PRACTICAL ENERGY ANALYSIS METHODS FOR MULTI-UNIT RESIDENTIAL BUILDINGS

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ABSTRACT

The multi-residential housing stock includes about 1.6 million dwelling units in low-rise buildings in Canada. This building class consists of duplexes, triplexes, and low-rise apartment buildings of less than 12 units. To provide reliable and quick energy analysis of large numbers of low-rise multi-residential buildings, simplified methods have been developed and added to HOT2000.

The HOT2000 energy analysis of multi-unit residential buildings is carried-out on a unit-by-unit basis and integrated to determine the energy use characteristics of the whole building. In addition, the energy analysis estimates the energy use for the domestic hot water and the base loads.

This paper briefly presents the field requirements for a quick and reliable energy analysis tool, details of practical and reliable approaches for energy analysis and energy rating calculations.

MULTI-UNIT HOUSING STOCK

During the past thirty years, the multi-unit residential building stock in Canada has been increasing at a faster rate than other forms of housing. The compact design and high densities offered by multi-residential housing allow for better utilization of transportation and utility infrastructure in urban settings. Table 1 shows the regional breakdown of the low-rise building stock. More than a total of 1.6 million dwellings are in low-rise apartment buildings of up to 3½ storeys above grade [CMHC, 2004].

A low-rise residential building is defined as a structurally separate set of living spaces having a private entrance either outside the building or from a common hall, lobby, vestibule or stairway inside the building. The entrance to the dwelling unit must be one that can be used without passing through anyone else's living quarters.

A living space is defined as a residential building or that part of a residential building which is intended to be used as a home, residence or sleeping place by one or more persons maintaining a common household (i.e, kitchen, bathroom and bedroom). Low-rise multi-unit residential building types are defined as follows:

- Duplex: a two- or three-storey structure that has two dwelling units super imposed one on top of the other; each unit has its own private entry (typical layout is shown in Figure 1).
- Triplex: a two- or three-storey structure that has three dwelling units superimposed on two or three floors; each unit has its own private entry point (typical layout is shown in Figure 2).
- Apartment or flat: all multifamily structures other than duplexes, triplexes, row-housing units, single or semi-detached houses. The low-rise buildings are up to three-and-a-half (3½) storeys and have between four (4) and twelve (12) units.

Table 1. Low-Rise Housing Stock.

Region	*Duplexes/ Triplexes*		*Apartment buildings with less than 6 units*	
Atlantic	21,567	5%	9,542	6%
Quebec	114,112	26%	97,779	63%
Ontario	228,947	52%	31,608	20%
Prairie	55,173	12%	10,417	7%
BC	24,035	5%	6,635	4%
Canada	443,834		155,981	

Over the years, there have been several field energy evaluations performed in different regions to characterize the energy use patterns in low-rise multi-unit residential buildings [CMHC 1994, Scanada 1991]. These surveys established that the energy consumption per unit floor area of these buildings was very similar to that of low-rise detached housing. These results were surprising, since the superior volume to building envelope ratio of multi-unit buildings would suggest that their energy consumption should be less than that of a house. The middle units, being less exposed to the exterior environment, also showed a relatively high percentage of space heating energy use. The energy evaluation surveys identified the following reasons for this anomaly:

- Low-levels of insulation in above-grade walls and roofs;
- High amounts of operable window glazing relative to the floor area and high heat losses through windows;
- Lack of proper air barriers and poor detailing of party walls (separations) resulting in high levels of uncontrolled air leakage;
- Extended floor slabs (without thermal breaks);
- Low levels of insulation in below grade walls, headers and sill plates and foundation floors;
- Inefficient heat and ventilation distribution;
- The use of low-efficiency heat generation systems; and
- Occupancy effects (i.e. whether the property is rented or owned and who pays the utility bill).

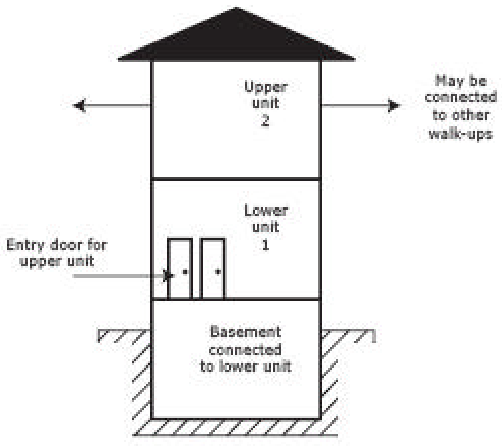

Figure 1. Typical duplex building.

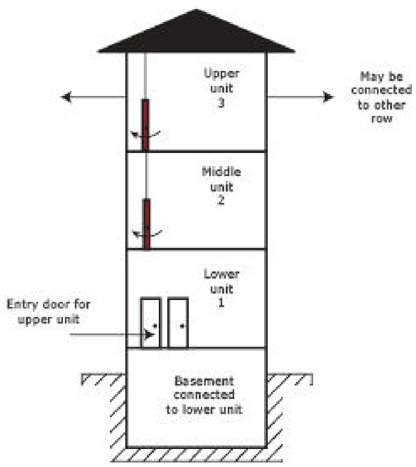

Figure 2. Typical triplex building.

These detailed surveys also identified that the indoor air quality in most of the evaluated units was lower than acceptable and, in many cases, uncomfortable to occupants.

ENERGY ANALYSIS CHALLENGES

Low-rise multi-unit residential buildings are somewhat unique as far as their energy-use profile is concerned. These buildings show different energy use patterns than single-family housing as well as small commercial buildings. The unique thermal and architectural characteristics are as follows:

- multiple, separate dwelling units under one building shell;
- each dwelling may have separate space heating, ventilation and hot water systems;
- dwellings may use different fuel sources for space and water heating;
- common areas shared by different dwellings;
- common outside entrance(s) to the building leading to different units;
- complex internal air flows;
- full or partial foundation and basement; and
- each dwelling can be maintained differently.

It is clear from the above list that the energy performance of low-rise multi-unit residences needs to be evaluated using software capable of multi-zone analysis. There are a number of complex multi-zone energy analysis tools available for commercial buildings that were considered for use with multi-unit residences. Many of these programs are based on the DOE-2 core (i.e., 2.1E or 2.2), such as EE4 and eQUEST, while others use more comprehensive engines such as ESP-r and EnergyPlus. Although commercial building multi-zone energy simulation programs are comprehensive, they are complex and have inherent limitations in their application to residential buildings. For example, the basement heat loss models do not take into account diurnal effects and the space heating and hot water system selections are more complex than those found in housing. Also, these programs require extensive training for the field energy evaluators.

To perform an energy evaluation of multi-unit residential buildings, one needs a simple but reliable energy analysis software tool. One of the key requirements for simplified inputs is default data for thermal and equipment characteristics based on vintage, type and region in which the house is located. The region and age-specific default data provides the field evaluator with sufficient guidelines and 'picturing' of the thermal behaviour expected for a specific building.

With these unique needs for energy analysis, the simplified three-zone energy analysis program, HOT2000, was modified to treat each dwelling unit as a separate entity in the building. This paper briefly presents details of the approach used for energy analysis and energy rating calculations.

ENERGY ANALYSIS PROCEDURES

HOT2000 Energy Analysis Program

In Canada, the HOT2000 Energy Analysis program is widely used for estimating the annual energy use of low-rise housing [HOT2000]. HOT2000 is used primarily for the energy compliance of R2000 homes and EnerGuide for Houses (EGH) energy ratings of new and existing houses. It has an extensive user base in Canada. The salient features are as follows:

- It is designed for single-family homes. It treats the house in three zones – the attic (if one exists), the above grade living areas (up to 3½ floors), and the basement, which can be sub-zoned into a heated crawlspace with other basement sections. These three zones share a common space heating system (with supplemental heating options) but can be maintained at different set-point temperatures.
- Users can develop detailed thermal specifications using the building envelope system builder for walls, windows, exterior doors, roof, headers, exposed floors and foundation components. Based on user specifications, the envelope builder can determine the effective heat loss coefficients for assemblies including the composite effects (such as thermal-bridging). The current module is capable of handling thermal bridging details of exposed slabs, balconies and shear walls which are specific to low-rise multi-unit buildings,
- The air infiltration model is based on the detailed AIM2 model (Walker et al, 1990). The air infiltration model considers the combined effects of the indoor and outdoor temperature difference, wind profile and the internal mechanical system flues.
- The mechanical systems module contains the particulars of common space heating equipment and air distribution systems available in Canadian housing. It also provides options for selecting primary and secondary space and water heating systems. The ventilation system module contains a number of commonly available ventilation strategies.
- Energy estimates are calculated using a monthly bin-like model [Erbs, Klein & Beckman, 1983] with 30-year average weather data. HOT2000 contains more than 200 weather sites in Canada and the U.S.

The above features are sufficient for determining the annual energy utilization for housing. The HOT2000 software has been validated against other software and is known to have consistently reliable results [NRCan, 1992, 1993].

A number of changes were introduced to HOT2000 to expand its capabilities to model multi-unit buildings.

Calculation Method for Multi-Unit Buildings

HOT2000 was modified to deal with each unit in a multi-unit residence as a separate "house entity". This was required to work-around the fixed zoning nature of HOT2000. Multiple runs are managed behind the scenes so that a multi-unit building with N units produces N+3 sets of results that are integrated to produce a combined result set for the whole building. In addition to individual runs for each unit, HOT2000 does separate runs for all units that are served by a central heating system, all units served by a central DHW system and all units served by a central ventilation system.

Optional automatic system sizing is done for each unit with an individual heating system and once again for all units served by a central heating system. The user provides hot water and ventilation system sizes.

In order to rate these buildings a standard set of conditions is applied that includes set-point temperature. Since each unit is assumed to be at the same standard temperature there are no inter-unit heat transfer calculations.

The space heating requirements can be met by a variety of fuel sources in each dwelling unit. The space heating equipment/system for the dwelling is simulated to meet the heating requirements on a month-by-month basis.

The purchased energy for the building is determined by summing the energy needs for all dwellings.

Data Input Process

In a typical multi-unit residential building, there are a number of suites, apartments or units. Each unit is connected to one or more adjacent units. In most cases, each unit has a portion of the envelope area subjected to the outdoor environment and the remaining portion is connected to other units or to a common area.

Each unit is described separately with its exterior envelope characteristics (walls, windows, roof, and doors), internal gains (household appliances, occupancy and other base loads) and solar gains (through windows and skylights). Air leakage characteristics are assumed to be the same for all units – a whole building value. Air leakage is allocated based on the exterior exposed area of each individual unit.

The full field evaluation procedure is described in the document titled, "*EnerGuide for Houses – Evaluation Procedures and Field Testing Protocols for Low-Rise Multi-Unit Residential Buildings.*" [NRCan, 2005.]

The HOT2000 energy analysis determines the energy balance for the whole building as well as energy balances on each individual unit (and common areas). In addition, the energy analysis estimates the energy use for the domestic hot water, ventilation and the base loads.

Figure 3 shows the data input screen for each dwelling unit for a triplex building. Up to 12 units can be described on an individual basis. For each unit, a specific space heating, water heating and ventilation system can be assigned.

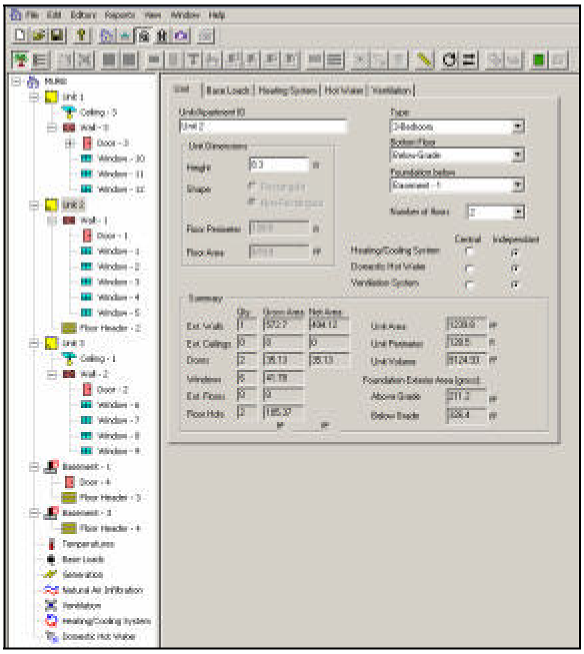

Figure 3. Data input description for each unit.

EGH IMPLEMENTATION

Since mid-1998, Natural Resources Canada has been promoting the EnerGuide for Houses (EGH) program to evaluate and rate energy efficiency of low-rise residential buildings. The main goal is to provide retrofit advice to homeowners based on the field assessment and careful estimate of energy use using the energy analysis software (NRCan 1998). Since the inception of the EGH program, more than 250,000 houses have been evaluated nationwide. With the introduction of the retrofit incentives in August 2003, on average, 7,000 houses are being evaluated every month.

The EGH evaluator investigates the energy-related features of a house; estimates the house's annual energy requirements using energy analysis software; provides a comparative energy efficiency rating; and provides a comprehensive report including recommended retrofits. Once a homeowner implements retrofits, a second EGH evaluation is performed to update the energy efficiency rating.

The EGH Program is now extended to include the low-rise multi-unit residential buildings. Using the HOT2000 energy evaluation software, the energy advisor estimates the energy use profile for the house and recommends appropriate measures. The HOT2000 software can also estimate the impact of potential retrofit measures.

EGH Rating Procedure

The energy efficiency rating is a numeric value between 0 and 100. A house that uses no purchased energy (off-grid) would be rated as 100. The following procedure is used for estimating the overall energy efficiency rating:

- The EnerGuide rating is defined as,

  *EE Rating =100 - ((Estimated Total Energy Consumption / Benchmark Energy Consumption) * 20)*

- The EnerGuide for Houses Estimated Total Energy Consumption is determined from the sum of the space heating consumption (**S**) and the Occupancy Consumption (**O**).

  Estimated Total Energy Consumption = **S** + **O**

  The space heating consumption (**S**) is determined using energy analysis. The occupancy consumption (**O**) is determined using the energy analysis program by assuming standard occupancy and operating conditions.

- Benchmark Energy Consumption = Space Heating Benchmark + DHW Benchmark + Base Load Benchmark

  Space Heating Benchmark = R x S x (49 x DD/6000) x (40+V/2.5)

  Where,

  R = multi-unit space heating budget modifier

  R = 1, for A / V greater than or equal to 0.9

  R = 0.55 + 0.45 (A / V), for A / V less than 0.9

A = exposed building envelope surface area of the heated space (including attic and basements), in square meters (m^2)

V = interior heated volume, including basement, in cubic meters (m^3)

S = space heating fuel factor (dimensionless)

S = 4.5 mega joules (MJ) for fuel-fired space heating systems

S = 3.6 mega joules (MJ) for electric space heating systems

DD = is the number of long term average degree days below the 18°C base

V = is the heated volume of the building in cubic meters.

$$DHW \quad Benchmark = 1.136 * SumDHW * \frac{55 - T_w}{(55 - 9.5)}$$

Where, *Tw* is an annual average local water mains or deep soil temperature in °C.

SumDHW = sum of base DHW load for different dwellings, as per the following table (MJ)

EGH Standard Operational and Occupancy Conditions

The following are standard occupancy and operational conditions used for the energy efficiency evaluations of multi-unit residential buildings:

Occupancy: Depending on the configuration of the dwelling unit, the following occupancy levels are assumed:

- Duplex: total 5, with 3 adults and 2 children
- Triplex: total 7, with 4 adults and 3 children
- 4-units: total 9, with 6 adults and 3 children
- more than 4 units: per unit occupancy of 3 total, with 2 adults and 1 child

Consumption of hot water: Table 2 shows the assumed daily hot water use.

Table 2: Typical hot water use patterns.

Type of Building	Hot water use L/day	Base Load MJ
Duplex	280	21,258
Triplex	425	32,266
4-units	560	42,515
more than 4 units: per unit	140	10,629

Electricity consumption: Table 3 shows the assumed daily electricity usage for appliances and lights.

Electricity consumption for common areas (rooms, corridors and utility/service areas) and exterior lighting is determined as follows:

- 0.086 kWh per day per square meter of floor area for common areas (rooms, corridors, stairways and utility/service areas)
- 3.0 kWh per day for exterior lights (also includes laundry and miscellaneous usage)

Table 3. Base loads in multi-unit buildings.

Type of structure	Appliances kWh/day	Lighting kWh/day	Other kWh/day	Total kWh/day	Total per unit
Duplex	18	3.4	3.4	24.8	12.4
Triplex	26	5.1	5.1	36.2	12.1
4-units	32	6.8	6.8	45.6	11.4
more than 4 units/ per unit	8	1.7	1.7	11.4	11.4

Set-point temperature: a temperature set-point of 21 °C for all living spaces and 19 °C for all common areas are assumed. Basements of two-storey apartments are also set at 19 °C.

Ventilation: Ventilation requirements are as follows:

- For dwelling units, apply a minimum monthly average ventilation rate of 0.30 air changes per hour (ac/h) during the heating season (October through April), including both natural air leakage and mechanical ventilation.
- For common areas (rooms, corridors and utility and service areas), apply a minimum monthly average ventilation rate of 0.2 air changes per hour (ac/h) during the heating season (October through April), including both natural air leakage and mechanical ventilation.

EGH Energy Analysis

Once the field data is collected, use HOT2000 to perform the energy analysis. The energy analysis is based on the following steps:

- **Step 1.** Enter building specific information from the walk-through evaluation.
- **Step 2.** Perform the heat loss and energy analysis.
  - Select an appropriate type of dwelling unit (bachelor, 1-bedroom, 2-bedroom, 3- or more bedrooms or common area).

- Assign building characteristics for each dwelling unit as a unit input in HOT2000.
- Specify the common area(s) as a unit input describing interior surfaces of exposed wall, roof and window areas (as deemed necessary).
- Input appropriate space heating and DHW energy sources and the ventilation systems.
- Input the airtightness of the building envelope for the whole building.

The energy analysis will provide the overall energy use and energy-efficiency rating of the building. The Step 2 computations will also provide an estimated heating load for each dwelling and common area(s).

- **Step 3.** Identify necessary energy upgrades and apply these to the whole building. Determine potential changes in the energy efficiency rating and the overall energy consumption.
- **Step 4.** Generate reports.

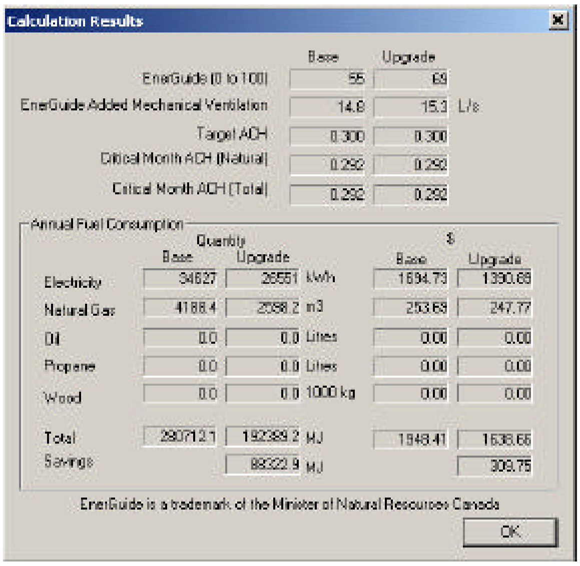

Figure 4. Typical screen display of energy analysis results.

Verification of Energy Use Estimates

As explained in the previous sections, the HOT2000 models have been compared and validated using the DOE-2, BLAST and more recently using the BESTEST.

In 2001, for verifying the EGH ratings and the standard operating conditions, NRCan conducted a detailed survey of 35 house files from EGH contractors [NRCan 2001]. Each file included details of house characteristics, appliance and house use profiles, and utility bills for a period of one to two years. The analysis was conducted using the HOT2000. Each data file was checked and verified using the field notes. Using the utility bills, these house files were reconciled. The test set covered different age groups, type of houses (one- and two-storey), main space heating fuels (natural gas, electric and oil) and airtightness characteristics. The data analysis and reconciliation exercises showed that, when compared with actual utility bills, HOT2000 predictions for space heating energy consumption ranged from about 18% under prediction to about 45% over prediction with an average of about 14% (over prediction). There were a number of limitations identified, for example:

- inability to vary the thermostat set-point temperature during the season; and
- lack of considerations for occupant behaviour.

The new model for the HOT2000 Multis uses the same algorithms for heat loss and heat gain calculations. The HOT2000 Multis mainly modified the input data construction so the user can define the geometric, thermal and heating systems information on a unit by unit basis.

Since November 2005, HOT2000 multis energy analysis procedure is being field tested for the evaluation of duplex, triplex and apartment buildings. Initial results of the energy analysis for eight buildings showed that the HOT2000 multis procedure over predicts the space heating energy consumption by 10 to 20%. With more data expected from different regions, a systematic validation exercises will be conducted mostly during the summer 2006.

DISCUSSION

The method used to perform energy analysis for multi-unit residential buildings depends, in part, on how the analysis results are to be used. In the case of the ***EnerGuide for Houses*** program, the energy analysis program was required to run quickly, require a minimum of inputs, be simple to use and control the scope of evaluations in an attempt to standardize results. The energy evaluators are not required to be expert building energy simulators so a tool that could be learned quickly and could be easily adapted for EGH purposes was selected. HOT2000 has served this purpose well.

The EGH program requires that the software report on unit-by-unit energy conservation opportunities in addition to whole building upgrades. This requirement is due to the type of ownership realized in multi-unit residential buildings. On an overall building, the energy analysis results show realistic energy use estimates. However, on a unit-by-unit basis, the energy use estimates vary greatly depending on the unit size, its location in building and the type of system(s) that serve the heating, DHW and ventilation needs. For this reason, the EGH rating is calculated for the whole building rather than for each individual dwelling unit.

The multi-unit buildings contain more than one dwelling and, therefore, may be more homeowners. The retrofit measures are recommended specifically for each dwelling as well as those which are common to the building.

CONCLUSION

Simplified methods have been developed and added to HOT2000 to provide reliable and quick energy analysis of large numbers of low-rise multi-residential buildings.

The HOT2000 energy analysis of multi-unit residential buildings is carried-out on a unit-by-unit basis and integrated to determine the energy use characteristics of the whole building.

These methods are being used to generate EGH ratings of multi-unit residential buildings. Field trials confirm these practical and reliable methods for energy analysis and energy rating calculations.

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