THE SIGNIFICANT FACTORS IN MODELLING RESIDENTIAL BUILDINGS: PART 2

Julia Purdy and Ian Beausoleil-Morrison

CANMET Energy Technology Centre, Natural Resources Canada, Ottawa Canada
(jpurdy@nrcan.gc.ca and ibeausol@nrcan.gc.ca)

ABSTRACT

For users and developers of energy simulation software tools, knowledge of which inputs have the greatest impact on the simulation results will dictate which areas of the building require additional development and input time.

This is the second reporting of a study examining the sensitivity of simulation results to modelling assumptions and user inputs. In this case, the sensitivity of the HVAC system's energy consumption to various furnace inputs, and the impact of the internal conditions on the annual heat load are examined.

The predicted furnace energy consumption was found to be sensitive to the simulated efficiency and the part load curve. The convective/radiant ratio of heat injection, and the set-point and set-back temperatures had the greatest impact on the predicted heating load.

INTRODUCTION

The building simulationist is forced to make numerous assumptions to abstract the complexities of reality to a model of manageable resolution — this is the art of building simulation. Deciding how to sub-divide the building into thermal zones, selecting which geometric features to include and exclude, and choosing whether to model shading by external objects are common decisions faced by the simulationist. Decisions regarding modelling resolution must be made: should an integrated air flow model be employed to calculate infiltration and inter-zone air flows or will prescribed values suffice? Should the sun be tracked to determine which internal surfaces absorb solar radiation or is it adequate to use a simpler approach?

It is obvious that excluding significant elements from the model can compromise the integrity of simulation results. However, the inclusion of unnecessary detail may also contribute to uncertainty. For example, subdividing a building into thermal zones may introduce errors if the significant heat transfer paths between the zones (inter-zone air motion, internal surface convection, and longwave radiation) are poorly characterized.

Each of these assumptions and decisions affects simulation predictions. Consequently, a solid grounding in the principles of building physics and considerable experience in the application of simulation are necessary when a tool presents the user with so many degrees of freedom. Coping with so many assumptions and decisions also requires significant time for data gathering and data input. These are two of the significant barriers impeding the further adoption of simulation by building design professions. Clearly the pragmatic design of user interfaces that focus the user's attention only on those factors that are truly significant for the problem at hand would contribute to addressing these issues. This is one of the objectives of the HOT3000 project (Haltrecht et al 1999). With this, a simplified user-friendly interface targeted at house designers and energy auditors is being integrated with a detailed building simulation program (the engine). This software relies heavily upon pragmatic assumptions and in-built defaults to streamline data entry.

The development of these pragmatic assumptions and in-built defaults is the topic of this paper. Specifically, the goal is to determine which factors have the greatest impact upon simulation results. These results will be used in the HOT3000 user interface design and in the translation of the simplified user input to the detailed simulation engine.

This paper represents the second reporting of this ongoing work and as such does not provide a comprehensive examination of the factors that impact simulation results. Part 1 of this work is to be published in the *Proceedings of the Building Simulation Conference* (Purdy and Beausoleil-Morrison, 2001). The method reported here will be extended to examine other factors in the future.

Part 1

Part 1 of this work examined factors as diverse as thermal bridging through the opaque envelope and wind shielding. The following gives a brief description of the factors examined and the conclusions determined in Part 1.

The following geometric and zoning factors were examined: sub-division of the living space into multiple thermal zones, simple versus explicit representation of windows, internal thermal mass, and shading by overhangs and surrounding objects. The impact of heat transfer paths through the building envelope, including: thermal contact with the ground, thermal bridging through the opaque envelope, window optical and thermal properties, and air infiltration, were examined. In addition, the impact of the modelling of conditions external to the building, such as: the distribution of diffuse solar radiation, exterior temperature, the longwave radiation exchange between the building and the surrounding ground, and the ground reflected solar radiation, were examined.

It was determined, that the simulated heat load was particularly sensitive to the following parameters: the sub-zoning of the living space, the simulation of the ground contact, the thermal bridging through the opaque envelope, the modelling of infiltration into the house, the external temperature, and the ground reflected solar radiation.

It is important to note that these papers, Parts 1 and 2, treat the specific case of residential buildings in cold climates where the objectives of the analysis are to predict energy consumption and the energy impact of design alternatives.

The simulation environment used in this study is first described. The sensitivity analysis approach is then outlined and the parameters to be investigated discussed. Results are presented and finally conclusions are drawn.

SIMULATION ENVIRONMENT

A developmental version of the HOT3000 program was used in this analysis. Development of the HOT3000 simulation engine is based upon the comprehensive and extensively validated simulation program ESP-r (ESRU 2000). The interested reader is referred to Haltrecht et al (1999) for a discussion on the rationale for selecting ESP-r as the starting point for the HOT3000 development.

ESP-r applies a finite-difference formulation based on a control-volume heat-balance to represent all relevant energy flows within the building. The building is discretized by representing air volumes (such as rooms), solid-fluid interfaces (such as the internal and external surfaces of walls and windows) and plant components (such as boilers and ducts) with finite-difference nodes. Numerous nodes are placed through each fabric element (walls and windows) to represent these multi-layered constructions. A heat balance is written for each node in algebraic terms, approximating the governing partial differential equations and linking all inter-node heat flows over time and space. A simultaneous solution is then performed to determine the state of each node and the inter-nodal heat flows. The equation set is reformed and resolved for each subsequent time step of the simulation. A comprehensive review of this approach is given by Clarke (1985).

Numerous modelling capabilities have been added to ESP-r's extensible structure to support the HOT3000 development. These include the BASESIMP ground heat transfer algorithm (Beausoleil-Morrison and Mitalas 1997), the AIM-2 air infiltration model (Walker and Wilson 1990), and models to predict the performance of residential HVAC equipment. This simulation environment is referred to as ESP-r/HOT3000 throughout the paper.

ANALYSIS METHOD

Differential sensitivity analysis (DSA) is employed in this analysis. As explained by Lomas and Eppel (1992), the DSA method enables a direct examination of the sensitivity of simulation results to input parameter changes. A **base case** building model is first created and simulated using best estimates for the parameters under consideration. A series of simulations are then performed on models modified from the base case. A single input is varied in each simulation while the remaining inputs remain at their base case values. The change in the predicted parameter thus represents the direct measure of the impact of the change made to a single input, $\Delta E = E_i - E_{base-case}$. Where E_i is the simulation result attained with the modified input parameter and $E_{base-case}$ is the result for the base case.

DSA is usually applied to building simulation in the context of uncertainly analysis and validation (Macdonald and Strachan, 2000). However, it is equally applicable for identifying the parameters which most significantly affect simulation results.

A number of input parameters are examined in this sensitivity study. The descriptions of the input parameter variations and simulation results have been divided into two groups: issues relating to the HVAC equipment, and the impact of the building's internal conditions on the annual heating load.

It is important to note that the results are not presented in terms of sensitivity coefficients ($\Delta change/\Delta input$), an inappropriate metric for this type of analysis. Rather, the results reflect the sensitivity to each modelling decision, over a realistic range of possible options. For example, the manufacturer determines the capacity of a furnace, so there is relatively little uncertainty associated with these inputs; whereas, there is a larger uncertainty involved in the modelling of the convective regime generated by the HVAC equipment.

In this work, the simulation results of interest are the heating load placed upon the house's HVAC system, integrated over the year as well as the HVAC system's energy consumption. Although the HVAC models have not yet been fully implemented in ESP-r/HOT3000, a complete furnace model is available for this analysis. The following section describes the base case for this study.

BASE CASE MODEL

The HOT3000 software is primarily targeted at modelling Canadian housing (although its approaches are equally applicable in other climates). Consequently, one of the houses at the Canadian Centre for Housing Technology (CCHT) was selected as the base case for this study. The CCHT houses (Swinton et al 2001) are built to the R-2000 energy efficiency standard (NRCan 1994) and as such represent a typical modern energy efficient Canadian house.

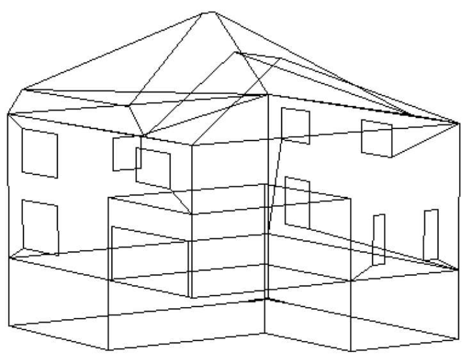

Figure 1: ESP-r/HOT3000 model of base case

The CCHT house is composed of two above-grade storeys and a fully conditioned basement. Its wood-framed construction is built upon a cast-in-place concrete foundation. With 240 m^2 of conditioned floor area (not including the basement) its size is typical of modern Canadian suburban construction. The house is well insulated: the nominal U-values of the above-grade walls and ceiling are 0.24 and 0.34 W/m^2K, respectively. The nominal U-values of the windows are 1.9 W/m^2K while RSI 2.72 covers the interior surfaces of the basement walls. As a result of careful envelope detailing, the airtightness rating of the house is 1.5*ach* at 50 Pa depressurization.

An ESP-r/HOT3000 model of the CCHT was constructed (see Figure 1). Four thermal zones were used to represent the house. The basement, the attic space, and the attached garage were each represented as thermal zones while the two storeys of living space were represented as a single zone. In the model, the living space and basement zones were conditioned by the house's HVAC system, a 19.8 kW condensing gas furnace, while the attic and garage were "free floating", varying in response to the thermal contact with the other zones and the outdoors. The contact between the basement zone and the ground was modelled with the BASESIMP model and the air infiltration was modelled with the AIM-2 model.

This ESP-r/HOT3000 simulation of the base case CCHT model predicted an annual heating load of 51.98 GJ. Since measured data were unavailable at the time, empirical validation of the ESP-r/HOT3000 model of the base case was not possible (empirical validation will be performed in the near future). The ESP-r/HOT3000 base case model, however, compared well in simulation predictions against the results of a more simplified calculation program (NRCan 2000).

HVAC SYSTEM

The following factors affecting the performance of the HVAC system were examined:

- Furnace steady-state efficiency.
- Furnace part-load curve.
- Damper control and flue opening area.
- Location of heat injection.
- Convective regime generated by HVAC equipment.

The purpose of this research is to determine which inputs are significant in simulation, to aide in the development of a user interface. As such, the factors chosen for analysis represent a reasonable data set that the user would have access to at the time of simulation. They do not, however, represent all the possible information required or available.

Furnace steady-state efficiency

The base case furnace was modelled as a condensing gas furnace with 94% steady-state efficiency. To test the significance of the furnace efficiency, the condensing gas furnace was modelled with two different efficiencies: 85% (a 9% reduction in energy efficiency), and 70% (a 24% reduction in energy efficiency).

Reducing the efficiency of the condensing gas furnace to 85% resulted in a 9.5% increase in the energy consumption of the HVAC system, see **85% efficiency** in Figure 3. This represents a one-to-one relationship between the reduction in energy efficiency and the increase in energy consumption. Further illustrating this relationship, reducing the efficiency of the condensing gas furnace to 70% resulted in a 25% increase in the energy consumption of the HVAC system. see **70% efficiency** in Figure 3.

Furnace part-load curve

The furnace will not operate at full capacity throughout the heating season, it will cycle on and off in accordance with the heating load placed upon it. Heat is injected into each zone to maintain the set-point temperature in the spaces. To account for the impact of this cycling on the furnace performance, the HVAC model in ESP-r/HOT3000, uses part load curves (Henderson, 1998 and Barringer, 1991).

The part load curve, Figure 2, is a representation of the part load efficiency based on the part load ratio for any given hour. The part load ratio (PLR) and part load factor (PLF) are defined as: *PLR = Hourly Load / Available Capacity* and *PLF = Part Load Efficiency / Steady State Efficiency*.

To examine the impact of the reduced efficiency at different part-loads, the HVAC input file for ESP-r/HOT3000 was modified to simulate a spark ignition furnace. It can be seen in Figure 2 that the spark ignition furnace has a significantly different part-load curve from the condensing furnace. It is important to note that all other parameters relating to the furnace, including but not limited to capacity and efficiency, remained at the base case values.

Figure 2 appears to show an anomaly for the condensing furnace. It indicates that the part load efficiency of the furnace can increase slightly at part load conditions. Henderson (1998) informs the reader that this effect is due to the oversized heat exchanger at the part load.

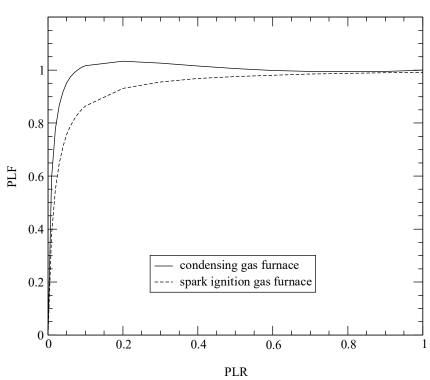

Figure 2: PLC for condensing & spark ignition furnaces.

As can be seen in Figure 3, the HVAC system's energy consumption is quite sensitive to the part-load curve selected. Changing from the condensing to the spark-ignition furnace increased the heating season energy consumption by 9.2%, see **spark ignition furnace** in Figure 3. Therefore, obtaining accurate information on the furnace type, i.e., the appropriate part-load curve, is warranted in this type analysis.

Damper control and flue opening area

For most furnaces, hot combustion air exits the house through the flue. A condensing furnace does not utilize a flue, instead using a small pipe through which the combustion air exits the house. For this reason, simulations to determine the model's sensitivity to damper control and flue diameter were performed using the spark ignition furnace.

The use of damper control has been shown to reduce the infiltration into the house, and therefore the annual heat load, see Purdy and Beausoleil-Morrison (2001). For this analysis, the impact on the furnace consumption was examined.

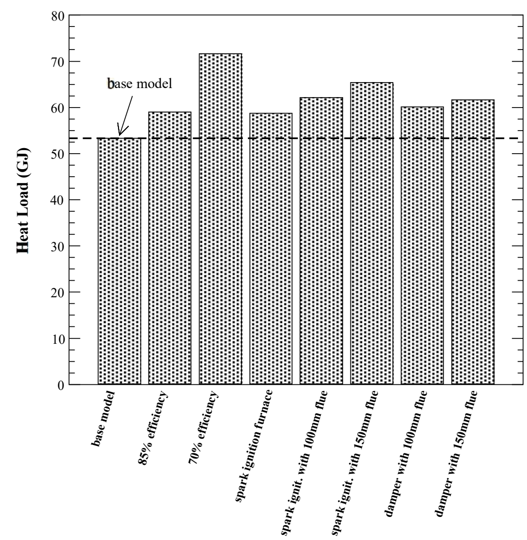

Figure 3: Sensitivity to HVAC parameters.

In the first two cases, the spark ignition furnace was modelled with a 100mm and 150mm flue, and then with damper control on the 100mm and 150mm flues. The flue diameter inputs are represented in the AIM-2 infiltration model, as they primarily impact the infiltration load on the house.

The use of damper control was shown to significantly reduce the furnace energy consumption. For the 100mm flue with damper control, see **damper with 100mm flue** in Figure 3, a 2.2% increase in furnace energy consumption throughout the heating season was calculated. This can be compared to the 5.4% increase in furnace energy consumption for the case with a 100mm flue and no damper control, see **spark ignit. with 100mm flue** in Figure 3. The difference is even more pronounced with the larger flue diameter. A 4.7% increase in furnace energy consumption as predicted for the case with damper control and a 150mm flue, see **damper with 150mm flue** in Figure 3. This is significantly lower than the 10.2% increase for the case without damper control, **spark ignit. with 150mm flue** in Figure 3.

Given this sensitivity, it can be concluded that detailed information concerning the diameter of the flue and damper control are required for this type of analysis.

Location of heat injection

Heat is injected convectively to the room air with a forced-air heating system. That is, the HVAC system acts immediately upon the room air temperature. Other HVAC systems, such as hydronic, electric baseboards, and in-floor heating, inject heat both radiatively and convectively into the room. These effects are captured in the ESP-r/HOT3000 simulation.

A number of simulations were performed to assess the significance of the location of the heat injection, specifically the ratio of radiant and convective heat injection. Simulations were performed whereby the percent of the heating load met by radiant injection sources were: 0%, 50%, and 100%. The same setpoint dry bulb temperature was used in all runs. The metric of interest in this analysis is the heat load as calculated over the heating season.

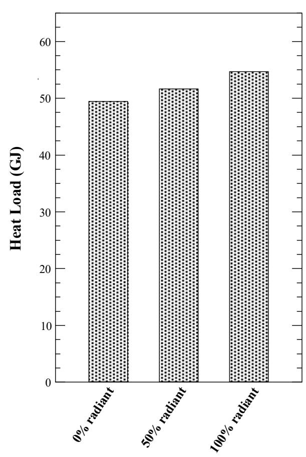

Figure 4: Radiant heat injection into main zone.

The 0% radiant case was taken as the base for this analysis, with a heating load of 49.44 MJ. It can be seen from Figure 4, that increasing the radiant portion of the heat injection to 50% increased the heat load by 4.3%, and simulating 100% radiant heat injection, resulted in a 9.6% increase in the heat load.

With radiant systems, wall and window surfaces are warmed, thus increasing the heat loss through the envelope. This accounts for the increase in heat load predicted in these cases. These results are significant and therefore, the conclusion can be drawn that an explicit representation of heat injection is warranted in this type of analysis.

Convective regime generated by HVAC equipment.

In his paper on ESP-r's adaptive convective algorithm, Beausoleil-Morrison (2001) examined the impact HVAC systems have on the convective regimes in rooms.

Six simulations were performed with the ACA—adaptive convective algorithm. In each case the internal surfaces of the living space were attributed with convection calculation control data to simulate different heating systems and device placements. The scenarios examined were:

- radiators placed under windows
- radiators placed by internal walls
- radiators placed by external walls but not underneath windows
- in-floor heating
- hydronic walls panels placed on internal walls
- forced-air heating system delivering air through registers located under windows[1].

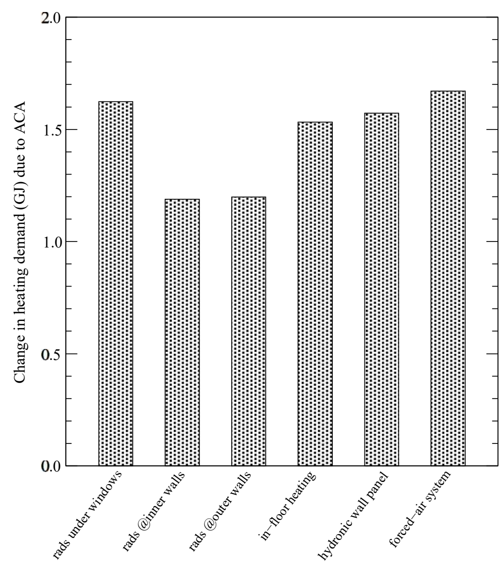

Figure 5: Impact of ACA on annual heating loads

The ACA resulted in greater annual heating load predictions in all scenarios, see Figure 5. Differences ranged from 2.4% to 3.3% of the house's total heating load caused by heat losses through the walls, windows, ceiling, basement, and due to infiltration.

As can be seen in Figure 5, the ACA can discriminate the impact that different HVAC systems have upon

[1] The ACA lacks h_c correlations for this configuration. As such, it was modelled with the closest match, a circulating fan heater.

heating loads. It is important to note that minor alterations to the convection calculation control data can affect these results. Factors such as which walls are adjacent to the radiator, and which surfaces receive the direct stream of the supply air can influence the selection of h_c correlations for each surface.

The interested reader is referred to Beausoleil-Morrison (2001) for further information on this subject.

INTERNAL CONDITIONS

The impact of the modelling of the following conditions internal to the building were examined:

- Set-point temperature.
- Set-back temperature.
- Internal gains.

Again, these specific factors were chosen as they represent a reasonable amount of information that the software user would have access to. Other factors contribute to a building's internal conditions, but they were not considered for this project.

Set-point temperature

The internal set-point temperature—the house's thermostat set-point temperature—for the base case was simulated as 21°C.

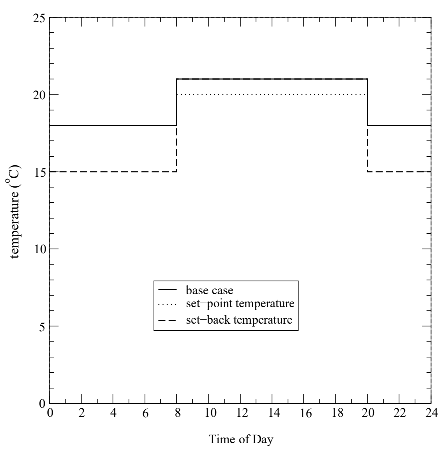

Figure 6: Set-back & set-point control strategies

As is common to energy efficient houses in Canada, nighttime thermostat set-backs were incorporated into the control system of the base case, The set-back control strategy can be seen in **base case** in Figure 6. During the night, between the hours of 8pm and 8am, the thermostat was set to 18°C and during the day—8am to 8pm— the thermostat was set to 21°C.

Reducing the set-point temperature during the day from 21°C to 20°C **set-point temperature** in Figure 6, had a significant impact on the heating load. It can be seen from **lower set-point** in Figure 7, that this 1°C difference, during the day, reduced the annual heating load by 6.3%. Given this sensitivity, accurately representing the set-point temperature of the house is warranted.

Set-back temperature

In this case, instead of reducing the set-point temperature during the day, the set-back temperature, i.e., the set-point temperature during the night, was reduced. As illustrated in **set-back temperature** in Figure 6. Between the hours of 8pm and 8am, the thermostat was set to 15°C and during the day, the internal temperature was maintained at the base case value of 21°C.

This reduction of 3°C during the night had a much smaller but significant impact on the annual heat load than did the 1°C reduction during the day. Reducing the set-back temperature to 15°C lead to a 4.9% decrease in heating load, **lower set-back** in Figure 7.

Information concerning the temperature controls on the furnace has been shown to be of considerable significance to the heating season energy consumption.

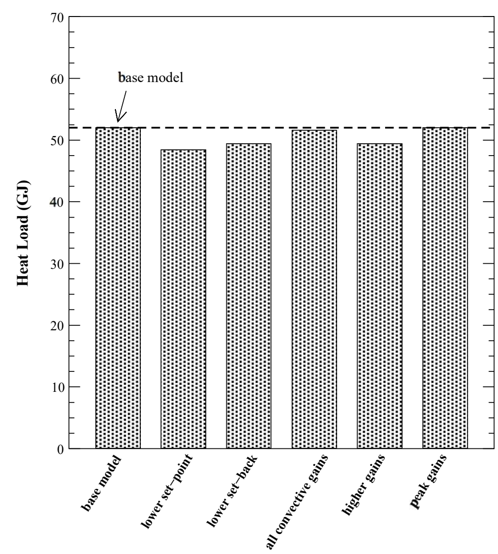

Figure 7: Sensitivity to internal conditions

Internal gains

Internal gains are simply indoor heat generating sources. ESP-r/HOT3000 accounts for the gains from a combination of occupants, lighting, and equipment sources. The user has control over the convection/radiant ratio of these gains as well as the option to define internal gains profiles over a the say. For the base case, a constant 610 W of internal gains were simulated each hour, 50% from convective sources and 50% from radiant sources.

To examine the impact of this convective/radiant ratio, a simulation was performed whereby all of the internal casual gains resulted from convective sources. It can be seen from **all convective gains** in Figure 7 that this lead to a very modest 0.8% decrease in the annual heat load.

Doubling the internal gains lead to a 9% decrease in the annual heat load by, as seen in **higher gains** in Figure 7. Although this represents a significant decrease in the heating load, it results from a very significant increase in internal gains—50%. It can be concluded that accuracy in obtaining the internal gains information is warranted.

In the previous simulations, the internal gains were maintained at a constant value of 610 *W* over the day. To examine the significance of the distribution of the gains over the day, a second simulation was performed, having the same energy addition integrated over the day, but with a lower base load and morning and evening peaks, see Figure 8.

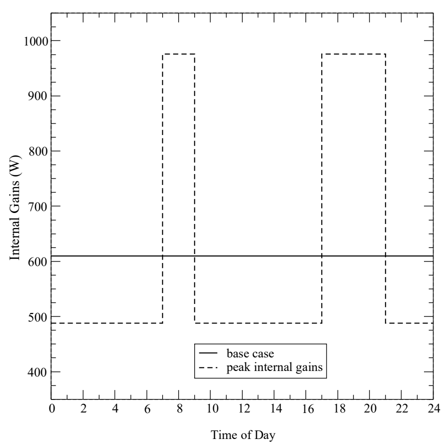

Figure 8: Constant and peak internal gain profiles

The heating load increased by a modest 0.1% (see **peak gains** in Figure 7). For the specific case of an annual heat load calculation, with basic control strategies, creating hourly profiles for the internal gains was not show to have a significant impact on the annual energy prediction.

This investigation did not, however, consider the impact of internal gains profiles on time of use or peak demands. To examine these factors would require a different modelling approach.

CONCLUSIONS

The appropriate degree of modelling resolution depends, of course, upon the objectives of the simulation, the building, and the climate. Predicting a house's annual energy consumption or examining the energy impact of design alternatives demands a very different modelling approach than, for example, estimating the illumination distribution within a daylight office, or predicting the peak electrical demand in a cooling dominated building.

The goal of this research was to determine which factors have the greatest impact on simulated heat loads. Those factors investigated in this second reporting are: the sensitivity of the HVAC system energy consumption, and the sensitivity of the heating load to the internal conditions.

It is important to note that these conclusions are valid for predicting annual residential heating loads in cold climates. Extrapolating these results to other building types and climates and other types of analyses would be inappropriate.

The predicted furnace energy consumption was found to be sensitive to the simulated efficiency and the part load curve. The convective/radiant ratio of heat injection, and the set-point and set-back temperatures had the greatest impact on the predicted heating load.

The next phase of research will involve an empirical comparison of the simulated data to monitored data from the CCHT.

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