Quebec Elementary School Enclosure Retrofit Performance Study under Future Climate

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Abstract

Schools are crucial yet often neglected public assets that require renewal to ensure quality education and asset preservation. This paper focuses on evaluating retrofit scenarios for energy efficiency and comfort in a typical Quebec elementary school using a building simulation model. The analysis highlighted that enhancing air tightness and insulation levels significantly lowers energy use intensity and improves comfort under current and future climate scenarios. The study assumed there were no cooling systems in place, which resulted in increased overheating hours during the cooling season. This study aims to demonstrate a method for parametric building retrofit performance simulation that can enable architects and school boards to quickly project building performance across different retrofit options.

Introduction

Schools are a common and underserved type of public infrastructure in Canada. It is in the best interest of the public to maintain schools in good condition to ensure a quality learning experience for the next generation and maintain the value of a public asset.

The objective of this paper was to create a building performance simulation (BPS) model which captures the performance characteristics of a typical school in Quebec and predicts key performance indicators under various retrofit scenarios and future weather conditions. The chosen building for this study was an elementary school in Rosemère, Quebec. The selected building represents an average school in floor area, number of students, classes and construction. The long-term objective of this research is to develop an archetype model for schools in Quebec and Ontario. This model will enable building professionals and school boards to rapidly simulate building performance for various retrofit scenarios. The goal is to facilitate low-carbon retrofits and offer guidance to schools on conducting analyses to engineer efficient retrofit designs.

Background

With the international target of Net Zero by 2050 fast approaching, retrofitting the existing building stock is critical. If properly designed, retrofitting aging buildings is efficient for cost, labour, material, time, and reduction of CO_2 emissions compared to full demolition and reconstruction, effectively giving a second life to an asset through reuse.

Buildings need to be retrofitted through a rigorous, analytical design process to meet future performance standards and weather conditions. It has been shown that reduction of CO_2 emissions and mitigation of construction and demolition waste are possible through optimized building retrofit (Shahi et al, 2020). Building retrofit also is less expensive than full demolition and reconstruction, allowing more schools in Quebec and Ontario to address their substantial maintenance backlogs.

Literature suggests that poorly maintained school buildings result in 5 to 15% more absences and 3 to 5% lower test scores (Illinois, 2003; Paladino, 2005; Schneider, 2002). Poor indoor environmental quality can lead to discomfort, asthma, colds, flus, allergies, difficulty concentrating, slow and reduced learning, tiredness, and headaches in children. This can lead to health problems, reduced learning and productivity later in life (Kats, 2006; Canada, 2017). It is critical to maintain healthy indoor environments in aging school buildings. This can be done through building retrofitting, and effective decision making can be supported by BPS.

Building performance simulation tools have commonly been used for school buildings in the literature. Many studies focus on natural ventilation, occupant behaviour modelling and new construction design performance evaluation or optimization. Parametric modelling has been used for air quality, acoustics, lighting, daylighting and thermal comfort optimization (Lorenz et al., 2021; Colarossi et al., 2022; Mahmoud et al., 2021). Schaffer et al. (2023) used BPS to evaluate the energy consumption and indoor environmental quality improvements of retrofitting schools in Denmark with double skin facades and ventilation and found this to be equally or better performing than traditional renovation techniques.

Du et al. (2011) simulated the impact of future climate projections for the United Kingdom on a new school's

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indoor temperatures and thermal loads. In Canada, overheating risk under future climate scenarios were simulated for two schools in Montreal built in 1960 and 1990 (Baba et al., 2023). The study investigated overheating risk mitigation measures such as exterior shading fins, a roof with high solar reflectance, exterior roller blinds and opening the windows at night and found them to be effective for future climate. Only passive cooling technologies excluding major envelope retrofit were studied.

This study aims to fill a gap in the literature because it parametrically evaluates the energy and indoor comfort impacts of major building envelope retrofit options on the typical aging school in Quebec's heating dominated climate under current and projected climate scenarios.

Magnitude of the Schools Problem

Over 5.7 million students in Canada were enrolled in elementary and high school in 2021 with 91% of them attending public schools (Statistics Canada, 2023). As of 2020 in Canada there are about 14 600 public schools with an average of 390 students per school; over 10 000 of these are elementary schools (Council of Ministers of Education, 2024). A metric commonly used for large scale property management and asset assessment is the Facility Condition Index (FCI). FCI is the simple ratio of the 5-year renewal cost to the asset replacement value as a percentage. The Quebec Ministry of Education defines a FCI of 15% or higher as indicative of a building being in poor or very poor condition (2022a). This indicates that the building has surpassed the end of its useful life, shows a high level of deterioration, and requires significant maintenance (Quebec, 2023).

As of February 2023, the Quebec Ministry of Education owns 4107 buildings (2022b). The mean FCI for schools is 22%, while 64% are in poor or very poor condition. Similarly, in Ontario there are about 4595 schools with a mean FCI of 31% while 73% can be classified under poor or very poor condition (Ontario, 2019).

Methodology

School Description

First, a typical two-storey elementary school in Quebec was selected for this case study (Figure 1). The school is in a suburban area. The building is about 4000 m^2 and it served 353 students in 17 classes in 2021 (CSSMI, 2022). The building orientation is southeast (133°), and it is unobstructed. The building has been maintained and extended over the years with the most recent extension taking place sometime between 1994 and 2002. The building is under 20 km from the Montreal International Airport (Climate Zone 5A).

Building Information Modelling

The CAD environment used to build the model geometry is Rhino 7. The geometry was turned into an energy model using Honeybee plug-in while HVAC system was scripted using IronBug. EnergyPlus was used as the simulation engine.

Figure 1: School Isometric (Google Earth, 2022).

Model Inputs

The model captures the essential characteristics of the representative geometry, boundary conditions, material properties, systems, occupancy, plug loads and operational schedules. The school geometry, assemblies and HVAC systems were modelled based on incomplete drawing sets provided by the school board.

The boundary conditions and zones are shown in Figure 2. The school is on a slope, so the highlighted blue surfaces are exposed to outdoor ambient conditions while the brown are below grade. The simulation model assumes 57 thermal zones, representing classrooms, offices, corridors, and others.

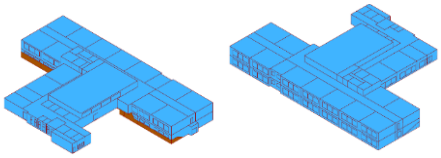

Figure 2: Front (left) and Back (right) View of the School.

The ventilated flat roof, typical wall, below grade wall, and floor assemblies were determined using renovation construction drawings from 1958, 1981 and 2012. Table 1 summarizes the existing enclosure assemblies. The baseline thermal properties are as shown in Table 2. Note that while the wall R value is typical for a building of this age the roof insulation level is high (RSI-11) due to several renovations throughout the years. The existing windows appear to be from 1981 and are fixed or horizontal sliders with one or two panes of glass with an aluminium frame. They are modelled as U = 5.7 W/m^2K (U_{IP} = 1.0 BTU/ $ft^2 \cdot °F \cdot h$), with a solar heat gain coefficient of SHGC = 0.80, and visible transmittance TVIS = 0.88. The current window to wall ratio is WWR = 19%. Based on the elevations, some former windows have been covered up and could be easily

recovered to increase WWR = 26%. The specific location of these potential windows was included in the model as optional additional window area controlled by a Boolean input.

Table 1: Baseline Enclosure Assemblies
(from exterior to interior)

Roof
elastomeric bitumen waterproofing membrane
16 mm (5/8") gypsum sheathing
16 mm (5/8") plywood
200 mm (8") air space
200 mm (8") blown cellulose insulation from 2012 renovation
300 mm (12") fibreglass batt insulation
100 mm (4") concrete
Wall
100 mm (4") brick
25 mm (1") air space
200 mm (8") concrete block
Below Grade Wall
300 mm (12") reinforced concrete
13 mm (1/2") air space
100 mm (4") concrete block
Floor
125 mm (5") reinforced concrete

Air tightness testing was not available for the school. To establish a baseline air tightness, a study by Shaw and Jones (1979) for the National Research Council of Canada was referenced. The study measured the air tightness of 11 schools built between 1952 and 1973 in Ottawa, which has a very similar climate and construction typologies to the case study. The average overall air leakage rate per unit area of exterior walls converted to 4 Pa pressure difference is Q_4 = 1.2 L/(s m^2). This value was used as the baseline air tightness since the building was constructed prior to 1958. Note that the National Energy Code of Canada for Buildings 2020 section 3.2.4.2 requires a normalized air leakage rate under 1.50 L/(s m^2) at 75 Pa which is equivalent to Q_4 = 0.22 L/(s m^2). This value was used as the upgraded building air tightness. Since the building has an exterior area of 6300 m^2 and volume of 14 200 m^3, the baseline air tightness is approximately 2.0 ACH_4 and the upgraded air tightness is approximately 0.35 ACH_4.

Table 2: Baseline Assembly Thermal Resistance Values

Assembly	RSI (m²K/W)	R-value (ft²·°F·h/BTU)
Roof	11	64
Above Grade Wall	0.54	3.1
Below Grade Wall	0.39	2.2
Floor	0.066	0.37

The existing HVAC system consists of a natural gas boiler and a 4.5 kW electric boiler connected to hydronic baseboard heaters. There is exhaust ventilation in the bathrooms and kitchen which were excluded in the baseline model. The model assumes one baseboard heater in each zone. There is no fresh air supply or mechanical cooling. The HVAC system was modelled in Grasshopper Ironbug. The hot water heater was modelled as natural gas-fired with a constant efficiency of 80%.

In 2021, there were 353 students in 17 classes (CSSMI, 2022) so an occupancy of about 353 students, 17 teachers and 9 support staff was assumed; this resulted in a total of 379 people in an area of 3988 m^2 (OCC = 0.095 people/m^2).

The lighting power density was assumed to be equal to LPD = 7.5 W/m^2 based on ASHRAE 90.1 2022 Table 9.5.1. The inputs for electric loads were P_{load} = 16.5 W/m^2, for the gas equipment (water heaters for heating and water supply) were P_{heat} = 35 W/m^2, while the hot water demand was assumed equal to Q_{H2O} = 0.086 L/h/m^2 and the heating setpoint was set at $T_{heating}$ = 21°C.

Performance Metrics

The intent of the study is to evaluate the performance improvement of retrofit scenarios using key performance indicators (KPI). The intention is to improve thermal comfort and reduce energy consumption.

For the case study, the major concern is overheating since there is no cooling system. Thermal comfort was assessed by estimating the average number of hours for overheating (hot hours, HH) across the classrooms from September 1 to June 30 from 6:00AM to 8:00PM, using a typical year weather file. The overheating threshold was set to be 24°C during occupied hours.

Occupant comfort was also evaluated using the average percentage of people dissatisfied (PPD) over all classrooms over the school year so one value can be reported per scenario. The PPD calculation uses hourly measurements of air temperature, mean radiant temperature and relative humidity with a metabolic rate of 1.1 met, for seated activity, and a clothing level of 0.7 clo, for typical indoor clothing. Note that while HH accounts only for overheating events, PPD also captures occupant discomfort caused by either cold windows or excessive solar heat gains.

Reducing the energy consumption of a building will reduce the operational costs and mitigate greenhouse gas emissions. The building energy performance was evaluated using the annual energy use intensity (EUI).

The KPIs used are limited, focusing only on energy use and comfort. In future analyses, the KPIs can be expanded to also account for thermal resilience and demand side management.

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Parametric Analysis

A parametric analysis was performed to assess the impact of various retrofit scenarios. The following list summarizes the different retrofit options that were evaluated, resulting in 144 design retrofit permutations. The window options are explained in more detail in Table 3.

Exterior Wall Insulation

- RSI 0.54 m²K/W (R-3.1) (Baseline)
- +100 mm insulation → RSI 4.05 m²K/W (R-23)
- +200 mm insulation → RSI 7.55 m²K/W (R-43)

Roof Insulation

- RSI 11 m²K/W (R-63) (Baseline)
- +100 mm insulation → RSI 14.5 m²K/W (R-83)
- +200 mm insulation → RSI 18.0 m²K/W (R-103)

Airtightness

- 1.2 L/s/m^2 (2.0 ACH) (Baseline)
- 0.22 L/s/m^2 (0.35 ACH)

Window-to-Wall Ratio

- 19% WWR (Baseline)
- 26% WWR

Window Assembly

- Single pane (Baseline)
- Double glazed low-e air fill
- Double glazed low-e argon fill
- Triple glazed low-e air fill

Table 3: Window Assembly

Description	U W/(m²K) (BTU/ft²·°F·h)	Solar Heat Gain Coeff	Visible Transmittance
Single Pane (Baseline)	5.7 (1.0)	0.80	0.88
Double glazed low-e air fill	1.7 (0.30)	0.42	0.64
Double glazed low-e argon fill	1.4 (0.25)	0.43	0.64
Triple glazed low-e air fill	1.2 (0.22)	0.39	0.57

Present vs Future Climate Analysis

In addition to the analysis performed using historic weather files, four runs were completed using future weather files under a global warming scenario of 1˚C (GW1) and 3.5˚C (GW3.5), summarized as follows: i) the baseline case, ii) improved air tightness only, iii) improved RSI4.05 (R-23.1) wall only, and iv) both improved air tightness and the RSI4.05 (R23.1) wall. The Montreal International Airport future weather files developed by National Research Council of Canada (2022) were used.

Results

Each performance point is plotted on a PPD vs EUI plot where lower is better for all metrics (Figure 4). The EUIs ranged between 130 and 526 kWh/m^2 and the PPDs ranged from 23% to 34%.

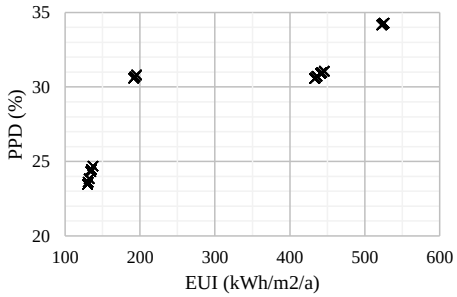

Figure 4: PPD vs. EUI Performance results of 144 simulations with historical weather file.

Four clear clusters of points stand out in Figure 4. Upon analysis, air tightness and wall insulation were the variations with the highest impact on EUI and PPD. The most efficient cluster (bottom left) represents 48 simulations where both airtightness and the wall insulation were improved; this cluster includes both improved wall insulation scenarios: RSI4.05 (R-23) and RSI7.55 (R-43). The second cluster from the left (EUI~193 kWh/m^2, PPD~31%) consists of 24 simulations where the air tightness is improved while the wall insulation remains as is. The next cluster (EUI~439 kWh/m^2, PPD~31%) consists of 48 simulations where the air tightness did not change but the wall insulation was upgraded. The final and worst performing cluster (EUI~524 kWh/m^2, PPD~34%) consists of all 24 scenarios with no changes regarding airtightness and wall insulation levels.

Additionally, each performance point is plotted on a HH vs EUI plot where lower is better for all metrics (Figure 5). The number of overheating hours averaged across classrooms ranged from 101 to 517 occupied hours per school year.

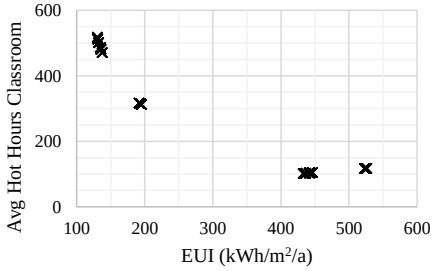

Figure 5: HH vs. EUI Performance results of 144 simulations with historical weather file.

The same four groups observed in Figure 4 appear here. The leftmost group with the most overheating hours and lowest EUI consists of 48 scenarios that all have improved air tightness and an improved wall insulation. The next cluster around HH~315 h and EUI~200 kWh/m^2 represents improved air tightness and baseline wall. The third and fourth clusters have similar overheating hours but different EUIs. The third cluster represents all 48 scenarios with baseline air tightness and an improved wall and has an EUI of about 439 kWh/m^2 and HH~103 h. The last group has baseline air tightness and wall with EUI 524 kWh/m^2 and HH 117 h. Each combination of the other variables exists within that cluster of points but it is clear they do not make a significant impact on the KPIs.

The current versus future weather scenarios are plotted on a PPD vs EUI plot (Figure 6). The EUIs ranged between 123 and 526 kWh/m^2 and the PPDs ranged from 24% to 34%.

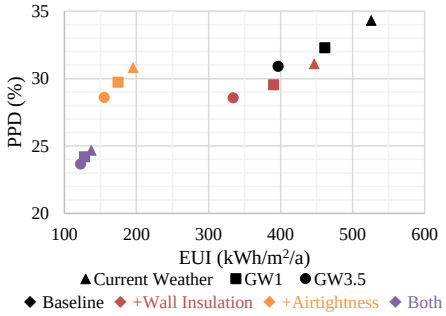

Figure 6: PPD vs. EUI Performance results of 4 key simulations with varied weather files.

The current versus future weather scenarios are plotted on an HH vs EUI plot (Figure 7). The overheating hours range from 104 to 618 average hours per school year across classrooms during daytime.

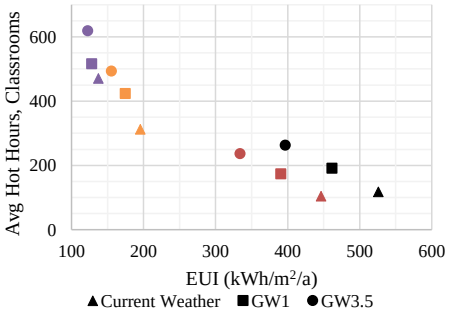

Figure 7: HH vs. EUI Performance results of 4 key simulations with varied weather files.

The number of overly cold hours under the heating setpoint of 20 °C was also calculated for each run but was less than 13 hours per year in all cases, caused by the time it takes for the room temperature to rise from the night to daytime set point.

Discussion

Figure 4 and Figure 5 illustrate that all the retrofit measures had a small impact on improving energy and comfort except for increasing air tightness and wall insulation. Adding wall insulation and air tightness improved EUI and PPD while worsening HH.

Wall

Upgrading the baseline wall RSI0.54 (R-3.1) to RSI4.05 (R-23) had a dramatic effect of reducing EUI by 19% (about 79 kWh/m^2) whereas adding another 100 mm (4”) of insulation had a small impact on the building performance (only reduced EUI by 10 kWh/m^2). In scenarios where other enclosure assemblies were improved, the effects of adding wall insulation dropped in magnitude since the overall EUI was lower to begin with, although the percent improvement of going from the baseline to RSI4.05 (R-23) jumped to an EUI reduction of 30%.

Upgrading the baseline wall RSI0.54 (R-3.1) to RSI4.05 (R-23) reduced PPD by about 3%, whereas adding another 100 mm (4”) of insulation had a small impact on the building performance (only reduced PPD by 0.3%). In a high-performance scenario (upgraded assemblies), going from RSI0.54 (R-3.1) to RSI4.05 (R-23) reduced PPD by 6% and RSI4.05 (R-23) to RSI7.55 (R-43) reduced PPD by only 0.9%. In scenarios where the other enclosure assemblies were improved, the effects of adding wall insulation dropped in magnitude since the overall PPD is lower to begin with, although the percent improvement increases.

With the baseline air tightness, adding 100 mm (4”) of wall insulation decreased the hot hours by a small 11% or about 13 hours. With the improved air tightness, adding wall insulation increased the hot hours by 158 hours or 50%.

Airtightness

Airtightness yielded even larger improvements in EUI than adding wall insulation for the baseline case (63% reduction or -330 kWh/m^2) and case with the most upgraded assemblies (70% reduction or -303 kWh/m^2). When the other enclosure performances are improved, the effects of adding air tightness drop in magnitude since the overall performance is improved to begin with, although the percent improvement increases.

Air tightness improved PPD by about 3.5% when the wall was baseline, 6% when the wall was R23 and 7% when the wall was R43 for all otherwise identical pairs of scenarios. Making the building more airtight increases the hours where it is too hot by one and a half (baseline) to four times (high performance case).

Other Improvements

The largest absolute EUI improvement within one cluster (i.e., without improving the air tightness or adding exterior wall insulation) was within cluster 3 and was only 3% or 14 kWh/m^2/a. The largest percent EUI improvement was in cluster 1 and was only 5% or 7 kWh/m^2/a. The largest PPD improvement within one cluster was in cluster 1 resulting in a reduction of 1.2 percentage points. The largest HH change within one cluster was in cluster 1 resulting in a 9% (or 46 hour) increase. The four scenarios are summarized in Tables 4 to 7. The minimal differences within each cluster demonstrate the fact that the enclosure retrofit options besides +R20 wall insulation and airtightness have a negligible effect (9% or less) on the KPIs, so they are not recommended for implementation. The largest percent difference in the KPIs for any single enclosure improvement while fixing the other retrofit options is presented in Table 8. The general trend of the KPIs is presented as well.

Since the window area was relatively small it makes sense that changes to the windows would have little impact on the KPIs. Although the existing window performance is below current standards, the windows form a small part of the enclosure area, so their poor performance is not reflected in the KPIs chosen for this study. However, in a real retrofit scenario window improvement may be valuable for achieving the desired airtightness levels and improving other performance issues such as noise and cold drafts. Adding extra window area may help with increasing views, mood, and natural daylight and reducing electricity costs for artificial light. This study found less than 1% change in the KPIs from adding window area.

The baseline roof (RSI-11, R64) is heavily insulated relative to the baseline walls (RSI-0.54, R3.1) due to past retrofits, so it makes sense that adding additional roof insulation has a negligible impact of under 4% for all KPIs.

Table 4: Largest Absolute EUI improvement within one cluster.

Retrofit Options	**Low**	**High**	
Wall	+R40	+R20	
Roof	+R40	Baseline	
ACH	0.35	0.35	
Window Area	Baseline	Baseline	EUI improvement 14 kWh/m^2
Window Assembly	Indifferent	Indifferent	
EUI (kWh/m^2)	**433**	**446**	

Table 5: Largest % EUI improvement within one cluster.

Retrofit Options	**Low**	**High**	
Wall	+R40	+R20	
Roof	+R40	Baseline	
ACH	0.35	0.35	
Window Area	Baseline	Extra	EUI improvement 3.9% diff
Window Assembly	Indifferent	Indifferent	
EUI (kWh/m^2)	**130**	**137**	

Table 6: Largest PPD improvement within one cluster.

Retrofit Options	**Low**	**High**	
Wall	+R40	+R20	
Roof	+R40	Baseline	
ACH	0.35	0.35	
Window Area	Extra	Baseline	PPD improvement 1.2% diff
Window Assembly	Indifferent	Indifferent	
PPD (%)	**23.5**	**24.7**	

Table 7: Largest HH deterioration within one cluster.

Retrofit Options	**Low**	**High**	
Wall	+R20	+R40	
Roof	Baseline	+R40	
ACH	0.35	0.35	
Window Area	Indifferent	Indifferent	HH change 9% diff 46 hours
Window Assembly	Indifferent	Indifferent	
HH (Hours)	**471**	**517**	

Table 8: Effects of Improvements on KPIs.

Improvement		**EUI**		**PPD**		**HH**			
		Trend	**Max % diff**	**Trend**			**Max % diff**	**Trend**	**Max % diff**
Wall Insulation	Add	↓	32	↓	7.1	↑	63		
Roof Insulation	Add	↓	2.1	↓	0.38	↑	3.3		
Air Tightness	Reduce	↓	70	↓	7.1	↑	410		
Window Area	Add	↓	0.11	↓	0.89	↑	0.04		
Window Assembly	Add Panes	--	0	--	0	--	0		

Future Weather

For any given enclosure scenario, the PPD and EUI performance improve with warmer weather (Figure 6). For all weather files, the trend of retrofit scenario improvement stays the same; the baseline has the worst performance, then either the wall insulation or airtightness single retrofit option, and finally doing both improvements yields the best performance. Adding wall insulation or air tightness improve PPD equally. The magnitude of absolute and relative PPD improvements from envelope upgrades lessens as weather warms, although the PPD is better overall in warmer weather.

Air tightness reduces EUI by 62% from the baseline whereas adding wall insulation only improves EUI by 15%. Using both retrofit strategies can reduce EUI by between 69 and 74%, with the percent savings decreasing in warmer weather. As the weather warms, EUI in low performing uncooled buildings in heating dominated climates will be reduced due to reduced heating demand.

For any given retrofit scenario, warming weather increases HH (Figure 7). Since future climate is warmer and the building is not cooled, overheating temperatures become more common. Adding wall insulation reduces HH by about 10% compared to the baseline for each weather scenario; this may be because in the instants where the outdoor temperature increases above comfortable, there is slightly more lag in the indoor temperature increasing. Adding air tightness increases the HH by about 200 hours under all weather scenarios because internal heat gains have a higher impact on indoor air temperature when there are fewer air changes. Increasing air tightness and wall insulation results in about 345 more overheating hours under all weather scenarios. Note that the overheating issue can be potentially mitigated with various natural ventilation strategies (e.g., night cooling), although this simulation study did not account for such strategies.

Since Montreal is a heating dominated climate, and the only HVAC system in this building is heating, the future warmer weather scenarios will reduce EUI. PPD is reduced since the outdoor temperature is more often closer to a comfortable indoor air temperature. This positive improvement would be dampened in a building which also has cooling systems since the climate warming would increase the demand for cooling. Overall, warming weather will significantly increase the time the indoor temperatures exceed comfortable conditions in buildings without cooling. Note that the key performance indicators used in this study are limited and do not capture some future weather climate considerations like increased extreme weather.

Conclusion

The study examined a representative elementary school near Montreal, Quebec, using building performance simulations to evaluate various retrofit strategies for energy conservation and comfort. The findings clearly demonstrated that enhancing air tightness and insulation can reduce energy consumption by 4 times and increase comfort by 10%, compared to the current state of the building. However, these changes will also create 5 times the overheating hours in an uncooled building, so any building upgrade plans in this climate, including air tightness and insulation, should also include cooling. The analysis also indicated that the proposed retrofits improve performance even in future weather scenarios, although to a lesser magnitude. The parametric analysis indicated that upgrading the building's envelope to attain an air tightness of 0.22 L/s/m^2 and enhancing wall insulation to RSI4.05 can significantly improve comfort and energy efficiency in both present and anticipated future climate conditions, although it will make it hotter indoors in June and September if cooling is not added.

Future Work

This study demonstrated analysis techniques for a parametric building envelope retrofit analysis of an existing school in Quebec for comfort and energy use with future weather conditions. This method can be used by architects and school boards to evaluate building performance under various retrofit scenarios.

Future steps involve calibrating the model with actual electricity and natural gas bill data and examining the effects on energy usage and greenhouse gas emissions from replacing a gas furnace with an air-source heat pump and the integration of a rooftop photovoltaic system. Additionally, incorporating key performance indicators to evaluate daylight autonomy, peak loads, visual comfort, climate resilience and greenhouse gas emissions will be a critical aspect of advancing the model's utility.

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