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Simplified Multi-Zone Thermal Modelling of a House for Demand Reduction & Control Applications

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Abstract
This paper examines the selection of appropriate multi-zone models for a test-house with the goal of finding opportunities to reduce peak electrical power demand due to space heating. Identification techniques for determining the effective value of parameters of these models are also explored. Data obtained from three thermal models of varying complexity is compared to measurements obtained in an unoccupied 2-storey house with garage and basement. It was found that a simplified grey-box model consisting of four low order models attached through connecting walls/floors/ceilings and inter-zonal convective terms is adequate for control applications. The chosen model was later used for temperature setpoint profile studies for individual zones, with the target of comparing different setpoint profiles for different zones. When compared to conventional operation of the building, the use of advanced setpoint profiles in individual zones can reduce peak electric heating demand by 30%.

Keywords - building modelling, control-oriented modelling, RC thermal networks

1. Introduction

This paper examines the selection of appropriate multi-zone models for a house with the goal of comparing control strategies. Parameter identification techniques are employed and opportunities for reducing the peak power demand associated with space conditioning are explored.

Suitable simplified multi-zone thermal models enable a rapid assessment of control strategies targeting energy reduction, peak power reduction or occupant thermal comfort. An area with promising potential for saving energy, better load regulation and improved occupant comfort is the implementation of advanced control strategies in buildings. These strategies could greatly benefit from adequate, simple models. Model predictions should be meaningful for energy and power results for the whole building level or at the zone level. Zone level detail allows for even greater potential for advanced controls.

Simplified models offer distinct advantages for district modelling [1], [2] and advanced control strategies [3]–[5]. Simplified models allow for rapid simulation of complex and/or large systems with acceptable accuracy and benefit from quicker calibration procedures [6]. Research has focused on single zone modelling and simplified modelling of multi-zone buildings [7]–[9]. One common approach for simplified building modelling is grey-box RC thermal networks [10], where system identification techniques are used to determine effective resistance and capacitance values for the model. Besides energy conservation measures, there is interest in ways to reduce peak power demand (due to space heating or cooling) at critical times [11], [12]. Simplified models allow for fast and easy simulations to help choose proper operation and control strategies in order to minimize peak demand; models can also be used for such anticipatory or MPC applications [13].

This paper contributes to the existing literature by investigating the use of simplified grey-box modelling in the development of advanced control studies at the zone level in typical Canadian homes for reducing peak power demand and energy consumption.

2. Methodology

The methodology employed for the identification, inspection and validation of simplified multi-zone models consists of the following steps:

1. Experiments were conducted at unoccupied test homes to study setpoint profiles and to get data for comparison with models.
2. Initial building thermal models were developed based on physical properties and geometry of the house.
3. Unknown values of parameters of the building models were identified through system identification techniques.
4. The simplified thermal model predictions were compared with measured experimental data.
5. A simplified model is used to study alternative temperature control for reduction of peak power demand.

3. Experimental Facility

The Experimental Houses for Building Energetics (EHBE) [14], built in 2011, were used for the experiments. The EHBE consists of two 2-storey detached homes with excavated basements, each with a livable area of 120m^2, excluding the attached garage and basement (Fig. 1). The homes are of normal construction for Québec with a building envelope consisting of (from exterior to interior) vinyl cladding or brick, air space, air barrier, fiberboard, RSI 3.5 fiberglass, rigid wall insulation panel, air space, drywall, and RSI 5.3 insulation in the roof instead of RSI 3.5. The windows are double clear glass with an air gap and no coatings, with a total window area of 19 m^2. The homes are heated with baseboard space heating in each room with no active air mixing and with individual room thermostats.

Fig. 1: EHBE exterior

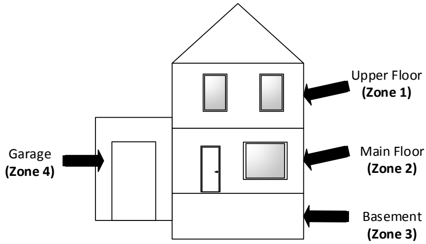

Fig. 2: Residential detached house modelled as 4 thermal zones

Nearly 500 sensors in each house and a weather station collect data at 15 minute intervals. Sensors measure room by room heating power, plug and light loads, air temperature, relative humidity, air velocity, globe temperature, surface temperatures of the structure and envelope elements, and temperature and water content of the surrounding soil.

In the center of the living room on the main floor (Zone 2) is a vertical array of thermocouples (5 thermocouples spaced vertically from floor to ceiling) with a spacing of 610mm, used to study the vertical air temperature stratification within this zone. During winter experiments it was observed that the average ΔT from the height where the thermostat is located (height = 1220mm) to the ceiling (height = 2440mm) was 0.6°C. The basement (Zone 3) has a similar thermocouple set up and the average ΔT from the height where the thermostat is located to the ceiling was 1.0°C. These average values were used for the calculations of inter-zonal convective heat transfer between vertically connected zones, as it was found that vertical heat transfer between zones is significant (even with closed interior doors) and should be considered if accuracy at the zone level is desired.

4. Modelling Assumptions for Low Order Models

Thermal models based on the physics of the system – typically in the form of resistance-capacitance (RC) models – are useful for control studies in buildings. Values of parameters are identified through an optimization technique, and should be interpreted as "effective" values rather than "exact" physical parameters [15]. Model details could be added or taken away depending on the needs of the user. Some important assumptions used to construct simplified thermal RC networks include:

- The temperature of each surface or cross section is uniform.
- The air in each zone is well mixed.

- Radiative and convective heat transfers are combined and constant.
- Air is a non-participating medium with respect to radiation.
- Conduction between each window and window frame is neglected

An optimization algorithm is used to determine unknown parameters, therefore having fewer equations is helpful. Several methods are available to reduce the complexity of a model: merging thermal zones, reducing the discretization of the walls, and merging several walls to combined surfaces.

5. Thermal Models Considered

Three models were created: one detailed model (DM) and two simplified models (SM1 and SM2) derived from the DM.

- **Detailed Model (DM):** has 4 zones, with separated walls, windows, doors, resulting in 32 capacitances for the house model. A zone represents a level/storey of the house, shown in Fig. 2. Fig. 3 depicts the DM RC network for the main floor (Zone 2). Several models can be connected to create a multi-zone model. The thermal mass of the envelope is modeled as a single layer (i.e. one capacitance). Inter-zonal resistances are not shown in the diagram.
- **Simple Model 1 (SM1):** SM1 combines surfaces into effective areas, creating 14 capacitances for the whole house model. The thermal mass layer of the envelope is modeled as a single capacitance. Fig. 4 shows an example for the main floor (Zone 2), containing 3 capacitances. T_adj is an adjacent zone (in this case Zone 1) and R_interzonal is the convective resistance between vertically adjacent zones.
- **Simple Model 2 (SM2):** SM2 is similar to SM1, but it omits the thermal mass layer in the floors/ceilings between the zones and lumping the inter-zonal conduction and convective transfers to one effective resistance value. SM2 is similar to SM1 but omits the red/bold portion which depicts the inter-zonal convective resistance. 12 capacitances total for the whole house model of four zones.

In all models, experimentally determined data of the zone air temperature stratification was used for the calculation of vertical inter-zonal convective heat transfer (heat transfer driven by a temperature difference).

6. Calibration Exercise and Model Selection

An optimization routine is used to find the parameter values that minimize an objective function. In this case, the objective function chosen was the regression coefficient squares errors (CVRMSE) between measured power and the prediction at 15 minute intervals, similar to [16].

Nelder-Mead Simplex was used for this study using Python language. The Simplex algorithm is used here; other algorithms can replace it depending on the user’s preference. Since the individual results of each zone and whole building power are of importance, the CVRMSE of each individual zone was minimized, and then whole building results were investigated. The objective function (CVRMSE) used is shown in (1):

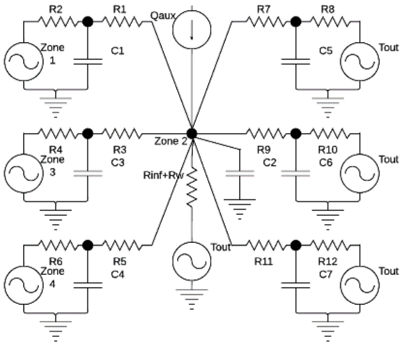

Fig. 3: DM schematic for main floor (Zone 2) (Interzonal resistances not shown)

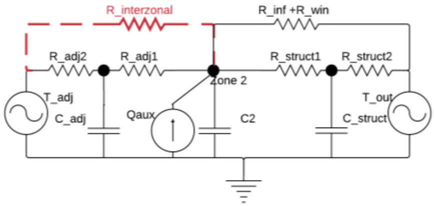

Fig. 4: SM1 (with red/bolded resistance) & SM2 schematics for main floor (Zone 2)

$$J(y,\hat{y}) = \frac{1}{\bar{y}}\sqrt{\frac{1}{n}\sum_{i=1}^{n}(\hat{y}_i - y_i)^2} \qquad (1)$$

where y is the experimentally measured data (thermal power) and $\hat{y}$ represents the model predictions. The building was modeled using the fully explicit finite difference method to solve the energy balance equations. Initial values of model parameters are based off of the known building material properties and estimates for infiltration, inter-zonal convective transfer and air capacitance multipliers.

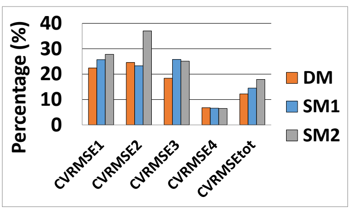

Fig. 5: CVRMSE after parameter identification

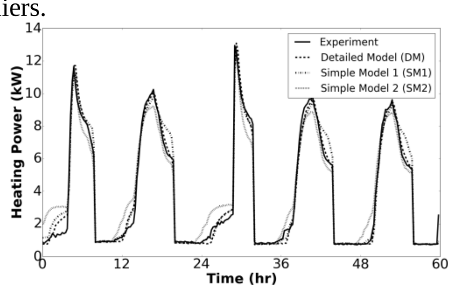

Fig. 6: Simulation vs. experimental power results

Figures 5 and 6 illustrate the results of the calibration exercise. In general, SM1 shows better results due to the simplifications created by SM2 of inter-zonal heat transfer. The SM1 of a 4-zone building was found to be superior at the zone level to the SM2 and has a CVRMSE value of 14.5% for the whole building, with CVRMSE for SM2 of 17.9% and DM having a whole building CVRMSE of 12.2%. These results suggest that modelling the capacitances between floors is important. After parameter estimation and calibration, SM1 was chosen for the control studies presented in Section 7.

7. Simulation Study Results

Setpoint profiles used in different zones are investigated through simulation and then evaluated according to their impact on peak reduction. It is assumed that occupants wake up at 6am. The setpoint profiles are:

- **Constant (C*XY*):** constant at all times. *XY* corresponds to temperature in Celsius.
- **Step-Change (SC):** different start times from night set back of 18°C to daytime 21°C (Fig. 7). Four SC profiles are considered.
- **Ramp (R):** 3 hour ramp with different start times from a night temperature of 18°C to daytime 21°C (Fig. 8). In a previous study [17], a 3 hour ramp was significantly superior to a 1 hour ramp or step change for reducing the peak, and gives a good compromise for increased energy consumption. Three R profiles are considered.

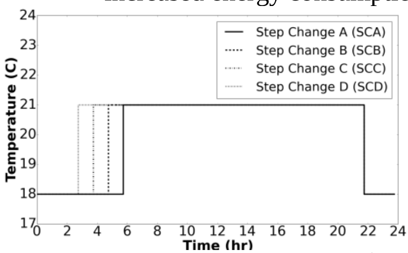

Fig. 7: Step-change (SC) temperature profiles

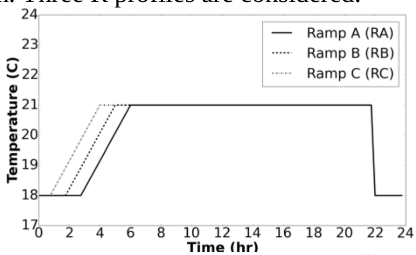

Fig. 8: Three hour linear ramps (R) with different start times

- **Preheating (PH):** a 3 hour linear ramp at different start times from nighttime temperature of 18°C to preheating of 23°C for different durations then to 19°C during peak morning hours, then daytime value of 21°C (Fig. 9). Three PH profiles are considered.

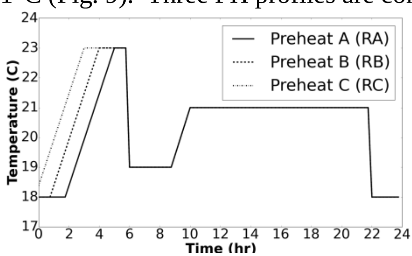

Fig. 9: Preheating (PH) temperature profiles with different start times

Two types of basement utilisations were assumed: (a) unoccupied basement (therefore it can remain low at 16°C) and (b) occupied basement. Sixteen simulation tests were conducted for the whole building, which incorporated different combinations of zone setpoint profiles. These simulations were performed for a very cold day where the minimum outdoor air temperature reached -26°C. Tests simulated using the SM1 are described in Table 1 and Table 2, with the associated zone temperature profiles depicted in Fig. 7, 8 and 9. The Tests 1 and 2 were assumed typical operation (base case) for a house with unoccupied basement, while Tests 9 and 10 are base cases for scenario of occupied basement. Tests with occupied basement were included to evaluate the potential of harnessing the thermal mass of the concrete foundation.

Table 1: Demand reduction simulation tests 1 to 8: unoccupied basement

	Test 1 Base Case	Test 2 Base Case	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8
Upper Floor (Zone 1)	C21	SCA	SCA	RA	RA	RA	RA	RA
Main Floor (Zone 2)	C21	SCA	SCD	RA	RC	PHA	PHB	PHC
Basement (Zone 3)	C16	C16	C16	C16	C16	C16	C16	C16
Garage (Zone 4)	C16	C16	C16	C16	C16	C16	C16	C16

Table 2: Demand reduction simulation tests 9 to 16: occupied basement

	Test 9 Base Case	Test 10 Base Case	Test 11	Test 12	Test 13	Test 14	Test 15	Test 16
Upper Floor (Zone 1)	C21	SCA	SCA	RA	RA	RA	RA	RA
Main Floor (Zone 2)	C21	SCA	SCD	RC	PHA	PHB	RB	RC
Basement (Zone 3)	C21	SCA	PHC	PHC	PHC	PHC	RC	PHB
Garage (Zone 4)	C16	C16	C16	C16	C16	C16	C16	C16

Fig. 10 and Fig. 11 show results of peak demand due to heating for the tests incorporating zone temperature setpoint profiles. Considering that customers are often billed on total energy use, profiles that reduce peak demand but significantly increase consumption may not be advisable in all situations. Of the tests conducted, Test 5 (unoccupied basement) and 12 (occupied basement) provide significant peak reduction while maintaining a good compromise in terms of energy use. Assuming the basement is rarely used, Test 5 provides the best overall results.

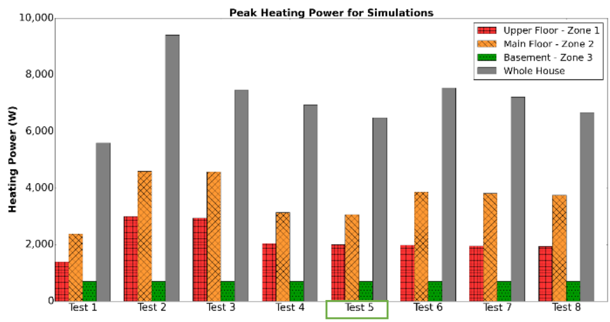

Fig. 10: Peak heating power simulation results for unoccupied basement tests

Selected strategy for unoccupied basement (Test 5). Overall, test 5 gave the best results for peak demand at 6.5 kW, compared to 9.4 kW of reference Test 2 (31% reduction). Test 5 consumes an additional 1 kWh compared to Test 2 during one day. In Test 5, the upper floor where the bedrooms are (Zone 1) has a three hour ramp starting at 3am and finishing at 6am, the main floor (Zone 2) has a three hour ramp starting at 1am and finishing at 4am, and the basement and garage are kept constant at 16°C. The type of zone-level setpoint configuration proposed in Test 5 spreads the whole building power peak over several hours instead of the common sudden peak due to a building-wide step change from 18°C to 21°C. Test 5 also provides good occupant thermal comfort by starting the ramp later in the bedrooms and does not significantly increase consumption.

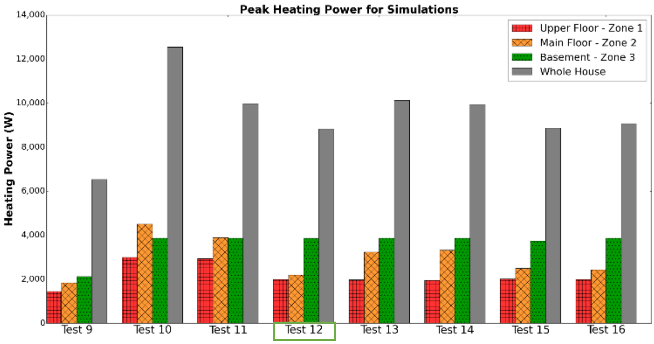

Fig. 11: Peak heating power simulation results for occupied basement tests

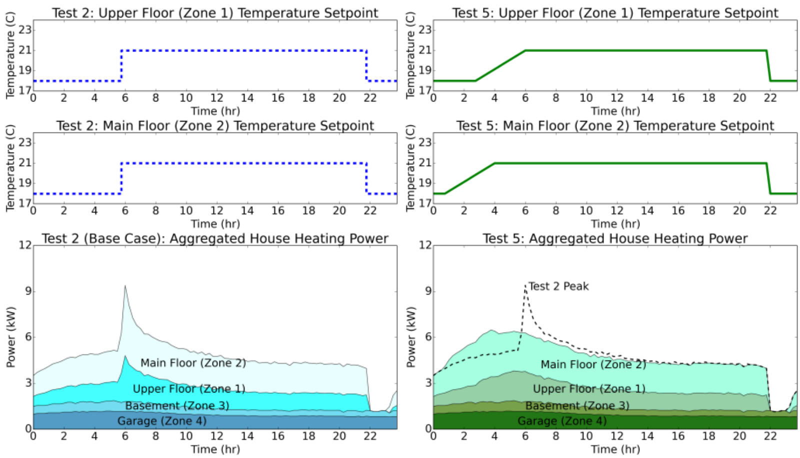

Fig. 12: Peak power results (unoccupied basement) for: (i) base case (Test 2) and (ii) advanced control strategy (Test 5)

Selected strategy for occupied basement (Test 12). Test 12 had a peak of 8.8 kW, compared to 12.5 kW for Test 10 base case with occupied basement (30% reduction). Test 12 consumes 4 kWh more than Test 10.

Test 12 is similar to Test 5, with the addition of a preheating setpoint schedule in the basement. The basement (Zone 3) has a three hour ramp from 18°C and is preheated at 23°C for three hours. It is then dropped to 19°C during the peak hours and finally raised back to the 21°C.

Fig. 12 shows results for Test 5 for Zones 1 and 2 (note that setpoint profiles remain unchanged for Zones 3 and 4). Fig. 13 shows results for Test 12 with occupied basement, versus Test 10 (Zone 4 results not shown).

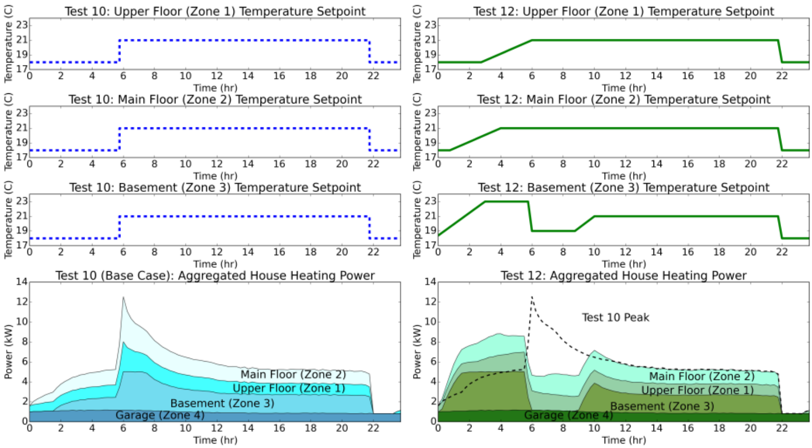

Fig. 13: Peak power results (occupied basement) for: (i) base case (Test 10) and (ii) advanced control strategy (Test 12)

It is clear from both Fig. 12 and 13 that the proposed setpoint profiles yield a significant reduction in the thermal peak loads in the morning.

8. Conclusions

It was found that a simplified model (denominated SM1 in this paper) was appropriate for multi-zone control studies. The selected model consists of four 3rd-order zonal models, which are connected through a conductive and convective term. For acceptable predictions at the zone-level, the thermal mass of the connections between zones must be considered and the conductance and convective terms should not be lumped together. The selected simplified model has a CVRSME of 14.5%. Note that the CVRSME of the benchmark detailed model is only slightly better (12.2%).

By using the selected simplified model (SM1), it was found that alternative setpoint profiles (Test 5 and Test 12) in individual zones can reduce peak power demand by 30%. By staggering a ramp profile between rooms or by incorporating preheating, peak demand can be considerably reduced.

Acknowledgment

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