The applicability of a simplified whole-building energy model for energy-efficiency retrofit analysis

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Abstract

Energy-efficiency upgrades of existing buildings represent an opportunity to achieve substantial greenhouse gas reductions and improve indoor environmental quality. Building energy modelling can enable better-informed design solutions and compliance with energy codes. However, it requires experience in energy modelling and knowledge of building physics and energy systems. This study investigates the capabilities of the simplified whole-building energy models to provide reliable predictions. Thus, we first developed and calibrated a detailed energy model of the existing low-rise commercial office building. Then, we reduced the complexity of the calibrated model regarding thermal zoning, envelope constructions, and energy systems. Next, scenarios with different energy retrofit solutions were applied, and discrepancies in the models' predictions were analyzed. The results show that while simplified models might predict total energy savings, certain simplifications may introduce inaccuracy in predicting cooling energy loads.

Keywords: Model simplification, Energy-efficiency retrofit, Whole-building energy modelling, Commercial buildings

Introduction

In the wake of the Paris Agreement, federal, provincial, and territorial governments have committed to achieving a 30% reduction in GHG emissions by 2030. Achieving this goal requires reductions of 207 million tonnes across the economy within the next 12 years (Standing Committee on Environment and Sustainable Development, 2019). Buildings are responsible for more than 30% of the total energy consumption in Canada. Approximately 22 % of Canada's greenhouse gas emissions come from heating, cooling, and powering residential and commercial buildings (Natural Resources Canada's Office, 2018-2019). Consequently, the built environment plays a crucial role in addressing climate change.

Building energy modelling is a robust technique for testing, analyzing, and optimizing innovative, high-performance building design solutions and systems (Sghiouri, 2018). Additionally, physics-based building energy models can identify the most cost-effective options for achieving carbon reduction targets based on the best available technologies. Hence, building energy modelling can enable better-informed design solutions and compliance with energy codes and standards. Over the past 50 years, a broad spectrum of free (e.g., EnergyPlus, eQuest) and commercial (e.g., IES, TRNSYS) whole-building energy simulation tools arrived on the market. Although these tools make the simulation of buildings reliable and detailed, modelling complicated structures can be time-consuming, sophisticated, and requires expert knowledge (Shen et al., 2018). One practical way to improve the accuracy of energy simulation models is to gain a better understanding of energy simulation tools and simplify the inputs (Sun et al., 2014. Heidarinejad et al., 2017.).

Several studies have investigated the effects of simplified models on energy consumption and model accuracy. Korolija and Zhang (2013) removed internal partitions and considered a single floor as a single zone in domestic houses. In their model, zone simplification resulted in a 30% reduction in simulation time and the mean absolute relative error of 10.6% for predicting annual heating demands. Heo et al. (2018) investigated the level of required modelling to support energy analysis in a case study of U.K. domestic buildings. According to this study, reducing the number of thermal zones to one per floor and one per house resulted in underestimating the annual heating demand by 17% and 26%, respectively, implying the importance of detailed thermal zones on domestic buildings.

Zhao et al. (2018) simplified the thermal zone, fenestration, and typical floor in their geometric modelling to investigate the proper level of simplification in geometric modelling on an office building. The results showed that combining windows and simplifying the floors impact the energy predictions slightly. Elhadad et al. (2020) analyzed the effect of reducing the number of thermal zones from modelling every space as a separate zone in a detailed model to modelling the building as a single zone in a case study of a residential building in a hot climate. Compared to the complex model, a marginal average deviation of less than

20% in total energy demand and thermal comfort across all simplification scenarios. The optimal strategy was combining rooms with similar thermal features into a zone, while the worst scenario was a single-zone model.

Most Canadian buildings were constructed before the first national standard for building energy performance in 1997 [3]. Thus, energy-efficiency upgrades of existing buildings represent an opportunity to achieve substantial greenhouse gas reductions and improve indoor environmental quality. El-Darwish and Gomaa (2017) discussed the effect of simple retrofit strategies on energy consumption. As part of the retrofitting of a building envelope, a reduction of energy consumption of 33% can be achieved through some critical measures such as window shading, glazing, airtightness, and insulation.

However, there is a lack of studies investigating the impact of model simplification on selecting energy-efficiency retrofit scenarios, and this study aims to fill this knowledge gap. Therefore, this paper consists of two parts. First, the number of thermal zones in a commercial office building is reduced from a detailed model to a two and single-zone model. Second, scenarios with different energy retrofit solutions, including adding exterior wall insulation, and changing windows and doors, were applied to three base models, and the differences in the models' predictions were analyzed.

Methodology

Detail Model Development and Calibration

The case building is a one-story, 1120 m^2 commercial office building located in Markham, Ontario, Canada, constructed in 1985 (see Figures.1 and 2). The facility mainly includes two parts: the office area and the warehouse. The office area is divided into seven thermal zones, and the warehouse is presented with one thermal zone (see Figures.3).

The measured and modelled data should be within the acceptable calibration values presented by ASHRAE 14 (2002), ±5% in CV(RMSE) for annual energy consumption, to have confidence in the model's predictions. In 2020, the measured electricity and natural gases were 343350.4 kWh/year and 90120 kWh/year, respectively. By analyzing the operational data from this building, we calibrated the parameters related to the performance gap during the modelling process. The calibration parameters are chosen based on previous studies (Gunay et al., 2013, Coakley et al., 2014). Actual weather data for 2019 and 2020 are collected from (national solar radiation database) nsrdb.nrel.gov containing hourly needed parameters in (epw.) format, which EnergyPlus can read. The calibrated model matched the measured data with the mean absolute relative error of 3.65%, 0.46% and 2.99% for natural gas, electricity and total energy used in this building for the billing period.

Working hours in this building are between 10:00 to 18:00 on weekdays with full occupancy of 15 people. The setpoints and setbacks in the warehouse do not change much, while the front office setpoints vary by 0.5°C. Besides, the Nest Eco Mode thermostat is used for setback temperature to save more energy in the office area after the thermostat senses that nobody is at the office. Nest Eco Mode thermostat gives a temperature range that can be selected when set on Eco Temperature. The Eco temperature range from 4 to 21°C for heating mode and 24 to 32°C for cooling mode. The genetic calibration algorithm chose setbacks in the office area at 16.25°C and 26.5°C for heating and cooling seasons. Table 1 shows the input parameters for the calibrated model in EnergyPlus.

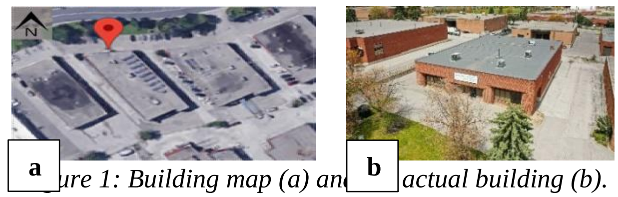

Figure 1: Building map (a) and actual building (b).

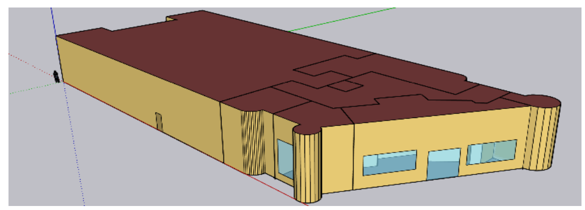

Figure 2. The modelled building in SketchUp.

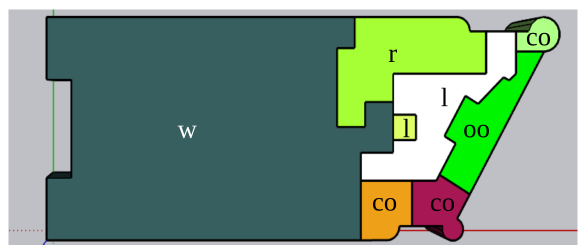

Figure 3. Thermal zones in the base model: Warehouse (w), Closed Office (co), Open Office (oo), Lobby (l) and Restroom (r).

Table 1. Input summary table.

Envelope			
External Wall Office area U-factor [W/m^2.K]	North Wall	East Wall (Office)	West Wall (Office)
	1.2	1.4	1.3
External Wall Warehouse area U- factor [W/m^2.K]	South Wall	East Wall (Warehouse)	West Wall (Warehouse)
	1.4	2.8	2.8
Windows	U-factor [W/m^2·K]		SHGC
	2.440		0.326
Doors U-factor [W/m^2.K]	6.665		

Continue Table 1. Input summary table

Internal Loads				
Occupancy	Schedule: All spaces except restroom: Weekdays: 1 [10:00-18:00] Otherwise: 0 Restroom: Weekdays: 1 [One hour in the whole day] Otherwise: 0			
HVAC				
Setpoints [℃]	Office		Warehouse	
	Summer	Winter	Summer	Winter
	22 ± 0.5	20 ± 0.5	22	22
Setbacks [℃]	Office		Warehouse	
	Summer	Winter	Summer	Winter
	16.25	26.5	20	20

Model Simplification

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 90.1 (2013) defines multiple spaces as one thermal zone that: 1, has the same exterior walls and windows orientation; 2, has the same air conditioning and heating systems; 3, has the same usage of the spaces. According to the Canadian standardization method EE4 (2008), spaces with the following features can be considered a thermal zone: 1, has the same HVAC systems, operations and functions as well as similar cooling and heating loads; 2, divide the space surrounding the building and the internal loads into different thermal zones; 3, define corridors, equipment rooms, power distribution rooms, stairs, and cloakrooms as a separate partition.

By simplifying models, both preparation and simulation time can be significantly reduced. Simplification of the detailed model (see Figure 3) first included a reduction to two zones: the office area and the warehouse. Then, the zones are merged into one and considered the building as a single zone.

Figure 4 shows an elevation view of the building in two and one zone models. The two-zone model is closer to the detailed model because the office and warehouse areas are still separated by implementing the zone simplification. The schedules defined for occupancy, lights, equipment, setpoints and setbacks are different in warehouse and office areas. However, by merging thermal zones in the office area and creating one office, the restroom is merged into adjacent offices. The restroom in the detailed model has distinct occupancy schedules and electric use for equipment. This zone is assumed to be daily one hour occupied during lunchtime with 1500W electricity use for devices. This zone is merged with other office areas by reducing thermal zones from eight to two. Therefore, it has the equivalent schedules and equipment energy consumption as other offices.

Specific parameters such as external wall R-values on the east and west sides of the building infiltration and ventilation rates differ between the office and warehouse areas. Therefore, to create a one-zone model, we applied weighted arithmetic mean. For instance, the U-value of the warehouse and office west wall are 2.8 and 1.3 W/m²K, respectively. Furthermore, around 60% of the area belongs to the warehouse and 40% to the office. Thus, the calculated U-value for the west wall in the one-zone model is approximately 2.2 W/m²K.

Retrofit Scenarios

Retrofit scenarios consisting of adding wall insulation, changing window materials, and changing exterior doors are implemented on detailed and simplified models to investigate the impact of every retrofit option on each model. The scenarios are developed to meet the National Energy Code of Canada for Buildings (NECB, 2017) prescriptive requirements. Table 2 summarizes the required thermal transmittance and resistance for the above-grade walls and all fenestrations. Considering the poor thermal performance of the building (see Table 1), the improvement of insulation levels is a priority, especially in the warehouse area with no insulation. Three exterior insulation materials from Rockwool company are selected for insulation materials due to several reasons. First, Rockwool has production in Ontario, Canada, the same province as the case building, making the retrofit process more cost-effective. Second, this company offers stone wool insulation, a versatile material ideal for buildings, horticulture, industry, transportation, and water management applications. Additionally, their products assist communities in adapting to climate change impacts and reducing their environmental impact.

High window thermal transmittan\ce in the case building gives us another retrofit option for saving energy. Therefore, three window materials with various frame types, U-values, and SHGCs from THERM software are chosen to evaluate the impact of window retrofit on energy performance. The door material in this office building is metal with high conductivity. As a result, changing exterior doors with less conductive materials is considered a retrofit option for more efficiency. Accordingly, two-door materials from the local market are selected. Table 3 presents chosen exterior insulation, windows and doors materials. The combination of three external wall insulation, three windows and two-door materials resulted in fifty-four retrofit scenarios.

Table 2. NECB U-value code requirement for walls and fenestration (NECB, 2017)

For above-ground building assemblies in Zone 6		
	Maximum Overall Thermal Transmittance [W/m^2.K]	Minimum Overall Thermal Resistance [m^2.K/W]
Walls	0.247	4.05
All Fenestration	1.9	0.53

Table 3. Selected retrofit materials for exterior wall insulation, windows, and doors.

Exterior Wall Insulation			
	Comfort board 80 (CB)	Curtain Rock (CR)	ROXUL SAFE 55&65 (RS)
Density [kg/m^3]	128	56	72
Thermal resistance [m^2.K/W]	0.7	0.74	0.74
Available thickness by the company [in]	1, 1.25, 1.5, 2, 2.5, 3, 4, 5	The product is available in 1" through 5".	4
Needed thickness [cm]	13.25	12.5	12.5
Window Material			
	Window type #1	Window type #2	Window type #3
Layer 1	SAS_35mm	6 LOW-E R 36_23_CL.TEG	COOL-LITE SKN 254 || 6mm.SGG
Gas	Air (12%)/ Argon (22%)/ Krypton (66%) – EN673	Xenon-EN673	Xenon-EN673
Layer 2	Planitherm ONE lami33-1. SGG	6 LOW-E R 36_23_CL.TEG	COOL-LITE SKN 254 || 6mm.SGG
Frame	Vinyl	Aluminum flush	Aluminum with thermal break
U-value [W/m^2.K]	1.485	1.576	1.744
SHGC	0.246	0.181	0.147
Door Material			
	Fibreglass	Pinewood	
Thermal resistance (R-value) [m^2.K/W]	6	2	

Results and Discussion

Simplification of Thermal Zones

Table 4 summarizes the annual heating, cooling and total energy consumption. In addition, Figure 5 presents the monthly heating and cooling energy consumption in detailed and simplified models. Overall, yearly and monthly energy consumption declined by reducing the number of zones. Compared with the detailed model, the heating energy consumption of two-zone and one-zone models diminished by 3.72% and 7.96%, respectively. This discrepancy is significantly higher for cooling energy consumption. Thus, the cooling energy demand of two and one-zone simplified models declined by 16.94% and 28.73%, respectively.

The comparison of monthly heating energy consumptions shows the difference between the detailed and single zone, ranging from 1.5% in September to 17.1% in October. This discrepancy was significantly smaller between the complex and two-zone models, ranging from around 0.5% in September to 4.1 % in February. The difference between models' monthly cooling energy consumption was particularly pronounced during the shoulder seasons, ranging from 44.8% in September to 61.1% in May. During the warmest months, it was between 16.9% in August to 33.2% in June.

Investigation of the results in simplified models shows that internal walls facing exterior windows are more sensitive to solar radiation and gain in summer when the solar gain is higher. The interior walls store this energy and disperse it into the zone later. A similar increase in solar heat absorption can also be found during summer when comparing the more complex zoning configuration results. Therefore, a possible reason for higher cooling energy consumption in the detailed model compared to the two-zone and one-zone models can be higher absorption of solar heat gain through internal walls. Moreover, the previous study investigated the underestimation of heating energy consumption by simplified models developed in EnergyPlus (Johari et al., 2022). Based on their findings, due to the increased convective heat gain on the internal surfaces in heating seasons, the increased convection coefficient leads to higher conduction losses from the building envelope, which raises the demand for more heating.

Table 4. Energy consumption breakdown in detailed and simplified models.

	Detailed Model	Two zones model	One zone model
Annual energy consumption [kWh/m^2]	268.4	255.3	242.17
Annual heating energy [kWh/m^2]	245.1	235.98	225.59
Annual cooling energy [kWh/m^2]	23.3	19.32	16.58

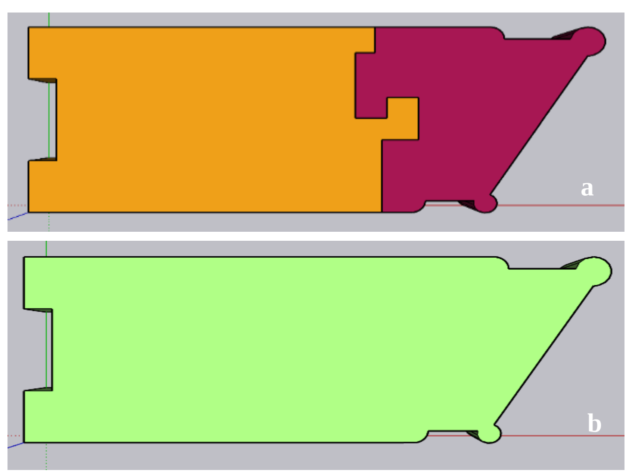

Figure 4. Two-zone (a) and one-zone (b) simplified models.

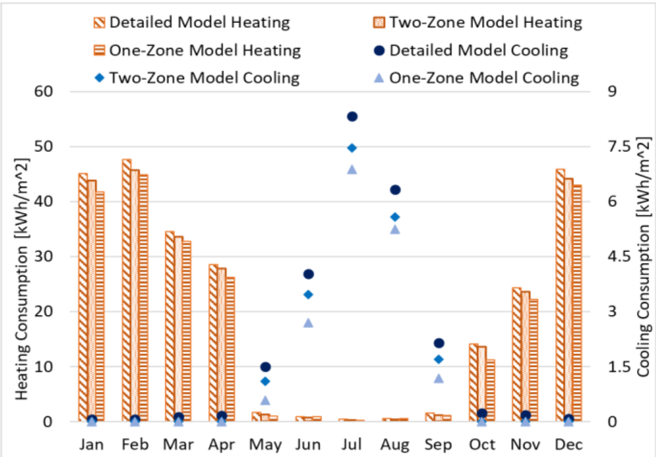

Figure 5. Monthly heating and cooling consumption in detailed and simplified models.

Implementation of Retrofit Scenarios

In heating-dominated climates like Canada, improving the building envelope with available options such as more insulated walls, roofs, and fenestrations is necessary to lower heating demand and energy consumption. In this regard, three retrofit options are implemented in the case study building to investigate the impact of retrofit on thermal zone simplification.

Box plots for detailed, two-zone and one-zone models presented in Figures 6 to 8 compare the heating and cooling energy consumption in fifty-four applied scenarios. Furthermore, Table 5 summarizes the percent energy saving ranges resulting from implementing the models' scenarios. A boxplot displays a vertical box from the first to the third quartile. The inner horizontal line inside the box represents the median, while from each quartile, whiskers lead to the minimum and maximum of the data. On each boxplot chart, energy consumption in scenarios is presented on the left axis and the base case study on the right axis. The boxes show the scenarios' energy consumption range, while squares and triangles depict the base cases' heating and cooling energy uses. The blue circle data on some box plot charts represents outliners.

All three models show a normal distribution in annual cooling energy consumption. The aggregation in annual heating demand with implemented scenarios is close to the first quartile in the detailed model. In contrast, the median value of the annual heating demand increased compared to the comprehensive model. The results also indicate that the detailed model's variation range of heating and cooling demands is between 181.61 to 189.48 kWh/m² and 13.57 to 14.62 kWh/m². These ranges decline in both simplified models. Also, the interquartile range of annual heating demand increases by reducing the number of thermal zones. The yearly cooling demand is constant between the detailed and two-zone models and decreases in the one-zone model. The saving percentages of retrofit scenarios are very close between the three model types. Furthermore, complex and simplified models had the same best retrofit option that considered a more energy-efficient envelope with R.S. as exterior wall insulation, fibreglass for the doors, the first window type for heating, and the third window type for cooling. This finding suggests that simplified models can be used in early-stage building and retrofit modelling.

Figures 9 to 11 show boxplots of the peak heating and cooling demand in detailed and simplified base and scenario implemented models. The peak heating hour for detailed and simplified models is February 27th at 14:00 with -3.7℃ dry bulb temperature, 22 m/s wind speed and 63% relative humidity. Although February 27th was not the coldest day, it had the highest average wind speed of 17.5 m/s compared to other clod days, thus increasing convective heat losses and the heating needs. Furthermore, the peak cooling demand for created models is on July 21st at 16:00 with 30.2℃ dry bulb temperature, 26 m/s wind speed and 33% relative humidity. Similarly, although July 21st was not the warmest day, it had the highest average relative humidity of 56 % compared to the warm days, thus increasing latent cooling requirements.

While the detailed and two-zone models have almost normal distributions of heating and cooling demands, the single-zone model has skewed to the left. Also, by reducing the number of zones from eight to two, peak heating demand decreases. The explanation might be in reducing the heating energy consumption of the two-zone compared to the detailed model that also reflected the peak demand. However, Figure 12 a) shows that peak heating demand increased in the single-zone model compared to the two-zone model.

Furthermore, Figure 12 b) illustrates that peak cooling demand rose considerably in the single-zone model compared to the other two models. Adjustments made to merge office and workshop areas in the single-zone likely explain these findings. In this respect, one of the adjustments included changing the properties of the external walls. For example, the exterior walls of the warehouse area contain brick and concrete, while the office area has a layer of interior insulation. Therefore, we first removed the insulation layer from the office section and then increased the thickness of the concrete layer of both areas using the weighted average approach. The omitting of the insulation layer from the external wall resulted in higher heat losses and gains on January 21st and July 21st, increasing peak heating and cooling energy demands.

Furthermore, because office and workshop areas had different setback temperatures, merging zones included changing setback temperatures in the single-zone model compared to the two-zone and detailed. Consequently, the cooling setback temperature increase led to reduced energy consumption during the unoccupied hours in the one-zone model (see Figure 12 b).

Table 5. Saving ranges in retrofitted detailed and simplified models.

	Detailed Model	Two-zone model	One-zone model
Range of annual savings in heating [%]	22.6-25.9	25.3-27	26.4-29.5
Range of annual savings in cooling [%]	37.1-41.6	43.1-48.6	40.2-43.7
Range of annual savings in total [%]	24-27	26.6-28.7	27.3-30.3

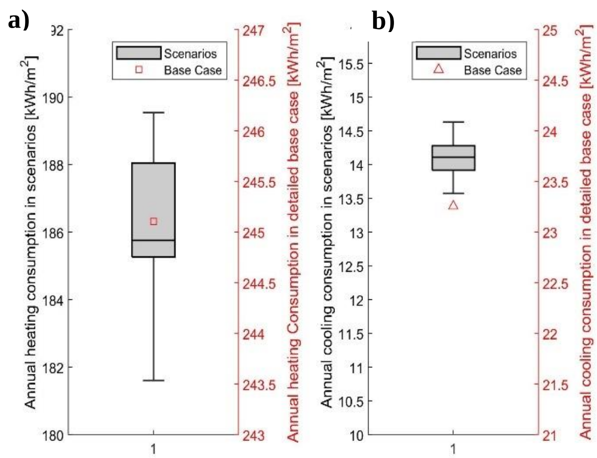

Figure 6. Annual heating (a) and cooling (b) consumption comparison between the detailed base case and scenarios.

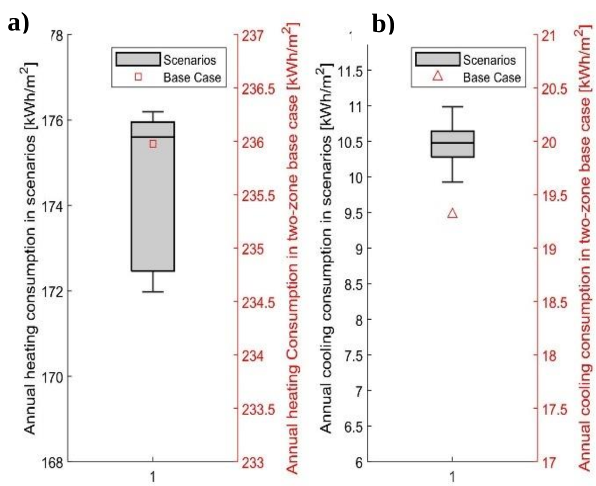

Figure 7. Annual heating (a) and cooling (b) consumption comparison between the two-zone base case and scenarios.

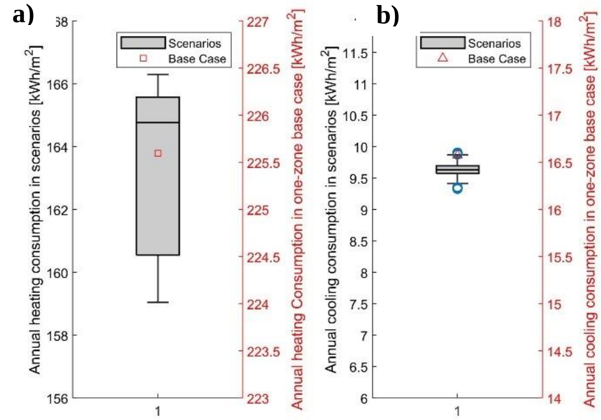

Figure 8. Annual heating (a) and cooling (b) consumption comparison between the one-zone base case and scenarios.

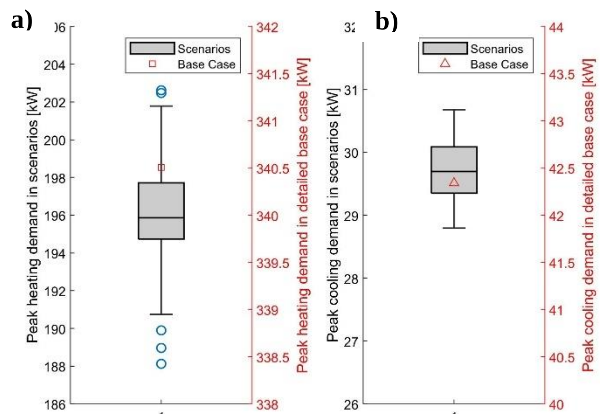

Figure 9. Peak heating (a) and cooling (b) demand comparison between the detailed base case and scenarios.

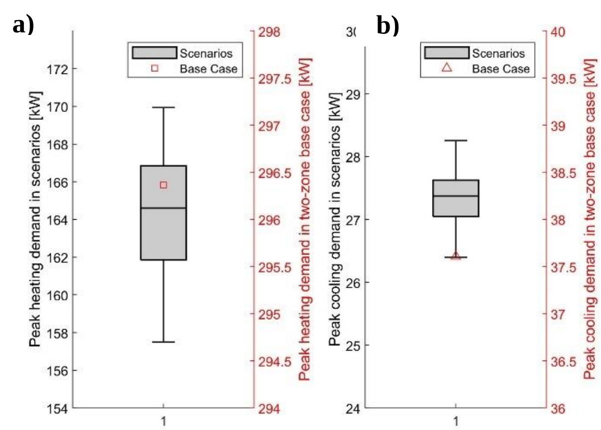

Figure 10. Peak heating (a) and cooling (b) demand comparison between the two-zone base case and scenarios.

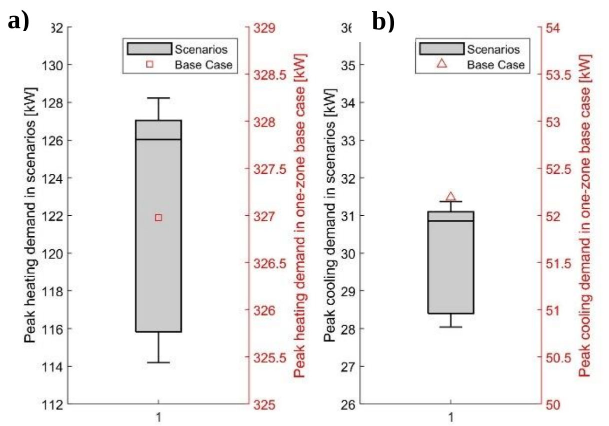

Figure 11. Peak heating (a) and cooling (b) demand comparison between the one-zone base case and scenarios.

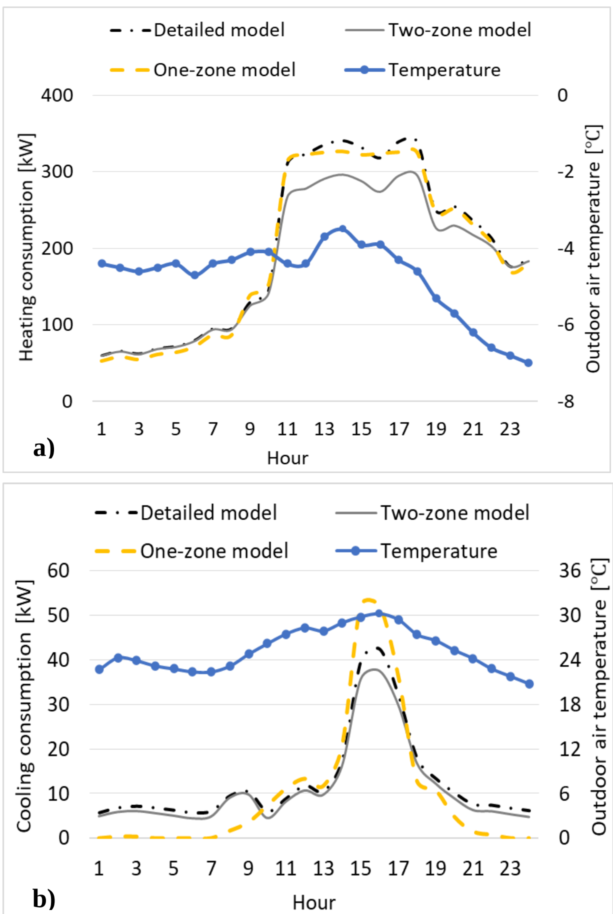

Figure 12. Hourly heating (a) and cooling (b) energy consumption on February 27th and July 21st, respectively.

Conclusion

Previous studies mainly focused on investigating the impact of model simplifications on prediction accuracy. They rarely investigated the use of simplified models in selecting energy retrofit options. This paper seeks to fill this research gap by analysing the effects of thermal zone simplification and retrofit options of building envelopes through a commercial office building case study. Although detailed and simplified models showed approximately the same range of energy savings by implementing retrofit scenarios, the simulation results showed that combining zones with entirely different functions into one zone resulted in underestimating heating and cooling demand by 7.96% and 28.73%. Moreover, the peak demand hour in all models happened simultaneously. However, peak heating and cooling demand increased in the single-zone model compared to the two-zone model. The possible reasons for the discrepancy between the models' predictions are several. First, in winter, fewer internal walls of simplified models lead to lower convective heat gain on the inner surfaces and higher conduction losses from the building envelope. Second, interior walls facing windows and glass doors absorb solar heat in summer with high solar radiation and discharge it into the zones. Therefore, removing internal partitions led to lower cooling needs in simplified models than in the detailed model. Furthermore, several adjustments to the external walls and setback temperatures needed to merge office and workshop areas caused the difference between the singe-zone and the other two models.

The comparison between simulation results and measured data suggests that simplified models can provide helpful guidance to modellers to limit retrofit options in early-stage modelling. However, while simplified models reduce the modelling complexity and simulation time, more detailed models enable a higher accuracy. Regarding our case study, simplifying the model from a complex to a two-zone model may benefit the early modelling stage and decisions about retrofitting. Nevertheless, reducing the number of zones to one resulted in a less reliable model because the model requires more simplifications in defined parameters such as schedules and exterior wall U-values.

The future work should include testing and evaluating the capabilities of simplified models to accurately select optimal energy-efficiency retrofit solutions and estimate resulting energy/carbon savings. Furthermore, further research should also investigate the uncertainties of the simplified models related to different building types, such as exploring the simplification potential of more complex buildings.

Acknowledgement

The authors gratefully acknowledge the financial support received from the Natural Sciences and Engineering Council of Canada (NSERC).

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