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Abstract

Space heating is the largest energy end use, consuming more than 7 quintillion joules of site energy annually in the U.S. building sector. A few recent studies showed discrepancies in simulated space-heating energy use among different building energy modeling programs, and the simulated results are suspected to be underpredicting reality. While various uncertainties are associated with building simulations, especially when simulations are performed by different modelers using different simulation programs for buildings with different configurations, it is crucial to identify and evaluate key driving factors to space-heating energy use in order to support the design and operation of low-energy buildings. In this study, 10 design and operation parameters for space-heating systems of two prototypical office buildings in each of three U.S. heating climates are identified and evaluated, using building simulations with EnergyPlus, to determine the most influential parameters and their impacts on variations of space-heating energy use. The influence of annual weather change on space-heating energy is also investigated using 30-year actual weather data. The simulated space-heating energy use is further benchmarked against those from similar actual office buildings in two U.S. commercial-building databases to better understand the discrepancies between simulated and actual energy use. In summary, variations of both the simulated and actual space-heating energy use of office buildings in all three heating climates can be very large. However these variations are mostly driven by a few influential parameters related to building design and operation. The findings provide insights for building designers, owners, operators, and energy policy makers to make better decisions on energy-efficiency technologies to reduce space-heating energy use for both new and existing buildings.

Keywords: Building simulation; design and operation; EnergyPlus; office buildings; performance benchmarking; space heating

1. Introduction

According to the 2010 United States Department of Energy (USDOE) Building Energy Databook [1], space heating is the largest end use in the U.S. building sector. Space heating consumes about 5.2 and 2.3 quintillion joules of annual site energy for residential and commercial buildings, respectively. The U.S. Energy Information Administration (EIA) 2003 Commercial Buildings Energy Consumption Survey (CBECS) [2] indicates that office buildings are the most common building type, comprising the largest floor area and consuming the most energy in the commercial building sector. In office buildings, space heating consumes about one-third of total site energy, according to the CBECS. It is therefore crucial to study the space-heating energy use of such buildings in order to reduce their energy use and carbon emissions.

The growth in energy use allocated to the commercial buildings sector averaged 2.8% annually from 1950 to 2006 [3]. In the past decade, energy-saving technology improvements in office buildings have received a lot of attention [3-9]. Andrew et al. [8] investigated issues affecting the adoption of energy-efficient heating technology in U.S. office buildings. The factors he studied included energy price, building location, floor area, rental, building vintage, window area, and office equipment. In his study, the multinomial logistic analysis of these factors employed spreadsheet manipulations and statistical calculations. Liu et al. [9] describe a mathematical modeling framework for energy systems to improve energy efficiency and environmental performance of commercial buildings, with the goal of achieving optimal energy designs. However, a systematic integration approach for truly achieving optimal energy-systems design in commercial buildings is still lacking. Recently, more new building designs aim to green buildings or zero net energy buildings, emphasizing the importance of energy-efficiency technologies and system designs, building operation and maintenance, and occupant behavior. Good operational practice and high building design efficiency could lower the energy use of space heating [10, 11]. Santin [12] looked at the relationship between user behavior and space-heating energy consumption, and concluded that behavior patterns could be used in space-heating energy calculations, and usage profiles with different behaviors could be discerned.

Pan et al. [13] simulated effects of external wall insulation thickness on annual cooling and heating energy uses of an office building in three Chinese climates. It was found that, for heating dominant climate like Beijing, more insulation reduced the combined annual cooling and heating energy uses of perimeter offices facing all four cardinal orientations. More insulation reduces annual energy uses of offices facing North, East, and West, but not necessarily for the south facing office. For cooling dominant climate like Guangzhou more insulation did not reduce annual energy use at all. Yang et al [14] surveyed envelope designs of existing office buildings in five major Chinese climates, and found the overall thermal transfer value of envelope was much higher than the current local energy code and almost double the ASHRAE Standard 90.1-2001. More insulation of exterior walls and roofs was recommended to reduce heating energy use for buildings in cold climate. Dovjak et al [15] studied problem of high heating energy use in Slovenian buildings with exergy and energy analysis. Their energy analyses showed that less thermal insulation contributed the most to the highest heating energy demand especially in colder climate. The results from exergy analysis drew similar conclusions - insulation has much bigger effect than effect of boiler efficiency. However, the most effective solution is to improve building envelope together with boiler efficiency. Yildiz et al [16] presented energy and exergy analyses for the whole process of space heating in buildings in Turkey climates using simplified steady state heating load and energy calculations. Three heating systems, liquid natural gas (LNG) fired conventional boiler, LNG condensing boiler, and air-to-air heat pump, were compared from the power plant through the building envelope using exergy analysis. Eskin et al [17] studied the interactions between different conditions, control strategies and heating/cooling loads in office buildings in the four major climatic zones in Turkey using building energy simulation. Calibrated energy models were used to examine energy conservation opportunities on annual cooling, heating and total building load at four major cities. The effect of the parameters like the climatic conditions, insulation and thermal mass, aspect ratio, color of external surfaces, shading, window systems including window area and glazing system, ventilation rates and different outdoor air control strategies on annual building energy requirements is examined and the results are presented for each city.

The lack of knowledge about the factors that determine total building energy use is a significant barrier to achieving substantial building energy efficiency. Recently, a few studies [18, 19] using simulations to calculate building performance showed relatively low space-heating energy use compared with rules-of-thumb and large discrepancies in space-heating energy use between different simulation programs, which raised concerns of whether simulation can be used to predict space-heating energy use. While various uncertainties are associated with building simulations, especially when simulations are performed by different modelers using different simulation programs for buildings with different configurations, it is crucial to identify and evaluate key driving factors to space-heating energy use to support the design and operation of low-energy buildings. These key driving factors can be categorized into six groups: climate conditions, building envelope, space-heating systems, building operation and maintenance, occupant behavior, and indoor environmental conditions.

The New Buildings Institute recently published a simulation study on total site energy use in midsize office buildings [20] to look at key driving factors of building energy use. Twenty-eight building characteristics were identified and grouped into design assets, operation practice, and tenant behaviors. Three systems and equipment-operation practices with respect to building energy use were identified by using different performance values for each characteristic parameter. Simulation results showed the key factors that affect total site energy use in midsize office buildings in 16 U.S. climates. Total site energy is a simple sum of electricity use and gas use — one unit of electricity is valued the same as one equal unit of natural gas; no generation or transmission or distribution loss is considered. As the total energy use of a building includes all end uses such as lighting, space heating, space cooling, service water heating, and plug-loads, the key driving factors of a building's total energy use would be very different from those of a specific end use like space heating. The use of source or primary energy would be a better indicator of building energy performance.

The objective of the current study is to identify, understand, and quantify important building design and operation parameters that can have significant impacts on space-heating energy use in office buildings, with different characteristics located in different heating climates, by computer simulations with EnergyPlus. The impact of weather data on space-heating energy use is also investigated by running simulations with multiple decades of historical weather data. The simulated results are further benchmarked with the space-heating energy use of comparable office buildings selected from the two well-known U.S. commercial building databases to investigate discrepancies between simulated and actual heating energy use.

It is not the intent of this paper, although the analysis and simulation method can apply, to analyze the total energy use of buildings; therefore, this study's results and findings should not be directly applied to the whole-building energy use, which includes other end uses. The heating systems discussed in this article are stand-alone systems powered by natural-gas hot-water boilers or electric resistance; they are not part of the district heating systems that are popular in Northern Europe countries and Northern China [21].

This study is part of a bigger effort to study key driving factors of energy performance of buildings under the International Energy Agency (IEA) Energy Conservation in Buildings & Community Systems (ECBCS) Annex 53 Total Energy Use in Buildings: Analysis & Evaluation Methods.

The first section of the paper describes analysis methodology, and the second section provides details of the selected building design and operation parameters, together with definitions of simulation runs. The third section presents and discusses the results. The conclusion section summarizes key findings and potential future research.

2. Analysis Methodology

Building simulations and benchmarking with building energy consumption databases are the two methods we used to study the space-heating energy use in office buildings. Two office buildings with different sizes and design configurations — the high-rise large office and the single-story small office — are studied. To look at the influence of climate, three typical climate zones that require significant space heating are studied. Based on design and operation practice, a few key parameters for the large- and small-size office buildings are identified and their impacts on space-heating energy use are evaluated by energy simulations. The simulated space-heating energy uses are benchmarked with two U.S. commercial building databases of measured whole-building energy use. Furthermore, 30 years of actual meteorological weather data, from 1980 to 2009, are used in the simulations to study the impact of weather changes year-over-year on space-heating energy use.

As defined in this study, space-heating energy use is the site's energy in the form of natural gas consumed by boilers in the large office building or furnaces in the small office building; it does not include the electricity use of the hot-water pump for the large office building, or the fans of the air-handling units for both office buildings during heating operations. For the large office building, the space-heating energy use includes hot-water energy consumed by the reheat coils in the zone terminal units (i.e., variable air volume [VAV] boxes) and the central heating coils located in the air-handling units. For benchmarking purpose, the space-heating energy is also presented in energy use intensity (EUI), defined as annual site energy in MJ (mega joules) of space heating per building total floor area in m^2.

2.1 Characteristics of the Large- and Small-Size Office Buildings

The large- and small-size office buildings were selected from the USDOE commercial reference buildings (CRBs) [21], which comply with the American Society of Heating, Refrigeration, and Air-conditioning

Engineers (ASHRAE) Standard 90.1-2004 [23]. As Standard 90.1-2004 has different efficiency requirements for buildings located in different climate zones, the efficiency levels of both office buildings, including envelope insulation, window types, and HVAC systems, depend on the building's location or climate zone. The internal loads, including interior lighting power and plug loads, occupant density, and operation schedules, stay the same across all climates.

2.1.1 The Large-Size Office Building

The large office building has 12 stories and a basement, with a total floor area of 46,320 m^2. The building has a rectangular shape with the long axis along the east-west and an aspect ratio of 1.5. Each floor has four perimeter zones and one core zone with about 30% and 70% of the total floor area, respectively. The window-wall ratio (WWR) is about 40%, excluding the basement wall area. The roofs are flat with insulation above deck. The building has central built-up VAV systems with hot-water zone reheat. The VAV boxes have reverse acting dampers with a maximum supply air temperature of 35°C. The reverse acting damper in a VAV box can open wider to meet zone heating loads, which differentiates it from a normal acting damper that stays at a fixed minimum position during heating operations. The supply air temperature leaving the cooling coils is set to 12.8°C during cooling mode. There is no heat recovery between outdoor air and exhaust air. There is no humidifier. The central plant has two water-cooled chillers and a hot-water gas-fired boiler. Figure 1(a) illustrates the 3-D and plan views of the building.

2.1.2 The Small-Size Office Building

The small office building has only one floor with an area of 511 m^2. The building has a rectangular shape with the long axis along the east-west and an aspect ratio of 1.5. Four perimeter zones and the core zone have about 70% and 30% of the total floor area, respectively; the perimeter-core ratio is the opposite of that of the large office building. The WWR is about 20%. The building has an attic, as shown in Figure 1(b). Each of the five zones is served by a packaged single-zone system: a constant-volume HVAC system with heating from a gas furnace and cooling from a direct-expansion (DX) unitary system.

2.2 Climate Zones

Three climates — Chicago, Minneapolis, and Fairbanks — were selected in this study to represent typical climates that require significant space heating in the United States. Based on the climate zones used in the ASHRAE Standard 90.1-2010 [24], Chicago belongs to the cool and humid zone 5A, Minneapolis belongs to the cold and humid zone 6A, and Fairbanks belongs to the subarctic zone 8. Table 1 lists the climate zone information for the three cities. In the table, HDD18 is the heating degree days with a base temperature of 18^oC, and CDD10 is the cooling degree days with a base temperature of 10^oC.

2.3 Weather Data

The typical meteorological year, third generation (TMY3) [25, 26], weather data of the three cities, available at the EnergyPlus web site, were used in the simulations. The TMY3s are data sets of hourly values of solar radiation and meteorological elements for a one-year period of 12 representative months compiled from 1976 to 2005. They are intended to be used for computer simulations of solar energy conversion systems and building systems to facilitate performance comparisons of different system types, configurations, and locations in the United States. Because they represent typical rather than extreme conditions, they are not suited for designing systems to meet the worst-case conditions occurring at a location.

Historical weather data, generated from actual weather measurements and observations from 1980 to 2009 for Chicago and Fairbanks, are used in the simulations to study the impact of weather on space-heating energy use for both office buildings. Such weather data were not available for Minneapolis during the study, so similar analysis is not done for Minneapolis.

2.4 Simulation Engine

The EnergyPlus version 7.2, released in October 2012, was used for the study's building simulations. USDOE developed it as a new-generation building energy simulation program that builds on the most popular features and capabilities of the Building Loads Analysis and System Thermodynamics (BLAST) and DOE-2. EnergyPlus has innovative simulation capabilities, including time steps of less than an hour, and modular systems simulation modules that are integrated with a zone heat balance simulation. It calculates space temperature, occupant thermal comfort, cooling and heating loads, HVAC equipment sizes, energy consumption, utility cost, air emissions, water usage, renewable energy, etc. EnergyPlus is a standalone simulation program without a "user friendly" graphical interface. It reads input and writes output as text files. Since the first release in April 2001, EnergyPlus has evolved to provide new and enhanced modeling features and improved usability.

EnergyPlus has been validated through three types of tests [27]:

1. Analytical tests compare EnergyPlus simulation results with analytical mathematical solutions for simple buildings:
   - HVAC tests, based on ASHRAE Research Project 865
   - Building fabric tests, based on ASHRAE Research Project 1052
2. Comparative tests compare EnergyPlus simulation results with those of other simulation engines such as DOE-2, ESP, and Transient System Simulation Tool (TRNSYS):
   - ANSI/ASHRAE Standard 140-2007
   - IEA Solar Heating and Cooling Programme (IEA SHC) BESTest (Building Energy Simulation Test) methods not yet in Standard 140
   - EnergyPlus HVAC component comparative tests
   - EnergyPlus Global Heat Balance tests
3. Empirical tests compare EnergyPlus simulation results with measurements of actual buildings. Although some applications compare and calibrate EnergyPlus simulation results with measured energy and performance of buildings, much more needs to be done with this type of test for actual buildings of various complexities of design and operations.

2.5 Building Databases

The simulation results are benchmarked with two databases of commercial buildings in the United States: the 2003 CBECS and the USDOE high-performance buildings (HPBs) database [28]. The CBECS is a national survey that collects information on energy consumption and expenditures of U.S. commercial buildings. In this database, commercial buildings include all those in which at least half of the floor area is used for a purpose that is not residential or industrial; they include building types that might not traditionally be considered "commercial," such as schools, correctional institutions, and buildings used for religious worship. The HPB database has more than 100 commercial buildings (mostly in the United States) that were built recently and have low energy consumption. The database has detailed building descriptions and either measured or simulated energy-consumption data. The space-heating energy use from the HPB database was mostly calculated from calibrated energy models.

For the CBECS, building location is grouped into four U.S. Census regions that are subdivided into nine divisions. The four regions are the West, Midwest, Northeast, and South regions. Fairbanks belongs to the Pacific division of the West region; Chicago to the West North Central division of the Midwest region; and Minneapolis to the East North Central division of the Midwest region.

A few buildings were selected from the two databases in order to match the simulated buildings as much as possible according to the criteria: (1) building type (office), (2) building size (large or small), (3) vintage, and (4) location.

3. Building Design and Operation Parameters

Based on office-building design and operation practice, 10 parameters with potentially significant impacts on space-heating energy use were selected for the study. The parameters were sorted into two groups — design and operation — as shown in Table 2, based on whether a parameter is mostly determined during building design or operation. The classification for design and operation parameters for space-heating energy use is listed in Table 2. The selected parameters include envelope insulation, window area, window type, internal loads, infiltration (rate and schedule), space-heating temperature setpoint, heating setback during unoccupied hours, terminal VAV box minimal damper position, and boiler/furnace efficiency. For each parameter, the reference value is set in the basecase models, which are based on ASHRAE Standard 90.1-2004; a better and a worse performance value are then determined based on building design or operation practice, applicable building-energy standards, and available measurement or analysis reports. The selection and determination of these parameters are from the perspectives of practical building design and operations. This differentiates the current study from sensitivity analyses that do not use or require a high fidelity of parameters, as the sensitivity is calculated as a ratio between the change in outputs and the change in inputs.

3.1 Design Parameters

3.1.1 Internal Loads

Internal loads include heat gains from interior lighting, plug-loads, and occupants. Internal loads reduce space-heating loads. For the basecase, interior lighting power density (LPD) is set to 10.76 W/m^2, based on ASHRAE Standard 90.1-2004. The plug-load (receptacle) equipment power density (EPD) is set to 10.76 W/m^2, based on the CRBs. For the High Internal Loads case, the LPD and EPD are set 50% higher than the basecase, while for the Low Internal Loads case, they are set 50% lower. The LPD of the High Internal Loads case is set to

16.14 W/m^2, which is based on the prescriptive requirement of interior lighting for the whole building in ASHRAE Standard 90.1-1989 [29]. The 50% lower LPD is based on the state-of-the-art lighting technologies for office buildings. The 50% lower EPD references Fisher's study [30], which shows plug-load energy use could be reduced over 50% by using energy-efficient appliances, installing an energy-management system, and most important, educating and training occupants on how to save energy.

3.1.2 Envelope Insulation

Better insulation of a building envelope reduces space-heating loads. For the basecases, the insulation levels of the wall and roof constructions are based on ASHRAE Standard 90.1-2004. For the More Envelope Insulation cases, the insulation levels are based on ASHRAE Standard 90.1-2010. For the Less Envelope Insulation cases, the insulation levels are set according to the pre-1980 offices from the CRBs. Table 3 lists a few key parameters of the office buildings constructed at three different ages.

3.1.3 Window Area

With more windows, space-heating loads tend to increase for most climates that require heating because windows usually contribute more heat loss than walls, even taking into account windows' solar-heat gains. For the basecases, the large office building has a WWR of 40%, while the small office building has a WWR of 20%. The High WWR cases double the window area: The large office building has a WWR of 68% (cannot reach 80% due to the assumption of no windows on the plenum walls), while the small office building has a WWR of 40%. The Low WWR cases reduce window area by 50% from the basecases: The large office building has a WWR of 20%, while the small office building has a WWR of 10%.

3.1.4 Window Type

Windows with lower U-factor and higher solar heat gain coefficient (SHGC) reduce space-heating loads. The U-factor is the heat transfer rate through the window per unit area and per unit temperature difference. The SHGC represents the fractional amount of solar energy that strikes the window and ends up warming the indoor environment. Visible transmittance (VT) is the fraction of visible light that comes through the glass. This is influenced by glass selection as well as the amount of the opening taken up by nontransparent components such as the frame. The basecases have double-pane windows. The worst cases use single-pane windows, while the better cases use triple-pane windows. Table 4 summarizes window-type performance for relevant cases at different climate zones.

3.1.5 Boiler and Furnace Efficiency

A higher efficiency of heating equipment reduces space-heating energy use. For the basecases, the large office building has a boiler of 80% efficiency, while the small office building has furnaces of 78% efficiency. The High Boiler/Furnace Efficiency cases, assuming the use of condensing boilers and furnaces, have a boiler of 91% efficiency for the large office building and furnaces of 88% efficiency for the small office building.

3.2 Operation Parameters

3.2.1 Air Infiltration Rate

Air infiltration during heating seasons increases space-heating loads. Parameters of air infiltration include peak infiltration rate and infiltration schedule. According to a report by National Institute of Standards and Technology [31, 32], peak infiltration rates measured for typical commercial buildings range from 2.04 to 9.14 L/(s·m^2), based on 75 Pa of pressure difference and per unit of gross exterior wall area. For EnergyPlus simulations, these infiltration rates are adjusted to the 4 Pa of pressure difference. The basecase infiltration rate is 2.04 L/(s·m^2) (equivalent to 0.65 air changes per hour), which is also defined in ASHRAE Standard 90.1-2010. For the High Infiltration Rate case, the 7.61 L/(s·m^2) (2.44 ach) is used in reference to the proposal to ASHRAE Standard 90.1-2013 for buildings without installation of a continuous air barrier. The high infiltration rate is 375% higher than the basecase. The 50% lower infiltration rate is used in the Low Infiltration Rate case for airtight buildings.

The peak air-infiltration rate depends to a great extent on a building's airtightness, especially the opening and closing of windows and doors, which are more related to building operation and occupant activity. Therefore, air-infiltration rate is categorized as an operation rather than a design parameter.

3.2.2 Air Infiltration Schedule

A schedule is used to describe the variation of air infiltration during occupied and unoccupied hours. For the basecases, air infiltration during occupied hours is assumed to be 25% of the peak infiltration rate. Values of 50% and 100% are used in the Medium and High Infiltration Schedule cases to represent buildings that are not airtight or that have poor air balancing during occupied hours.

3.2.3 Space-heating Thermostat Setting

A higher space-heating temperature setpoint increases space-heating loads. The basecases set the space-heating temperature for occupied hours to 21°C, which is typical for office buildings in the United States. The High Heating Setpoint case raises the heating thermostat setting to 23°C, while the Low Heating Setpoint case lowers it to 18°C.

3.2.4 Space-heating Setback Control

Setback control is usually used to lower space-heating thermostats for office buildings during unoccupied hours. The basecases assume a heating setback to 10°C during unoccupied hours, which may be too aggressive. Hence, two heating-setback cases are considered: One is set back to 15°C to represent the typical operation of most office buildings, and the other is to have no setback at all to represent the worst-case scenario.

3.2.5 VAV Box Minimum Damper Position

The large office building is served by central VAV systems, which use reheat coils at the zone terminal boxes to provide space heating. The terminal boxes have reverse acting dampers, which can open beyond the minimum position during the heating mode to meet zone heating loads. The higher the minimum damper position, the more reheat energy can be consumed. The basecases have the VAV box minimum damper position set to 30%, based on a typical design that meets recent building energy standards [33]; the High Minimum VAV Box Damper Position case sets it to 50%, based on surveys of office buildings [34]; and the Low Minimum VAV Box Damper Position case sets it to 15%, based on proposals to update 2008 California and 2010 ASHRAE building energy-efficiency standards.

4. Simulation Runs

Table 5 lists the parametric of the simulation runs for the two office buildings. There are 126 EnergyPlus simulation runs in total, including 22 runs for the large office building and 20 runs for the small office building for each of the three cities. These runs include the basecase, the High and Low Internal Loads cases, the High and Low Infiltration Rate cases, the High and Medium Infiltration Schedule cases, the High and Low Minimum VAV Box Damper Position cases for large office only, the High and Low Heating Setpoint cases, the High and Low WWR cases, the Single and Triple Pane Window cases, the More and Less Envelope Insulation cases, and the High Boiler/Furnace Efficiency cases. Each run varies only one parameter from the basecase, except the High Heating case and the Low Heating case, which combine the worse and better values (based on the influence on space-heating energy) of the selected parameters, respectively. In the High Heating and Low Heating cases, the value of the WWR stays the same as that of the basecase for both office buildings. The High Heating and Low Heating cases aim to capture the worst case of buildings that consume the most heating and the best case of buildings that consume the least heating.

In addition to the above-mentioned 126 runs, there are 60 runs using the 30 historical years of weather data for Chicago and Fairbanks.

5. Results and Discussions

5.1 Impact of Design and Operation Parameters

Figure 2 shows the percentages of change in space-heating EUIs calculated by comparing the space-heating EUI from each parametric run to that of the basecase for the large office building in the three climates. Figure 3 shows similar data for the small office building. Both figures are sorted by the percent changes for the Chicago climate.

Looking at results in Figure 2 for the large office building, it can be seen that: (1) Based on the relative impact of the building operation, the most influencing operation parameters are high minimum VAV box damper position setting, thermostat without setback during unoccupied hours, high heating setpoint, and high infiltration rate; (2) for the building design efficiency aspect, the most influencing parameters are low and high internal load, window type, and window area; and (3) other parameters, including low air infiltration rate, low minimum VAV box damper position setting, infiltration schedule for the operation aspect, and boiler efficiency and envelope insulation for the building design aspect have less impact on space-heating energy use.

From the operation aspect of the large office building, there are several significant findings:

- The impact of minimum VAV box damper position setting ranges from -12% to 128% for Chicago, -7.5% to 78% for Minneapolis, and -2.5% to 31% for Fairbanks; the Low Minimum VAV Box Damper Position cases show small impact on space-heating energy use. Oversizing the VAV box or setting the minimal damper position too high can result in huge space-heating penalty.
- The cases of Thermostat No Setback during unoccupied hours increase the space-heating EUIs by 50% to 102% from the basecases for the three climates while the cases of Thermostat Setback to 15°C during

unoccupied hours have increases from 10% to 12%. Thermostat setback is an effective operation strategy to reduce space-heating energy use during unoccupied hours.

- The impact of space-heating setpoint ranges from -44% to 65% for Chicago, -32% to 44% for Minneapolis, and -19% to 22% for Fairbanks. Lowering the heating thermostat setpoint is an easy way to save space-heating energy use during occupied hours.
- The cases of High Infiltration Rate show significant increase in space-heating energy use by 42%, 38.5%, and 38.9% for Chicago, Minneapolis, and Fairbanks, respectively. However, the cases of Low Infiltration Rate have small impact on space-heating energy use in all three climates, which may be because the low infiltration rates are only 50% lower than the basecases while they are 375% higher for the High Infiltration Rate cases.

From the design-efficiency aspect of the large office building, it can be seen that:

- Triple-pane windows can save space-heating energy by 51%, 43%, and 29% for Chicago, Minneapolis, and Fairbanks, respectively. On the other hand, single-pane windows increase space-heating energy by 46% for Chicago, and 34% for both Minneapolis and Fairbanks. High-performance windows with low U-factors have great potential to reduce space-heating energy use for cold climates.
- Window area also plays an important role. High WWR cases could increase space-heating energy use by 23% to 38%; on the other hand, low WWR cases could save space heating by 24% to 33%.
- Internal loads can change space heating from -30% to 48%, compared with the basecase in Chicago; -30% to 40% in Minneapolis; and -28% to 30% in Fairbanks. Internal loads from lighting, equipment, and occupants directly reduce space-heating loads.
- Wall insulation has less influence compared with other building-design parameters mainly due to the basecase has good insulation. From the simulated results, the More Envelope Insulation cases used the latest version of the ASHRAE standard published in 2010, however, this high insulation level reduces space-heating energy use by less than 5%.

The relative impacts of the significant parameters on space heating are consistent across the three climates, with Chicago showing the largest impact, followed by Minneapolis and Fairbanks. Fairbanks shows the least impact due to its high space-heating EUI of the basecase compared with the other two climates.

Similarly, the results in Figure 3 for the small office building reveal that, based on the relative impact for the operation aspect, the most influencing parameters are high and low space-heating setpoint, thermostat without setback during unoccupied hours, high air infiltration rate, and high infiltration schedule. For the building-design efficiency aspect, the most influencing parameters are internal loads, triple-pane windows, and less envelope insulation. All the parameters described above except window type and envelope insulation can be controlled by building occupants or operators. Other parameters, including low WWR, high furnace efficiency, and single-pane windows for the building design parameters; and low infiltration rate and thermostat setback to 15°C during unoccupied hours for the operation aspect have smaller impact on space-heating energy use. Small office buildings show very similar patterns to the large office buildings — operation parameters have greater impact than design parameters.

From the operation aspect of the small office building, a few key results are:

- The impact of the space-heating setpoint ranges from -61% to 61% for Chicago, -50% to 46% for Minneapolis, and -33% to 26% for Fairbanks. The heating setpoint could be easily controlled by occupants in small office buildings because in packaged single-zone systems, thermostats are usually located in office spaces. Decreasing the heating setpoint by 3°C could save more than 50% in space-heating energy, while increasing the heating setpoint by 2°C would consume more than 50% of space-heating energy in cold climates. Fairbank belongs to the subarctic region; it needs more space-heating energy than other climates at the same building design and operation conditions. Thus the percentage changes to space-heating energy use are smaller than other climates by adjusting the same degrees of the heating setpoint.
- Not setting back the heating thermostat during unoccupied hours can increase space heating from 37% to 42% for the three climates.
- Similar to the results of the infiltration rate cases for the large office buildings, a high infiltration rate can significantly increase space heating by 41%, 37%, and 30% for Chicago, Minneapolis, and Fairbanks, respectively. The cases of Low Infiltration Rate in the three cities demonstrate relatively small impact compared with other cases with same reason mentioned above.

From the large office building design parameters, it can be seen that:

- Internal loads can change the space heating from -40% to 52% for Chicago compared with the basecase, -33% to 39% for Minneapolis, and -21% to 21% for Fairbanks. The variations of space-heating energy use due to changes to internal load are similar to the large office building in each city. Internal loads from lighting, equipment, and occupants directly reduce the needs of space-heating loads.
- The High WWR cases increase the space heating from 12% to 15% in the three climates; on the other hand, the Low WWR cases could save space heating by about 5% to 10%.
- Triple-pane windows can save space heating by 27%, 25%, and 16% for Chicago, Minneapolis, and Fairbanks, respectively.
- In all three climates, less window area and the use of single-pane windows show relatively small influence on space-heating energy use, which can be due to the tradeoff between the window conduction heat losses and solar heat gains.
-

Figure 4 benchmarks the space-heating EUI of the High and Low Heating cases against the basecases for both office buildings across the three climates. There are huge differences in heating energy use between the High Heating (the worst) cases and the Low Heating (the best) cases — by factors of about 60, 30, and 15 for both office buildings in Chicago, Minneapolis, and Fairbanks, respectively. The space-heating EUI ranges from 14.3 to 828.5 MJ/m^2 (3.97 to 230.1 kWh/m^2), 31.0 to 978.3 MJ/m^2 (8.61 to 271.8 kWh/m^2) and 87.5 to 1315 MJ/m^2 (24.3 to 365.3 kWh/m^2) for the large office buildings in Chicago, Minneapolis, and Fairbanks, respectively. For the small office buildings, the ranges are 6.5 to 482 MJ/m^2 (1.81 to 133.9 kWh/m^2), 19.7 to 671 MJ/m^2 (5.47 to 186.4 kWh/m^2), and 93.4 to 1185 MJ/m^2 (25.9 to 329.2 kWh/m^2) in Chicago, Minneapolis, and Fairbanks, respectively.

Compared with the basecases, the High Heating cases significantly increase space-heating energy use by a factor of 3 to 5 for the large office buildings in these climates; while for the small office buildings, the increase in space-heating energy use is by a factor about 3. Similarly, compared with the basecases, the Low Heating cases dramatically decrease space-heating energy use to 1/8, 1/5, and 1/3 for the large office buildings in Chicago, Minneapolis, and Fairbanks, respectively; and to 1/17, 1/9, and 1/4 for the small office buildings.

For the large office building served by VAV systems with zone reheat, potential reheat during the summer cooling season is a waste of energy and thus increases space-heating energy use. Figure 5 shows monthly space-heating EUIs of the large office building in Chicago. It can be seen that most of the heating is used during winter, especially December and January. A relatively small amount of heating may occur during summer for the large office building, mainly due to heating the basement. There is almost no reheat during summer except for the High Minimum VAV Box Damper Position case and the High Heating case. This agrees with common operational practice that setting the VAV box damper wide open is one of the major causes of high reheat energy during summer.

Based on above analysis, it can be seen that space-heating energy use can be significantly reduced by more efficient building design and even more so by improving the operation of space-heating systems. To improve the accuracy of the prediction of space-heating energy use by simulations, it is crucial to have proper inputs to the most important design and operation parameters as identified in the study.

5.2 Impact of Weather Data

To look at the impact of weather data on space-heating energy use, a percentage change of space-heating energy use is calculated by comparing the space-heating energy use of a historical year (from 1980 to 2009 for Chicago and Fairbanks) to that of the basecase using the TMY3 weather. Figure 6 and Figure 7 show that the impact of weather data on space-heating energy use is significant for the large and small office buildings in both Chicago and Fairbanks.

For Chicago, the large office building shows that space-heating energy use varies from -18% to +33%; while the small office building shows variations from -24% to +33%. The results indicate that 1985 was the coolest year and 2006 the warmest year for both office buildings across the 30-year period. Most warm years occurred from 1998 to 2006, while most cool years occurred from 1980 to 1986.

For Fairbanks, the large office building shows that space-heating energy use varies from -20% to +24%; while the small office building shows variations from -17% to +22%. The results indicate that 1999 was the coolest year and 1981 was the warmest year for both office buildings across the 30-year period. Most warm years occurred from 2000 to 2003, while most cool years occurred from 1988 to 1999.

The impact of weather on space-heating energy use is very consistent across both office buildings in the same climate, but is very different across both climates — the coolest and warmest years occurred differently during the period from 1980 to 2009.

It should be noted that space-heating energy use from simulations using TMY3 weather data can underestimate by up to 33% or overestimate by up to 25% compared with using historical weather data. For Fairbanks, simulated results using TMY3 underestimate space-heating energy for most of the years during the 30-year period.

Comparing the space-heating energy use of the coolest year to the warmest year for Chicago, the increase is 51% and 57% for the large and small office buildings, respectively; while for Fairbanks, the increases are 44% and 39%. Thus it is crucial to run simulations with multiple decades of weather data to fully evaluate the impact of weather on the energy performance of space-heating systems in buildings.

5.3 Benchmarking with Building Databases

To form a clear picture of how space-heating energy use varies in actual buildings, we selected ones from the two databases for Chicago and Minneapolis that were similar to the simulated large and small office buildings in terms of building type or function, size, location, and construction age. Figure 8 to Figure 11 show both the simulated and the actual space-heating EUIs. Each horizontal line represents result from a selected building in one of the two databases. The solid lines represent buildings selected from the CBECS database, while the dashed lines representing buildings from the HPB database.

In general, space-heating EUIs vary significantly for the selected buildings from both databases and even more across the two databases.

Figure 8 shows the benchmark results for the large office in Chicago. From CBECS, 10 buildings were found with floor area ranging from 18,580 to 46,450 m^2, vintage 1990 to 2003. The space-heating EUIs for these buildings vary from 136.7 to 559.72 MJ/m^2 (38.0 to 155.5 kWh/m^2). Figure 9 shows the benchmark results for the small office in Chicago. The selection criteria for the CBECS are set as follows: (1) floor area from 93 to 9,290 m^2, (2) vintage 1990 to 2003, and (3) location in Chicago. Seven such small office buildings were found from the CBECS with a space-heating EUI from 249 to 1023 MJ/m^2 (69.2 to 284.2 kWh/m^2). Two small office buildings were found from the HPB database that are near Chicago and have a floor area of 1,390 and 3,716 m^2. The two offices have space-heating EUIs of 208.8 and 335.2 MJ/m^2 (58.0 to 93.1 kWh/m^2).

For Chicago, the simulated results are always much lower than the databases except for the High Heating case. Although the High Heating case results overlap with some low-end results from the databases, it is much lower than the high-end results — by more than 20%. This implies that there might be other important parameters that should be considered in simulations; for example, design and operation problems or faults of the space-heating systems.

Minneapolis belongs to the East North Central division of the Midwest region in the CBECS. Figure 10 shows the benchmark results for the large office building, and Figure 11 shows the small office building. In Figure 10, three buildings, selected based on the criteria of floor area larger than 9,290 m^2 and vintage 1990 and 2003, have space-heating EUIs ranging from 150.7 to 299.3 MJ/m^2 (41.9 to 83.1 kWh/m^2, by a factor of 2). On the other hand, eight small office buildings were selected based on floor area from 93 to 9,290 m^2 and vintage 1990 to 2003. The space-heating EUI of the eight buildings vary from 122.7 to 845 MJ/m^2 (34.1 to 234.7 kWh/m^2, by a factor of 7). Only one small building was found from the HPB with floor area of 1,104 m^2. The space-heating EUI of this office is 75.9 MJ/m^2 (21.1 kWh/m^2).

It should be noted that there are uncertainties associated with the two benchmark databases: (1) the space-heating energy uses are not from actual measurements; rather, they are calculated from statistical analysis (CBECS) or energy modeling (HPB); (2) the floor area used to calculate the EUI might not accurately match the actual floor area of the buildings. Furthermore, the buildings selected from the databases may not exactly match the simulated buildings in terms of floor area, vintage, and location. This contributes to discrepancies between the simulated and benchmarked space-heating energy uses.

6. Conclusions

The simulated space-heating energy use of the small- and large-size office buildings across the three heating climates can vary significantly, depending on details of a few key building design and operation parameters. The most influencing parameters are space-heating temperature setpoint and setback strategies, air infiltration, VAV terminal box damper minimum position settings for the large office, window type, WWR, and internal loads. The relative impacts of these parameters vary with building type and climate.

Compared with the basecase, the High Heating case consumes more than double the space-heating energy, while the Low Heating case consumes less than half for both office buildings in all the three climates.

For the two climates with the 30-year historical weather data, the simulated space-heating energy use for a particular year can vary dramatically, compared with the average results across the 30-year period. For the basecase, the simulated space-heating energy use with the TMY3 weather data can overpredict by 24% and underpredict by 34%, compared with the results with the historical weather data. To understand the long-term impact of weather on space-heating energy use, it is critical and necessary to run simulations with multiple decades of actual weather data, considering the availability and affordability of such data and low extra cost of running such simulations on current PCs with high computing power. Besides, dynamic analyses should be introduced to study the integrated effect of driving factors to space heating energy use.

The actual space-heating energy use for the similar office buildings from the CBECS and HPB databases also vary significantly, with wide ranges that well overlap the variation ranges of the simulated results. Based on the study, simulations do not necessarily always under- or overpredict space-heating energy use. The simulated space-heating energy use depends on building type, configuration, and climate, with a few special key influential building design and operation parameters.

High-efficiency designs and better operation of buildings can reduce space-heating energy use, but the latter plays a more important role. For building designers, paying more attention to the most influential design parameters has significant potential to reduce space-heating energy use for new buildings. For building owners and operators, improving building operations through commissioning and retrofits to control key operation parameters is an effective way to reduce space-heating energy use for existing buildings. Finally, for energy policy makers, enforcing more stringent regulations on these design and operation parameters can significantly reduce space-heating energy use in new and existing buildings.

To lower space heating energy use in office buildings, the following steps are recommended: 1) lower space-heating temperature setpoint while maintaining thermal comfort, 2) use heating thermostat setback during unoccupied hours, 3) reduce air infiltration rate by improving air tightness of the building envelope, 4) decrease the minimum damper position settings of VAV terminal boxes if applicable, and 5) replace with better insulated windows.

This study did not look at other influencing factors of space heating, such as building occupancy level and operational faults of space-heating systems. Building occupancy levels vary case by case, and insufficient data is available for this study. Future research can study the impact of HVAC operational faults on space-heating energy use. Other potential causes of high space-heating energy in actual buildings might relate to occupants opening windows during heating season, space overheating due to lack of temperature controls, heat losses from air ducts, hot-water piping, and boilers that might not be counted well or at all in energy-modeling programs. Similar analysis can be done for other building types and climates, and to aggregate the impacts at the regional and national levels.

Acknowledgement

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Glossary

ASHRAE	American Society of Heating, Refrigeration, and Air-conditioning Engineers
BESTest	Building Energy Simulation Test
BLAST	Building Loads Analysis and System Thermodynamics
CBECS	Commercial Buildings Energy Consumption Survey
CDD	cooling degree day
CRB	commercial reference building
DX	direct expansion
EIA	Energy Information Administration
EPD	equipment power density
EUI	energy use intensity
HDD	heating degree day
HPB	high-performance building
IEA	International Energy Agency
IEAD	insulation entirely above deck
LPD	lighting power density
MJ	mega joules
NFRC	National Fenestration Rating Council
SHC	Solar Heating and Cooling Programme
SHGC	solar heat gain coefficient
TRNSYS	Transient System Simulation Tool
WWR	window-wall ratio
VAV	variable air volume
VT	visible transmittance

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Table 1. Characteristics of selected cities and climate zones.

City	ASHRAE Climate Zone	CBECS Census Region	HDD18	CDD10
Chicago	Cool-Humid, 5A	West North Central, Midwest	6176	3251
Minneapolis	Cold-Humid, 6A	East North Central, Midwest	7981	2680
Fairbanks	Subarctic, 8	West Pacific	13940	1040

Table 2. Selected design and operation parameters for space heating.

Design parameters	Operation parameters
Window type	Air infiltration rate
Boiler/furnace efficiency	Air infiltration schedule
Internal loads (lighting and plug-loads)	Space-heating thermostat setting
Envelope insulation	Heating setback control
Window area (window-wall-ratio)	VAV box minimum damper position setting

Table 3. Parameters for three building types.

Vintage	Roof construction U-factor (W/m^{2}K) (Large/Small office)	Wall construction U-factor (W/m^{2}K) (Large/Small office)
Less Insulation, (USDOE CRBs, Pre-1980)	IEAD/IEAD*	Steel/ Mass
	5A, 0.358/0.358	5A, 0.698/0.505
	6A, 0.358/0.358	6A, 0.591/0.477
	8, 0.273/0.273	8, 0.454/0.363
Basecase, (ASHRAE 90.1-2004)	IEAD/Attic	Mass/ Mass
	5A, 0.358/0.193	5A, 0.698/0.698
	6A, 0.358/0.153	6A, 0.591/0.591
	8, 0.273/0.153	8, 0.454/0.454
More Insulation, (ASHRAE 90.1-2010)	IEAD/Attic	Mass/ Mass
	5A, 0.273/0.153	5A, 0.511/0.511
	6A, 0.273/0.153	6A, 0.454/0.454
	8, 0.273/0.119	8, 0.403/0.403

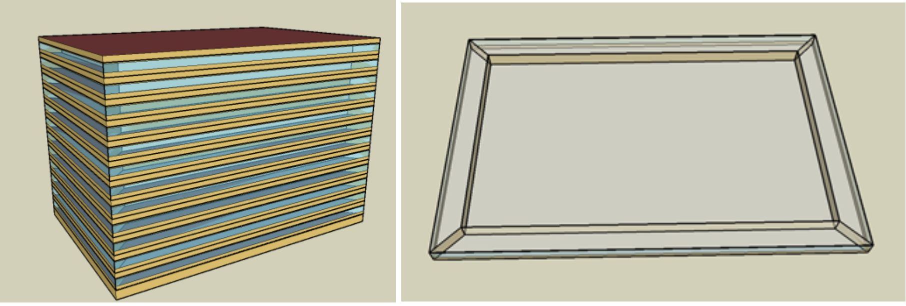
* IEAD: insulation entirely above deck

Table 4. Window type.

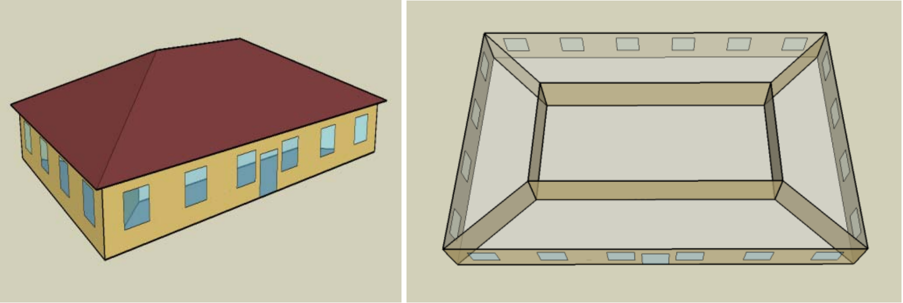
NFRC Rated Values	U-factor (W/m^{2}K)	SHGC	VT
Base case: Double-pane window, low-e			
Chicago	3.24	0.385	0.305
Minneapolis	3.24	0.385	0.305
Fairbanks	2.62	0.296	0.212
Single-pane Window, clear	5.81	0.822	0.882
Triple-pane Window, spectral selective, clear, low-e	0.87	0.285	0.451

Table 5. Parametric of the simulation runs.

Description of Runs	LPD (W/m^2)	EPD (W/m^2)	WWR (large/small office)	Infiltration Rate (m^3/s·m^2)	Infiltration Schedule (occupied hours)	Min. VAV box Damper Position (large office)	Heating Setpoint/ Setback (^{o}C)	Boiler/Furnace Efficiency	Envelope Construction	Window type
Basecase	10.76	10.76	0.4/0.2	0.000302	0.25	0.3	21/10	78%/80%	90.1-2004	90.1-2004
High Internal Loads	16.14	16.14	0.4/0.2	0.000302	0.25	0.3	21/10	78%/80%	90.1-2004	90.1-2004
Low Internal Loads	5.38	5.38	0.4/0.2	0.000302	0.25	0.3	21/10	78%/80%	90.1-2004	90.1-2004
High WWR	10.76	10.76	0.68/0.4	0.000302	0.25	0.3	21/10	78%/80%	90.1-2004	90.1-2004
Low WWR	10.76	10.76	0.1/0.1	0.000302	0.25	0.3	21/10	78%/80%	90.1-2004	90.1-2004
High Infiltration Rate	10.76	10.76	0.4/0.2	0.001133	0.25	0.3	21/10	78%/80%	90.1-2004	90.1-2004
Low Infiltration Rate	10.76	10.76	0.4/0.2	0.000189	0.25	0.3	21/10	78%/80%	90.1-2004	90.1-2004
High Infiltration Schedule	10.76	10.76	0.4/0.2	0.000302	1	0.3	21/10	78%/80%	90.1-2004	90.1-2004
Medium Infiltration Schedule	10.76	10.76	0.4/0.2	0.000302	0.5	0.3	21/10	78%/80%	90.1-2004	90.1-2004
High Minimum VAV Box Damper Position	10.76	10.76	0.4/0.2	0.000302	0.25	0.5	21/10	78%/80%	90.1-2004	90.1-2004
Low Minimum VAV Box Damper Position	10.76	10.76	0.4/0.2	0.000302	0.25	0.15	21/10	78%/80%	90.1-2004	90.1-2004
High Heating Setpoint	10.76	10.76	0.4/0.2	0.000302	0.25	0.3	23/10	78%/80%	90.1-2004	90.1-2004
Low Heating Setpoint	10.76	10.76	0.4/0.2	0.000302	0.25	0.3	18/10	78%/80%	90.1-2004	90.1-2004
Single-pane Window	10.76	10.76	0.4/0.2	0.000302	0.25	0.3	21/10	78%/80%	90.1-2004	Single
Triple-pane Window	10.76	10.76	0.4/0.2	0.000302	0.25	0.3	21/10	78%/80%	90.1-2004	Triple
Thermostat Setback to 15^{o}C	10.76	10.76	0.4/0.2	0.000302	0.25	0.3	21/15	78%/80%	90.1-2004	90.1-2004
Thermostat No Setback	10.76	10.76	0.4/0.2	0.000302	0.25	0.3	21/21	78%/80%	90.1-2004	90.1-2004
Less Envelope Insulation	10.76	10.76	0.4/0.2	0.000302	0.25	0.3	21/10	78%/80%	Pre-1980	90.1-2004
More Envelope Insulation	10.76	10.76	0.4/0.2	0.000302	0.25	0.3	21/10	78%/80%	90.1-2010	90.1-2004
High Boiler/Furnace Efficiency	10.76	10.76	0.4/0.2	0.000302	0.25	0.3	21/10	91%/88%	90.1-2010	90.1-2004
High Heating	5.38	5.38	0.4/0.2	0.001133	1	0.5	23/15	78%/80%	Pre-1980	Single
Low Heating	16.14	16.14	0.4/0.2	0.000189	0.25	0.15	18/10	91%/88%	90.1-2010	Triple



(a) The 3-D and plan views of the large-size office building.



(b) The 3-D and plan views of the small-size office building.

Figure 1. The large- and small-size office buildings from the USDOE commercial reference buildings.

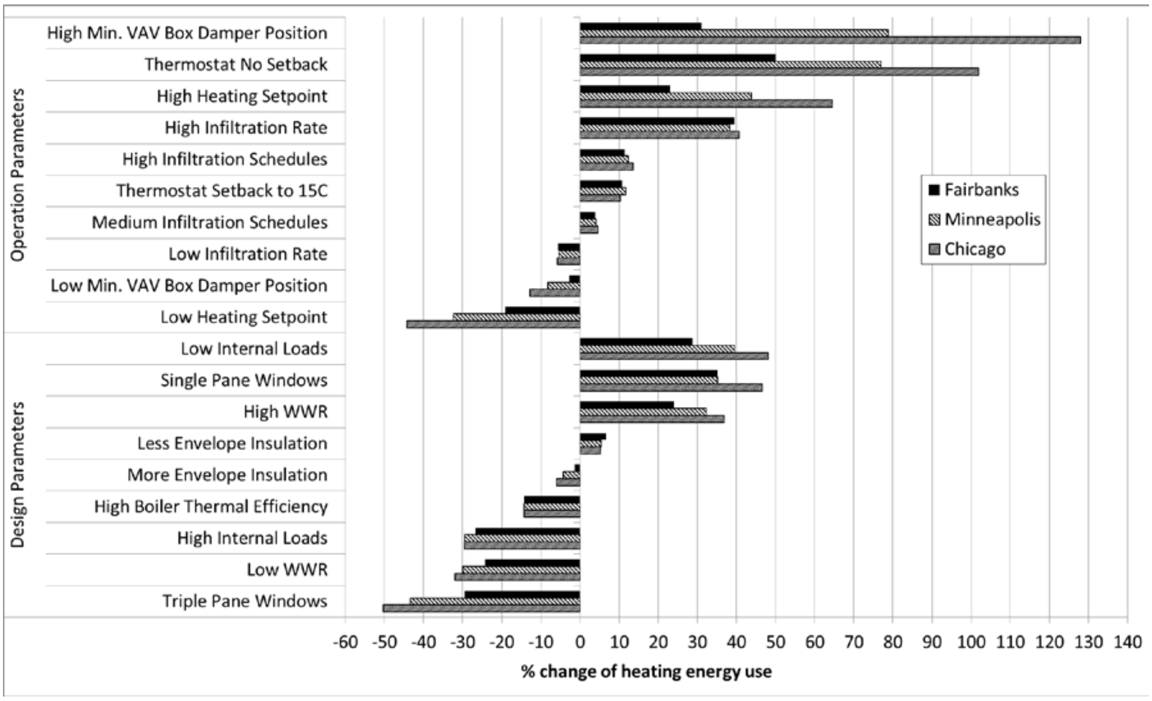


Figure 2. Impact of design and operation parameters on space-heating energy use of the large office building.

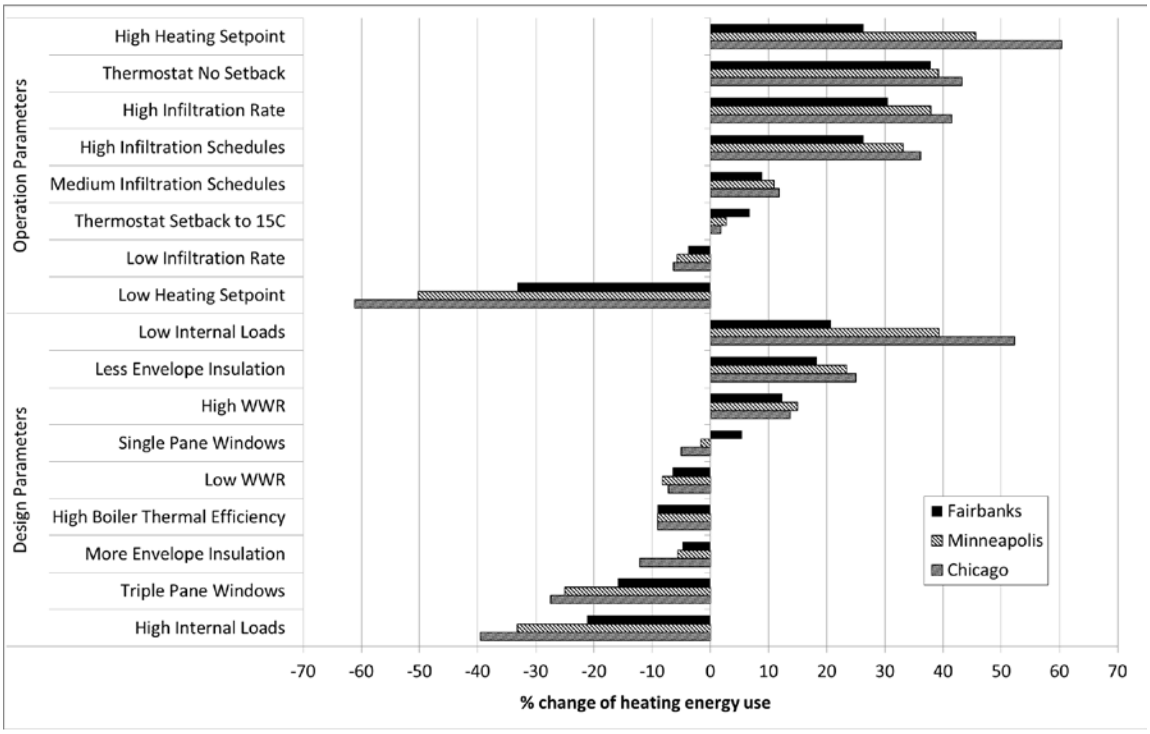


Figure 3. Impact of design and operation parameters on space-heating energy use of the small office building.

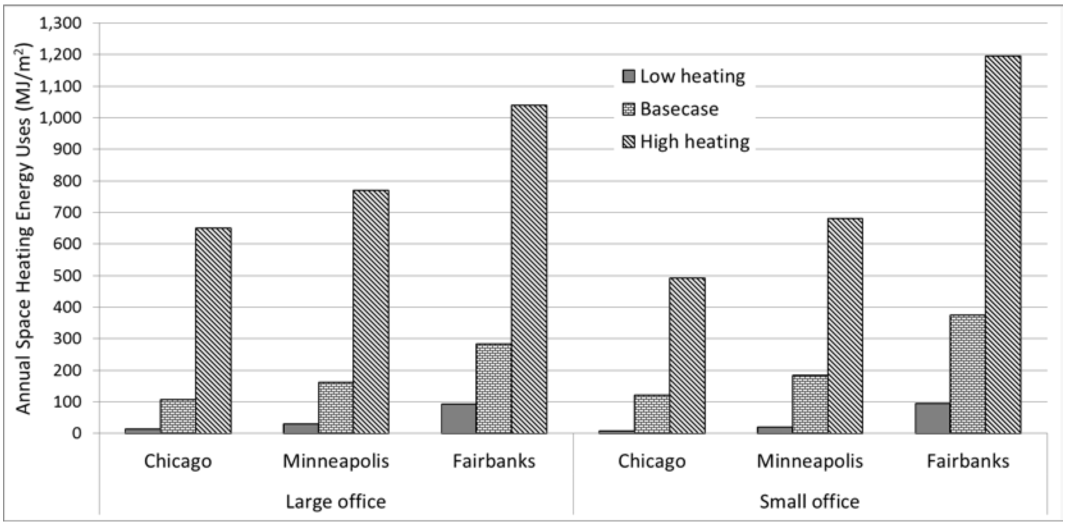


Figure 4. Comparison of space-heating energy use among the High Heating cases, the basecases, and the Low Heating cases for the large and small office buildings.

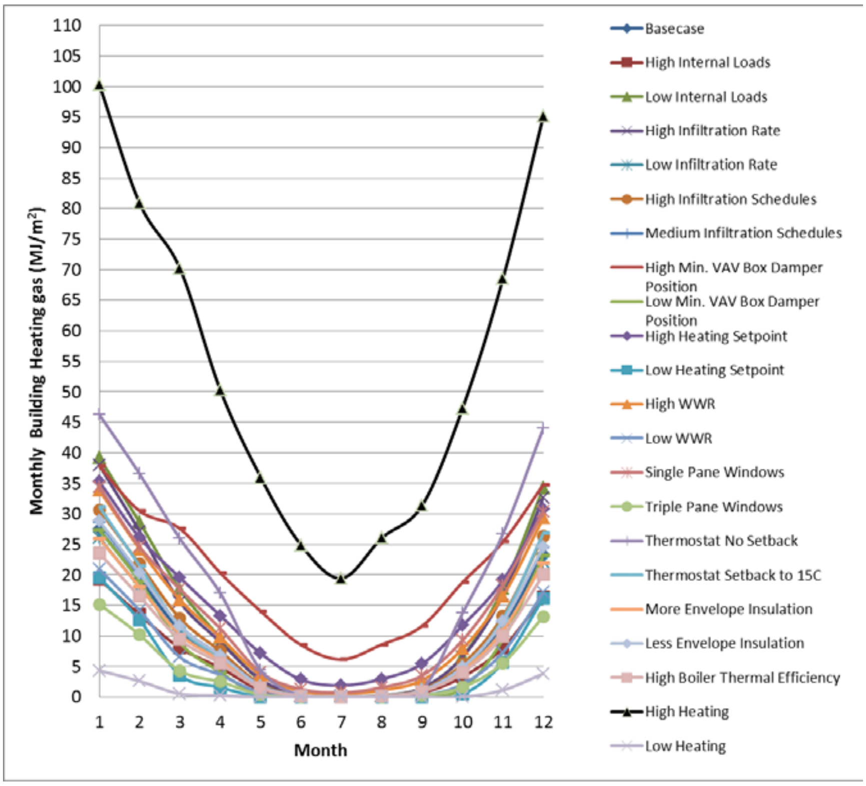


Figure 5. Monthly space-heating energy use of the large office building in Chicago.

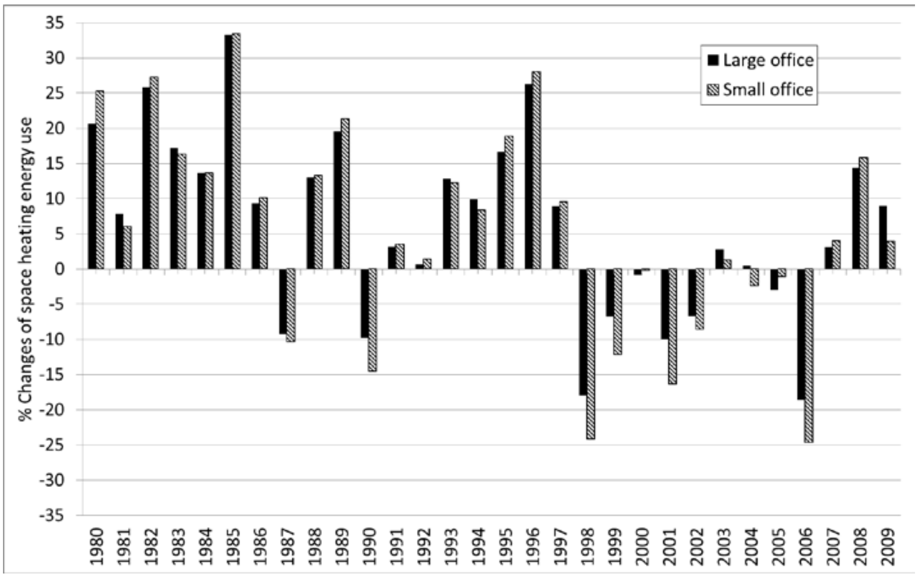


Figure 6. Multiyear space-heating energy use in Chicago.

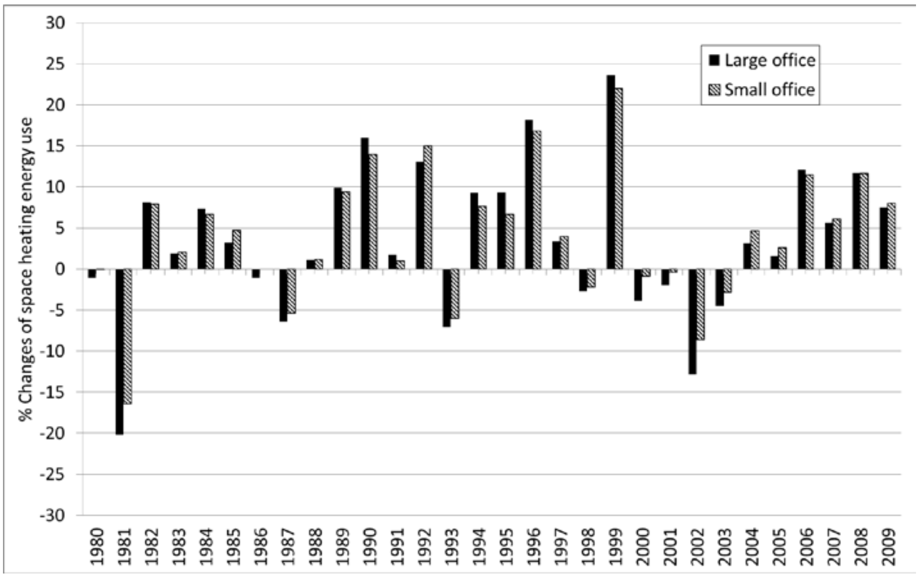


Figure 7. Multiyear space-heating energy use in Fairbanks.

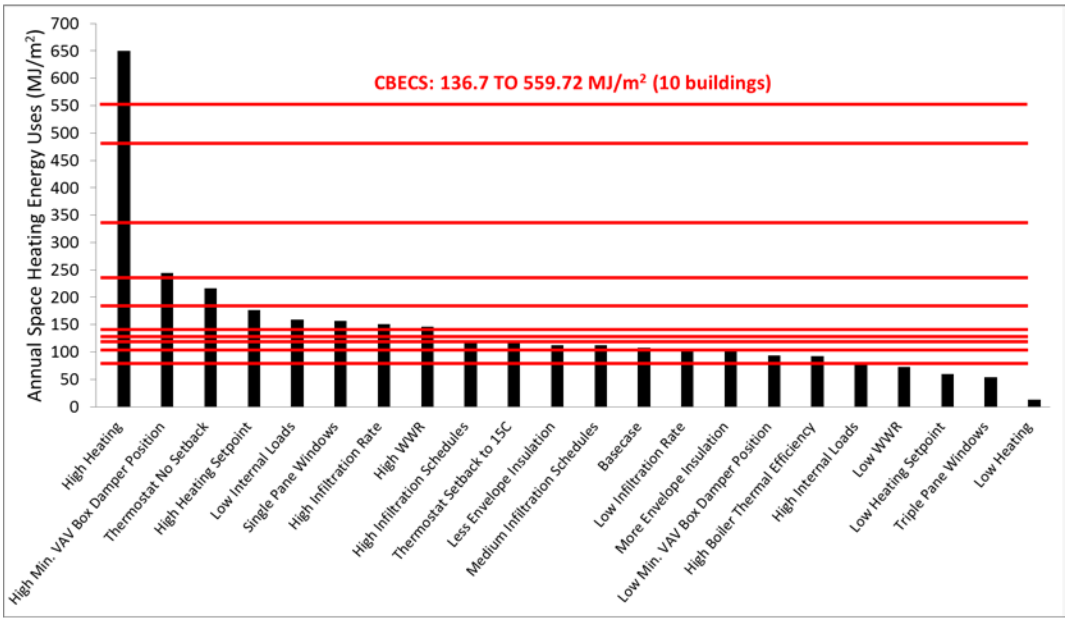


Figure 8. Benchmarking simulation results with the building databases for the large office building in Chicago.

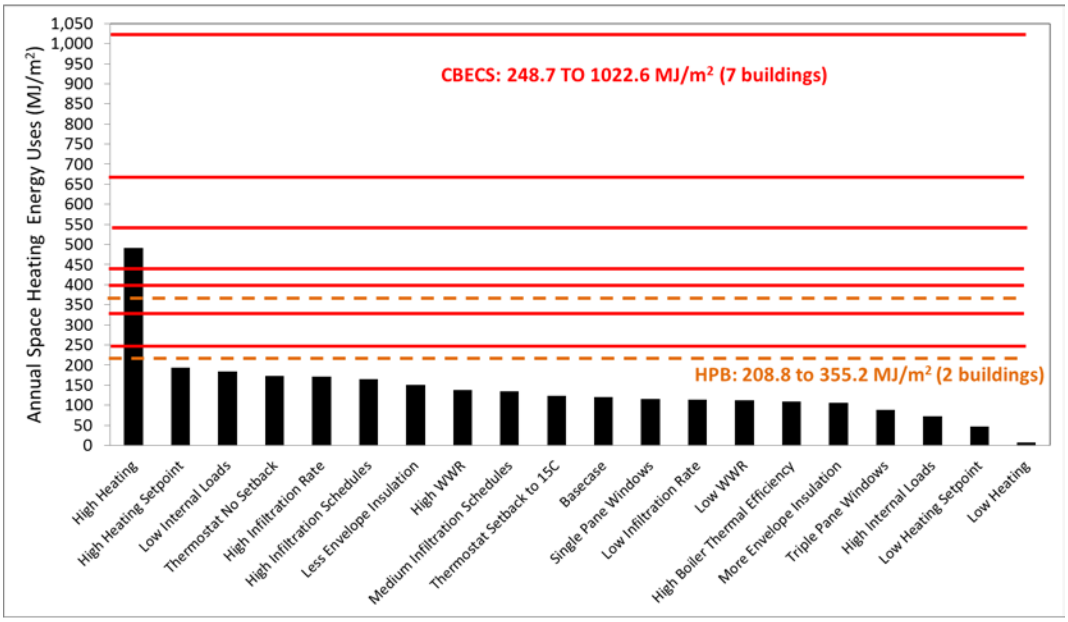


Figure 9. Benchmarking simulation results with the building databases for the small office building in Chicago.

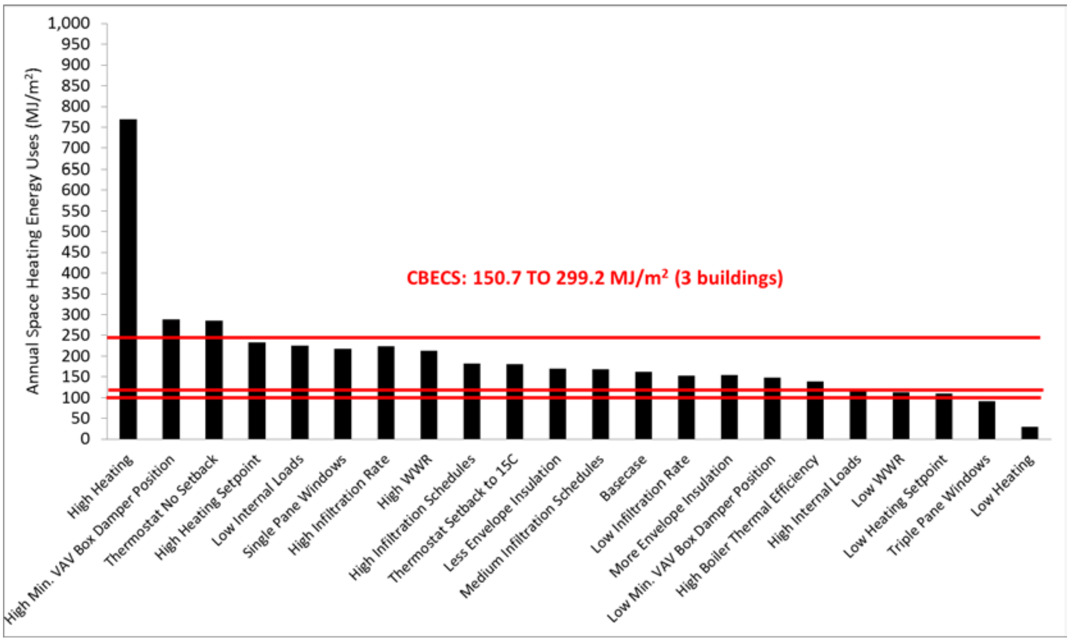


Figure 10. Benchmarking simulation results with the building databases for the large office building in Minneapolis.

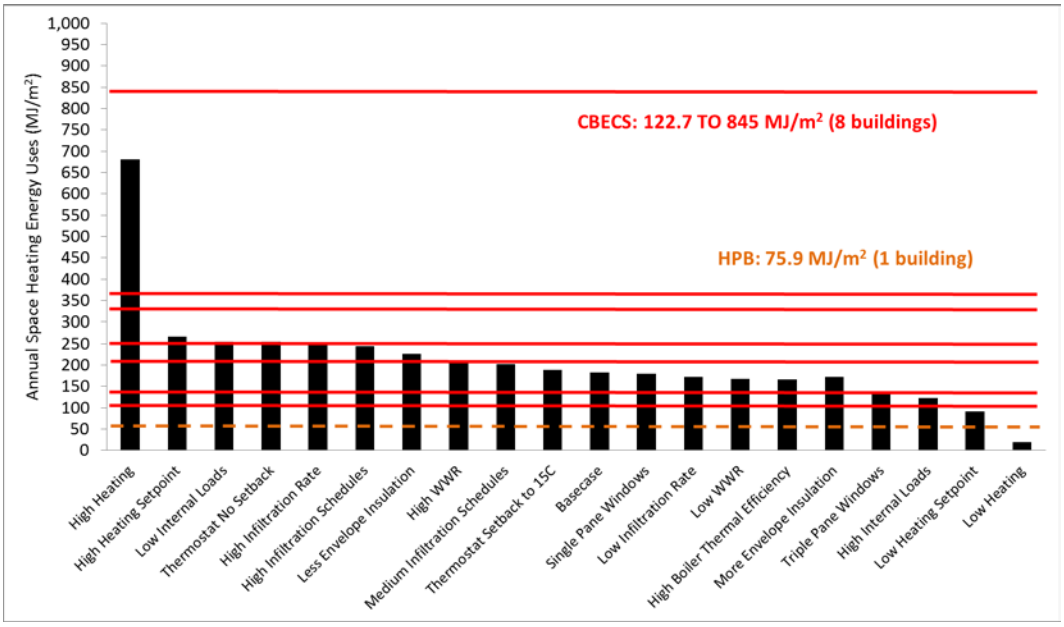


Figure 11. Benchmarking simulation results with the building databases for the small office building in Minneapolis.