Energy use analysis and simulation of MUN CSF Building using BEopt

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***Abstract*—This paper presents yearly energy use data of MUN Core Science Facility (CSF) building. The data shows that 12,876,967 kWhr of electricity and 38,432,359 kBTU of heat energy was used by the CSF building in 2022. Thermal model of CSF building is developed in Building Energy Optimization Tool (BEopt) using the collected building envelope parameters. Envelope parameters include R values of walls, windows, roofs, floors, and HVAC parameters such as total heating/cooling capacity, fan power, and outside air minimum ventilation. A comparison between actual energy consumption and consumption predicted by BEOpt is also included. The Simulink thermal model of CSF building is also developed to demonstrate that the building indoor temperature can follow varying set point temperature. Results show that the heat energy calculated by our BEopt model is 35,824,572 kBTU, which is only 6.8% less than the real CSF building heat energy use.**

Keywords—building power consumption, building simulation, BEopt

I. Introduction

Buildings consume a lot of energy due to various reasons, such as heating, cooling, lighting, and appliances. In Newfoundland and Labrador, Canada, the end-use demand is 180.6 PJ in 2019, ranked the fourth largest energy demand based on per capita [1]. According to the electricity cost [2], the total cost is an estimated number between \$3.26B and \$10.43B. As for buildings in college/university, the relatively dense population and experiments carried out in scale require even more energy consumption and higher carbon dioxide emissions than residential buildings. In Canada, the national median value of site energy use intensity (EUI) for college/university is 1.01 GJ/m2 in 2021, while this number for multifamily housing is 0.82 GJ/m2 [3]. In 2022, the Newfoundland and Labrador regional median greenhouse gas (GHG) emissions intensity for college/university is 23.0 kg CO2e/m2 and 18.8 kg CO2e/m2 for multifamily housing [4]. With the typically spacious campus and large building area, the total energy consumption and the CO2 emission of buildings in college/university can be large. Energy analysis of buildings in universities should be carried out to obtain the energy profile to prepare targeted energy-saving techniques in the future.

Paper [5] compared the system loads of measured data in real home with simulated data by BEopt. First, current, voltage, and power data were measured by sensors and stored in data loggers. Then, the building modeling was realized by BEopt. Comparison between circuit-level metering results and BEopt simulation outputs indicated a few findings based on different time levels. HVAC OUTSIDE in BEopt consumed less energy during one year than in real life. Monthly energy usage of data from metering was consistently larger than simulation results.

Authors of [6] conducted a sensitivity analysis of BEopt input parameters to find the most important parameter that affected energy consumption. First, the authors built a parameter pool by finding the most common parameters existed in three building simulation softwares (including BEopt) and three webtools. The analyzed parameters that were found to significantly impact energy consumption include building orientation, air leakage, space conditioning equipment, space conditioning schedule, water heater, and terrain. Following this, a sensitivity analysis was conducted by varying each parameter while keeping the remaining parameters constant until all options in the parameter pool were evaluated. The results indicated that space conditioning schedule, water heating equipment, and space conditioning equipment were the three most influential parameters in terms of energy consumption.

In article [7], the author examined the power usage for a year of two homes in St. John's, Newfoundland. Weather data during one year, thermostat settings, and occupancy statistics were used in the simulation to analyze the energy optimization. Each residence was equipped with data collecting technologies to give a realistic assessment of energy usage. BEopt software was utilized to conduct a comprehensive analysis of the houses, which revealed that the annual energy consumption closely aligns with the measured energy consumption of both residences.

The objective of this paper is to use BEopt to simulate the energy usage in the Core Science Facilities (CSF) building at St.

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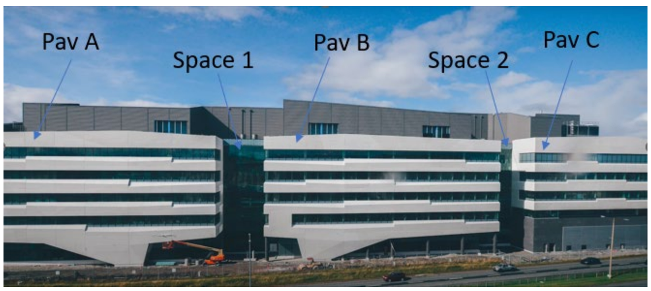
John's campus, Memorial University of Newfoundland, Canada. The simulation result will be verified with actual energy source usage during 2022. The rest of this paper is organized as follows: Section 2 describes the data we collected from Facilities Management at MUN and the proposed design in BEopt. Section 3 presents the dynamic modeling of the whole building. Section 4 covers the results and analysis of Section 2 and 3. Section 5 is the conclusion.

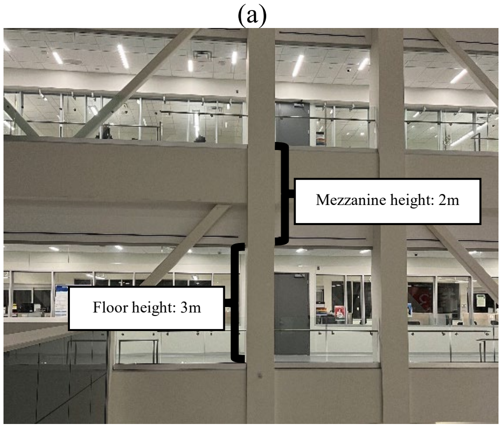
II. Proposed Design in BEopt

A. *CSF Building Details*

Located in St. John's campus, CSF building is a large area with around 184 m in length and around 42 m in width. There are three pavilions in CSF building. Pav A and Pav B both have five floors, while Pav C has an extra floor between Floor 1 and Floor 2. Fig. 1 is the outside and inside views of CSF building.



(a)



(b)

Fig.1. (a) MUN CSF Building overview, (b) Floor height and mezzanine height in CSF building.

Collected from campus facility department, the monthly oil consumption for heating in kBtu is presented in Fig. 2. The yearly sum of energy used for heating is 38,432,359 kBtu.

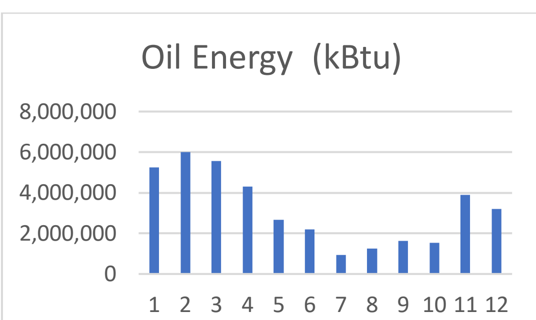


Fig. 2. Oil energy consumption in 2022 of CSF building.

B. *BEopt Options*

The specific parameters that are inputted into the BEopt software vary based on the building and the goals of the analysis. Below is the brief introduction of the input options collected or calculated. The units given are converted accordingly, if required, by using appropriate formulas. For the other input options where the information is not accessible, they are kept default values of BEopt.

- **Building Geometry**

The whole building is 184*42 square meters, which is 83183 square feet. The area of Pavilion A and B is around 33454 square feet and 16275 square feet for Pavilion C. The height of CSF building is 27 meters. Project north is about 30°W of the true north. Window aera is about 40% of overall envelope aera.

- **VERTICAL GLAZING U-FACTOR**

For vertical glazing option in software U- value is taken as input. U value is basically heat co-efficient value whose unit is Btu/h-ft². For the building its value is U-0.29 Btu/h-ft²-°F, COG; U-0.42 Btu/h-ft²-°F, assembly.

- **VERTICAL GLAZING SHGC**

Solar heat gain coefficient (SHGC) is the percentage of solar radiation that is allowed through a window, door, or skylight either directly transmitted or absorbed, then later released as heat within a home. We can see direct option to input the value of SHGC in windows and door option. Its proposed design value is 0.38.

- **TOTAL COOLING CAPACITY**

The ability of an air conditioning system to extract heat from a space and make it cooler is known as its cooling capacity. The total cooling capacity for this is 7 x 856 kW. And in the software in space conditioning option we can input this value in tons (1 kW = 0.284 Tons, in thermal domain).

- **OUTSIDE AIR MIN VENTILATION**

The value for outside air ventilation is 7 x 62,106 CFM. And we can input this value in software in airflow option. The term CFM refers to cubic feet per minute. It is a measurement of the amount of air that a fan moves in a minute, expressed in cubic feet.

Fig. 3 shows the designed BEopt input options.

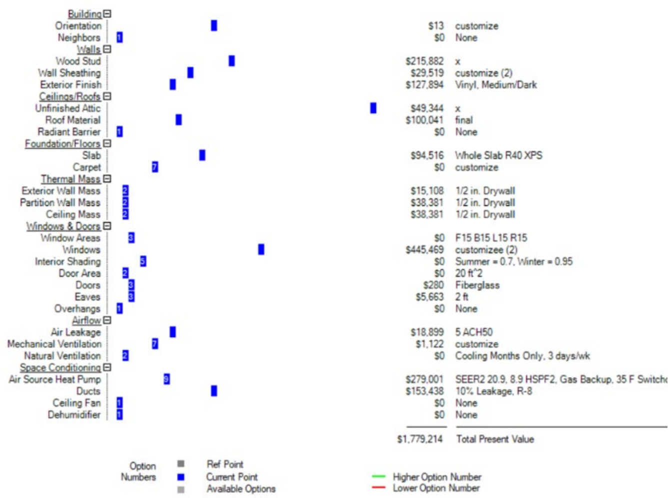


Fig. 3. Overview of BEopt designed inputs.

Monthly energy consumption calculated by BEopt is shown in Fig. 4.

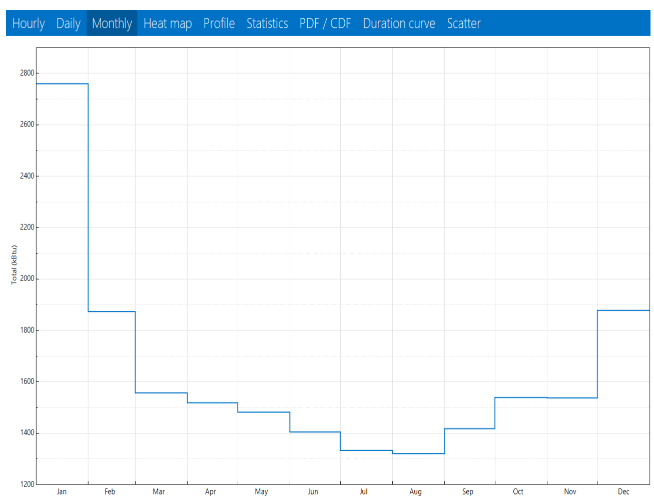


Fig. 4. BEopt results: Monthly energy consumption.

Yearly sum for Pav A, B, and C is 14,310,508.36, 14,310,508.36, and 7,203,555.64 kBtu, respectively. Total sum for the overall CSF building is 35,824,572.2 kBtu, which is 6.8% less than real energy consumption of 38,432,359 kBtu.

III. Proposed Design of Control

A. Heater & Chiller Command Generation

To begin with, the control objective is to fix the indoor temperature within a fixed range. In this work, the set point indoor temperature is set as 22 degrees Celsius, and the minimum and maximum indoor temperature is 21 and 23 degrees Celsius, respectively.

The control objective is achieved by the thermostat which functions as the controller. The difference of setpoint temperature and indoor temperature is fed into the controller as the error signal. Then the error signal is converted into binary signal representing ON/OFF states to control the heater and the chiller to turn on and off. When the error is more than or equal to 1, the heater/cooler needs to function to raise/lower the indoor temperature. Control mechanism for chiller follows the same way. The control process can be summarized as Table 1 shows.

TABLE I. Different States About Relay and Temperatures

Set Point Temperature	Indoor Temperature	Temperature Error	Notes	Chiller Relay Output	Heater Relay Output
	>23	<-1	Chiller works.	1	0
22	21~23	-1~1	Both chiller and heater do NOT work.	0 or 1, depending on previous working system.	0 or 1, depending on previous working system.
	<21	>1	Heater works.	0	1

The simulation of controller is realized in Matlab/Simulink as in Fig. 5. It's fast response with the setpoint temperature and robustness against outdoor temperature is presented in Section 4.

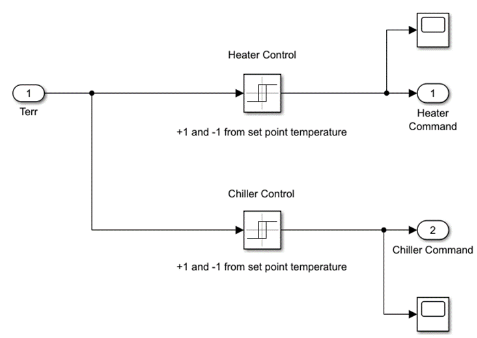


Fig. 5. Thermostat/Controller Simulink model.

B. Heater & Chiller

The heater works by firstly heating the air to a setpoint temperature, and then blowing it to other places at a constant rate. Air functions as the heat medium, to either absorb the heat or release the heat. The chiller works in a similar way by cooling the air and then distributing it across the target place. (1) and (2) are the equations describing the dynamic model of the heater and the chiller.

$$\frac{dQ_{heater}}{dt} = (T_{heater} - T_{room}) \cdot Mdot \cdot c \tag{1}$$

$$\frac{dQ_{chiller}}{dt} = (T_{chiller} - T_{room}) \cdot Mdot \cdot c \tag{2}$$

$T_{heater}, T_{chiller}, T_{room}$ are temperature of hot air from heater, cold air from chiller, and current room air temperature. $\frac{dQ_{heater}}{dt}, \frac{dQ_{chiller}}{dt}$ are heat flow from the heater, and cold flow from the chiller, into the building. $Mdot$ is air mass flow rate through the heater or the chiller (kg/hr). According to Energy Report, it is 231350 L/s, which is 8.33×10^8 kg/hr. c is the heat capacity of air at constant pressure. The realization in Simulink is shown in Fig. 6. Input 1 is the room temperature which represents the building temperature. Input 2 is the thermostat command which controls whether to start the heater. Input 3 is the thermostat command which controls whether to start the chiller. Output 1 is the heat flow by the heater and output 2 is the cold flow by the chiller.

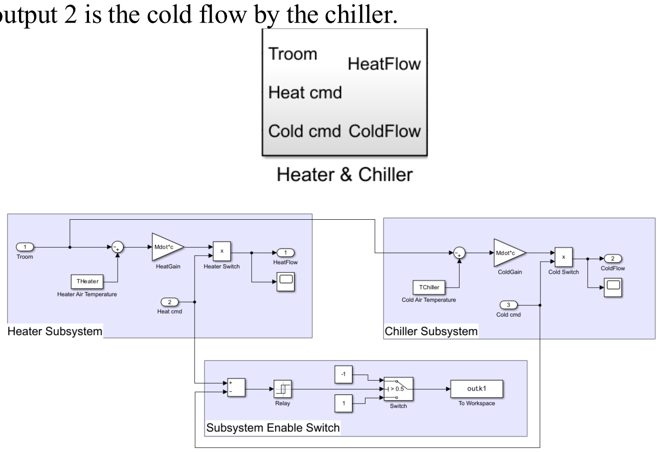


Fig. 6. Heater and Chiller Simulink model.

The heater subsystem and chiller subsystem follow (1) and (2). If the heat command or cooling command is off, the heat flow or the cold flow will stop.

C. Building

After the hot air generated by the heater is distributed across the building, heat loss from the building to the outside environment should also be considered. Building subsystem contains this dynamic process by (3) and (4).

$$\frac{dQ_{loss}}{dt}=\frac{T_{room}-T_{out}}{R_{eq}}=\frac{-(T_{out}-T_{room})}{R_{eq}} \tag{3}$$

$$\frac{dT_{room}}{dt}=\frac{1}{M_{air}\cdot c}\cdot\left(\frac{dQ_{heater}}{dt}+(-1)\frac{dQ_{loss}}{dt}\right) \tag{4}$$

Similarly, after cold air is generated, there is heat gain from outside environment. The dynamic process is presented by (5) and (6).

$$\frac{dQ_{gain}}{dt}=\frac{T_{out}-T_{room}}{R_{eq}} \tag{5}$$

$$\frac{dT_{room}}{dt}=\frac{1}{M_{air}\cdot c}\cdot\left(\frac{dQ_{chiller}}{dt}+\frac{dQ_{gain}}{dt}\right) \tag{6}$$

M_{air} is mass of air inside the building. R_{eq} is the equivalent thermal resistance of the building.

Comparing the heating and cooling equations, it is easy to find out that they follow identical structure, while the only difference is positive/negative signs for some terms. Therefore, the two dynamic processes can be concluded in one. Fig. 7 is the realization in Simulink. Input 1 is the outdoor temperature. Input 2 and input 3 are the heat flow and the cooling flow, which are also the output of the heater & chiller subsystem. Output is the room temperature, which is also the input 1 of the heater subsystem.

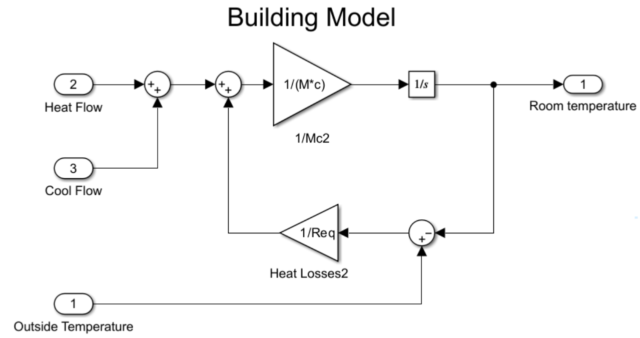


Fig. 7. Building Simulink model.

D. Overall System

Thermostat controls whether to start the heat flow or the cooling flow. When the outside temperature falls within a fixed range centered at a fixed temperature setpoint, heat flow or cooling flow will stop. When the temperature falls below the lower bound temperature, heat flow will start to be generated. After the indoor temperature is raised larger than or equal to the higher bound temperature, the cooling flow will be produced.

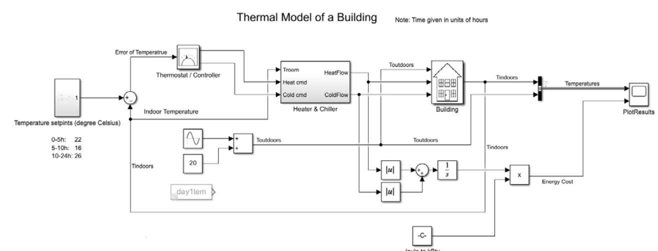


Fig. 8. Overall system Simulink model.

IV. Results and Analysis

Firstly, the outdoor temperature is represented by sinusoidal form, and temperature setpoint is varied, to fully test the control performance of indoor temperature. The result is shown in Fig. 9. This is for illustration use only, the flow rate was not correctly input. Blue line is the outdoor temperature represented by a sinusoidal waveform with minimum and maximum value of 0°C and 50°C. Black line is the indoor temperature fluctuating from 21°C to 23°C. Dashed yellow and orange lines are 21°C and 23°C. Regardless of the value of outside temperature, indoor temperature remains relatively constant around 22°C which is the set point. This proves that the designed control system is robust against the disturbance of outside temperature.

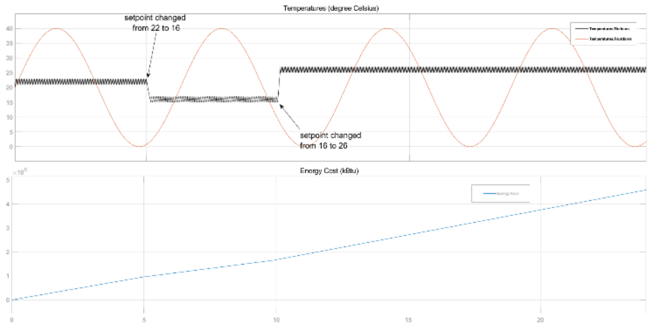


Fig. 9. Indoor temperature and energy cost, when outside temperature is theoretical.

At Hour 5, the temperature setpoint decreased from 22°C to 16°C. At Hour 10, the setpoint increased from 16°C to 26°C. Then the indoor temperature keeps fluctuating between ±1°C around the setpoint. The duration between two steady states is 8.28 minutes, as shown in Fig. 10.

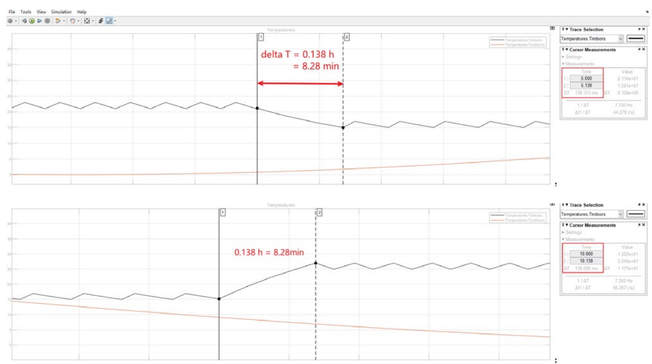


Fig. 10. Indoor temperature change period.

Then, the outdoor temperature is set to be real temperature data in St. John's in 2022. The result is shown in Fig. 11. The indoor temperature is within the temperature band as well. However, the yearly energy cost for heating is around 1.4×10^8 kBtu which is higher than 38,432,359 kBtu in Part 2 Section A. The possible reasons include real temperature setpoint is different from 20°C, and solar heating to the CSF building is not considered.

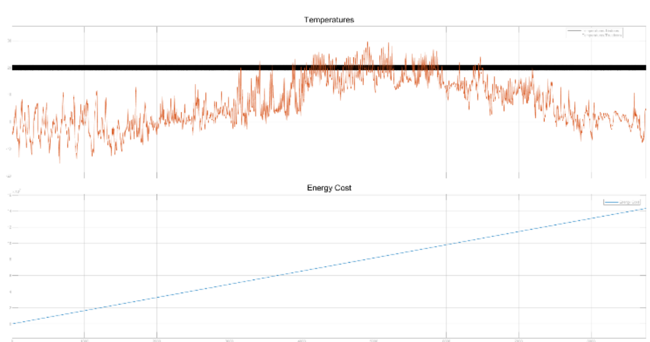


Fig. 11. Indoor temperature and energy cost, when outside temperature is real 2022 St. John's temperature.

V. Conclusion

This paper built the MUN CSF building model by collecting building envelope parameters, and accordingly constructing the model in BEopt. Envelope parameters include R value of walls, windows, roofs, and floors, HVAC parameters such as total heating/cooling capacity, fan power, outside air minimum ventilation. Input values are calculated and set to obtain an accurate BEopt model. The Simulink model of CSF building is also developed to demonstrate the building indoor temperature can follow varied setpoint temperature. First, outdoor temperature is represented by sinusoidal form, to present dynamic process of indoor temperature. Then, one year St. John's temperature data is set to be outdoor temperature. BEopt energy consumption result shows only 6.8% less than real MUN CSF building energy bill. After this verification of yearly sum of energy consumption, BEopt-generated CSF building hourly load data can be utilized to investigate renewable energy system sizing in the future.

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