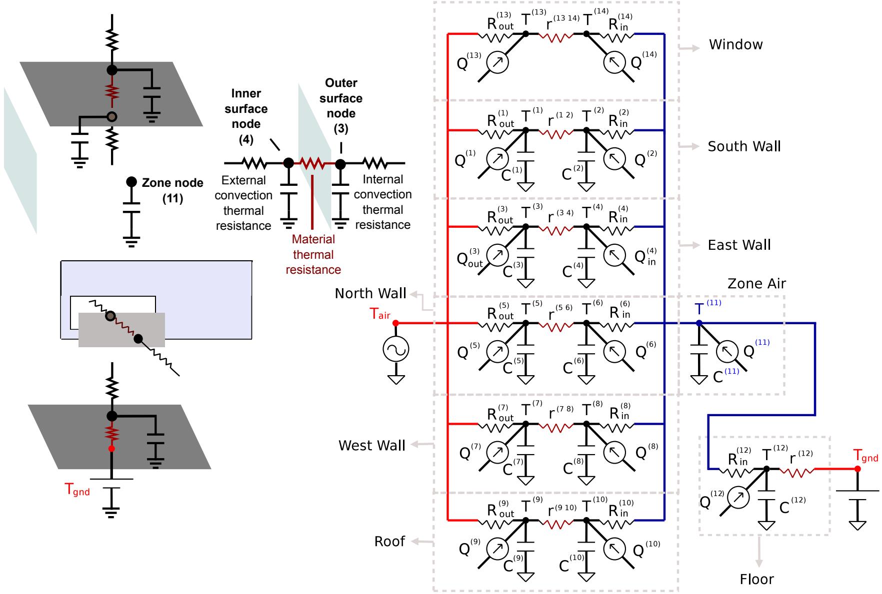

Figure 1: Building and its RC network representation (material resistances displayed in red, convection resistances in displayed in black)

- A time dependent vector Q(t), containing all the thermal power components such as solar and long wave radiation thermal gains.

The time evolution of the temperatures at the RC network nodes (included in a vector $T(t)$), can be described by a system of ODEs which include [C(t)],[R(t)] matrices and $Q(t)$ vector and are similar to the Kirchhoff current laws for electrical circuits:

$$[C(t)]\frac{dT(t)}{dt} = [R(t)]T(t) + Q(t) \tag{1}$$

The above continuous system is approximated by SRC at a set of F time instances, by a discrete system of equations, using a finite difference, forward numerical scheme with variable time step. This discrete system includes: the time step δt_f, the samples of [R(t)], [C(t)] matrices ($[R_f]$, $[C_f]$) and the samples of Q(t) vector (Q_f), at $f \in \{1,...,F\}$ and is expressed by:

$$T_{f+1} = [A_f]T_f + \bar{Q}_f, \quad [A_f] = I_f + \delta t_f [C_f]^{-1}[R_f], \quad \bar{Q}_f = \delta t_f [C_f]^{-1} Q_f \tag{2}$$

By induction on (2), T_f is expressed as: $T_f = L(T_0, \bar{Q}_0, ..., \bar{Q}_{f-1})$, where L is a linear operator w.r.t temperature vector T_0 and vectors $\bar{Q}_0, ..., \bar{Q}_{f-1}$. A smaller system referring to the zone temperatures can be formed, by extracting from the previous induction solution, the equations referring to the zone temperatures $T_f^{(z)}$:

$$T_f^{(z)} = L_z(T_0^{(z)}, \bar{Q}_0^{(z)}, ..., \bar{Q}_{f-1}^{(z)}) + L_o(T_0^{(o)}, \bar{Q}_0^{(o)}, ..., \bar{Q}_{f-1}^{(o)}) \tag{3}$$

where the superscript (o) refer to the "other" than the zone node vector entries. L_z and L_o are linear operators w.r.t their arguments. The reduced thermal power input at zone nodes (z) at time instant f in (3), $\bar{Q}_f^{(z)}$ can be expressed by:

$$\bar{Q}_f^{(z)} = \sum_{i \in O_z} o_{i,f} \bar{Q}_{i,f}^{op,(z)} + \sum_{j \in H_z} h_{j,f} \bar{Q}_{j,f}^{hv,(z)} + \bar{Q}_f^{oth,(z)} \tag{4}$$

O_z is the set operable opening indexes of zone z, $o_{i,f}$ is the state of opening i, at time instant f ($o_{i,f} = 1$ opening i is opened, $o_{i,f} = 0$ opening i is closed) and $\bar{Q}_{i,f}^{op,(z)}$ is the reduced thermal power input of opening i to zone z, at time instant f, when transitioned from the closed to the opened state. Similarly, H_z is the set of HVAC device indexes of zone z, $h_{j,f}$ is the state of HVAC j, at time instant f ($h_{j,f} = 1$ HVAC j is on, $h_{j,f} = 0$ HVAC j is off) and $\bar{Q}_{j,f}^{hv,(z)}$ is the reduced thermal power input of HVAC j to zone z, at time instant f, when transitioned from the off to the on state. HVACs are modeled as constant airflow devices, therefore:

$$Q_{j,f}^{hv,(z)} = \rho_a \dot{V}_{hv}^{vent} \left[c_{p_{da}} (T_{hv}^{out} - T_f^{(z)}) + c_{p_{wv}} (H_{hv}^{out} T_{hv}^{out} - H_f^{(z)} T_f^{(z)}) \right] \tag{5}$$

with ρ_a the density of air, $c_{p_{da}}$,$c_{p_{wv}}$ the specific heat of dry air and water vapor, $\dot{V}_{hv}^{vent}$, T_{hv}^{out}, H_{hv}^{out} the unit's output airflow rate, temperature and humidity ratio and $H_f^{(z)}$ zone's z humidity ratio at time f. Finally, $\bar{Q}_f^{oth,(z)}$ includes the "other" reduced thermal power input components to the zone z, at time instant f, such as thermal power input from infiltration (obtained by SRC at every simulation step).
Differentiating (3) w.r.t. $o_{i,f}$ and $h_{j,f}$ while taking into account (4), yields a first order approximation for the perturbation of the zone temperature vector $\Delta T^{(z)} = \{\Delta T_1^{(z)}, ..., \Delta T_n^{(z)}, ..., \Delta T_F^{(z)}\}$:

$$\Delta T^{(z)} \approx [S_{op}] \delta \bar{o} + [S_{hv}] \delta \bar{h} \tag{6}$$

where $\delta \bar{o} = \{..., \delta o_{i,f}, ...\}$ is the perturbation of the state vector of the openings, $\delta \bar{h} = \{..., \delta h_{j,f}, ...\}$) is the perturbation of the state vector of the HVACs, $[S_{op}]$ is a $F \times (O * F)$ matrix with entries populated by SRC using the terms $\frac{\partial L_z}{\partial \bar{Q}_f^{(z)}}$ and $\bar{Q}_{i,f}^{op,(z)}$ and $[S_{hv}]$ is a $F \times (H * F)$) matrix with entries populated by SRC using the terms $\frac{\partial L_z}{\partial \bar{Q}_f^{(z)}}$ and $\bar{Q}_{i,f}^{hv,(z)}$.

3. Proposed thermal control method

The proposed thermal control method uses the matrices $[S_{op}]$ and $[S_{hv}]$ of (6) obtained by SRC, in order to bring the zone temperature vector $T^{(z)}$ as close as possible to a ”desired” zone temperature vector $T_d^{(z)}$ defined by: $T_{d,f}^{(z)} = \{T_d^{(z)}$, if $f \in N_{oc}^{(z)}$, $|$ $T_f^{(z)}$, o.w.$\}$. Set $N_{oc}^{(z)} \subset \{1, ..., F\}$ is a subset of the set of all time instances during which, zone z is occupied. $T_d^{(z)}$ is a target temperature of zone z, taken as the middle temperature of a thermal comfort range. The method, summarized by the diagram of figure 2, can be described by the following steps:

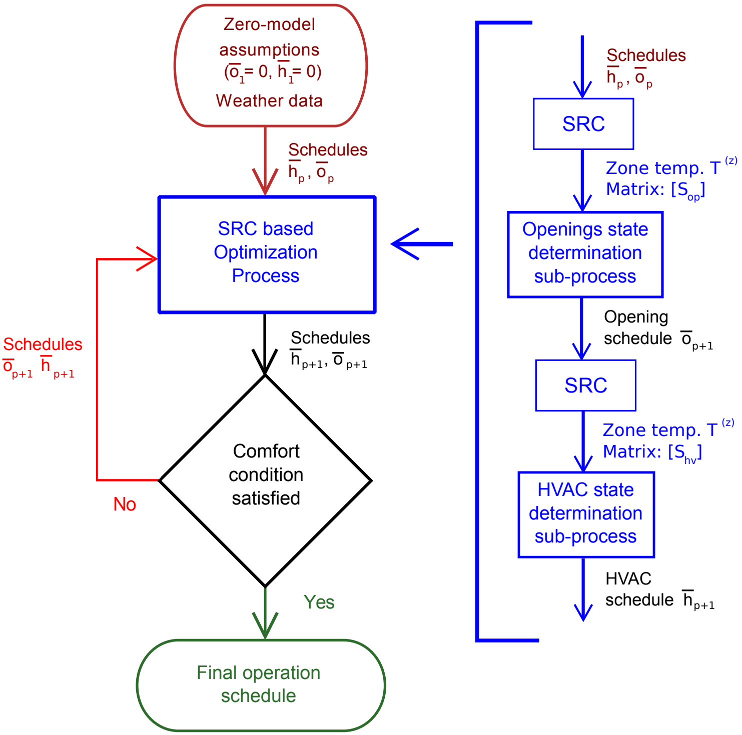

Figure 2: Block diagram of the proposed iterative thermal control method

1. Initially zero-model assumptions are considered which include all the openings and HVACs in the zero operating state: $\bar{o}_p = 0$ and $\bar{h}_p = 0$ with $p = 1$.
2. Given the state vectors $\bar{o}_p$ and $\bar{h}_p$ as an input, an optimization process is then executed, which includes:

(a) An SRC execution which provides the zone temperatures $T^{(z)}(\bar{o}_p, \bar{h}_p)$, the desired zone temperatures $T_d^{(z)}$ and matrix $[S_{op}]$.

(b) An **openings' state determination sub-process** which derives the new opening state vector $\bar{o}_{p+1}$ as the solution of the following convex optimization problem:

$$\bar{o}_{p+1} = \arg\min_{\bar{o}} ||T^{(z)}(\bar{o}_p, \bar{h}_p) + \Delta T_{op}^{(z)}(\bar{o}) - T_d^{(z)}||_2 \tag{7}$$

with $|o_{i,f}| < 1, \quad \forall i \in O, \quad \forall f \in \{1, ..., F\}$ and $\Delta T_{op}^{(z)}(\bar{o}) = [S_{op}](\bar{o} - \bar{o}_p)$.

(c) An SRC execution which given $\bar{o}_{p+1}$ and $\bar{h}_p$, provides the zone temperatures $T^{(z)}(\bar{o}_{p+1}, \bar{h}_p)$, the desired zone temperatures $T_d^{(z)}$ and matrix $[S_{hv}]$.

(d) An **HVACs' state determination sub-process** which derives the new HVAC state vector $\bar{h}_{p+1}$ as the solution of the following convex optimization problem:

$$\bar{h}_{p+1} = \arg\min_{\bar{h}} ||T^{(z)}(\bar{o}_{p+1}, \bar{h}_p) + \Delta T_{hv}^{(z)}(\bar{h}) - T_d^{(z)}||_2 \tag{8}$$

with $|h_{j,f}| < 1, \ \forall j \in H, \ \forall f \in \{1, ..., F\}$ and $\Delta T_{hv}^{(z)}(\bar{h}) = [S_{hv}](\bar{h} - \bar{h}_p)$. The HVAC state vector entries $h_{j,f}$, of $\bar{h}_{p+1}$, are rounded using the following threshold function: $h_{j,f}|_r = \{1, \text{ if } h_{j,f} \geq S_{th}, \ | \ 0, \text{ if } h_{j,f} < S_{th}\}$.

3. Vectors $\bar{o}_{p+1}, \bar{h}_{p+1}$ should satisfy $PTTD_p \leq PTTD_{min}$, in order to be selected and the algorithm to terminate. $PTTD_p$ is the percentage of time thermally dissatisfied defined as:

$$PTTD_p = \frac{\sum\limits_z N_{dis,p}^{(z)}}{\sum\limits_z N_{oc}^{(z)}} \tag{9}$$

where $N_{oc}^{(z)}$ defined previously as the set of time instances when zone z is occupied, $N_{dis}^{(z)}$ is a subset of $N_{oc}^{(z)}$ satisfying $\forall f \in N_{dis}^{(z)}, \ |T_f^{(z)} - T_d^{(z)}| > \delta T$. $N_{oc}^{(z)}$ is essentially, the set of time instances the occupants are thermally dissatisfied. δT is an allowable temperature swing. If $PTTD_p > PTTD_{min}$ the algorithm returns back to step 2 with input the vectors $\bar{o}_{p+1}, \bar{h}_{p+1}$ and repeats the steps with $p \to p+1$.

To ensure termination a maximum allowable iteration number is predefined. If the number of iterations exceed this maximum number, the termination condition $PTTD_p \leq PTTD_{min}$ is relaxed by increasing $PTTD_{min}$ and the algorithm is executed again from the begining.

4. Example

The proposed thermal control algorithm is applied on a rectangular two-zone building, with two external openings on its large side facing south, displayed in figure 3. The first zone of the building (west room in figure 3) has two external openings (one door, with index 1 and one window with index 2) and an internal door common with the second zone (east room in figure 3) which has no other openings. This configuration appears in many buildings where an office (zone 1 in this example) has a “blind” storage space attached to it (zone 2 in this example). Since zone 2 does not have any external openings, its solar gains are smaller than the solar gains of the office and therefore its cool environment is used by the proposed method via inter-zone mixing, to cool down zone 1.

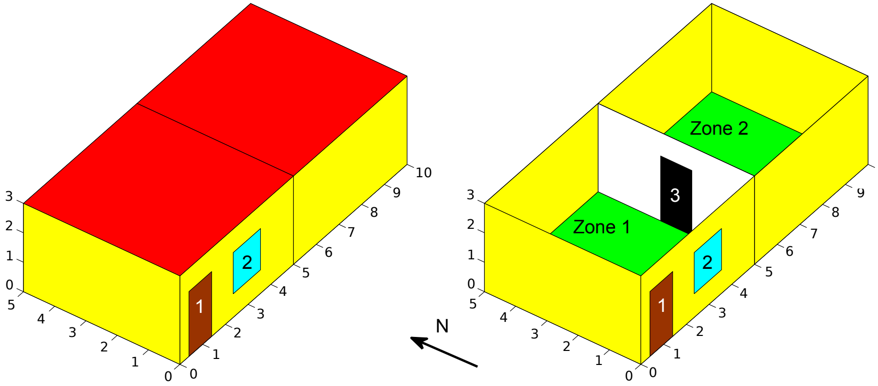

Figure 3: Geometry of the two-zone test building. Units are in meters

The external walls of the building, the roof and the floor are insulated consisting of multiple layers referring to realistic constructions. The variable simulation time step has maximum upper bound $\delta t_{max} = 10min$. The building was simulated during the 15^{th} of September 2009 using the San Fransisco airport weather file for this time period. This time horizon was chosen as it exhibits a large outside air temperature swing from 13 °C to 30 °C. Both zones of the building were assumed to be occupied during the morning between 8:50 am (53rd interval) - 12:00 pm (72nd interval) and in the afternoon between 1:00 pm (78th interval) - 8:00 pm (120th interval). During the occupancy periods, the desired zone temperatures were considered $T_d^{(z)} = 24.5°$C (z=1,2), the allowable temperature swing $\delta T = 2.5°$C and as a result, the lower and upper comfort limits were 22 and 27°C respectively. The minimum acceptable percentage of time thermally dissatisfied was set at $PTTD_{min} = 0\%$.

One **HVAC** unit was assigned every room with index i, equal to the zone index z. Each unit had the following characteristics: output air rate: 0.1 $\frac{m^3}{sec}$, heat set point: 22.5°C (an $dT = 0.5$°C offset was added to the lower comfort margin of 22°C, to avoid oscillations), cool set point: 26.5°C (an $dT = 0.5$°C offset was subtracted by the upper comfort margin of 27°C, to avoid oscillations), hot output air temperature 40°C and cold output air temperature 10°C. The threshold value, used to determine the HVAC state was $S_{th} = 0.99$.

The proposed algorithm is compared with a rule-based control algorithm described by the following rule set:

1^{st} **rule (openings)**

$$o_{i,f} = \begin{cases} 1, & \left[(T_{i,f}^{(z)} > T_{i,f}^{(out)}) \wedge (T_{i,f}^{(z)} > T_U)\right] \vee \left[(T_{i,f}^{(z)} < T_{i,f}^{(out)}) \wedge (T_{i,f}^{(z)} < T_L)\right] \\ 0, & \text{o.w.} \end{cases} \tag{10}$$

2^{nd} **rule (HVACs)**

$$h_{i,f} = \begin{cases} 1, & (\text{Zone of opening i is occupied}) \wedge o_{i,f} = 0 \\ 0, & \text{o.w.} \end{cases} \tag{11}$$

where: $T_{i,f}^{(z)}$ is the zone temperature of the zone opening i belongs to at time instant f, $T_{i,f}^{(out)}$ is the temperature of the air of the outside space (zone or air) of opening i, at time instant f, T_U and T_L are the upper and lower comfort temperature limits of the opening. For the example under consideration: T_L=22.5°C, T_U=26.5°C and the internal opening with index i=3 belongs to zone 1, with zone 2 being its outside space.

5. Results

The plots of figures 4 and 5 indicate that substantial energy savings can be achieved by applying the proposed method instead of the rule-based technique on the building for the time period under consideration. More precisely, after 19 iterations the proposed method converged to an operation schedule requiring the HVACs of the zones to be open only for 37 time intervals (see figure 5) achieving $PTTD = 0\%$ while for the same comfort level the rule-based controller required the HVAC to be on for 74 time intervals as illustrated by the last plot of figure 4. The total reduction of HVAC operation time is 6h and 10 min or 50%. These energy savings are achieved by: turning off the HVAC of the zones for the time instances 78-120, while opening the internal door connecting the two zones, allowing inter-zone air mixing and slightly opening the external openings in order to heat up zone one.

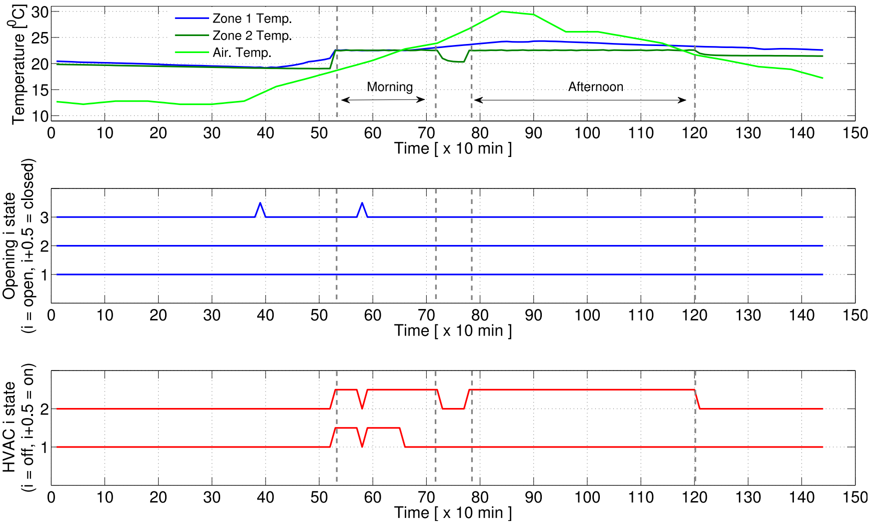

Figure 4: Rule-based control results

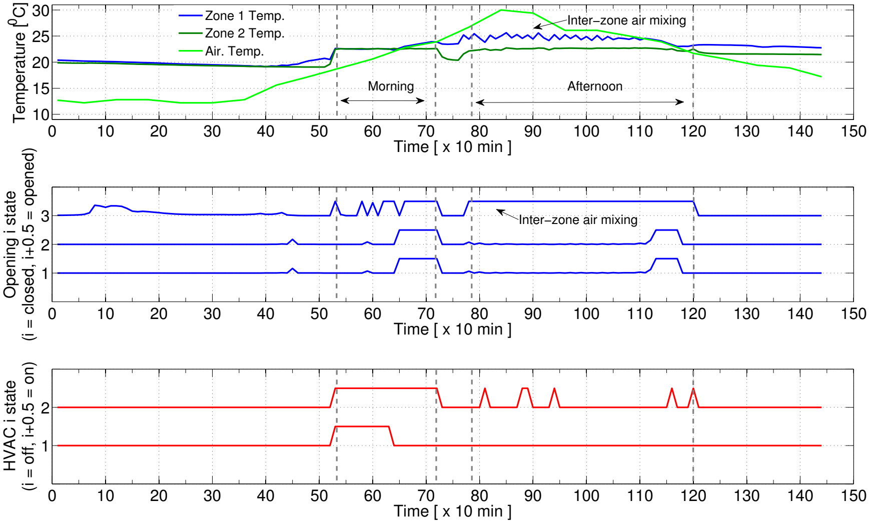

Figure 5: Proposed method results

6. Conclusions

The presented thermal control method uses the mathematical structure of the model formed by SRC program, in order to derive the operation schedules (state vectors) of passive as well as active building devices which manage to maintain thermal comfort in building interiors. It has been demonstrated that such method achieves lower energy consumption compared with a rule based control algorithm without violating the comfort conditions during building occupancy periods. The method takes into account the thermal dynamics of the whole building, as it uses SRC's model parameters directly, enabling inter-zone conditioning strategies to be performed. Finally, in order to reduce the computation time in large buildings the method can be adapted to include only specific openings and zones, including the thermal coupling of the whole building.

7. Acknowledgement

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