An In-depth Analysis of Space Heating Energy Use in Office Buildings

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ABSTRACT

Space heating represents the largest end use in the U.S. buildings and consumes more than 7 trillion Joules of site energy annually [USDOE]. Analyzing building space heating performance and identifying methods for saving energy are quite important. Hence, 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.

In this study, the prototypical small and large-size office buildings of the USDOE commercial reference buildings, which comply with ASHRAE Standard 90.1-2004, are selected. Key design and operation factors were identified to evaluate their degrees of impact for space heating energy use. Simulation results demonstrate that some of the selected building design and operation parameters have more significant impacts on space heating energy use than others, on the other hand, good operation practice can save more space heating energy than raising design efficiency levels of an office building. Influence of weather data used in simulations on space heating energy is found to be significant. The simulated space heating energy use is further benchmarked against those from similar office buildings in two U.S. commercial buildings databases to better understand the discrepancies.

Simulated results from this study and space heating energy use collected from building databases can both vary in two potentially well overlapped wide ranges depending on details of building design and operation, not necessarily that simulation always under-predicts the reality.

Introduction

For the whole sectors of energy end use in the U.S. buildings, space heating is the largest one [USDOE]. The U.S. Energy Information Administration [EIA] 2003 Commercial Building Energy Consumption Survey (CBECS) indicates that office buildings are the most common building type, comprise the largest floor area, and consume the most energy in the commercial building sector. In office buildings, space heating energy use always occupied the largest sector, and consumes about one-third of total site energy according to the 2003 CBECS. Therefore studying the space heating energy use of office buildings is crucial in order to reduce overall building energy use and carbon emissions.

Recently, more new building designs target green building or net zero energy building goals, which emphasize the importance of energy efficiency technologies and system designs, building operation and maintenance, and occupant behavior. Good operational practices and high efficiency designs in buildings lower the energy use of space heating [Branco 2004, Linden 2006]. Santin [2011] looked at the relationship between user behavior and space heating energy consumption concluding that behavior patterns could be used in space heating energy calculations and usage profiles for different behaviors could be discerned.

New Building Institute recently published a simulation study using eQuest (DOE-2.2) on total site energy use in mid-size office buildings [Heller 2011] 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 different system and equipment operation practices with respect to building energy use were identified by using different performance values for each characteristic parameter. Simulation results show key factors affecting the total site energy use in mid-size 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 for end user. On the other hand, user could find how much site energy they use from the bill notice it the reason site energy be adopted in this study. As the total energy use of a building includes all end uses such as lighting, space heating, space cooling, water heating, and plug-loads, the key driving factors to a building's total energy use would be very different from those to a specific end use like space heating. Space heating is the largest end use for buildings in the U.S., and the NBI study did not address key driving factors to this specific and important end use.

The purpose of this study is to identify and understand important building design and operation parameters that can have significant impacts on space heating energy use of office buildings by computer simulations with EnergyPlus. The impact of weather data on space heating energy use is investigated by running simulations with multiple-year, 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, one is the 2003 CBECS and the other is USDOE high performance buildings (HPB) database [HPB]. Detail information for those two databases were described at the following section.

Analysis Methodology

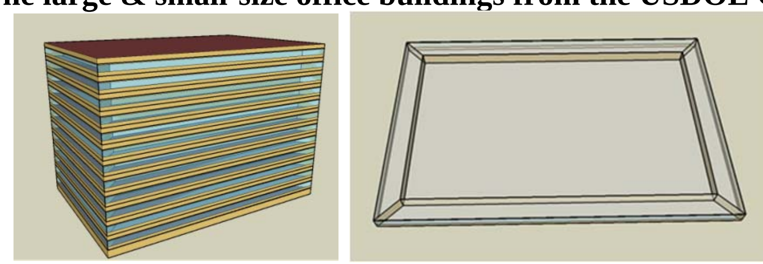
Building simulations and benchmarking with databases of building energy consumption are the two methods employed here to study the space heating energy use of office buildings. To look at the influence of climate, three typical climate zones, Chicago, Minneapolis, and Fairbanks are studied by TMY3 weather data. 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 buildings databases that contain measured whole building energy use. To study the impact of weather on space heating energy use for both office buildings, two historical weather data, from 1980 to 2009 for Chicago and from 1961 to 2005 for Fairbanks, are used in the simulations.

The TMY3 weather data was used in the simulations. The TMY3 weather data represented typical weather conditions during 1991 to 2005 and was available for download at EnergyPlus web site [Wilcox 2008].

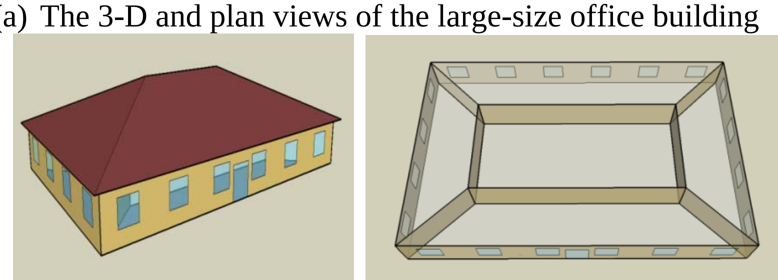
EnergyPlus version 6 was used for the building simulations in the study. It is developed by USDOE as a new generation building energy simulation program. EnergyPlus has innovative simulation capabilities including time steps of less than an hour, and modular systems simulation modules that are integrated 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.

The large- and small-size office buildings are selected from the USDOE commercial reference buildings (CRBs) for new constructions [Field 2010] which were built during the last five years. The large office building has 12 stories and a basement with a total floor area of 46320 m^2, the small office has one floor with an area of 511 m^2. Both buildings have a rectangle shape with the long axis along the East-West and an aspect ratio of 1.5. For each floor, four perimeter zones and one core zone have about 30% and 70% of the total floor area respectively for large office building, and 70% and 30% for the small building. The window-wall-ratio (WWR) is about 40% and 20% for the large office and the small office, respectively. Large office building has central built-up variable air volume (VAV) systems with hot-water zone reheat. The VAV boxes have reverse acting dampers with maximum supply air temperature of 35°C. 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. Small building has an attic as shown in Figure 1(b). Each of the five zones is served by a constant volume HVAC system with heating from a gas furnace and cooling from a direct-expansion (DX) unitary system. Three climates, Chicago, Minneapolis, and Fairbanks, were selected for this study. **Error! Reference source not found.** lists the climate zone information for the three cities based on ASHRAE Standard 90.1-2010. In the table, HDD18 is the Heating Degree Days with a base temperature of 18^{o}C, and CDD10 is the Cooling Degree Days with a base temperature of 10^{o}C.

Figure 1. The large & small-size office buildings from the USDOE CRBs



(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

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

The simulation results are benchmarked with two databases of commercial buildings in the U.S.: the 2003 CBECS and the USDOE high performance buildings (HPB) database [HPB]. The CBECS is a national survey that collects U.S. commercial building information on their energy consumption and expenditures. The HPB database has more than 100 recently constructed commercial buildings with low energy consumption. The database has detailed building descriptions and energy consumption data, either measured or simulated. The space heating energy use from the HPB database was mostly calculated from calibrated energy models.

Building Design and Operation Parameters

Based on design and operation practice of office buildings, a few parameters with potentially significant impacts on space heating energy use are selected for the study. For each parameter, the reference value is set in the Basecase models which are based on ASHRAE standard 90.1-2004; then better and worse values are determined based on building design or operational practice, applicable building energy standards, and available measurement or analysis reports.

Design Parameters

The building design parameters in this study contain internal loads, window type, boiler/furnace efficiency, envelope insulation and window area. The internal loads include heat gains from interior lighting, plug-loads, and occupants. For the High Internal Loads case, the lighting power density (LPD) and equipment power density (EPD) are set to be 50% higher than the Basecase which is based on the prescriptive requirement of interior lighting for the whole building in ASHRAE standard 90.1-1989, while for the Low Internal Loads case, they are set to be 50% lower, which is achievable with state-of-the-art lighting technologies for office buildings. The 50% lower EPD references a study [Fisher 2006] that shows plug-load energy use could be reduced over 50% by using energy efficient appliances, installing energy management system, and the most important is educating and training occupants on how to save energy.

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 USDOE commercial reference buildings.

More windows tend to increase space heating loads for most climates that require heating, because windows usually contribute more heat losses than walls even after considering the solar heat gains through the glass. The High WWR cases double the window area: the large office has a WWR of 68% while the small office has a WWR of 40%. The Low WWR cases for the large office has a WWR of 20%, while 10% for the small office.

Windows with lower U-factor and higher solar heat-gain coefficient (SHGC) reduce space heating loads. The worse cases use single-pane windows, while the better cases use triple-pane windows. The visible transmittance (VT) is an optical property that indicates the amount of visible light transmitted. VT theoretically varies between 0 and 1, the higher the VT, the more light is transmitted.

Table **2** summarizes performance data of the window types.

Table 2. Window Type

	U-factor (W/k.m^2)	SHGC	VT
Basecase: Double Pane window			
Chicago	3.24	0.385	0.305
Minneapolis	3.24	0.385	0.305
Fairbanks	2.62	0.296	0.212
Single Pane Window	5.81	0.822	0.882

Triple Pane Window	0.87	0.285	0.451

Higher efficiency of heating equipment reduces space heating energy use. The High Boiler/Furnace Efficiency cases, assuming the use of condensing boilers and furnaces, have a boiler of 91% efficiency for the large office and furnaces of 88% efficiency for the small office.

Operation Parameters

The operation parameters in this study contain air infiltration rate, air infiltration schedule, space heating thermostat temperature setting, heating setback temperature control and VAV box minimum damper position setting. Parameters of air infiltration include the peak infiltration rate and the infiltration schedule. 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 [Emmerich 2005, Persily 2008]. For EnergyPlus simulations, these infiltration rates are adjusted to the 4 Pa of pressure difference. For the High Infiltration Rate case, the 7.61 L/(s-m^2) is used in reference to the proposal to ASHRAE Standard 90.1-2013 for building without installation of continuous air barrier. The 50% lower infiltration rate is used in the Low Infiltration Rate case for air tight buildings. A hypothetical schedule is used to describe the variation of air infiltration during occupied and unoccupied hours. Values of 50% and 100% are used in the Medium and High Infiltration Schedule cases to represent buildings that are not air tight or have poor air balance during occupied hours.

The High Heating Setpoint case raises heating thermostat setting to 23°C, while the Low Heating Setpoint case lowers the setting to 18°C. Two heating setback cases are considered: one is setback to 15^{o}C to represent typical operation of most office buildings, and the other has no setback at all to represent the worst-case scenario. The Basecases have the VAV box minimum damper position set to 30%, while the High Minimum VAV Box Damper Position case sets it to 50% and the Low Minimum VAV Box Damper Position case sets it to 15%.

Results and Discussions

Table 3 lists the parametric of the simulation runs for the two office buildings. 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. The High Heating case and the Low Heating case aim to capture the worst-case buildings that consume the most heating and the best-case buildings that consume the least heating.

Impact of Design and Operation Parameters

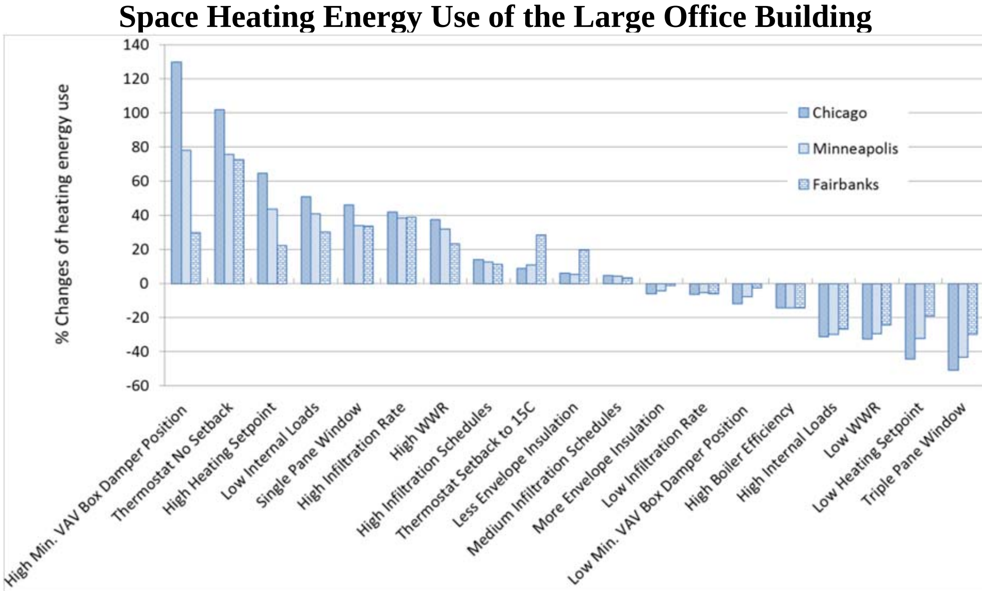
Figure 2 shows the percentages of change in space heating EUIs calculated by comparing the space heating EUI from each parametric run to that of the Basecase for the large office building in the three climates. **Figure 3** shows similar data for the small office building. Both figures are sorted by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

- Based on the relative impact, the most influencing parameters are minimum VAV box damper position setting, space heating setback control, space heating thermostat setting, internal loads, window type and window area. Most of these parameters can be controlled by building occupants or operators. Other parameters, including air infiltration rate, boiler efficiency, infiltration schedule, and envelope insulation, have smaller impact on space heating energy use. Most of these parameters are design parameters except air infiltration rate and schedule. Hence, good operation practice can save more space heating energy than design efficiency levels of an office building.

Table 3. Parametric of the Simulation Run

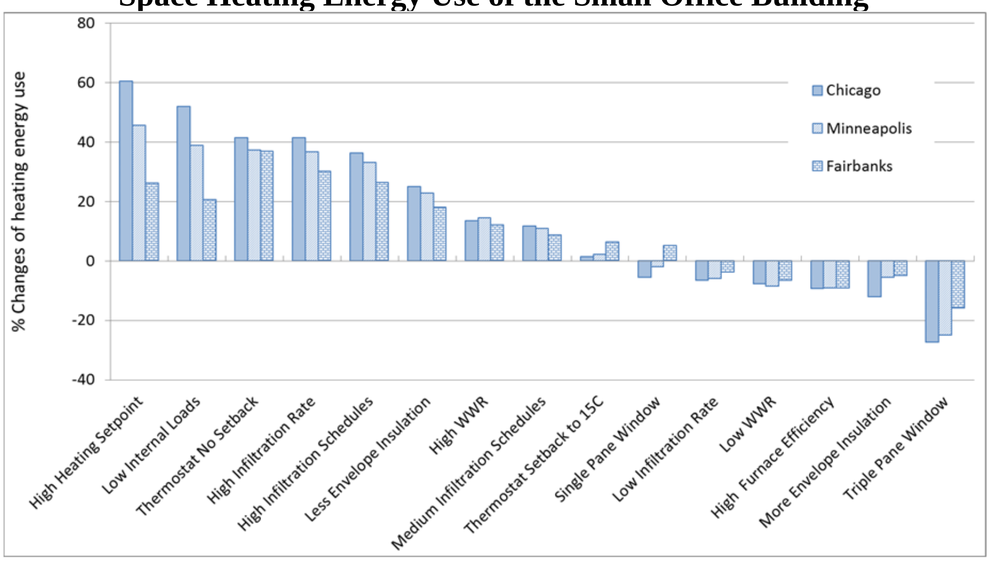
Description of Runs	Internal load (W/m^2)	WWR (Large/Small office)	Infiltration Rate ($m^3/s\text{-}m^2$)	Infiltration Schedule (occupied hours)	Min. VAV box Damper Position (Large office)	Heating Setpoint/ Setback (°C)	Boiler/ Furnace Efficiency	Envelope Construction	Window type
Basecase	10.76	0.4/0.2	0.000302	0.25	0.3	21/10	78%/80%	90.1-2004	90.1-2004
High Internal Loads	16.14	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	0.4/0.2	0.000302	0.25	0.3	21/10	78%/80%	90.1-2004	90.1-2004
High WWR	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	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	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	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	0.4/0.2	0.000302	1	0.3	21/10	78%/80%	90.1-2004	90.1-2004
Medium Infiltration Schedule	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	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	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	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	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	0.4/0.2	0.000302	0.25	0.3	21/10	78%/80%	90.1-2004	Single
Triple Pane Window	10.76	0.4/0.2	0.000302	0.25	0.3	21/10	78%/80%	90.1-2004	Triple
Thermostat Setback to 15°C	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	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	0.4/0.2	0.000302	0.25	0.3	21/10	78%/80%	Pre-1980	90.1-2004
More Envelope Insulation	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	0.4/0.2	0.000302	0.25	0.3	21/10	91%/88%	90.1-2010	90.1-2004
High Heating	5.38	0.68/0.4	0.001133	1	0.5	23/15	78%/80%	90.1-2004	Single
Low Heating	16.14	0.1/0.1	0.000189	0.25	0.15	18/10	91%/88%	90.1-2010	Triple

Figure 2. Impact of Design and Operation Parameters on Space Heating Energy Use of the Large Office Building



- 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 to the other two climates.
- For Fairbanks, by order of increasing space heating energy use from the Basecase, the first case is the Thermostat No Setback during unoccupied hours, followed by the cases of High Infiltration Rate and Single Pane Window. For the other two climates, the High Min. VAV Box Damper Position is the most influencing factor in increasing the heating energy use from the Basecase, followed by the Thermostat No Setback during unoccupied hours and the High Heating Setpoint.
- For Chicago and Minneapolis, by order of decreasing space heating energy use from the Basecases, the first are the cases of Triple Pane Window, followed by the cases of Low Heating Setpoint, Low WWR and High Internal Loads. On the other hand, for Fairbanks, by the order of decreasing heating energy use from the Basecase, the first is the case of Triple Pane Window, followed by the cases of High Internal Loads and Low WWR.

Figure 3. Impact of Design and Operation Parameters on Space Heating Energy Use of the Small Office Building



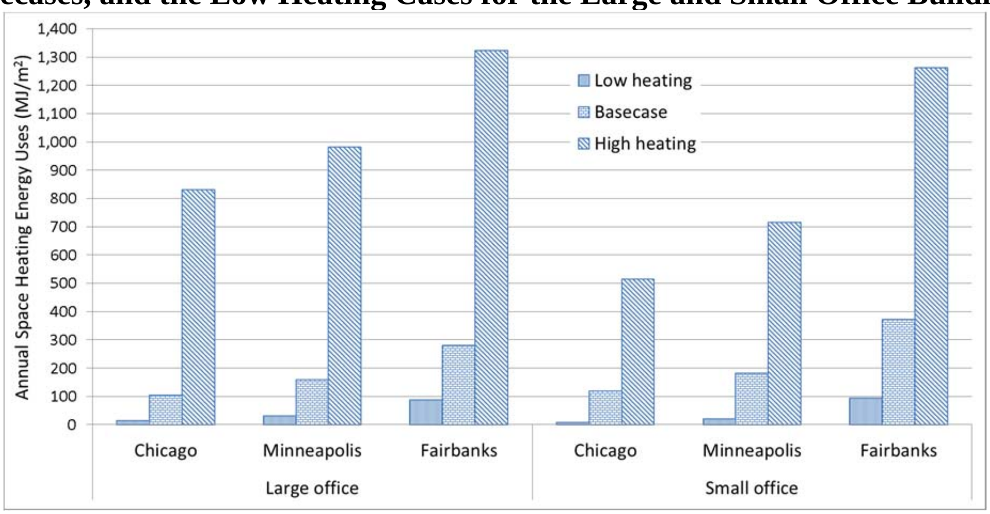
Similarly, the results in **Figure 3** for the small office building reveal:

- Based on the relative impact, the most influencing parameters are space heating thermostat setting, internal loads, space heating setback control, air infiltration rate, and window type. All these parameters except window type can be controlled by building occupants or operators. Other parameters, including window area, boiler efficiency, infiltration schedule, and envelope insulation, have smaller impact on space heating energy use. Small office buildings show very similar patterns to the large office buildings – operation parameters have greater impacts than design parameters.

- 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.
- Similar to the results of the infiltration rate cases for the large office buildings, 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 to other cases.
- For Fairbanks, by order of increasing heating energy use from the Basecase, the first case is the Thermostat No Setback during unoccupied hours, followed by cases of High Infiltration Rate and High Infiltration Schedule, and High Heating Setpoint. For Chicago and Minneapolis, the first are the cases of High Heating Setpoint, followed by cases of Low Internal Loads and Thermostat No Setback during unoccupied hours or High Infiltration Rate.
- For all three climates, by the order of decreasing heating energy use from the Basecases, the first are the cases of Low Heating Setpoint, followed by cases of High Internal Loads and Triple Pane Window.

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 cases and the Low Heating cases - by a factor of about 60, 30 and 15 for both office buildings in Chicago, Minneapolis and Fairbanks, respectively.

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



Compared to the Basecases, the High Heating cases significantly increase space heating energy use by a factor from five to 12 for the large office building in these climates; while for the small office building, the increase in space heating energy use is by a factor of about three. On the contrary, the Low Heating cases dramatically decrease space heating energy use to 1/7, 1/5, and 1/3 for the large office building in Chicago, Minneapolis, and Fairbanks, respectively; and to 1/17, 1/9, and 1/4 for the small office building. For the historical weather data by 30 years in Chicago and 45 years in Fairbanks, space heating energy use has strong linear correlation (as indicated by the regression R^2) with the HDD18 as shown in Figure 5 and Figure 6. This implies that HDD can be used as a simple weather indicator in the linear regression to estimate annual space heating energy use if there are no noticeable changes to the building design and operations.

Similar buildings--in terms of building type or function, size, location, and construction age--to the simulated large and small office buildings are selected from the two databases for Chicago. Figure 7 and

Figure **8** show both the simulated and the database space heating EUIs. Each horizontal line represents result from a selected building in one of the two databases. Different line patterns represent buildings from different databases. In general, the space heating EUIs vary significantly for the selected buildings in either database and even more across different databases.

Figure 5. Correlation Between Space Heating EUIs and HDD18s in Chicago

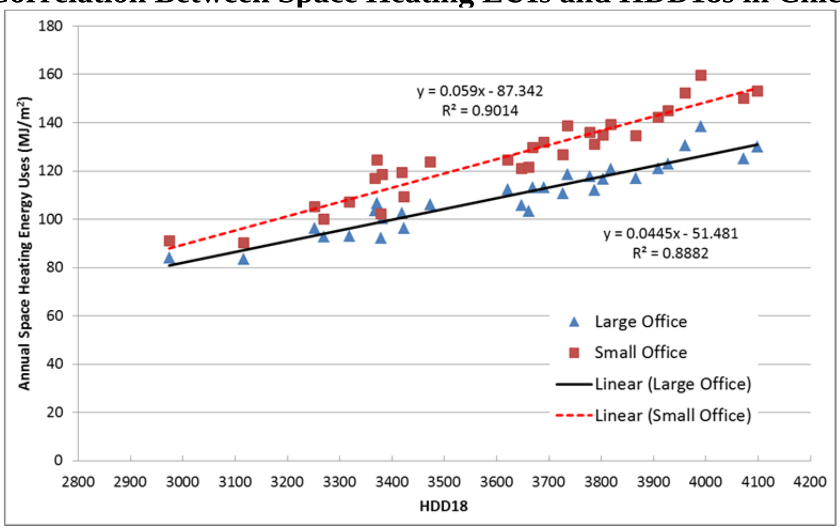


Figure 6. Correlation Between Space Heating EUIs and HDD18s in Fairbanks

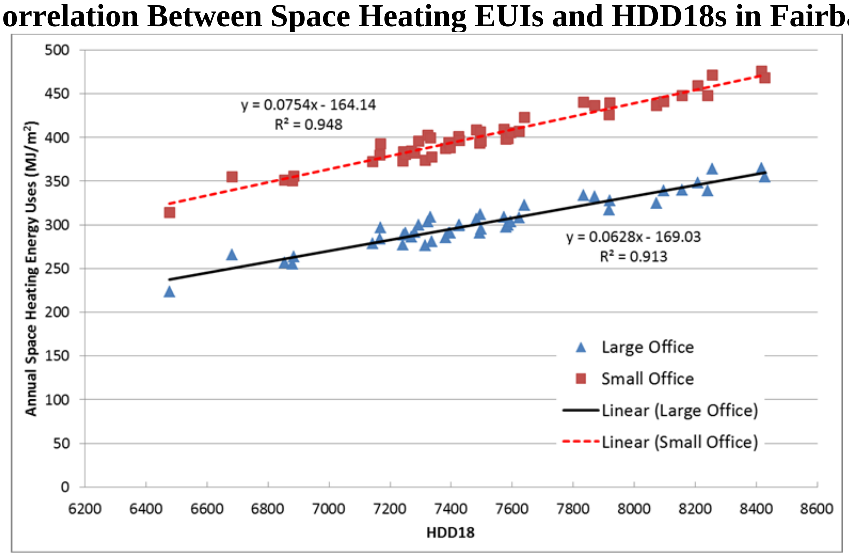


Figure 7 shows the benchmark results for the large office in Chicago. From CBECS 10 buildings are found with floor area ranging from 18580 to 46450 m^2, and vintage from 1990 to 2003. The space heating EUIs for these buildings vary from 136.7 to 559.72 MJ/m^2.

Figure **8** 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 9290 m^2, 2) vintage from 1990 to 2003, and 3) location of Chicago. Seven such small office buildings are found from the CBECS with their space heating EUI from 249 to 1023 MJ/m^2. Two small offices were found from the HPB database that are near Chicago and have floor area of 1390 and 3716 m^2. The two offices have space heating EUI of 208.8 and 335.2 MJ/m^2.

Figure 7. Benchmarking Simulation Results with the Building Databases for the Large Office Building in Chicago

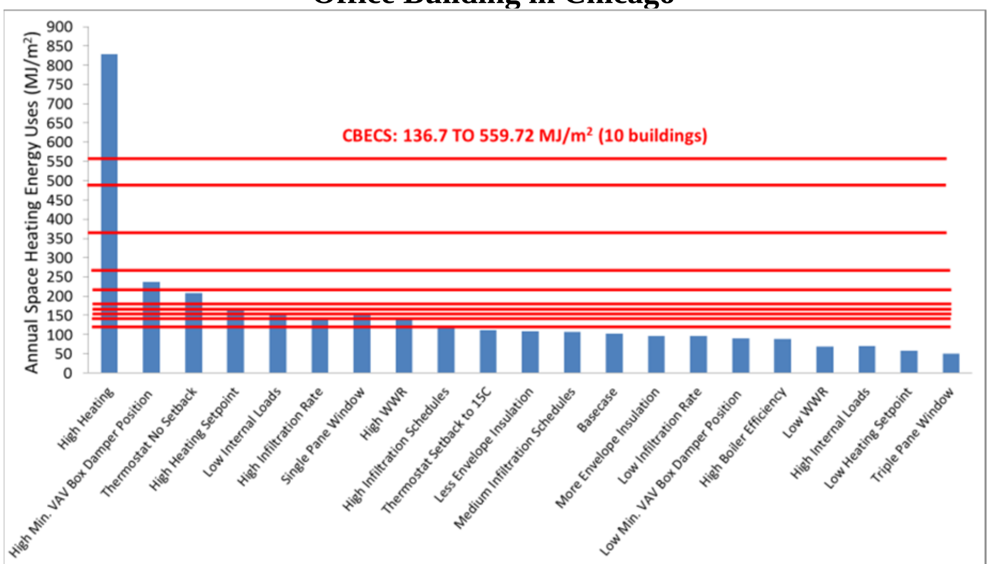
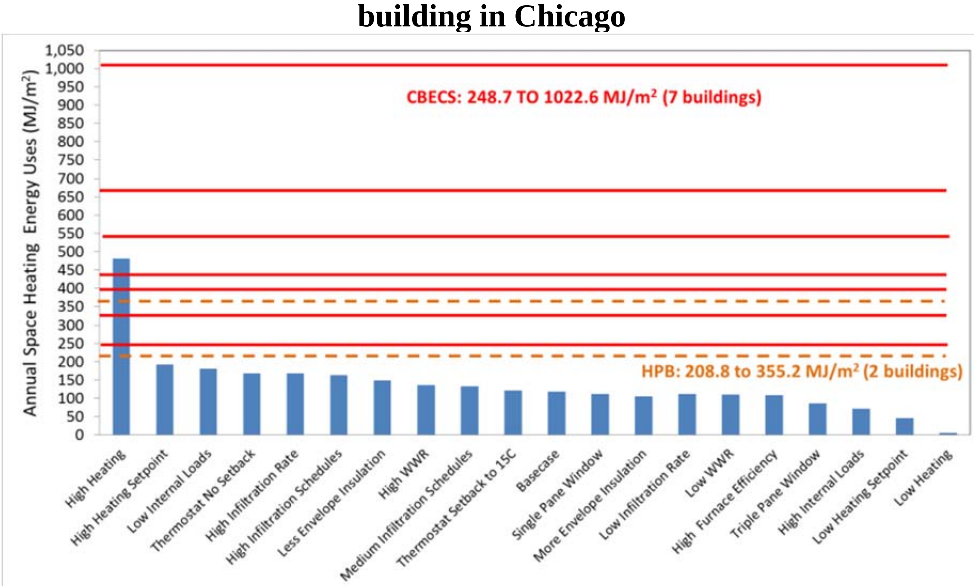


Figure 8. Benchmarking simulation results with the building databases for the small office building in Chicago



For Chicago, the simulated results are always much lower than the databases except for the High Heating case. The High Heating case result overlaps all the building cases from the databases, however, there still exists more than 50% gaps for the high-end results. This implies that there are other important parameters beyond the selected ones that play decisive roles for buildings with very high space heating energy. These can be design and operation problems or faults of the space heating systems that were not considered or modeled in the simulations.

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 for most buildings (HPB); 2) the floor area used to calculate the EUI might not be accurate to match the actual floor area of the buildings. Furthermore, the selected buildings from the databases may not match exactly the simulated buildings in terms of floor area, building vintage, and location. This contributes to the discrepancies between the simulated and benchmarked space heating energy uses.

Conclusions

Depending on details of a few key building design and operation parameters, the simulated space heating energy use of the small and large-size office buildings across the three climates can vary significantly. 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, window-wall-ratio, and internal loads. The relative impacts of these parameters vary with building type and climate. In summary, good operation practice can save more heating energy than higher design efficiency level of an office building. Compared to the Basecases, the High Heating cases consume more than double space heating energy, while the Low Heating cases consume less than half for both office buildings in all three climates.

The actual space heating energy use for the similar office buildings from the CBECS and HPB databases also vary significantly in wide ranges which largely overlap with the ranges of the simulated results, especially for the High Heating cases. Simulations do not necessarily always under- or over- predict the space heating energy use. The simulated space heating energy use depends upon building types, configurations, and climates, especially a few key influencing building design and operation parameters. High efficient designs and better operation of buildings can both reduce space heating energy use, but the latter plays a more important role. Improving building operations through commissioning and retrofits is an effective way to save space heating energy use for existing buildings. Moreover, using energy efficient appliances, installing energy management system, educating and training occupants are also excellent methods to save energy.

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