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A screening methodology for implementing cost effective energy retrofit measures in Canadian office buildings

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ABSTRACT

Private and public sectors own and operate an array of office buildings that consume energy and contribute to the emission of greenhouse gases (GHG). Energy demands can be reduced by applying energy retrofit measures (ERMs) to existing buildings. The choice of ERMs involves evaluation of applicability, energy end uses and cost of application versus energy savings. This paper describes a methodology developed to screen office buildings for their current level of energy consumption and potential for retrofit application. Selection of an optimal set of ERMs is influenced by climate, occupancy, heating and cooling systems, envelope properties and building geometry. When assessing the implications of applying ERMs to a large building stock it is vital to screen the complete building set for optimal retrofit opportunities. This can be accomplished by characterizing office building stock into a manageable set of archetypes and simulating building operation using energy simulation software. Using regression analyses, a model was developed for estimating the energy consumption. Present value analysis was used to optimize the evaluation of the various ERMs. The methodology developed can be used to simplify the ranking of buildings for retrofit; to select and combine ERMs, and to plan energy and GHG reduction activities.

1. Introduction

The escalation of energy costs and impacts of energy consumption on the environment have compelled government agencies and researchers to develop tools and retrofit measures to conserve energy in existing buildings. On the demand-side, a multi-country effort under the International Energy Agency has led to the gathering, evaluation and documentation of the largest collection of energy retrofit measures (ERMs) for commercial, residential and industrial buildings. This effort has recently published the "Energy Process Assessment protocol" which describes how to assess typical buildings for the application of ERMs and to select suitable ERMs for each building type [1]. Various modelling techniques for estimating the energy consumption of buildings have been developed. Some predictive tools use recorded and/or generated energy consumption data along with statistical methods such as regression methods, artificial neural networks (ANN), or decision trees, to forecast the energy consumption of buildings [2–6]. Others, including EnergyPlus, DOE 2.1 and eQuest®, use more fundamental approaches such as the mass and heat balance technique to simulate the building thermal loads [7–9]. The predictive tools are simple, limited to the scope of the building archetypes, easy to use and provide good predictions of the building energy consumption. The fundamental programs, such as the energy simulation software approved by the Leadership in Energy & Environmental Design (LEED®), can model the thermal performance of most buildings, but their use is limited to trained professionals. Employing these fundamental tools to assess the energy reduction opportunities of a large number of specific buildings is neither feasible nor practical.

The reduction of energy consumption in existing buildings can be achieved through the implementation of ERMs that range from physical changes to a building to changes in operational practices including advanced controls and efficient lighting. A means for determining the effects of ERMs on energy consumption and accounting for the wide variety of building characteristics was developed. This methodology incorporates climate region, pre/post retrofit energy consumption, ERM implementation and energy costs, interest and inflation rates. The ultimate goal was to develop a standardized process by which general building properties can be used to estimate energy consumption and thus optimize the selection of the most desirable and cost-effective energy retrofit measures and measure sets.

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Nomenclature

$(P/A, i, N)$	series present worth factor [23]: $[(1+i)^N - 1]/[i(1+i)^N]$
AMD	difference in the annual maintenance costs (assumed a constant difference, otherwise zero) ($)
AFC_e	annual electricity unit costs for year one ($/kWh)
AFC_g	annual natural gas costs for year one ($/kWh)
S_e	calculated annual electrical savings (kWh)
S_g	calculated annual natural gas savings (kWh)
g_e, g_g	annual growth rate expected on fuel costs, electrical and natural gas source
i_f	inflation adjusted interest determined using the inflation rate (f) obtained from the Bank of Canada and the minimum acceptable rate of return (MARR) on investment.
$i_{fe}{}^{\circ}$	growth adjusted interest rate for electricity based on inflation and MARR
$i_{fg}{}^{\circ}$	growth adjusted interest rate for natural gas based on inflation and MARR
N	payback period (years)
$(A/P, i, N)$	capital recovery factor [23]: $i(1+i)^N/[(1+i)^N - 1]$
LOP	loss of production
L	loan amount (known)
N_L	agreed upon number of payments to payback loan
i	interest rate associated with the loan
f	inflation rate

The methodology proposed uses the concept of building archetype modelling to develop a database on the effects of ERMs on energy consumption. The goal of this database is to formulate a set of mathematical equations that can be used to estimate the energy consumption of office buildings based on a set of key variables. This approach allows the rapid estimation of a building's energy consumption before and after the implementation of ERMs. By combining the energy calculation model with an economic analysis, a screening methodology is developed to determine the feasibility and cost effectiveness of implementing ERMs in office buildings.

2. Energy modelling

In order to develop a calculation tool for estimating the energy consumption of a building, one must first select an appropriate energy modelling software package. The modelling package needs to be adaptive to many different office-building configurations, as well as accepted by the industry for its robustness and accuracy in estimating energy consumption. There are a wide variety of software programs currently available that have the capability of modelling the energy consumption of various types of buildings. A review of 20 energy modelling programs was performed and each tool was analyzed for the specific features pertaining to this study [10]. This included an analysis of how building characteristics are defined as well as an examination of how each program handles economic assessments, environmental emissions, weather characteristics and results reporting. The suitability of EnergyPlus was further evaluated by comparing the metered energy consumption of nine office buildings to simulated results. The buildings ranged in construction age from 1931 to 1986 and possess many different building attributes [11]. The results from the simulations, corresponding to electrical and natural gas/fuel oil consumptions, were found to have a strong agreement with the metered consumption values [11]. The normalized mean bias error (NMBE) for the nine buildings was calculated to assess the calibration of the Energy Plus model and found equal to 6% for electricity and 8% for natural gas. These results are within the ASHRAE Guideline 14 stipulated limits of ±10% [12,13]. The percent error in the root mean square error of the monthly (RMSE) data was also evaluated and found equal to 9% for electricity and 12% for natural gas. Moreover, the maximum percent error in the model prediction of the electricity and natural gas consumption is, respectively, 9% and 15% of the metered value for the nine buildings [11]. As a result of this assessment, EnergyPlus [14] was selected for use in the development of the screening methodology.

3. Building archetypes

Office buildings vary by fuel source used, age, size, occupancy characteristics, heating and cooling systems, location, orientation and building envelope construction practices. To capture the majority of construction possibilities, buildings were grouped into a set of archetypes reflecting the age, size, type of construction, and location. Accordingly, three building archetypes were proposed. They were based on several distinct years for which major changes in construction practices occurred; Archetype #1 – buildings constructed prior to 1950, Archetype #2 – buildings constructed between 1950 and 1975, and Archetype #3 – buildings constructed post-1975. For each of the archetypes, a set of predefined building types was also assigned. These building types were selected to capture the three main types of structures prevalent in the Canadian office building stock. Two of these buildings possess brick veneer/concrete block walls and have a low window to wall ratio. This is typical for low-rise structures and is more common in older medium-rise structures. A third building type, composed primarily of curtain-walls with a high window to wall ratio, was chosen to represent the majority of newer high-rise office buildings. Conforming to the archetype categories presented, the three building types selected were, Building Type LV – Large (12 storey, 24,000 m^2) with a brick Veneer/concrete block backup exterior wall, Building Type LC – Large (12 storey, 24,000 m^2) with an exterior Curtain wall, and Building Type S – Small (2 storey, 4200 m^2) with a brick Veneer/concrete block backup exterior wall. The primary source of information concerning the construction characteristics of the walls, roof and fenestration came from guidelines and standards available at the time of construction, namely ASHVE [15,16] and ASHRAE [17–19]. The building archetypes description, construction and equipment properties are presented in Table 1.

4. Simulation strategy

A strategy for simulating each variable change was developed to capture the effect that changing individual and multiple variables has on the energy consumption of a building. It centres on how the archetype scheme was developed. Since three archetypes were chosen to represent stages in building construction practices, the variables associated with these three time periods were first defined and set as a starting point for variable alteration. First the "Base Level" model was simulated for its energy consumption. The "Base Level" variables were adjusted, individually, to reflect a change in the archetype. For example, for a building of the pre-1950s era, the base lighting load was set to 26 W/m^2, then the lighting load was updated to 17.8 W/m^2 to reflect the difference between pre-1950s levels and 1950–1975 levels. This process was repeated for each of the variables and for each of the archetypes, including a "Retrofit" archetype that contained additional upgraded levels. A total of 12 ERMs were chosen to reflect the progress made in the construction and HVAC industry to reduce energy consumption. The first was to reduce the lighting load to a value of 10 W/m^2, reflecting the impact of changing the lighting fixtures within a building to high efficiency fluorescent units (T8 lamps) from lower

Table 1
Building types Large brick Veneer (LV), Large Curtain wall (LC) and Small brick veneer (S) with archetype descriptions and ERMs.

Attributes	Building LV	Building LC	Building S
No. of storeys	10 above and 2 below ground	10 above and 2 below ground	2 above ground
Floor area	24,150 m^2	24,150 m^2	4200 m^2
Volume	84,525 m^3	84,525 m^3	14,700 m^3
Heating	Hot water (natural gas)	Hot water (natural gas)	Hot water (natural gas)
Cooling	Chilled water (electricity)	Chilled water (electricity)	Chilled water (electricity)
External walls	Brick veneer on concrete block with plaster and insulation	Curtain wall with aluminum siding and insulation	Brick veneer on concrete block with plaster and insulation
Roof	Metal roofing deck	Metal roofing deck	Built-up concrete
Windows	Single glazed	Double glazed	Single glazed
Shading	None	Medium reflectivity blinds	No blinds

Archetypes	Pre-1950	1950–1975	Post-1975	Current
Retrofit		Double glazed windows; add medium reflectivity blinds		Daylighting with light dimming; 60% air to air heat recovery
Lighting load (W/m^2)	26	17.8	17.8	10.0
Equip/appliance load (W/m^2)	10	20	30	30
Elevator load (kW)	4 × 30 [LV,LC]; 30 [S]	4 × 30 [LV,LC]; 30 [S]	4 × 30 [LV,LC]; 30 [S]	4 × 30 [LV,LC]; 30 [S]
Occupant density (m^2/person)	30	25	20	18
Fenestration (%)	30 [LV,S]	40 [LV,S]; 85 [LC]	50 [LV,S]; 100 [LC]	50 [LV,S]; 100 [LC]
Fenestration *U*-value ($W/m^2\,°C$)	6.42 (SGHC = 0.81)	4.50 (SGHC = 0.68)	3.40 (SGHC = 0.47)	1.8 (SGHC = 0.41)
Wall *U*-value ($W/m^2\,°C$)	1.21	1.21 [LV,S]; 0.37 [LC]	1.16 [LV,S]; 0.37 [LC]	0.55 [LV,S]; 0.37 [LC]
Roof *U*-value ($W/m^2\,°C$)	1.41 [LV]; 1.36 [S]	0.74	0.64	0.47
Infiltration (ACH)	1.0	0.75	0.5	0.5
HVAC system	Ventilation type: CAV Heating eff.: 0.75 Cooling COP: 1.8	Ventilation type: CAV Heating eff.: 0.75 Cooling COP: 2.5	Ventilation type: VAV (turndown ratio = 0.3) Heating eff.: 0.75 Cooling COP: 5.2 [LV,LC]; 2.5 [S]	Heating eff.: 0.95 w/gas preheat Add economizer

efficiency T12 units. The second, third and fourth ERMs involved improving the fenestration *U*-value and the *U*-values of the Walls and Roof. Improved *U*-values represent advances made through the years with the introduction of new insulating materials and construction practices. The other ERMs considered were: perimeter daylighting with light dimming, where the internal lighting levels are adjusted to reduced levels during hours when sunlight penetration into a building provides sufficient light for office workers to function efficiently; replacing an existing boiler with a newer, high efficiency condensing boiler; and the incorporation of a 60% sensible air to air heat recovery system.

In addition to the energy retrofits described, there were also modifications made to reflect changing occupancy considerations. These include an increase in the occupant density of the building and additions to the equipment and appliance loads. The former represents an increase in the number of occupants per floor area, while the latter represents the introduction of computers and other office equipment. The variables explored in the simulations are: lighting load; equipment load; occupancy density; fenestration; fenestration *U*-value; wall *U*-value; roof *U*-value; infiltration rate; heating efficiency; cooling COP; heat recovery efficiency; blinds; turndown ratio; daylighting; and gas pre-heat w/economizer.

In addition to the individual variable change simulations, several multiple interaction simulations were also performed. These additional simulations were restricted to the variables for which the associated individual effect on energy consumption exceeded 10% and were limited to 3 level interactions. The simulations performed using EnergyPlus were repeated for three Canadian cities representing different climatic regions, namely, Edmonton, Ottawa and Vancouver. Edmonton has a relatively dry humid continental climate with extreme seasonal temperatures. It has 5212 heating degree-days below 18 °C and 67 cooling degree-days above 18 °C. Edmonton receives 477 mm of precipitation annually and 2299 h of sunshine per year. It is one of Canada's sunniest cities. Ottawa has a more humid continental climate with 4520 heating degree-days below 18 °C and 253 cooling degree-days above 18 °C. Average annual precipitation is about 943 mm. There are usually about 2060 h of sunshine annually. Summers are warm and humid in Ottawa. Vancouver has a moderate oceanic climate with summer months that are typically dry. The remainder of the year is rainy. Vancouver is the second warmest of Canada's major cities, although its summers are cooler than most other major cities. Vancouver has 2631 heating degree-days below 18 °C and 72 cooling degree-days above 18 °C.

5. Results of building archetype modelling

The results for the base cases of the building types allow for an examination to be made on the differences that exist between buildings of similar construction characteristics situated in various climatic regions within Canada. By first observing the breakdown in percentage of the use of energy for each of the components of the buildings, presented in Tables 2 and 3, key observations can be made.

i. The consumption of energy to supply the systems of lighting and appliances (process and computer loads) are consistent and unaffected by weather characteristics. This is an expected result and is useful in ensuring that the base models have been developed correctly.
ii. The percentage of total energy used for chiller operation was found to be the highest for buildings located in Vancouver followed by Ottawa and Edmonton. This trend was found to be consistent over all building types. The percentages are calculated based on total energy consumption (electrical + natural gas) and not solely electrical consumption.
iii. The percentage of energy used for heating a building is higher in Edmonton than in the other locations, with Vancouver requiring the least percentage for heating.

In determining the effects of location on the base case results for the building archetypes, it is also useful to calculate the difference in

Table 2
Energy consumption breakdown for building types LV, LC and S built pre-1950 and 1950–1975.

		Energy consumption (%)								
		Building Type LV			Building Type LC			Building Type S		
	Location	Vancouver	Edmonton	Ottawa	Vancouver	Edmonton	Ottawa	Vancouver	Edmonton	Ottawa
Pre-1950	Lights	21.0	16.6	17.2	–	–	–	20.1	17.0	15.4
	Process	4.0	3.2	3.3	–	–	–	5.5	4.6	4.2
	Computers	6.7	5.3	5.5	–	–	–	7.7	6.5	5.9
	Pumps	0.9	0.8	0.9	–	–	–	1.1	1.0	1.1
	Fans	33.4	31.4	35.8	–	–	–	30.7	30.9	35.1
	DHW	0.6	0.5	0.5	–	–	–	0.7	0.6	0.5
	Chiller	12.5	9.7	12.3	–	–	–	16.9	13.9	16.5
	Boiler	20.9	32.7	24.5	–	–	–	17.2	25.5	21.2
1950–1975	Lights	16.8	13.3	14.8	14.8	11.6	11.7	17.1	14.2	13.8
	Process	4.7	3.7	4.1	4.1	3.2	3.3	6.8	5.7	5.5
	Computers	15.7	12.4	13.8	13.8	10.9	10.9	18.2	16.0	15.5
	Pumps	1.0	0.9	1.1	1.1	0.9	1.0	1.3	1.1	1.3
	Fans	32.4	30.2	35.0	38.4	36.2	36.3	22.2	21.6	22.9
	DHW	0.9	0.7	0.8	0.8	0.6	0.6	1.0	0.9	0.8
	Chiller	10.4	8.1	5.1	11.6	9.2	10.4	12.2	9.7	11.5
	Boiler	18.3	30.8	25.3	15.5	27.3	25.9	20.3	30.8	28.7

Table 3
Energy consumption break-down for building types LV, LC and S built post-1975 and current standards.

		Energy consumption (%)								
		Building Type LV			Building Type LC			Building Type S		
	Location	Vancouver	Edmonton	Ottawa	Vancouver	Edmonton	Ottawa	Vancouver	Edmonton	Ottawa
Post-1975	Lights	20.3	16.7	16.7	18.4	15.0	15.2	19.1	16.6	16.3
	Process	5.7	4.7	4.7	5.1	4.2	4.2	7.7	6.7	6.6
	Computers	28.5	23.5	23.4	25.9	21.1	21.3	32.2	27.9	27.5
	Pumps	1.5	1.3	1.5	1.5	1.4	1.5	1.6	1.4	1.6
	Fans	21.4	20.1	20.5	25.1	23.7	23.6	11.8	11.7	12.0
	DHW	1.3	1.1	1.1	1.2	1.0	1.0	1.5	1.3	1.2
	Chiller	5.5	4.5	5.4	6.6	5.1	5.9	11.1	8.9	10.7
	Boiler	15.4	28.1	26.9	16.1	28.6	27.4	15.1	25.6	24.1
Current Standards	Lights	11.5	9.2	9.4	8.9	6.9	6.9	7.2	5.9	5.8
	Process	8.5	7.5	7.4	8.1	7.0	7.1	7.8	7.1	6.8
	Computers	42.8	37.5	37.3	41.0	35.3	35.5	32.7	29.7	28.4
	Pumps	1.9	1.8	2.0	2.1	1.9	2.1	1.4	1.4	1.9
	Fans	2.4	2.4	2.4	3.0	3.1	3.0	0.8	0.8	0.8
	DHW	2.1	1.9	1.9	2.1	1.8	1.8	1.6	1.5	1.4
	Chiller	5.4	4.2	5.2	6.0	4.7	5.6	3.3	2.7	5.3
	Boiler	25.5	35.6	34.4	28.9	39.3	38.0	45.2	50.8	49.5

consumption among the cities modelled. By normalizing the results with the consumptions found in Ottawa, it was possible to examine the increased or decreased energy consumption requirements. In Table 4, it is observed that Edmonton buildings consume the most energy for heating where as buildings located in Vancouver consume the least. When expressed in energy consumption (kWh), it was observed that Ottawa was the highest consumer of energy for cooling followed by Edmonton then Vancouver. Overall, Vancouver buildings consume the least amount of energy.

Table 4
Base case consumption normalized to Ottawa.

	Ottawa	Edmonton	Vancouver
Building Type LV			
Pumps	100%	84%	79%
Fans	100%	91%	76%
Chiller	100%	82%	83%
Boiler	100%	138%	70%
Building Type LC			
Pumps	100%	90%	80%
Fans	100%	100%	84%
Chiller	100%	89%	88%
Boiler	100%	106%	47%
Building Type S			
Pumps	100%	81%	80%
Fans	100%	80%	67%
Chiller	100%	76%	79%
Boiler	100%	109%	62%

6. Regression analysis

From the energy consumption information extracted from the EnergyPlus results using the simulation scheme, equations for estimating energy consumption for the individual building types were developed. Each energy end use was individually analyzed and equations were developed to estimate each one separately. The following end uses were considered: lighting, equipment, pump, fan, domestic hot water (DHW), chiller, and boiler loads. Separating the overall energy consumption into the individual uses provides a clearer definition of the effect of an ERM. A reduction in the lighting load, for example, has a direct influence on the energy required for lighting. However, it also has an effect on the heating and cooling system requirements due to a reduction in internal heat gains, this in turn reduces the energy demands on the pumps and fans. It can then be seen how knowledge of the interactive influences of implementing an ERM on each energy component is useful for gaining a full understanding of the resulting changes in consumption.

The general format of the regression equations is as follows:

$$Y = b_0 + \sum_{i=1}^{35} b_i x_i \quad (1)$$

where Y represents one end use energy consumption, b_i the coefficients and x_i the variables. The main variables are lighting load, equipment load, occupancy density, % fenestration, fenestration U-value, wall U-value, roof U-value, infiltration rate, heating efficiency, cooling COP, blinds, turndown ratio, daylighting, heat recovery efficiency and gas pre-heat w/economizer. It should be noted that the formation of optimally defined regression equations is an iterative process and involves the continual re-evaluation of the adequacy of each function. The procedure employed for determining the equations was divided into the following steps.

a. Develop an initial equation using least squares regression assuming a linear interaction between the variables and responses.
b. Examine the results of the regression performed in Step 1 by exploring the normality of the residuals as well as plots of the residuals versus: fitted values, observation number and variables.
c. From the examination of the residual plots determine the necessity for including higher order terms in the regression equation.
d. Re-develop the equation using the results from Step 3 and re-analyze the normality of the residuals and plotted responses.
e. Repeat until an optimal regression equation is achieved.

The software application Minitab [20] was used for the regression analyses. By examining the coefficient of determination, R^2, in conjunction with the associated mean squared error, MSE, several observations were made regarding accuracy of each of the equations developed [21]. The regression equations that were used to model the individual components of consumption were also assessed for their level of fit within the ASHRAE 14 Guidelines [12]. This was achieved by comparing the regression model predictions to the values simulated using EnergyPlus. RMSE, NMBE and percent error in RMSE were calculated, Table 5, and the results reveal that the errors are within the specified limits [12].

The lighting load regression equations provide a high level of fit for all building types with the lapses in accuracy stemming only from the inclusion of the daylighting retrofit option, where the errors associated with the residuals are the largest and are in the range of 20%. For all building types and for all three locations, the equations for estimating the equipment and DHW loads were determined with a high level of accuracy as indicated by a 1.0 coefficient of determination and MSE value approaching zero. These optimal fits are not unexpected since the equipment load of each building is directly related to the archetype in which it belongs, while the DHW load is linked primarily to the occupancy level, schedule and hot water heating system properties of the building. This implies that the regression equations are not affected by variations in other building parameters, including climatic effects. Pump loads were well estimated for all building types over each of the locations modelled, with the maximum errors associated with the regression equation remaining below 10%.

The analysis of fit of the fan load equations revealed possible links to internal gains and the errors associated with the regression model. When the internal gains of each building were set at the extreme values, high/low the errors in the calculated fan consumption were the greatest. This observation stems from the simulation scheme used, as a relatively low number of simulations were performed at these high and low levels, the equations are incapable of properly predicting the effects on the fan systems. This indicates that additional simulation points, focusing on multiple variations of the internal gains of a building, may be useful for improving the accuracy of the models. The errors associated with these scenarios are reasonable however, and are below 20% for all buildings.

The regression equations for the chiller loads were the least representative of each building type, indicated by a high contrast between the high R^2 value and the large associated MSE. The buildings that were coupled with these higher error values were again found to be connected with the simulated models for which the internal gains experience large changes. This reveals the necessity for future exploration into the effects that large changes to the equipment and lighting loads have on these components of consumption. The boiler consumption values were estimated well for

Table 5
Building types LV, LC and S: NMBE, RMSE and % error in RMSE.

	LV NMBE	LV RMSE	LV RMSE (%)	LC NMBE	LC RMSE	LC RMSE (%)	S NMBE	S RMSE	S RMSE (%)
Ottawa									
Lights	1%	31,995	2%	1%	70,049	6%	1%	5,594	2%
Equipment	0%	0	0%	0%	0	0%	0%	0	0%
Pumps	1%	2,055	2%	1%	2,749	2%	1%	334	2%
Fans	4%	149,265	6%	3%	145,434	5%	5%	36,466	8%
DHW	0%	36	0%	0%	53	0%	0%	0	0%
Chiller	3%	44,385	5%	5%	61,090	8%	3%	10,941	4%
Electrical	2%	187,554	3%	2%	212,106	3%	2%	44,652	3%
Boiler	3%	117,733	4%	4%	141,717	6%	4%	24,161	6%
Edmonton									
Lights	1%	32,441	2%	1%	69,321	6%	1%	5,823	2%
Equipment	0%	0	0%	0%	0	0%	0%	0	0%
Pumps	1%	1,951	2%	2%	2,533	2%	1%	604	3%
Fans	4%	137,625	5%	2%	87,618	3%	5%	34,026	9%
DHW	0%	36	0%	0%	53	0%	0%	0	0%
Chiller	3%	37,205	5%	5%	64,906	9%	4%	10,846	6%
Electrical	2%	173,220	3%	2%	168,219	2%	2%	48,449	4%
Boiler	3%	131,174	5%	3%	125,044	5%	4%	24,575	6%
Vancouver									
Lights	1%	28,365	2%	1%	64,135	5%	1%	4,872	2%
Equipment	0%	0	0%	0%	0	0%	0%	0	0%
Pumps	2%	2,111	3%	2%	2,213	2%	1%	309	2%
Fans	4%	112,272	5%	2%	71,920	3%	4%	20,930	6%
DHW	0%	36	0%	0%	53	0%	0%	0	0%
Chiller	3%	36,034	5%	6%	74,300	11%	3%	9,959	5%
Electrical	2%	148,705	2%	2%	160,396	2%	2%	28,265	2%
Boiler	5%	93,821	7%	7%	125,931	10%	4%	12,993	5%

Table 6
Summary of retrofit implementation costs.

Building	Archetype	Measure	Cost
Building LV and Building LC	All	Lighting load = 14.24 W/m^2	\$599,600
	All	Boiler efficiency = 95%	\$119,200
	All	Roof U-value = 0.476 W/m^2 °C	\$15,300
Building LV	Pre-1950	Wall U-value = 0.61 W/m^2 °C	\$462,700
	1950–1975	Wall U-value = 0.61 W/m^2 °C	\$396,300
	Post-1975	Wall U-value = 0.61 W/m^2 °C	\$330,000
Building S	All	Lighting load = 14.24 W/m^2	\$103,600
	All	Boiler efficiency = 95%	\$32,700
	All	Roof U-value = 0.471 W/m^2 °C	\$15,800
	Pre-1950	Wall U-value = 0.61 W/m^2 °C	\$121,400
	1950–1975	Wall U-value = 0.61 W/m^2 °C	\$81,000
	Post-1975	Wall U-value = 0.61 W/m^2 °C	\$67,500

all locations and for each building type. The errors were consistently below 10%.

7. Payback period of energy retrofit measures

Installation and material costs were obtained from RSMeans [22]. The payback period is determined by equating the present value of savings ($PV_{Savings}$) to the present value of the costs (PV_{costs}) associated with a retrofit measure. $PV_{Savings}$ and PV_{costs} are determined according to the following expressions:

$$PV_{Savings} = AMD * \left(\frac{P}{A},\ i_f, N\right) + AFC_e * S_E * \left(\frac{P}{A},\ i^{\circ}_{fe},\ N\right) * \frac{1}{1+g_e} + AFC_g * S_g * \left(\frac{P}{A}, i^{\circ}_{fg}, N\right) * \frac{1}{1+g_g} \quad (2)$$

$$PV_{costs} = LOP + L * \left(\frac{A}{P}, i, N_L\right) * \left(\frac{P}{A}, f, N_L\right) \quad (3)$$

The payback periods for four types of energy retrofit measures were explored when applied to the three building types for each of the archetypes. The retrofit measures assessed were an upgrade to the lighting system from T12 to T8 lamps, the addition of an exterior insulating finishing system (EIFS) to improve the insulation capacities of walls, adding roofing insulation and upgrading an existing boiler. For these calculations several assumptions need to be defined:

i. Cost of implementing each retrofit opportunity will be paid for using a loan for the value of the installation costs under the assumption that the number of months to be used for the re-payment of the loan will be 48.
ii. Costs associated with loss of production due to the application of ERMs will be neglected.
iii. Maintenance cost will be neglected.
iv. Minimum Acceptable Rate of Return (MARR) of 10% will be assumed.
v. Interest and inflation rates will be taken as 4.5% and 2.2%, respectively [24].
vi. Growth rates for electricity and natural gas were taken as 2.13% and 2.05%, respectively. [25]
vii. Cost of each retrofit will include overhead and profits, Table 6.
viii. Initial cost of energy will be taken as \$0.07/kWh for electricity and \$0.04/kWh for natural gas.

The payback calculations revealed a period of 6.5 and 5.8 years, 6.5 and 5.8 years, and 7.3 and 7.5 years for lighting load improvement of a pre-1950 Building LV and Building S, located in Ottawa, Edmonton and Vancouver, respectively. For a boiler replacement, the payback period was found to be 3.9, 4.9 and 8.8 years, 3.6, 3.8 and 6.8 years, and 9.1, 16.1 and 24.5 years for Building LV, Building LC and Building S, located in Ottawa, Edmonton and Vancouver, respectively. For pre-1950 Building LV and Building S, the roofing insulation retrofit yielded a payback period of 0.3 and 0.5 years, 0.4 and 0.7 years, and 0.5 and 0.9 years for the cities of Ottawa, Edmonton and Vancouver, respectively. In summary, the following observations were made:

(a) Retrofitting the lighting fixtures is slightly more beneficial to the buildings located in Edmonton and Ottawa in comparison to those in Vancouver.
(b) Retrofitting the boiler system is more beneficial for larger buildings and for buildings located in colder climates. A factor of approximately three in the payback period is observed between buildings located in colder climates (Ottawa and Edmonton) and moderate climate (Vancouver). Focusing on buildings LV and LC, it can be observed that longer payback periods occur for the curtain wall type structure.
(c) The payback period for upgrading the roofing insulation is influenced by the size of the building and the climate region. Building S had a shorter payback period in comparison to buildings LV and LC.
(d) Upgrades to the exterior walls using EIFS is cost ineffective for all three types of buildings as well as for all three climate regions. The payback periods for this ERM exceeded feasible limitations with estimations in excess of 100 years for each building. However, the incorporation of EIFS as an ERM was modelled under the assumption that solely the U-values of the envelope are affected. This assumption may be underpredicting the benefits of the ERM as the building air tightness might also be improved as a result.

8. Summary and conclusions

The goal of this research project was to develop a methodology for screening office buildings for energy efficiency and retrofit potential. From the results, the following conclusions are drawn:

1. The properties of office buildings, including materials, HVAC and construction practices used, varied widely between pre-1950, 1950–1975 and post-1975. The proposed building archetypes provide a controlled approach to model the main differences between the age levels and still allow for the variations in building design to be captured.
2. EnergyPlus was evaluated using metered data from nine office buildings. Its predictions of energy consumptions are within ASHRAE specified limits. Accordingly, EnergyPlus was used to model the energy consumption of the building archetypes.
3. Non-linear regression analyses were used to develop simple models capable of adequately predicting office building energy

consumption based on key variables of lighting, equipment and occupancy loads, envelope properties and HVAC system types.

4. A proposed decision-making protocol that uses energy consumption data and cost of retrofit implementation was found effective in determining the expected payback periods and the overall rate of return on investment.
5. The information gathered from the equations can be used to assess broader trends in the energy consumption and cost analysis of ERM applications to various building types. For example, the following can be observed:
   a. the application of a boiler upgrade is more cost effective for smaller buildings than for larger buildings;
   b. small buildings are benefited to a greater degree than larger buildings when roofing upgrades are performed; and
   c. EIFS incorporation is not a cost effective alternative when the insulating properties are the only consideration.

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