# DEVELOPMENT OF AN OPEN SOURCE HOURLY BUILDING ENERGY MODELING SOFTWARE TOOL

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## ABSTRACT

Computer building energy simulations are an important tool in the design of low-energy buildings. Building energy modeling is used to predict annual energy consumption, determine peak loads for sizing equipment, complete cost-payback analysis to select appropriate energy efficiency measures, and show compliance with standards. While energy modeling is a cost effective tool to assist in design, there are a number of challenges in the current building energy modeling industry. Most energy modeling programs are too technical to be used by architects, and too complex for early design when many mechanical system parameters are not known. Programs that are easy to use lack accuracy and the ability to model new, innovative systems. Programs that allow the simulation of new systems are very complex and have a high learning curve.

A computer program to model building energy loads and energy consumption of mechanical systems has been developed. The program, titled "Building Energy and Loads Analysis" or BELA, has a transparent, open architecture to allow additions and changes, and facilitates the simulation of both simple early design and detailed later design. BELA is currently a simple, single-zone model but could be expanded in accuracy and in its range of capabilities.

This paper presents the theory and calculations used in the BELA program. To demonstrate the application of this program, a group of sample office buildings are modeled in both BELA and eQuest, a popular energy modeling program. The annual energy consumption calculated by each program for the sample group of buildings is compared, and it is seen that there is between 5% and 15% difference between the total energy consumption results of the BELA and eQuest programs.

## INTRODUCTION

As climate change, pollution and energy supply become more of a concern, it is important to find ways to reduce energy consumption in all areas of society. According to the 2005 Energy Use Data Handbook, buildings accounted for 32% of total energy consumption in Canada in the year 2003 (NRCan 2005). It is clear that buildings consume a significant amount of energy, and it is important that the building industry continues to work to reduce building energy consumption as new buildings are designed and constructed.

The average Canadian office building in 2005 had an energy intensity of 444 kWh/m$^2$ (NRCan 2004), though modern, low energy office buildings can consume less than 100 kWh/m$^2$. There are many common energy efficient measures that can be employed to reduce energy consumption in new buildings to realize these low energy buildings. For example, some common energy efficiency measures include: higher levels of insulation, better insulating windows, enclosures without significant thermal bridges, efficient mechanical systems, heat recovery, and renewable energy systems. Many energy efficiency measures have an added initial cost and the energy saved must be weighed against the project budget and payback period of the additional investment. Computerized building energy simulation models give designers a cost-effective tool to simulate the energy consumption of a proposed building and predict the energy savings that would be realized from the energy efficiency measures being considered. Designers can use this information to calculate payback periods and select the energy efficiency measures appropriate for their project. Energy modeling has become an important part of many building projects.

## ENERGY MODELING AND DESIGN

In practice, the design of a new building requires input from many consultants with multidisciplinary skill sets. Although many members of the design team effect the energy consumption or energy efficiency of a building, it is not clear who is responsible for ensuring a low energy design.

The design decisions by the architect and nearly all consultants impact the energy performance of a building. However, in many cases only the mechanical or modeling engineer completes energy simulations. Though architects are often responsible for managing the design team, most energy modeling programs require a person with more technical understanding such as an engineer. One drawback of current modeling programs is that they usually cannot be used by an architect and thus the benefits of modeling may not be gained during the initial, highly iterative conceptual design stage.

The relationship between the architect and the mechanical engineer is a particularly important one with respect to energy consumption. Architects design the enclosure systems that define the loads on the building. Mechanical engineers design the heating, cooling and ventilation systems to meet the loads. In other words, architects are responsible for loads while mechanical engineers are responsible for systems energy. A poor architectural design will force high mechanical systems energy, while a poor mechanical design will spoil energy savings from good architectural design.

The distinction between loads and mechanical systems energy is important. The load on a building space is the total instantaneous heat transfer that occurs to or from that space. Loads may be created by heat loss through a wall from conduction, air leakage through cracks in the enclosure, heat gain from solar radiation through a window, and other heat sources (for example lights and equipment) in the space. System energy is the amount of energy consumed by the mechanical equipment to offset the heating or cooling load. For example, system energy may consist of the energy to power a boiler, fans and pumps to generate and distribute heating to a space. Since none of the mechanical systems that produce or distribute heat in this example are 100% efficient, the system energy will always be more than the load.

Loads are quite predictable during early design stages as they are governed primarily by the building enclosure. Accurate calculation of systems energy requires detailed knowledge of the HVAC systems, which is often not known until later design stages. From an energy modeling standpoint, it can be useful to model and provide feedback on loads and systems separately so that early design decisions can be evaluated based on how they affect the loads on the building. Another drawback of some energy modeling programs is that they do not output loads separately from systems energy. (Though, it should be noted that when the building parameters are well known it is beneficial to combine loads and systems as the HVAC system may impact the building loads. For example heat produced by fans and pumps will add to the cooling load on a space. These effects are negligible in early design stages.)

There is always a trade-off between accuracy and complexity in energy modeling programs. More accurate programs tend to be difficult to use, while easy to use programs are less accurate and may not have the capability to model a wide range of systems. A number of modeling programs allow users the flexibility to create new systems models for innovative, emerging, one-off systems. However, this often comes with a high learning curve as users need to learn the program code. Programs that are popular for their ease of use often require workarounds or hand calculations for newer or innovative systems.

A number of challenges with existing building energy modeling programs have been identified. They cannot be used by many architects, do not facilitate early, high-level design, and often do not provide clear feedback on loads. Easy to use programs cannot simulate new or innovative systems, while programs that can simulate innovative systems are more complex and have a high learning curve.

This paper documents the engineering calculations used for a simple software program that models annual building energy consumption. The program, titled Building Energy and Loads Analysis (BELA), is a spreadsheet-based program since this is a recognizable and universally available tool that all engineers and architects know how to use. A number of excellent energy modeling programs are available for performing accurate, detailed simulations by experienced professionals. This program is not intended to replace or compete with these programs. Rather, the intent is to demonstrate the application of first principles to estimate annual energy consumption to aid in the design of low energy buildings.

## MODEL DESCRIPTION

Figure 1 shows the general structure of the BELA program. The program takes inputs that describe the building and calculates the building energy consumption on an hourly basis. BELA has three input sheets: Building Information, Weather Data and Schedules. The Building Information requires the user to input such details as dimensions, window to wall ratio, enclosure insulation values, and so on. The weather data tab takes hourly weather data for a year pasted from a standard weather file such as Canadian Weather for Energy Calculations (CWEC) or Typical Meteorological Year (TMY), which are available free of charge from government bodies (Environment Canada, US Department of Energy). Schedules control when the building is consuming energy and can be adjusted by the user.

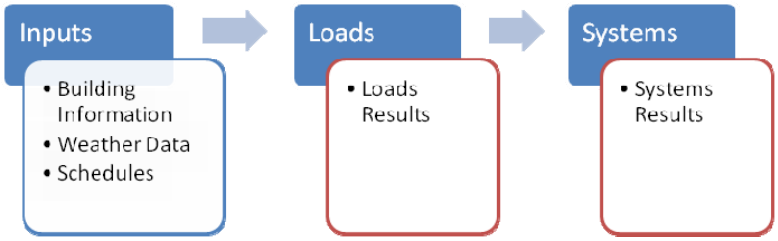


**Figure 1: BELA program structure.**

BELA uses building inputs to calculate loads on the building and also calculates the total system energy. It is important to distinguish between load energy and system energy. Loads are the required heating and cooling demand, or lighting and equipment energy. For example, heat loss due to conduction that occurs through an exterior wall causes an instantaneous load in kilowatts. The total heating or cooling load is the sum of all sources of heat transfer acting on the building. Systems energy is the actual building energy consumption, in other words, the energy that passes through a meter. Systems energy incorporates the efficiency of meeting the loads on the building. For example, on a winter day with a net heating load, the system energy is the total energy consumed by the boiler, pumps and fans to create and distribute heat to the space to maintain a constant indoor temperature. The program calculates load and system energy separately, and displays the results for each separately.

### Building Inputs

A complex building can be reduced to a simple box for the purpose of energy modeling, often with little loss in accuracy. Complexities may be in the form of non-rectangular shapes, multiple enclosure assemblies, different types of windows, multiple zones, and so forth. The program in its current form makes a number of simplifications that could be expanded upon in future versions. The required building inputs to the program include:

- Dimensions
- Window to Wall Ratio
- Enclosure Thermal Resistance
- Window Thermal Conductance
- Window Solar Heat Gain Coefficients (SHGC)
- Infiltration Rate
- Roof and Wall Solar Absorptance
- Occupant Density
- Lighting and Plug Load Density
- Indoor Temperature Setpoints

As with most energy modeling programs, this program uses hourly weather data for one year. A number of files with this information exist; two such data sets are Canadian Weather for Energy Calculations (CWEC), and Typical Meteorological Year (TMY). The weather metrics currently used by this program are based on the CWEC data format but could be easily altered based on other data formats. These metrics include dry bulb temperature (degrees Celsius), dew point temperature (degrees Celsius), relative humidity (%), atmospheric pressure (Pa), global horizontal radiation (W/m$^2$), wind speed (m/s), wind direction (degrees), and ground temperature (degrees Celsius).

The model uses daily and weekly schedules to account for variations in building use. The model does not currently have annual schedules, though this could be easily implemented. Schedules have currently been implemented for lighting, plug loads and occupancy. Schedules could also be created for heating and cooling temperature set points and infiltration.

**Loads Calculations**

The space heating and cooling loads are calculated at each hour for a year. The following heat transfer mechanisms contribute to the space heating and cooling load,

- Conduction through the walls, windows, doors and roof
- Conduction through the foundation
- Solar heat gain through windows
- Infiltration
- Heat gain from occupants, lights and plug loads

In addition to space heating and cooling loads, the electrical lighting and plug loads are totalled. Domestic hot water (DHW) loads are currently not calculated but could be easily added to the model.

Conduction through the walls, windows, doors and roof is determined by first calculating the surface temperature. Surface temperature is calculated using an energy balance where energy transfer to the inside and outside is equal to absorbed solar radiation,

$$\mathbf{I_s\alpha - (T_s - T_{out})h_c - (T_s - T_{in})U = 0}$$

Where $I_s$ = Solar radiation on surface, W/m$^2$
$\alpha$ = Solar absorbtance
$T_s$ = Surface temperature, °C
$T_{out}$ = outdoor air temperature, °C
$T_{in}$ = indoor air temperature, °C
$h_c$ = surface film coefficient, W/m$^2$-K
U = overall heat transfer coefficient (U-value) of wall or roof assembly, W/m$^2$-K

Solving for $T_s$ gives,

$$T_s = \frac{I_s\alpha + T_{out}h_c + T_{in}U}{h_c + U}$$

The surface temperature is calculated for each wall elevation and the roof. The heat transfer by conduction, $Q_{cond}$, through each surface with area A is (ASHRAE 2009),

$$Q_{cond} = UA(T_s - T_{in})$$

The value of the surface film coefficient, $h_c$, is difficult to determine as it depends on wind speed and surface roughness. A number of relations for $h_c$ are provided in ASHRAE Fundamentals (2009). The program currently uses the average surface film coefficient for exterior surfaces, 17 W/m$^2$-K (Straube 2005). A better model of wind dependent surface film coefficient could be investigated for future versions of the program.

Solar radiation on a horizontal surface from the CWEC weather file is projected onto vertical north, south, east and west surfaces to determine the solar radiation falling on windows at each elevation. The solar heat gain is then calculated by summing the solar heat gain at each elevation (ASHRAE 2009),

$$Q_{SHG} = \sum q_i A_i SHGC_i$$

Where $q_i$ = Solar radiation hitting elevation i, W/m$^2$
$A_i$ = Window area at elevation i, m$^2$
$SHGC_i$ = Solar heat gain coefficient of windows at elevation i
i = {North, South, East, West}

Air infiltration creates a sensible load and a latent load. The air infiltration rate is a user input, in l/s per m$^2$ floor area. The sensible infiltration load is (ASHRAE 2009),

$$Q_{inf,s} = \dot{q}A\rho c_p(T_{out} - T_{in})$$

Where $\dot{q}$ = Air leakage rate, l/s per $m^2$ wall area
A = Floor area, $m^2$
$\rho$ = Indoor air density, $kg/m^3$
$c_p$ = Specific heat capacity of air, J/kg-K

The latent infiltration load is only calculated when greater than zero (that is, when dehumidification is required). Therefore, it is assumed that no humidification is needed or used since many buildings do not have humidification systems. Humidification could be added to the model if desired. The total latent load is (McQuiston 2005; Straube 2005),

$$Q_{inf,l} = \dot{q}A(W_{out} - W_{in})(2501 + 1.805T_{in})$$

Heat gain from occupants is the occupant density (people/$m^2$) times heat gain per person (W/person) times the floor area ($m^2$). Occupants create both a sensible heat load and a latent heat load. The sensible and latent heat gains per person are entered separately. Heat gain due to lights and plug loads is the lighting or plug load density input by the user (W/$m^2$) times the floor area ($m^2$).

The heating or cooling load at any particular time differs from the instantaneous gains and losses calculated previously due to heat absorbed by thermal mass and released at later times. There are various methods of accounting for this effect; discussion of the various methods can be found in ASHRAE Fundamentals Chapter 19 (ASHRAE 2009).

The weighting factor method was selected for this program for its simplicity. This method applies weighting factors to each instantaneous (hourly) gain. The weighting factors are transfer functions that relate heating or cooling load to instantaneous gain. This method is explained in greater detail by Stephenson and Mitalas (1967) and Mitalas (1972). The weighting factor model is simple to apply but not as accurate as other methods; a better model such as the Radiant Time Series method should be implemented for future versions of this program.

Weighting factors differ for each heat transfer source and vary with the amount of thermal mass in the building. Weighting factors have been calculated for a number of scenarios; McQuiston and Spitler (1992) provide tables with weighting factors for a number of configurations. In DOE-2 based programs, weighting factors are automatically generated based on user inputs about the building (mainly the amount of thermal mass). In this program, the user must manually input weighting factors. A better algorithm could be developed to have the program choose from a list of pre-defined weighting factors based on the user's input of the building thermal mass.

The weighting factors are used with the current and past instantaneous gains/losses and the past weighted load as follows (ASHRAE 2009),

$$Q_\theta = V_0 q_\theta + V_1 q_{\theta-1} - W_1 Q_{\theta-1}$$

Where $Q_\theta$ = Heating or cooling load at hour $\theta$
$Q_{\theta-1}$ = Heating or cooling load at hour $\theta - 1$
$q_\theta$ = Instantaneous heat gains or losses at hour $\theta$
$q_{\theta-1}$ = Instantaneous heat gains or losses at hour $\theta - 1$
$V_0$, $V_1$, $W_1$ = Weighting factors

Weighting factors are applied to heat transfer that occurs by conduction, solar heat gain, people, equipment and lighting. Weighting factors are not applied to heat transfer due to infiltration since this is assumed to be an instantaneous load not affected by thermal mass.

The ventilation loads are calculated separately from the heating and cooling loads in order to clearly separate ventilation from space heating and cooling. The required ventilation inputs are,

- Ventilation rate per person and per $m^2$ floor area
- Minimum ventilation rate
- ERV and HRV efficiency

The ventilation rate per person and per $m^2$ floor area from the inputs section are used to calculate the total ventilation rate for the building,

$$\dot{Q} = R_p n_p + R_a A_{floor}$$

Where $\dot{Q}$ = Required ventilation rate, l/s
$R_p$ = People outdoor air rate, l/s-person
$n_p$ = Number of people
$R_a$ = Area outdoor air rate, l/s-m$^2$
$A_{floor}$ = Floor area, m$^2$

In many buildings, the ventilation is reduced further during unoccupied hours. A minimum ventilation rate is entered by the user, and this value is used by the program when the building is unoccupied.

The sensible heating or cooling load due to ventilation air is,

$$\boldsymbol{Q_s = \eta_{HRV}\left[\dot{Q}\rho c_p(T_{out} - T_{in})\right]}$$

Where $\eta_{HRV}$ = Heat Recovery Ventilator sensible efficiency, %
$\dot{Q}$ = Ventilation rate, l/s
$\rho$ = Air density, kg/m$^3$
$c_p$ = Specific heat capacity of air, J/kg-K
$T_{out}$, = Outdoor air temperature, °C
$T_{in}$ = Indoor air temperature, °C

The model accounts for latent load only when latent heat removal is required (dehumidification). This assumes that there is no humidification present in the system, and so any latent heat addition (humidification) is ignored. Latent heat addition could easily be added if a humidification system were present. The latent cooling load due to ventilation air is,

$$\boldsymbol{Q_l = \eta_{ERV}\left[\dot{Q}(W_{out} - W_{in})(2501 + 1.805T_{in})\right]}$$

Where $\eta_{ERV}$ = Energy Recovery Ventilator latent efficiency, %
$W_{out}$ = Outdoor air absolute humidity, kgv/kga
$W_{in}$ = Indoor air absolute humidity, kgv/kga
$T_{in}$ = Indoor air temperature, °C

**Systems Energy Calculations**

HVAC systems typically serve two main functions: (1) Heat and/or cool the building and (2) Provide outdoor ventilation air to the building. Currently the BELA system model simulates a Dedicated Outdoor Air (DOAS) ventilation system with radiant heating and cooling. This system was selected as it is a modern, low energy system. CAV was not modeled as it is rarely used in new buildings, though this system could be created fairly easily. A Variable Air Volume (VAV) system, likely one of the most popular systems in existing buildings, was not modeled at this time due to its complexity. A VAV system model could be attempted for future versions of the program. The BELA HVAC Systems model takes the results of the Loads model and applies a mechanical system in order to determine the total annual building energy consumption.

DOAS systems often involve multiple fans and non-linear duct paths with various losses. The details of the system are often not known until later design stages. Still, the energy consumption of these systems can be approximated by assuming a single, equivalent system with a single, equivalent airflow rate and pressure drop.

In addition to the inputs required to calculate the ventilation load, inputs required to calculate ventilation heating and cooling energy and fan power are,

- Heating source efficiency
- Cooling source efficiency
- Fan and motor efficiencies
- Maximum design fan airflow rate
- Maximum design fan pressure

Outdoor air often must be heated, cooled or dehumidified before it can be distributed to the space. If heating is required,

$$Q = \frac{Q_s}{\eta_{heat}}$$

Where Q = Energy to heat ventilation air, W

$Q_s$ = Sensible ventilation heating load, W

$\eta_{heat}$ = Heating source efficiency, % or COP

If sensible and/or latent cooling is required,

$$Q = \frac{Q_s + Q_l}{COP}$$

Where Q = Energy to cool and dehumidify ventilation air, W

$Q_s$ = Sensible ventilation cooling load, W

$Q_l$ = Latent ventilation cooling (dehumidification) load, W

COP = Cooling source coefficient of performance

The maximum design fan power is calculated from the fan efficiency, maximum design airflow rate and maximum design pressure drop input by the user,

$$Q_{f,max} = \frac{\dot{Q}_{f,max} P_f}{1000\eta_f \eta_m}$$

Where $Q_{f,max}$ = Maximum design fan power, W

$\dot{Q}_{f,max}$ = Maximum design fan airflow rate, l/s

$P_f$ = Maximum design fan pressure, Pa

$\eta_f$ = Fan efficiency, %

$\eta_m$ = Motor efficiency, %

Two common types of fans are on/off fans and variable speed drive fans (VSD, also known as variable frequency drive or VFD). On/off fans simply run at full speed and full power draw when ventilation is required and zero speed/power when ventilation is not required. The systems model program calculates energy consumption at one-hour intervals. To model on/off fans, it is assumed that the fan runs for the full hour when ventilation is required for that hour.

VSD fans vary the flow rate so that when less ventilation is required, less fan power is used. The theoretical power drawn by a VSD fan running at a lower-than-design rate can be calculated using fan laws,

$$Q_{f,i} = \frac{1}{\eta_f \eta_m} Q_{f,max} \left( \frac{\dot{Q}_i}{\dot{Q}_{f,max}} \right)^3$$

Where $Q_{f,i}$ = Fan power draw at hour i, W

$Q_{f,max}$ = Maximum design fan power, W

$\dot{Q}_i$ = Ventilation rate at hour i, l/s

$\dot{Q}_{f,max}$ = Maximum design fan airflow rate, l/s

$\eta_f$ = Fan efficiency, %

$\eta_m$ = Motor efficiency, %

Fan relations for VSD power are theoretical because of additional losses from the electronics. A more accurate model of VSD fan energy consumption would use a fan curve input from manufacturer's data to calculate fan energy consumption at each hour. Alternatively, this model uses the relation provided in ASHRAE Standard 90.1-2004 Appendix G (G3.1.3.15),

$$P_{fan} = 0.0013 + 0.147PLR_{fan} + 0.9506PLF_{fan}{}^2 - 0.0998PLR_{fan}{}^3$$

Where $P_{fan}$ = Fraction of full load fan power

$PLR_{fan}$ = Fraction of fan load (current load / design load)

Radiant heating and cooling systems circulate heated or chilled water throughout a building to heat or cool the space. Two common forms of radiant systems are in-floor systems and ceiling panel systems. In-floor systems have tubes embedded in concrete floor slabs that run throughout the building flooring.

Ceiling systems have metal panels dropped from the ceiling covering tubes for water. The water temperature that can be used with radiant in-floor cooling must be carefully selected so that condensation will not form on the floor. This limit also applies for ceiling systems, though it is often slightly better since heat transfer is not slowed by surface covers such as carpet, flooring or furniture.

Radiant heating and cooling has a number of benefits. Water-based radiant systems are generally more efficient than air-based systems since water has a higher specific heat capacity than air and therefore can transport heat more efficiently. Radiant heating systems operate with lower water temperatures since they have a large surface area over which heat exchange occurs. This means primary heating equipment such as heat pumps can operate more efficiently. Radiant systems are often more thermally comfortable than traditional air-based systems as they create a more uniform thermal environment. (Olesen 2008)

The maximum heating and cooling that can be provided to the space is calculated from the user inputs (McQuiston 2005),

$$Q_{max} = \dot{m} c_p \Delta T$$

Where $Q_{max}$ = Maximum heating or cooling, W

$\dot{m}$ = Mass flow rate of water, kg/s

$c_p$ = Specific heat capacity of water, kJ/kg-K

$\Delta T$ = Difference between supply and return water temperature, °C

The amount of heating or cooling energy required to condition the space for a given hour is calculated from the load and the source heating or cooling efficiency. When heating is required,

$$Q = \frac{Q_s}{\eta_{heat}}$$

Where Q = Energy to heat space, W

$Q_s$ = Sensible space heating load, W

$\eta_{heat}$ = Heating source efficiency, % or COP

When cooling or dehumidification is required,

$$Q = \frac{Q_s + Q_l}{COP}$$

Where Q = Energy to cool and dehumidify space, W

$Q_s$ = Sensible space cooling load, W

$Q_l$ = Latent space cooling (dehumidification) load, W

COP = Cooling source coefficient of performance

The maximum required pump power is calculated from the design pump flow and head (McQuiston 2005),

$$W_{p,max} = \frac{\dot{Q}_{p,max} \rho H_p g}{1000 \eta_p \eta_m}$$

Where $W_{p,max}$ = Maximum design pump power, W

$\dot{Q}_{p,max}$ = Maximum design pump flow rate, l/s

$\rho$ = Water density, kg/m$^3$

$H_p$ = Maximum design pump head, m

g = acceleration due to gravity, m/s$^2$

$\eta_p$ = Pump efficiency, %

$\eta_m$ = Motor efficiency, %

As with fans, pumps can be on/off or variable speed drive (VSD). A VSD pump model is currently not included but should be developed for future versions. Pump energy is calculated at one-hour intervals, though on/off pumps will not run for the full hour when a fraction of the maximum heating or cooling load is required. To model this, it is assumed that the pump runs for a fraction of the hour proportional to the percent of the maximum heating or cooling required. That is,

$$W_p = W_{p,max} \frac{Q_{load}}{Q_{max}}$$

Where $W_p$ = Pump power at given hour, W
$W_{p,max}$ = Maximum design pump power, W
$Q_{load}$ = Heating or cooling load at given hour, W
$Q_{max}$ = Maximum design heating or cooling load, W

**CASE STUDY**

The BELA program is used to create a model of a small office building. The total energy consumption results of the BELA program will be compared to the results of eQuest. A comparison of the loads calculated by BELA and eQuest may be found in Hanam (2010). The purpose of this analysis is to view the differences between a simple model built upon fundamental principles to a more developed but less transparent program. The goal is not to achieve the same numerical results in BELA as in eQuest, nor is it a "validation" of the BELA program. Rather, the intent is to view how the results would differ for a high level building where detailed parameters are not known.

Plans for a typical small office building were adapted from *Design with Energy in Mind* by Barbara M. Ross (2010). This research study identifies typical enclosure parameters for four energy performance levels: exemplary, high performance, institutional and market. Architectural inputs to the program for the four scenarios are shown in Table 1.

The only HVAC system currently modeled in the BELA program is DOAS ventilation with radiant heating and cooling. Ventilation rates are taken from ASHRAE Standard 62.1-2007, *Ventilation for Acceptable Indoor Air Quality*. The mechanical input parameters for the building are shown in Table 2. A few work-arounds were required to model this building in eQuest since eQuest cannot directly model DOAs systems nor radiant heating and cooling. To model a DOAS system in eQuest a dummy zone is created and 100% outdoor air is provided to this zone at the flow rate of the actual ventilation system. The radiant heating and cooling system is approximated with fan coil units with zero fan power. Other simplifications had to be made in eQuest, for example fans, heating and cooling run 24 hours per day, 7 days per week with no setback since these schedules do not exist in BELA yet. The inputs for the boiler and chiller parameters, as well as the pump and fan parameters, are different in eQuest than in BELA. The eQuest parameters were left as defaults. The parameters could have been calibrated in either program in order to force the outputs to line up, however the goal of the exercise is not to force the results to be the same but to view how the results differ for a high level building where detailed parameters are not known (and default program inputs would likely be used).

Table 3 shows the total annual energy consumption results of the BELA and eQuest simulations for each of the four buildings modeled. The difference total energy consumption calculated by the two programs is generally low. This shows that it is possible to obtain approximate energy consumption values using the BELA program during early design stages when detailed parameters are not known. The difference between the eQuest and BELA results is in the 5% to 15% range for all scenarios modeled.

Further insight may be gained by studying the distribution of energy consumption in the BELA and eQuest model results. Cooling energy consumption varies from 0.9% difference (Institutional) to 22% difference (High Performance), though all cases have low absolute difference since the cooling energy consumption is relatively low. Heating energy consumption percent difference varies from 3% (market) to 24% (institutional). It is not known why percent difference is larger for some models and smaller for other models. As noted previously, the heating and cooling system inputs could have been adjusted in eQuest to provide the same output as BELA, however that was not the goal of this exercise.

Fan and pump power is much higher in all eQuest models than in the BELA models. This may be caused by the default eQuest parameters that were used. Further analysis should be completed regarding pump and fan power in eQuest and BELA. Lighting and plug load energy consumption is slightly larger in eQuest than in BELA; lights are 7% higher in eQuest and plug loads are 9% higher in eQuest. The reason for the difference in these values is not known; both models used the same $W/m^2$ input for the whole building and the same schedules.

**Table 1: Case Study Model Inputs for Small Office Building (adapted from Ross 2010)**

| | Units | Exemplary | High Performance | Institutional | Market |
|---|---|---|---|---|---|
| Location | | Toronto, ON | | | |
| Number of Stories | | 2 | | | |
| N-S Dimension | m (ft) | 23 m (77 ft) | | | |
| E-W Dimension | m (ft) | 23 m (77 ft) | | | |
| Floor to Floor Height | m (ft) | 3.7 m (12 ft) | | | |
| Window to Wall Ratio | % | 30% | | | |
| Air Leakage rate | ACH | 0.1 | 0.3 | 0.5 | 0.9 |
| Wall Effective R-Value | $m^2$-K/W ($hr-ft^2$-F/Btu) | 6.3 (36.0) | 4.2 (24.0) | 2.8 (16.0) | 1.3 (7.6) |
| Roof Effective R-Value | $m^2$-K/W ($hr-ft^2$-F/Btu) | 8.5 (48.0) | 5.3 (30.0) | 3.7 (21.0) | 0.9 (5.0) |
| Foundation Insulation Effective R-Value | $m^2$-K/W ($hr-ft^2$-F/Btu) | 1.76 (10.0) | 0.9 (5.0) | None | None |
| Overall Window U-Value | W/$m^2$-K (Btu/hr-$ft^2$-F) | 1.19 (0.21) | 1.48 (0.26) | 1.99 (0.35) | 3.12 (0.55) |
| Window SHGC (SC) | | 0.29 (0.33) | 0.62 (0.71) | 0.73 (0.84) | 0.73 (0.84) |
| Lighting | W/$m^2$ (W/$ft^2$) | 14.0 (1.3) | | | |
| Plug Loads | W/$m^2$ (W/$ft^2$) | 16.0 (1.5) | | | |
| Overall Occupant Density | $m^2$/person ($ft^2$/person) | 14 (155) | | | |

**Table 2: Case Study Mechanical Model Inputs for Small Office Building**

| | |
|---|---|
| **Ventilation Inputs** | |
| Ventilation Rate per Person | 2.5 l/s-person (5.3 cfm/person) |
| Ventilation Rate per $m^2$ floor area | 0.3 l/s-$m^2$ (0.06 cfm/sf) |
| Overall Fan Efficiency | 51% |
| Design Fan Flow | 600 l/s (1270 cfm) |
| Design Fan Power | 1.53 kW (5220 Btu/h), Calculated using ASHRAE 90.1 Appendix G |
| **Radiant Heating and Cooling Inputs** | |
| Heating Efficiency | 85% |
| Cooling COP | 3.5 |
| Overall Pump Efficiency | 67% |
| Cooling Delta T | 5°C (41°F) |
| Heating Delta T | 10°C (50°F) |
| Cooling Temperature Setpoint | 24°C (75°F) |
| Heating Temperature Setponit | 21°C (70°F) |

**Table 3: BELA and eQuest case study simulation results, kWh/$m^2$.**

| | Exemplary | | High Performance | | Institutional | | Market | |
|---|---|---|---|---|---|---|---|---|
| | BELA | eQuest | BELA | eQuest | BELA | eQuest | BELA | eQuest |
| Pump Power | 2.1 | 8.8 | 2.7 | 13.3 | 3.0 | 11.8 | 4.1 | 17.2 |
| Space Heating | 72.5 | 68.7 | 139.6 | 164.2 | 283.0 | 227.6 | 452.9 | 464.7 |
| Space Cooling | 29.4 | 27.4 | 32.6 | 26.7 | 22.9 | 22.7 | 23.8 | 26.8 |
| Fan Power | 3.0 | 8.3 | 3.0 | 8.3 | 3.0 | 8.3 | 3.0 | 8.3 |
| Lights | 38.4 | 41.5 | 38.4 | 41.5 | 38.4 | 41.5 | 38.4 | 41.5 |
| Plug Loads | 43.8 | 47.9 | 43.8 | 47.9 | 43.8 | 47.9 | 43.8 | 47.9 |
| **Total** | **189.3** | **202.3** | **260.1** | **301.9** | **394.2** | **359.9** | **566.0** | **606.4** |
| Difference | 6% | | 14% | | 10% | | 7% | |

## CONCLUSIONS

An important stage in the design of a low energy building is modeling the building to predict energy consumption and evaluate the energy efficiency measures being considered. Challenges with the building energy modeling process have been identified. Though architects have a great impact on a building's energy consumption, many energy modeling programs are too technical to be used by architects, and too complex for early design when many parameters are not known. Programs that tend to be easy to use are typically not able to model innovative systems, while programs that allow the simulation of new or innovative systems are technically complex and tend to have a steep learning curve.

A simple energy modeling program, Building Energy and Loads Analysis or BELA, was developed using fundamental principles. The goal of this program is to demonstrate a simple, transparent and adaptable energy simulation program that can be used in both early and later design stages. The program was used to model a typical small office building. The results were compared to those from eQuest in order to view the differences between a simple model built upon fundamental principles to a more developed but less transparent program such as eQuest.

It is important to recognize the limitations of BELA. This program is currently a single zone model with many simplifications. There are many ways in which the program could be improved to be more accurate, more useable and to simulate a wider range of buildings and systems.

There are many excellent energy simulation programs available for detailed and accurate energy modeling by experienced professionals, and the intent is clearly not to replace or compete with these options. Rather, this project demonstrates that: (1) it is possible to use fundamental principles to simplify energy simulation, and (2) a transparent and easy to use tool can be useful in early design stages or for less technically oriented users to approximate building energy consumption and savings.

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