Dynamic Modelling of Building Envelope on Energy Usage

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Abstract
This study investigates the influence of the building envelope on the energy usage of a chosen building using the simulation program TRNSYS. The building located at Carleton University, Ottawa, Canada is a small building retrofitted as part of the Natural Resources Canada’s Prefabricated Exterior Energy Retrofit (PEER) project. The project’s aim is to develop prefabricated technologies to be used for retrofitting existing building envelopes of homes in Canada. The thermal resistance (RSI) of the existing walls were improved from 1.80 m²K/W to about 6.40 m²K/W after installation of the prefabricated retrofit wall system. Analytical verification of the whole building performance simulation software is performed using a solitary heat transfer mechanism under simplified boundary conditions with known analytical solution. The warm-up period necessary to ensure heat is distributed in the building thermal mass at the start of the simulation is quantified. The thermal performance of the whole building envelope is quantified using the time-lag effect and decrement factor and energy requirement for heating and cooling.

1. Introduction
Buildings account for about 40% of the global energy consumption [1]. A large proportion of this energy is consumed by Heating Ventilation and Air Conditioning (HVAC) systems in maintaining thermal comfort and air quality. Building energy use is expected to grow by more than 40% in the next 20 years [2]. More than two-third of Canada’s over 11 million low-rise, semi and row-attached dwellings were built before the existence of residential energy efficiency standards [3]. The situation is similar for the United States, Europe, and other places. The United States Census Bureau 2013 survey as cited in [4] found that more than 60% of the United States’ housing stock is 30 years old and energy inefficient. According to Ríos Fernández et al. [5], about 35% of the EU’s buildings are existing buildings over 50 years old. Even though exterior walls account for 25 to 35% heat loss in residential buildings, retrofitting of exterior walls remains an uncommon practice [3]. Lengthy completion time, uncertain costs and disturbance of people around are some reasons hindering retrofitting of these buildings. Detailed studies of the different options for retrofitting the existing building based on certain design constraints are important in providing house owners with the best retrofit solution. The best solution takes into consideration the local climatic condition and should maximize energy savings while minimizing the factors that hinder retrofitting of buildings within a reasonable payback period.

Ensuring adequate thermal resistance and thermal mass is equally important for designing new buildings. A building envelope appropriately designed for the local weather can result in significant energy savings. Weather conditions contribute to the building energy loads in a coupled manner with the building envelope design factors [6]. More massive external walls are preferred in colder climates while in warmer climates, more massive roofs are preferred to be able to utilize their thermal inertia during the cooling season characterized by high solar radiation [7]. The best solar passive design would be a dynamic arrangement of insulation, thermal mass and window that alters depending on the season, time of the day, weather and/or building operation since different arrangements are more suited than others for a particular season and/or part of the day [8]. The incorporation of adaptive building elements, such as phase change materials (PCM) and glass façade, in building envelope is becoming popular to create a more vivacious indoor living environment. There is a need for accurate building energy modelling software to be able to predict the energy performance of different building configurations in order to choose the optimal solution specific to the local weather.

Building simulation involves the use of computer programs to create a virtual model of a building. This virtual model is utilized in performing various studies about the building. The virtual model takes into consideration the geometry, location, and construction of the building. Building simulation is used for estimating the dynamic heating and cooling loads, sizing and comparing performance of different HVAC systems and developing optimal control strategies that minimize HVAC operating cost. It is also useful in determining the most economical building design, or retrofit based upon heating, cooling, equipment, and material costs and for designing passive solar components [4]. The weather

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condition is easily incorporated in most simulation programs and the effect of incorporating renewable systems in a building design can also be analyzed using building simulation tools. Some examples of building simulation programs are TRNSYS, Energy Plus, IDA ICE, ESP-r, and DOE-2. Correct and efficient use of building performance simulation (BPS) software is important in ensuring the designed building meets the predicted requirement.

As the outdoor conditions associated with the sun rising and setting are periodic (cyclic) in nature, heat gain or loss through the building envelope is consequently periodic [9]. The building envelope acts as a buffer with a finite thermal mass and brings forth delay and attenuation under the effect of the cyclic outdoor condition [9]. This internal store of heat by the building envelope needs to be accounted for at the start of the simulation to prevent the building model from being biased by the warm-up period or transient response time. The warm-up period is the time it takes for the building model to attain steady state at the start of the simulation. Building simulation softwares like EnergyPlus, ESP-r include warm up days to correct for this bias. However, the simulation software chosen for this study, TRNSYS does not include any feature to correct for warm-up period in its building model (Type 56). Although, according to Delcroix et al [10] a commonly adopted strategy in TRNSYS when initial conditions are important is to discard the results of the first month after running the simulation for an extra month. This process is scarcely documented in the open literature.

In this study, daily outdoor sinuosodial temperature representing a typical summer day, winter day and a day with the need for alternate heating and cooling are used to study the energy usage due to the heat transfer mechanism through the building envelope. These temperature variations are not specific to the location of the building. However, it is chosen in a manner that the amplitude of the summer and winter days are the same while their mean values are equally displaced from the building indoor set point temperature. The mean of the temperature variation with the need for alternate heating and cooling is selected to be equal to the indoor set temperature of the building. All forms of radiative heat transfer are zeroed for analytical verification [11] of the results with known solutions obtained by hand calculations. The hand calculations involved taking heat balance at the outdoor and indoor faces of each of the building envelope surfaces. The warm-up period for the building is estimated. The ability of the building envelope to maintain an indoor temperature with large fluctuation in outdoor temperature is studied using outdoor temperature variation for a day with the need for alternate heating and cooling. The energy requirement of the building due to convective heat exchange between outdoor air and outer building envelope surfaces, conduction through the building envelope surfaces and convective heat exchange between the indoor building envelope surfaces and indoor air is estimated. All these are important for verification of the whole building performance simulation software and efficient use of it in modelling real scenarios.

2. Weather description and building details

2.1 Weather Description

Ambient temperature is assumed to be a sine wave with a 24-hrs period, midpoint values occur at 0 hr, 12 hr and 24 hr, while maximum and minimum values occur at 6 hr and 18 hr respectively as shown in Fig 1. The sinewave outdoor temperature is calculated as a function of the time of the day according to

\[ T_t = \frac{T_{\text{max}} - T_{\text{min}}}{2} \sin(15^\circ t) + \frac{T_{\text{max}} + T_{\text{min}}}{2} \]

Here, \( T_t \) is the temperature at a given time of the day in °C, \( T_{\text{max}} \) and \( T_{\text{min}} \) are the maximum and minimum temperatures, respectively, in °C and \( t \) is the time of the day in hour. All other weather variables required by the TRNSYS Type 56 are set to zero. The variables include relative humidity, horizontal radiation, and effective temperature for longwave, ground reflectance for sky diffuse radiation shading, solar zenith angle and solar azimuth angle. The weather file for a week (168 hr) was created in MS Excel, saved as a text file, and read in TRNSYS using a data reader.
2.2 Building description

The building is located at Carleton University, Ottawa, Ontario, Canada. The building is part of Natural Resources Canada’s Prefabricated Exterior Energy Retrofit (PEER) project. Fig 2 is a photo of the building. The goal of the project is to develop technologies and processes for applying prefabricated components to retrofit existing homes and buildings from the exterior [3]. Assessment of hygrothermal performance of the prefabricated retrofit is ongoing. To perform this assessment, temperature, relative humidity, and moisture content sensors are placed at different locations of the wall assembly. The sensors are used for taking hourly readings.

The orientation of the building is South-Southeast. The building is conditioned using a heat pump connected to a digital thermostat and the set point temperature is 20°C. The building is a single floor, and it is modelled as a single thermal zone. The dimensions of the surfaces are given in Table 1 and the building parameters are shown in Table 2.
Table 1. Construction type, area, thickness, and U-value for building surfaces

<table>
<thead>
<tr>
<th>SURFACE</th>
<th>CONSTRUCTION TYPE</th>
<th>AREA [m²]</th>
<th>Thickness [m]</th>
<th>U-value [W/m²K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 2</td>
<td>WALL</td>
<td>11.81</td>
<td>0.295</td>
<td>0.141</td>
</tr>
<tr>
<td>3, 4</td>
<td>WALL</td>
<td>28.67</td>
<td>0.295</td>
<td>0.141</td>
</tr>
<tr>
<td>5, 6</td>
<td>ROOF</td>
<td>29.83</td>
<td>0.309</td>
<td>0.138</td>
</tr>
<tr>
<td>7</td>
<td>GROUND FLOOR</td>
<td>41.36</td>
<td>0.164</td>
<td>0.174</td>
</tr>
</tbody>
</table>

Table 2. Building model specification

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Quantity</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground floor area</td>
<td>-</td>
<td>41.36</td>
<td>m²</td>
</tr>
<tr>
<td>Ground floor to ceiling height</td>
<td>-</td>
<td>2.4</td>
<td>m</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>-</td>
<td>3.34</td>
<td>-</td>
</tr>
<tr>
<td>Window to wall ratio</td>
<td>-</td>
<td>3.2</td>
<td>%</td>
</tr>
<tr>
<td>Wall U-value</td>
<td>-</td>
<td>0.141</td>
<td>W/m²K</td>
</tr>
<tr>
<td>Ground floor U-value</td>
<td>-</td>
<td>0.138</td>
<td>W/m²K</td>
</tr>
<tr>
<td>Roof U-value</td>
<td>-</td>
<td>0.174</td>
<td>W/m²K</td>
</tr>
<tr>
<td>Window U-value</td>
<td>3</td>
<td>1.01</td>
<td>W/m²K</td>
</tr>
<tr>
<td>Window SHGC</td>
<td>3</td>
<td>0.61</td>
<td>-</td>
</tr>
<tr>
<td>Window U-value</td>
<td>1</td>
<td>1.66</td>
<td>W/m²K</td>
</tr>
<tr>
<td>Window SHGC</td>
<td>1</td>
<td>0.62</td>
<td>-</td>
</tr>
</tbody>
</table>
2.3 Modelling with SketchUp

The geometry of the building is modelled using TRNSYS 3D Plug-In for SketchUp based on the architectural drawing. The thermal zone, geometry, and boundary condition of all the surfaces of the building envelope are described in the SketchUp model. The SketchUp model is shown in Fig 3. The model is imported to TRNBUILD (TRNSYS Type 56). The boundary condition for all exterior surfaces, including the ground (see Fig 2), are subjected to the ambient air at the prescribed temperature and the interior surfaces are subjected to the zone air temperature. The standard values of the convective heat transfer coefficient of 3.06 W/m²K and 4.44 W/m²K for inside and outside surfaces respectively are used as boundary conditions.

![Fig 3: Model of the building in SketchUp](image)

2.4 Modelling with TRNBuild

The overall heat transfer coefficient (U value) and the thickness of each construction type are given in Table 1. TRNSYS calculates the U-value for the surfaces for reference only. The U-value is calculated with combined heat transfer coefficients of 7.7 W/m²K inside and 25 W/m²K outside.

2.5 Windows and doors

There are four windows and two doors in the building. Windows are divided into two parts, the glazing and frame for modelling in TRNSYS. The window properties in the DOE-2 report format created by the Lawrence Berkeley National Laboratory WINDOW program is read by TRNSYS. The closest match windows were selected from the TRNSYS windows database as the specific windows are not available. The identification numbers of the selected windows are 7393001 and 7343. The description of the modelled and in-situ window properties are provided in Table 3. The U-value of the frame material of the selected windows (wood) were modified in TRNBuild to the U-value of the building window frame (Polyvinyl Chloride PVC) which is 1.7 W/m²K. The area of each of the windows is 0.65 m². The frame to window area ratio of 0.199 is used for all the windows. SHGC in Table 2 denotes the Solar Heat Gain Coefficient.
Table 3. In-situ and modelled window properties

<table>
<thead>
<tr>
<th>Window Type</th>
<th>Quantity</th>
<th>Frame Material</th>
<th>Glazing</th>
<th>Fill</th>
<th>U-value [W/(m²K)]</th>
<th>SHGC</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-situ</td>
<td>3</td>
<td>PVC</td>
<td>Triple pane</td>
<td>Argon</td>
<td>1.08</td>
<td>0.37</td>
</tr>
<tr>
<td>Modelled</td>
<td>3</td>
<td>Wood</td>
<td>Triple pane</td>
<td>Argon</td>
<td>1.01</td>
<td>0.61</td>
</tr>
<tr>
<td>In-situ</td>
<td>1</td>
<td>PVC</td>
<td>Triple pane</td>
<td>Argon</td>
<td>1.70</td>
<td>0.53</td>
</tr>
<tr>
<td>Modelled</td>
<td>1</td>
<td>Wood</td>
<td>Triple pane</td>
<td>Argon</td>
<td>1.66</td>
<td>0.62</td>
</tr>
</tbody>
</table>

There are two doors in the building. The doors are modelled as windows on Sketch Up and defined as 100% frame window on TRNBuild. The U-value of the frame is specified as 1.25 W/(m²K) which is the U-value of the door system. The area of each door is 1.625 m².

3. Simulation Procedures

3.1 TRNSYS Simulation SetUp

The simulation setup is shown in Fig 4. The Data Reader (Type 9e) labelled as Weather Input reads user-defined weather input described in Section 2.1. This is connected to the Total Horizontal Only Known Solar Radiation Processor (Type 16) labelled as Radiation Processor and the TRNBuild (Type 56) labelled as Building Model. The radiation processor calculates the radiation for each surface based on the orientation of the surface. This radiation processor requires horizontal radiation values and calculates the total incident radiation, diffuse radiation, and incident angle for all the surfaces. The surface tracking mode is set at 1 (fixed surfaces) since the surfaces are not moving. The default Reindl model mode is set for the tilted surface radiation model. The starting day is set a 1 day (the day of the year corresponding to the simulation start time). The latitude of Ottawa 45.42° N is specified and the shift in solar time (SHIFT) which accounts for the differences between solar time and located time is calculated using the equation

\[
\text{SHIFT} = L_{st} - L_{loc}
\]

Here, \( L_{st} \) denotes the standard meridian for the local time zone and \( L_{loc} \) represents the longitude of the location. The shift in solar time is calculated and specified as 0.69 degrees. The weather input and the radiation processor are linked to the building. The simulation results are displayed using a Printers (Type 25) labelled result. The simulation is run for 168 hours (7 days).

3.2 Simulation cases

The following four different scenarios are simulated in TRNSYS

1. Outdoor temperature varying between 0 °C and 40 °C. The heating and cooling systems are switched off. Infiltration, ventilation, and internal gains are not considered. The indoor temperature variation is simulated. The large temperature variation is specified to show the effect of the building envelope thermal resistance and thermal mass/inertia on fluctuating outdoor temperature.

2. Outdoor temperature is prescribed to vary between a minimum value of 25 °C and a maximum value of 35 °C representing a summer-like temperature variation. The indoor temperature is set at 20°C. The heat transfer through the building envelope due to convective heat exchange between outdoor air and outdoor building surfaces, conduction through the building envelope and convective heat exchange between the indoor building surface and indoor air is simulated. The attenuation and delay are calculated.
3. Outdoor temperature is prescribed to vary between a minimum value of 5°C and a maximum value of 15°C representing a mild winter-like temperature variation. The indoor temperature is set at 20 °C. The convective heat flux to the outside surface from the ambient air and the convective heat flux from the inside surface to the indoor air is simulated. The attenuation and delay caused by the building structures are determined.

4. Outdoor temperature is prescribed to vary between 0 °C and 40°C. The indoor temperature is fixed at 20 °C. This results in alternate cooling and heating. The heat transfer through the building envelope due to convective heat exchange between outdoor air and outer building surfaces, conduction through the building envelope and convective heat exchange between indoor building surfaces and indoor air is simulated. The attenuation, decrement factor and delay are then calculated. These scenarios are chosen for the purpose of analytical verification of the whole-building energy simulation program since the physical behaviour of their solutions are known. The physical behaviour of the solution for the second and third scenarios are mirror of each other about the horizontal axis. For the first and fourth scenarios, the mean values of the sinusoidal outputs are zero.

For this study, the simple model longwave radiation exchange within a zone is used for turning off inside longwave radiation. Outside longwave radiation in the building walls is removed by modifying the emissivity of each wall to zero. Outside longwave radiation in the windows is removed by modifying the window frame emissivity to zero and the front emissivity of the first window glazing in the building input description file (BIU) to zero. The inside and outside convective heat transfer coefficients of the walls and windows are set at 3.056 and 17.778 W/m²K respectively.

4. Mathematical description

4.1 The equation for convective heat flux to the air node

TRNSYS calculates the convective heat flux to the air node $\dot{Q}_i$ as

$$\dot{Q}_i = \dot{Q}_{\text{surf},i} + \dot{Q}_{\text{infl},i} + \dot{Q}_{\text{vent},i} + \dot{Q}_{\text{g,cl}} + \dot{Q}_{\text{cplg},i} + \dot{Q}_{\text{solair},i} + \dot{Q}_{\text{ISHCCI}}$$

Here, $\dot{Q}_{\text{surf},i}$ is the convective exchange from surfaces, $\dot{Q}_{\text{infl},i}$ is the infiltration gains, $\dot{Q}_{\text{vent},i}$ is the ventilation gains, $\dot{Q}_{\text{g,cl}}$ is the internal convective gains, $\dot{Q}_{\text{cplg},i}$ is the gains due to airflow from other air nodes, $\dot{Q}_{\text{solair},i}$ is the fraction of solar radiation entering the air node through external windows immediately transferred as convective gain to the internal air and $\dot{Q}_{\text{ISHCCI}}$ is the absorbed solar radiation on all internal shading devices of the zone directly transferred as a convective gain to the internal air. For all the studied scenarios, since infiltration, ventilation, internal gains due to people, equipment, etc. and solar radiation are neglected, Equation 3 reduces to

$$\dot{Q}_i = \dot{Q}_{\text{surf},i}$$

This implies the heat gain/energy usage of the building for sensible heating and cooling is due to surface gain because of the cyclic outdoor temperature.

TRNSYS models the heat gain due to the surface using the transfer function relationships of Mitalas and Arsenault [12]. Namely,

$$\dot{q}_{s,i} = \sum_{k=0}^{n_{bs}} b_{s} \cdot k^{T_{s,i}} - \sum_{k=0}^{n_{cs}} c_{s} \cdot k^{T_{s,i}} - \sum_{k=1}^{n_{ds}} d_{s} \cdot k^{T_{s,i}}$$

$$\dot{q}_{s,o} = \sum_{k=0}^{n_{bs}} a_{s} \cdot k^{T_{s,o}} - \sum_{k=0}^{n_{bs}} b_{s} \cdot k^{T_{s,o}} - \sum_{k=1}^{n_{ds}} d_{s} \cdot k^{T_{s,o}}$$

Here, $\dot{q}_{s,i}$ is the outside heat flux, $\dot{q}_{s,i}$ is the inside heat flux, $T_{s,i}$ is the temperature of the wall surface outside, and $T_{s,o}$ is the temperature of the wall surface inside. Equations 5 and 6 are time series equations evaluated at equal time intervals $k$. The current and previous times are represented by $k = 0$ and $k = 1$ respectively. The transfer function coefficients $a$’s $b$’s $c$’s and $d$’s are discrete-time series calculated by TRNSYS Type 56 using the Direct Root Finding (DRF) method [10]. The time step for computing these coefficients is termed as the “time base” in TRNSYS. This is necessary to differentiate between the simulation time steps. The simulation time step should be a multiple of the time base and can be smaller than or equal to the time base. The minimum time base of 0.2 hr was selected for calculating the transfer function coefficients. TRNSYS is known to have problems with very thick or highly insulated walls.
especially for shorter time steps and the stair-step phenomenon becomes noticeable when the ratio between the time step and the time base becomes lower [10]. The simulation time step is set at 0.2 hr, the same as the time base.

Although a window is thermally considered as an external wall, its thermal mass is negligible and Equations 4 and 5 are valid with

\[ a_s^0 = b_s^0 = c_s^0 = d_s^0 = U_{g,s} \]  \hspace{1cm} (7)

\[ a_s^k = b_s^k = c_s^k = d_s^k = 0 \text{ for } k > 0 \]  \hspace{1cm} (8)

The time lag, decrement factor and attenuation of the heat flux from the exterior of the walls of the building envelope are calculated using the following equations

\[ \text{Time Lag (Delay)} = t_{q_{si, max}} - t_{q_{so, max}} \]  \hspace{1cm} (9)

\[ \text{Decrement factor} = \frac{q_{si, max} - q_{si, min}}{q_{so, max} - q_{so, min}} \]  \hspace{1cm} (10)

\[ \text{Attenuation} = q_{so, max} - q_{si, max} \]  \hspace{1cm} (11)

Subscript max and min represent the maximum and minimum value of the variable respectively.

4.2 Initialization

The wall surface temperatures and thermal zone temperature are started off at 20°C and the outside and inside heat fluxes are initialized at zero. The previous timesteps temperature and heat flux values determined based on the number of transfer function coefficients are started off at 20°C and zero respectively.

5. Results and discussion

TRNBuild generates the transfer function coefficients based on the wall’s specification and the selected time base. The transfer function coefficients are used in Equations 5 and 6 for calculating the outside and inside heat fluxes. The results for the 4 cases are presented in the following subsections.

5.1 Case 1: The effect of thermal resistance and thermal mass/inertia of the building envelope

This scenario focuses on the ability of the building envelope to provide inertia against indoor temperature fluctuation. The effect of the thermal resistance and thermal mass of the building envelope is shown in Fig 5. As the outside temperature fluctuates between a minimum value of 0°C and a maximum value of 40°C, most of the heat gained when the outdoor temperature is higher than 20°C is stored in the building envelope and used to balance the heat loss when the outdoor temperature is below 20°C. Consequently, the temperature fluctuation is dampened by the thermal mass and the inside temperature fluctuates between 20 ± 2°C. This is useful for passive design and can be activated to reduces heating and/or cooling load depending on the climate and/or the day of the year. There is less than a 2% change in the maximum and minimum daily temperature between the second and third days. This shows it takes about 48 hours (2 days) for the TRNSYS results to stabilize based on the initial conditions.
5.2 Case 2: Cooling load for a summer temperature variation

In this scenario, the temperature variation is summer-like with only cooling requirement for indoor temperature control. The convective heat flux from the ambient air to the outside surface is shown to be attenuated by 3910 kJ/hr in Fig 5 due to the thermal capacitance of the building envelope. The daily maximum and minimum heat flux from the inside surfaces to the indoor air are 1349 kJ/hr and 809 kJ/hr respectively. The time lag between the maximum heat fluxes to the outside surface from the ambient air and that from the inside surfaces to the air is calculated as 10.6 hr and the decrement factor is 0.0604.

Fig 6: Plot of convective heat fluxes for summer temperature variation between 25°C and 35°C
The sensible cooling load is the sum of the convective heat flux from the inside surfaces to the air and the convective heat flux through the fenestration. The maximum and minimum daily values are 1349 kJ/hr and 809 kJ/hr respectively. There is less than 1% change in the maximum and minimum daily sensible cooling load between the second and third days as shown in Fig. 6. This shows steady-state is achieved after 48 hours (2 days).

5.3 Case 3: Heating load for a winter temperature variation
The scenario with only heating requirement is shown in Fig 7 and the results are similar to that for the scenario with only cooling. The plots in Figures 6 and 7 are a mirror of each other about the horizontal axis with the exception of the plot of convective heat flux through the fenestration. This is because both temperature fluctuations are of the same amplitude of 5°C and the mean of the summer-like temperature variation (30°C) and the mean of the winter like temperature (10°C) variation are both 10°C apart from the indoor set point temperature of the building. The plots of the convective heat flux from the fenestration in Figures 6 and 7 are not a mirror of each other because the U value of the window glazing are calculated for each time step and vary depending on the temperature dependent properties of the fill gas (argon). The daily maximum and minimum heat flux from the inside wall surfaces to the air in the building are 1158 kJ/hr and 656 kJ/hr respectively. The time lag between the maximum heat fluxes is 10.6 hr and the decrement factor is 0.0604. The maximum and minimum sensible heating loads are 1363 kJ/hr and 824 kJ/hr respectively. There is less than 1% change in the maximum and minimum daily sensible heating load between the second and third days. This shows steady-state response is achieved after 48 hours (2 days).

5.4 Case 4: Temperature variation switching on the heating and cooling alternatively
In this scenario, heating and cooling are switched on alternatively as the outdoor temperature fluctuates between 0°C and 40°C and the results are shown in Fig 8. The mean value of the convective heat flux to the outside surface from ambient air and the convective heat flux from the inside surface to the air are approximately zero as expected. The reason for this is the indoor set point temperature is the mean of the prescribed outdoor sinusoidal temperature variation. The mean of the convective heat flux from the fenestration is not zero since temperature dependent properties of the gas fill (argon) are used in calculating the U value of the windows for each time step. The heat flux from the inside wall surfaces to the air in the building is attenuated by 15,640 kJ/hr. The daily maximum sensible cooling load is 1071 kJ/hr while the maximum heating load is 1086 kJ/hr. The decrement factor and time lag are 0.0604 and 10.6 hr respectively.
6. Conclusion

The warm-up period (transient time) for TRNSYS building models is scarcely documented in open literature. Our work has quantified the warm-up period for the building using outdoor sinusoidal temperature variation. The results show that it takes about 48 hours (2 days) to obtain accurate steady-state results for the building. It is important to consider this warm-up period during simulations to account for heat distribution in the building thermal mass at the start of the simulation. In this study, the effect of the thermal inertia/mass of the existing walls improved from 1.80 m²K/W to about 6.40 m²K/W is illustrated using a sinusoidal outdoor temperature variation between 0°C and 40°C. The thermal inertia of the building envelope dampens the effect of the outdoor temperature fluctuation, and the indoor temperature varies between 20 ± 2°C.

Heat balance at the outdoor and indoor faces of each of the building envelope surfaces and the conduction through the wall using the conduction transfer function coefficients were taken to verify the simulation result by hand calculation. The time lag and decrement factor of the building envelope are calculated to be 10.6 hr and 0.0604. The effect of summer-like outdoor temperature variation on the cooling load and winter-like outdoor temperature variation on the heating load is estimated. Both outdoor temperature variations have the same amplitude (5°C) and the mean point of both are 10°C from the indoor setpoint temperature. The maximum and minimum daily sensible cooling loads are 1349 kJ/hr and 809 kJ/hr respectively while the maximum and minimum sensible heating loads are 1363 kJ/hr and 824 kJ/hr respectively. The energy usage is estimated for a temperature variation between 0°C and 40°C, cooling and heating are switched on simultaneously to maintain the indoor temperature at 20°C set point. The maximum sensible cooling and sensible heating loads are 1071 kJ/hr and 1086 kJ/hr.

In our next step, we will be including the local weather condition and exploring different options for retrofittting the building based on certain design constraints to get the best retrofit solution. The use of Phase Change Materials and/or Building Integrated Photovoltaics in energy management of the building will also be modelled using TRNSYS simulation software.

7. Acknowledgements

This work is partially supported by Natural Science and Engineering Research Council of Canada. The authors are indebted to CanmetENERGY and Natural Resources of Canada. In addition, we are most grateful to Brock Conley for all the timely help he has provided.
8. References


