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THE SIGNIFICANT FACTORS IN MODELLING RESIDENTIAL BUILDINGS

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ABSTRACT

For users and developers of energy simulation software tools, knowledge of which inputs have a significant impact on the simulation results is very important, as this will dictate which areas of the building justify additional development and input time.

In the form of a sensitivity study, those factors generally considered to have the largest impact on simulated heating load, were compared against a base case model—a typical Canadian house in Ottawa.

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.

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 subdivide 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 first reporting of this ongoing work and as such does not provide a comprehensive examination of the factors that impact simulation results. The method reported here will be extended to examine other factors in the future.

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

The simulation environment utilized 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 modelling 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.

In this work, the simulation result of interest is the heating load placed upon the house's HVAC system, integrated over the year. The heating load is used as the metric rather than the HVAC system's energy consumption because the HVAC models have not yet been fully implemented in ESP-r/HOT3000. DSA is usually applied to building simulation in the context of uncertainly analysis and validation (e.g. 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. Factors as diverse as thermal bridging through the opaque envelope and wind shielding are treated. The descriptions of the input parameter variations and simulation results have been divided into three groups along logical groupings. Geometric and zoning issues are explored in the first group. The second group examines the impact of heat transfer paths through the building envelope, while the third group considers the impact of conditions external to the building. 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.

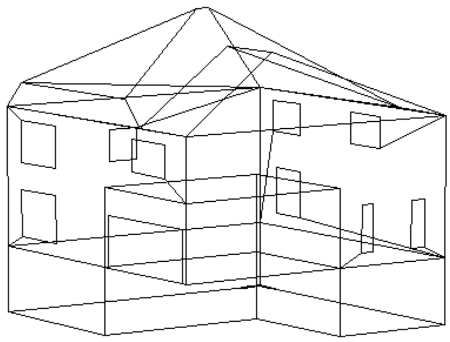

Figure 1: ESP-r/HOT3000 model of base case

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 (excluding 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 1.5ach 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 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).

GEOMETRY AND ZONING

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.
- Shading by overhangs and surrounding objects.

Sub-zoning the living space

Explicitly representing internal partition walls and sub-dividing the house's living space into multiple thermal zones would demand significant user input. Therefore, it would be desirable to represent the entire living space of the house as a single thermal zone. To test the significance of this modelling abstraction, the living space was divided into three thermal zones: the main floor, the second floor, and the stairwell connecting the basement and the above-grade floors. Heat was injected into each zone to maintain the same set-point temperature in the spaces. Internal air flow was ignored in this simulation, and as such, energy could only be transferred between the three zones through the partition walls.

This multi-zone configuration resulted in a 7.5% increase in the heating load (refer to Figure 2). This difference is clearly significant; however, it is unclear whether the one-zone or three-zone representation of the living space is more accurate. One of the dominant modes of energy transfer between rooms is convection caused by bulk air movement. The bulk air movement is generally caused by air flow through door openings and caused by air-based HVAC systems (e.g. forced air furnace). To test the significance of internal air movement, a simple ventilation network was imposed on the model: 50 L/s of air to circulate between the main floor, stairwell, and second floor. With this configuration, the multi-zone model's heating load is 6.5% greater than that of the base case (refer to Figure 2).

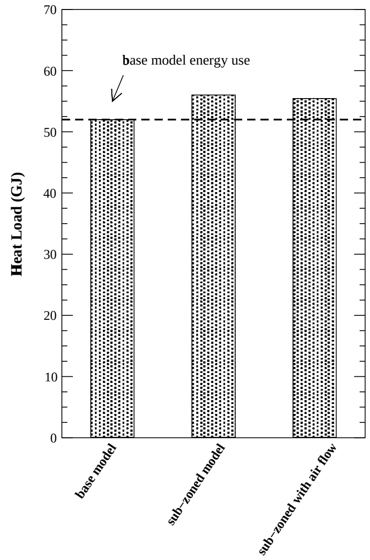

Figure 2: Sensitivity to zoning approach

Given the differences between the multi-zone and single-zone representations of the living space, the issue of sub-zoning warrants further attention. Key to this will be accurately characterizing the significant heat transfer paths between zones without demanding substantial data description.

Simple versus explicit representation of windows

As can be seen in Figure 1, the geometry of the nine windows located in the house's living space is explicitly represented. The size and location of the windows corresponds the house's construction. Capturing this information from the user would demand significant data input.

To examine whether this level of information is justified, the model was reconfigured with an abstract representation of the windows. A single window was placed on each wall. The area of each window was equal to the sum of the areas of the windows located on that wall. The windows were placed near the geometric centre of the walls. Therefore, the total window area was not altered nor was the area exposed to each cardinal direction.

As can be seen in Figure 3, the house's heating load is relatively insensitive to the representation of the window geometry. Grouping the windows on each face of the building into a single window in the model only increased the annual heating load by 0.2%. Therefore, the data input requirements demanded by an explicit representation of window geometry are not warranted in this type of analysis.

Internal thermal mass

Internal partition walls and furnishings can represent significant thermal mass and as such can alter a house's energy balance. Two simulations were performed to determine the model's sensitivity to thermal mass to determine whether it is worthwhile to capture detailed information from the user on the house's internal thermal mass.

In one case, the density of the gypsum board located at the inner face of the external walls was quadrupled. This represents a significant increase in the thermal mass located between the zone air and the insulation in the walls. In the second case, a 100mm thick slab of concrete was added to the top of the living space floor. Neither change had a significant impact on the predicted heating load. The higher density gypsum reduced the heating load by 0.5% whereas the addition of the concrete layer increased the heating load by 1.1% (refer to Figure 3).

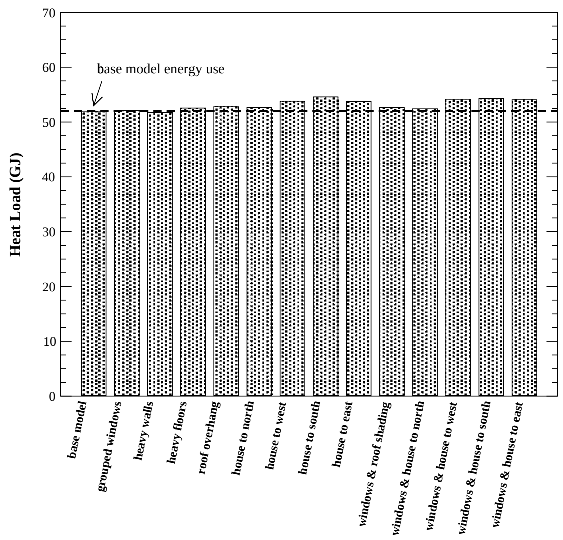

Figure 3: Sensitivity to geometric factors

Given this insensitivity, it can be concluded that an approximation of house's internal thermal mass is sufficient for this type of analysis.

Shading by overhangs and surrounding objects

Obstructions to solar radiation occur naturally around almost every house, whether from the roof, a nearby tree, or a neighbour's house. This can have a significant impact upon the house's energy balance. Many simulation programs account for the shading from roof or window overhangs, but few account for the shading from surrounding objects.

A number of simulations were performed to assess the significance of this shading. Shading by overhangs and external objects was ignored in the base case. In each case considered here, a obstruction was added. A simulation was then performed whereby the geometric relation between the windows, the object, and the sun were explicitly calculated (as a function of time) to determine the reduction in solar radiation striking the windows.

To further examine whether a simple geometric representation of windows is acceptable, two sets of simulations were performed with the added obstructions: in one case the nine windows were explicitly represented; in the other case the windows were grouped together as before.

The first obstruction examined was the roof overhang. A 0.6m wide obstruction was added around the house to represent the roof overhang (a typical dimension recommended by Carmody et al 1996). The overhang increased the heat load by 1.5% when the windows were explicitly represented (see *roof overhang* in Figure 3). With the simple window representation, the overhang increased the heat load by 1.3% (see *windows & roof shading* in Figure 3).

Objects representing neighbouring houses (located 3m from the house under consideration) were then added to the model. Four scenarios were examined, with the neighbouring house located either north, south, east, or west of the house under consideration. As can be seen in Figure 3, the shading caused by neighbouring houses significantly affects the heating load (differences of up to 5% were found). As well, the results are significantly sensitive to the location of the neighbouring house (compare *house to north*, *house to west*, *house to south*, and *house to east* in Figure 3).

When shading by neighbouring houses was considered, grouping (as opposed to explicitly representing) windows was found to have a minor impact on the heating load (for example, compare *house to south* to *windows & house to east* in Figure 3). Therefore, the conclusion drawn earlier that an explicit representation of window geometry is not warranted in this type of analysis is still valid.

These results demonstrate that the solar shading caused surrounding buildings (and by extension other large objects such as trees) has a significant impact of the heating load, and this impact is more significant than the shading caused by a typical roof overhang.

BUILDING ENVELOPE

The following factors were examined:

- Thermal contact with the ground.
- Thermal bridging through the opaque envelope.
- Window optical and thermal properties.
- Air infiltration.

Ground contact

As described earlier, heat transfer from the basement and the ground was calculated with the BASESIMP model in the base case. BASESIMP is a regressionbased frequency domain response factor method that accurately treats the heat transfer between the basement and the deep ground and the ground surface. With this, the user defines the placement and thermal resistance of the insulation, and the time-varying ground temperatures.

To examine the sensitivity of modelling this heat transfer path, a simulation was performed in which the BASESIMP model was replaced with a simpler treatment of the ground. The ground was represented by two parallel heat transfer paths. For one heat transfer path, the below-grade basement walls were connected to the outdoor air temperature through an added insulation layer. The resistance of this added insulation was calculated as a function of the path length of the heat transfer through the soil layer using a technique recommended by ASHRAE (1997). For the second heat transfer path, layers of soil were added to the bottom of the basement and garage floors. These ground layers continued to a depth of 12m below grade, where monthly ground temperatures are considered constant. It should be noted that simplified approaches such as this are common in simulation programs.

As seen in Figure 4, the method used to model the heat transfer to the ground was found to have a significant impact on the heating load. The heating load increased by 10% when the simplified approach was used. Of all the building envelope factors examined, the simulation method for the ground contact was shown to have the largest impact on the heat load. It is therefore worthy of the time and investment to implement a comprehensive ground heat loss model.

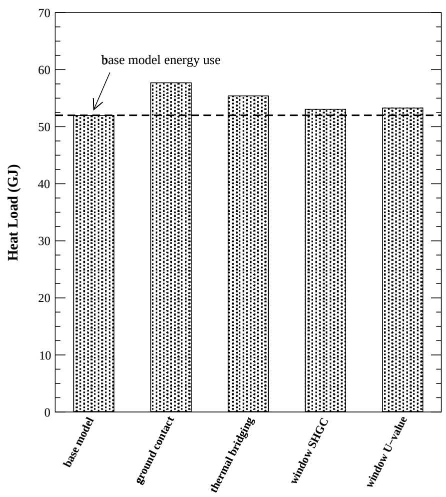

Figure 4: Sensitivity to envelope factors

Thermal Bridging through Opaque Envelope

According to the ASHRAE Handbook of Fundamentals (1997), one of the detrimental effects of thermal bridging is increased energy use. Many building simulation software programs do not account for the thermal bridging through the opaque envelope, probably because the characterization of thermal bridging demands significant data input.

Thermal bridging was ignored in the base case. To test the significance of this simplification, a simulation was performed in which the thermal properties of the opaque envelope assemblies were modified to account for thermal bridging through the wood framing. The conductivity of the insulation layer was increased using a technique recommended by NRC (1997) whereby the density and specific heat were adjusted so that the mass and specific heat of the assembly was equal to that of the sum of the materials (including the wood framing).

The heating load increased by 6.5% with this reconfigured model. Therefore, accounting for thermal bridging was found to have a significant impact. As a result, the data input demands required to accurately characterize thermal bridging through the opaque envelope are justified as is the inclusion of a technique to accurately account for this effect.

Window Optical and Thermal Properties

There is considerable uncertainly in characterizing a window's thermal and optical properties. For example, the frame and spacer can significantly influence the overall thermal resistance of the window assembly. Glazing coatings, internal shading from blinds, and even the state of cleanliness can alter optical properties.

Two simulations were performed to test the sensitivity to window thermal and optical properties. In one simulation, the solar transmission was reduced by 10% at all angles of incidence. This is equivalent to reducing the solar heat gain coefficient (SHGC) by 10%, a significant reduction. This resulted in a 2% increase in heat load.

In the second simulation, the resistance of the window's air gap was reduced such that the nominal U-value of the window was increased by 10%. Again, this represents a significant alteration of the window's properties. This resulted in a 2.4% increase in heat load.

Altering the window's thermal and optical properties had a moderate impact on the simulation results, significant, but substantially less than the impact of the other building envelope factors considered here.

Infiltration

As described earlier, air infiltration through the envelope was calculated with the AIM-2 model in the base case. This model calculates the natural air infiltration caused by the combined influence of stack and wind effects. With the implementation in ESP-r/HOT3000, the user characterizes the leakage paths through the envelope with a flow exponent which is derived from a house depressurization test, and leakage distribution factors. The leakage path through the furnace flue (and the flues for other HVAC equipment) is similarly described. As the simulation progresses, the model calculates the indoor-outdoor pressure differences generated by stack and wind effects, and subsequently calculates the air infiltration through the envelope.

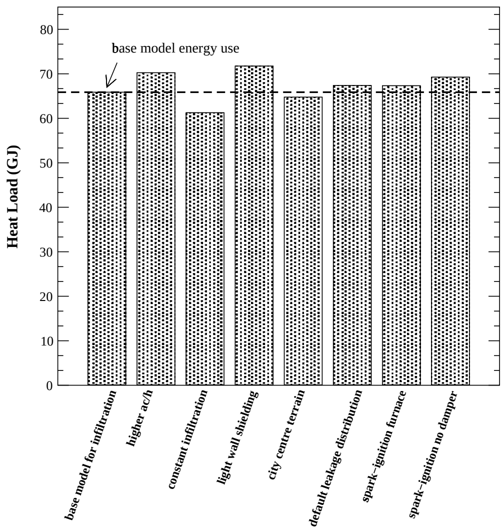

Figure 5: Sensitivity to infiltration factors

Numerous data are required from the user to characterize the leakage distribution and terrain surrounding the building. A number of these data are subject to uncertainty. A series of seven simulations were performed to assess the sensitivity to a number of these factors. Due to the CCHT's very airtight construction, there was little infiltration in the base case model. Therefore, to assess the sensitivity to infiltration modelling in more typical housing, the base case was reconfigured. Its airtightness rating was increased from 1.5 to 3.0 air changes per hour (ac/h) at 50 Pa depressurization. This increased the heating load by 27%.

As stated above, the airtightness rating is used to determine a leakage coefficient for the envelope. This rating can be accurately determined through a house depressurization test using a blower door device. In the absence of such test results, the user would typically choose a representative value based upon the general construction techniques. This latter technique is obviously subject to uncertainty. To assess the sensitivity of simulation results to a modest change in a house's airtightness, a simulation was performed in which the airtightness rating was increased from 3.0 to 3.5 ac/h at 50 Pa depressurization. This change represents a low estimate of the uncertainty when a blower door test is not performed. Significantly, this increased the heating load by 6.6% (refer to *higher ac/h* in Figure 5) indicating the significance of the airtightness rating on simulation results.

Many simulation programs lack a model for predicting the time-varying stack and wind effects which drive infiltration, instead having the user prescribe infiltration as a constant rate. The model was reconfigured to assess the sensitivity to accounting for the time-varying infiltration rate. The AIM-2 model was replaced with a time-invariant infiltration rate, set to the mean value predicted by the AIM-2 model over the heating season (0.167 ac/h). As such, the total infiltration rate integrated over the heating season was the same in both cases. The heating load decreased by 7% (see *constant infiltration* in Figure 5), indicating the significance of calculating the time-invariant qualities of infiltration.

The implementation of the AIM-2 model in ESP-r/HOT3000 uses a procedure to relate the wind speeds recorded in the weather file to the wind force acting on the building envelope (Walker and Wilson 1990; Wieringa 1986). This requires that the user describe (in qualitative terms) the wind sheltering provided by other buildings and surrounding objects (e.g. trees) and to characterize the local terrain. Clearly, this is an area of uncertainty.

Two simulations were performed to assess the significance of these user inputs. In one case the wind shielding on the walls was reduce from "very heavy" to "light". This change increased the wind effect driving infiltration through the envelope and resulted in a significant 8.9% increase in the heating load (see *light wall shielding* in Figure 5). In the second case the terrain description was changed from "suburban" to "city centre". This had a more modest impact on the heating load, decreasing it by 1.7% (see *city centre terrain* in Figure 5)

In addition to specifying the overall envelope leakage coefficient, the user must characterize the locations of the leakage in the envelope. This is done through specifying ceiling, floor, and wall leakage fractions. Again, there is significant uncertainty in specifying this input. To test the sensitivity to this leakage distribution, the leakage fractions were altered from 0.2 (ceiling) / 0.65 (wall) / 0.15 (floor) to 0.3 / 0.5 / 0.2. This resulted in a 2.3% increase in the heating load (see *leakage distribution* in Figure 5). This impact is significant, but not as great as some of the other infiltration factors examined.

As described above, the implementation of the AIM-2 model in ESP-r/HOT3000 considers the air leakage path through the furnace flue. The base case has a condensing gas furnace with a sealed combustion unit. As such, the furnace is aerodynamically isolated from the house and therefore does not affect the air infiltration. To examine the significance of the flue as an air leakage path, the model was reconfigured to include a furnace with a damper that draws dilution air from the basement. This added air leakage resulted in a 5.1% increase in the heat load (see *spark-ignition no damper* in Figure 5).

A controlled damper was then added to the furnace flue. This damper constricts (but does not eliminate) the air leakage through the flue when the furnace is not operating. ESP-r/HOT3000 captures this effect by simulating, on a time-step basis, the fraction of time that the furnace is operating. With this damper, the heat load was 2.2% greater than the infiltration base case (see *spark-ignition furnace* in Figure 5).

It should be noted that these simulations do not consider the impact of the furnace drawing combustion air from the basement. This aspect of the furnace's operation also impacts the air infiltration by unbalancing the house's ventilation rate. This was not considered here since this capability has not yet been fully implemented in ESP-r/HOT3000. Notwithstanding, these results demonstrate the significant impact that furnace flues and furnace operation have upon simulation results.

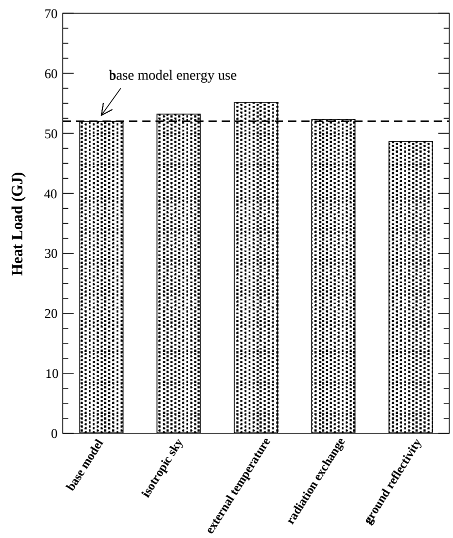

Figure 6: Sensitivity to external conditions

EXTERNAL CONDITIONS

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

- The distribution of diffuse solar radiation.
- Exterior temperature.
- The longwave radiation exchange between the building and the surrounding ground.
- The ground reflected solar radiation.

Distribution of diffuse solar radiation

A non-isotropic model (Perez et al 1987) was employed in the base case to estimate the diffuse radiation incident upon the non-horizontal surfaces (e.g. windows). Many simulation programs use a simpler treatment, assuming the distribution of diffuse radiation to be isotropic. To examine the significance of this factor, a simulation was performed with an isotropic sky model. This resulted in a moderate 2.3% increase in the heating load.

External temperature

Another external condition which can have a significant impact on the heating load is the external temperature, as this drives the convective heat transfer from the external surfaces and impacts upon infiltration. The base case was modelled with an Ottawa CWEC (Canadian Weather for Energy Calculations) weather file. CWEC files are derived from long-term weather records and are conceived to represent typical conditions. There is considerable uncertainty in weather data due to annual variations and due to the lack of data outside major centres.

To test the significance of the uncertainty in weather data, the Ottawa CWEC file was manipulated to reduce the dry bulb temperature by 1°C for each hour of the year. This resulted in a 6% increase in the heating load.

Radiation exchange with the ground

ESP-r/HOT3000 employs the Boltzmann equation, $q''_{rad} = \varepsilon\sigma(T^4_{surface} - T^4_{environment})$ where ε is the surface emissivity and σ is the Stefan-Boltzmann constant, to calculate the net longwave radiation exchange between exterior envelope surfaces and the environment. $T_{environment}$ is an "equivalent" temperature characterizing the radiative exchange and is equal to a weighted average (based on view factors sensitive to the local terrain, e.g. urban) of the sky, ground, and surrounding object temperatures.

The ground surface temperature is calculated based on a model that operates on monthly averaged ground temperatures at a depth of 1.2 m. The base case employed ESP-r/HOT3000's default temperature profile at 1.2 m. To test the significance of this, a simulation was performed using ground temperatures more representative of Ottawa. This increased the heating load by 0.5%.

Ground reflected solar radiation

The ground-reflected component of the solar radiation incident upon windows can significantly augment solar gains to the house. The base case simulation assumed that the ground reflectivity was constant at 0.2. The presence of snow can significantly augment the ground reflectivity (Siegel and Howell 1981, for example, suggest 0.82 for snow's reflectivity), and thus the solar gains to the house. As well, the condition of the snow and the length of time elapsed since the last snow fall can influence its reflectivity.

A simulation was performed with the ground reflectivity set to a constant 0.5 (ESP-r/HOT3000 cannot currently model time-varying ground reflectivity). This reduced the heating load by 6.5%. Given this sensitivity, a model that more accurately determines the ground reflectivity as a function of snow cover is warranted.

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 initial reporting were: geometric and zoning issues, the impact of heat transfer paths through the building envelope, and the impact of external conditions.

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

The significant heat load differences calculated for the multi-zone and single-zone representations of the living space, indicate that the issue of sub-zoning is of particular importance. Accurately characterizing the heat transfer paths between zones without demanding substantial data description from the user is an area requiring significant attention.

In addition to the thermal zoning of the house, factors having particular significance on the predicted heat load calculated were: the simulation of the ground contact, the thermal bridging through the opaque envelope, the modelling of infiltration into the house, the ambient external temperature, and the ground reflected solar radiation.

The next phase of research will investigate the impact of modelling of HVAC systems and internal conditions. Issues to be examined are: the steady-state efficiency and the part-load curve of furnace, the damper control and flue opening area, the location of heat injection, and the convective regime generated by HVAC equipment. In addition, the impact of set-back and set-point temperatures and internal gains will be investigated.

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