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Investigation of some large building energy conservation opportunities using the DOE-2 model

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Abstract

Owing to their complexity, the design and efficient operation of HVAC systems in commercial buildings can be greatly enhanced by using accurate thermal simulation models. The DOE-2 model was validated using monitored data for a large (28,000 m^2) commercial building. The model provided a means to evaluate some conservation measures which included window glazings, occupancy sensors, cold deck temperature set point and reduced ventilation air. Reductions in cold deck temperature and ventilation air were attractive as no-cost options which could be easily returned to original settings if problems arose. The potential energy savings for occupancy sensors was substantial and could prove economical. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Energy retrofits and the implementation of conservation measures can be a cost-effective means of reducing building energy consumption. Changing building HVAC operating strategies work equally well [1, 2] and can result in savings through reduced equipment purchases as a result of peak load shaving [3].

In this paper, a whole building energy analysis is performed on a large five-storey building (approximately 28,000 m^2) located on the University of Saskatchewan campus. A fairly intensive monitoring of the energy inputs to this building was conducted at various times over a one-year period. The U.S. Department of Energy building simulation software (DOE-2.1E)

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was compared to the monitored performance. These measured results provided the basis for verification and tuning the model. This model has generally been found to be reasonably accurate, provided building design or construction parameters and HVAC operating conditions are well defined [4–6], otherwise extensive model tuning can be required to fit the experimental data [7].

The verified model was used as a means to examine some energy conservation opportunities. These included modifications to the building envelope, the use of occupancy sensors, cold deck temperature set point changes to reduce air flow and ventilation air reduction during certain unoccupied periods.

2. Building description

The building under study is located in Saskatoon, Canada, which is at 52.2 degrees latitude and 106.7 degrees longitude. The climate in Saskatoon features large heating loads in winter and relatively small cooling loads in summer.

The building is on the campus of the University of Saskatchewan and is used for agriculture research and teaching. It is a five-storey building, containing offices, classrooms, cafeteria, a large environment chamber area, underground parkade and a large central atrium. The building is relatively new with construction completed in 1991. The mechanical equipment is housed in a penthouse above the top floor.

The general layout of the building consists of three wings as shown in Fig. 1. The central wing faces north and features the large atrium, cafeteria and two main entrance vestibules. The other two wings extend from the central wing at 45 degree angles to face northeast and northwest. The wing that faces northwest contains half of the environment chamber area, while the other half is located in the central wing. The environment chamber area is located on the first floor of the building. The laboratories and classrooms are located in the core areas of these wings, while the offices are located on the perimeter. The total floor area of the building is approximately 28,000 m^2 (300,000 ft^2).

The majority of the exterior wall of the building is of curtain wall construction. The curtain wall consists of 6 mm (0.25 in) spandrel glass on the exterior, a 23 mm (0.9 in) air space, 114 mm (4.5 in) of rigid expanded polystyrene insulation, a 22-gauge galvanized steel back panel, a 15 mm (0.6 in) air space, and a 1 mm (0.04 in) aluminum interior finish. The interior walls are generally of a 200 mm (7.9 in) wide concrete block construction.

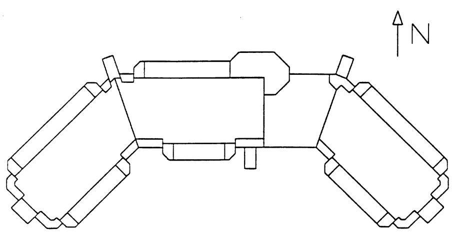

Fig. 1. Simplified building floor plan.

The roof construction is of the built-up type consisting of a 50 mm (2.0 in) exterior layer of gravel over a permeable fabric under which is the rigid 100 mm (4.0 in) layer of expanded polystyrene insulation, a layer of bituminous roofing and the 200 mm (7.9 in) concrete roof slab.

The building has a relatively large amount of window area. Excluding the penthouse, windows occupy close to 40% of the exterior wall area. Two types of double-paned windows are used. The first type, located primarily in the atrium, has a transmittance of 68% and reflectance of 14%. The second type of window is more reflective, having a reflectance of 31% and transmittance of 45%.

The HVAC system consists of three main air handling systems which are two fan, dual duct VAV with mixing boxes as the terminal units to apportion the hot and cold deck air volumes to achieve the desired supply air temperature. The heating and cooling for the building is provided by steam and chilled water from a central plant. However, the building does have chillers for providing environmental control for the growth chambers. Heat rejected from these chillers are is for ventilation air and DHW heating. Also, energy is recovered from the common fumehood and parkade exhaust systems using a run-around coil type heat recovery system. This recovered energy can supply as much as 50% of the heating load requirements in winter.

3. Model data input

A whole-building energy analysis was performed for the building based on hourly weather data and utility costs [8]. The thermal simulation model was created using DOE-2.1E. The flexibility of DOE-2.1E allows it to handle thermal mass effects, perimeter daylighting and coupled interaction and part-load performance of primary and secondary HVAC equipment. An economics subprogram can calculate the cost of fuels or utilities used by the building to satisfy loads. The user can also analyse nearly any output parameter on an hourly basis.

The building thermal zones had to be modified into a simpler form to fit the space limitations of the DOE-2.1E input. Care was taken in this modification to ensure that no significant differences were present in floor area, exterior wall area, and orientation compared to the actual geometry.

All the conditioned zones in the building have set points of 24°C (75°F) for cooling and 21°C (70°F) for heating, except for the parkade which is maintained at 15°C (59°F) during the heating season. The VAV mixing boxes are controlled through proportional thermostats. Ventilation rates are maintained at the ASHRAE recommended minimum of 9.4 L/s (20 cfm) per person during the occupied hours of operation [9]. The heat gain from people is assumed to be 117 W (400 Btu/h) per person [10]. Lighting loads were determined from drawings and surveying the space.

Infiltration was estimated in terms of volume air changes per hour (ACH). Typical infiltration rates in North America vary from about 0.2 ACH for newer buildings with good wall tightness to about 2.0 ACH for older, less well constructed buildings [10]. Infiltration rates can be as much as ten times higher in entrance spaces, such as vestibules [11]. This building is relatively new with good wall tightness. For modeling purposes, the infiltration rate for the building was assumed to be 0.3 ACH. For the vestibules and parkade, infiltration rates were assumed to be 10.0 ACH and 2.0 ACH, respectively. These rates were assumed to occur during the daytime when the HVAC systems were in operation. When the systems were operating at part loads in the evenings and weekends, infiltration rates were assumed to be 30% of these values. Internal heat gains for occupancy, lighting and equipment were calculated from user-defined peak loads and frequency for each hour of the simulation. Solar heat gain due to direct and diffuse radiation components was found from measured data or calculated from a cloud cover model based on hourly sun position.

4. System measurements and verification

The model predictions were verified by comparison with measured data for two-week periods in the winter, spring and summer seasons. The measurements were performed in the different seasons to obtain peak operating conditions of all systems, as well as a wide range of part-load operation. The winter measurements were made from 17 February 17 to 3 March, 1995, spring measurements from 17 May to 31 May, 1995, and summer measurements from 26 June to 10 July, 1995.

Many different energy transfer quantities were required to verify the building model. For winter, these quantities were electrical demand, steam demand, air flow rates for all major supply, return and exhaust fans, the pressure drop across these fans and corresponding fan power consumption, air temperature drop across heat recovery coils and the liquid flow rate and temperature drop in the chiller heat reclaim loop. Added to this list in the spring and summer seasons were the cold deck air flows and corresponding air temperature drop across the cooling coils. The fan pressure drops and power demands were measured to determine the fan efficiencies. The air temperature drops for the recovery coils and liquid flow and temperature drop for the chiller reclaim loop were monitored to determine the heat recovery load. In the spring and summer, the cold deck flows and cooling coil temperature drops were measured to estimate the cooling load.

A large amount of data were collected at several points throughout the building. To perform the task of collecting this measured data, a combination of instrumentation devices and logged data on the campus control system was used.

The electrical demand was determined on an hourly basis by measuring the building electrical current hourly with an ammeter and using average values for the power factor and voltage. In addition, the electrical consumption for each two-week period was determined by noting the start and end values on the building electrical meter. A comparison between the electrical consumption inferred by the current measurements and the meter reading showed agreement within 2.0% for all three seasons.

The steam demand was measured hourly using a steam orifice plate. It was discovered that this orifice plate was not calibrated for the correct range of steam demands. This problem was not identified until after the winter and spring measurements had been performed. Before the summer measurements, the range of the orifice plate pressure drop was increased to the expected steam demand range, and once the actual peak steam load was measured in the following winter, the orifice plate could then be recalibrated according to the International

Organization for Standardization (ISO) standard [12]. The steam flow measurements for this investigation, however, were used but with some degree of uncertainty, especially for low flow rates.

The air flow rates for all major supply, exhaust and return fans in the building were measured with flow meters at the fan inlets and were logged on an hourly basis. In addition to these flow rates, several air temperatures were monitored. The air temperatures that were not available from the control system, but required for this energy analysis, were measured and recorded with portable thermistors and data loggers. In the chiller reclaim loop, the liquid supply temperature was measured with a brass well temperature sensor and logged on the control system hourly. The liquid return temperature was not available on the control system, so it was measured with a portable data logger with a thermistor probe placed in a brass well with heat conductive compound. The liquid flow rate in the chiller reclaim loop was measured with an orifice meter. All the above quantities were monitored on an hourly basis for comparison to the model predictions.

4.1. Cold weather verification

The winter data collection period occurred mostly during late February. The average temperature during this period was about −12°C with extremes of −32°C and 5°C. These conditions were sufficient to generate near peak loading on the heating equipment.

The consumed energy comparison for this two-week period is presented in Table 1. The electrical and heat recovery energy values agree to within 5% for this measurement period, while the steam consumption shows significant error, likely because of the improper sizing of the orifice plate and pressure sensors used for steam flow measurement, which in turn skews the total heating energy value. Cooling was not monitored for the winter season measurement period because the economizer provided free outside air cooling. With the exception of the steam energy quantity, the DOE-2 model and the measured data show good agreement.

Table 1
Comparison of energy use predicted by the DOE-2 model and measured winter data

Type of energy	Method	Amount	Difference (%)
Electrical (kWh)	DOE-2	448,800	4.6
	Measured	469,400	
Total heat (GJ)	DOE-2	1769	12.9
	Measured	1567	
Steam (GJ)	DOE-2	851	33.0
	Measured	640	
Recovered (GJ)	DOE-2	917	1.0
	Measured	926	
Cooling (GJ)	DOE-2	0	0
	Measured	0	

4.2. Spring season verification

The spring and fall represent times of the year when both heating and cooling are often required but not at the design maximum for either. A two-week period during the spring (mid to the end of May) was chosen as representative. The average temperature during this period was about 12°C with extremes of 32°C to −2°C, providing a wide range of climatic data. Although temperature swings are higher during spring and fall, the upper extreme temperature recorded of 32°C is not that common in the spring.

The comparison of measured energy use to DOE-2 predicted energy use is shown in Table 2. The predicted electrical energy use matches very well with the measured results for this measurement period as well. The recovered energy agrees to within 15% of the measured data which does not agree as well as the winter data. This difference may suggest that the model is not as accurate at the low end of the range, since not as much recovered energy is required in the spring as in the winter. The problem with the steam metering is again apparent for the spring measurement period, as seen by the large difference between the predicted and measured values, causing the total heating energy values to show greater error. The cooling energy predicted by the DOE-2 model agrees closely with the cooling energy that was inferred from the cooling coils. The predicted and measured energy usage agree well for the intermediate spring measurement period, with the expected exception of the steam usage.

4.3. Summer season verification

The final two-week measurement period to verify the DOE-2 model, particularly for cooling conditions, occurred from late June to early July. The average temperature during this period was about 19°C. The variability of the temperature was less than the other seasons with extremes of 31°C and 5°C.

Table 3 shows the comparison of energy use between the DOE-2 predictions and the measured data for the summer measurement period. The electrical energy use matches well for the two quantities for the hot weather period. The predicted recovered energy shows about

Table 2
Comparison of energy use predicted by DOE-2 model and measured spring data

Type of energy	Method	Amount	Difference (%)
Electrical (kWh)	DOE-2	408,900	5.7
	Measured	432,200	
Total heat (GJ)	DOE-2	497	29.3
	Measured	384	
Steam (GJ)	DOE-2	91	262
	Measured	25	
Recovered (GJ)	DOE-2	407	13.2
	Measured	360	
Cooling (GJ)	DOE-2	226	0.7
	Measured	227	

Table 3
Comparison of energy use predicted by DOE-2 model and measured summer data

Type of energy	Method	Amount	Difference (%)
Electrical (kWh)	DOE-2	408,600	5.8
	Measured	432,200	
Total heat (GJ)	DOE-2	214	52.1
	Measured	327	
Steam (GJ)	DOE-2	17	486
	Measured	97	
Recovered (GJ)	DOE-2	198	15.8
	Measured	229	
Cooling (GJ)	DOE-2	379	12.7
	Measured	426	

15% disagreement with the measured data, but for the summer months, this is not a very important quantity. At this point, the monitoring range of the steam orifice meter had been lowered to accommodate the estimated peak loads, and the measured readings now overestimate the steam energy compared to the DOE-2 model. This may have occurred because at very low steam flow rates, as in the summer, the meter is likely outside of the measurement range. The cooling energy calculated and measured values agreed within 15% for this measurement period.

All of the major energy transfer quantities were investigated in order to verify the DOE-2 building model. For the most part, the DOE-2 model predicted the measured energy use and demands reasonably accurately, except in the case of steam metering, where no verification could be made because of inaccurate measured data. In the following analysis, it is assumed that the steam usage and peak loads predicted by the DOE-2 model are accurate.

5. Energy conservation opportunities

Using the verified building energy simulation model, several different opportunities for energy conservation were investigated. In many cases, a detailed whole-building simulation model would not be required unless the primary energy conversion equipment is to be replaced, or the building envelope is to be modified. In this project, the building model is used to investigate four specific energy conservation opportunities. The first investigation involves modifications to the building envelope. The purpose of this investigation is not only to evaluate any economic savings available with these types of modifications but also to determine how sensitive energy consumption and demand are to envelope changes. In the second investigation, the advantages of using office occupancy sensors to reduce lighting and air handling energy use are determined. The third investigation determines the savings associated with lowering the cold deck temperature set point to reduce the amount of airflow and fan energy required to meet loads. The final investigation involves reducing outside ventilation air for the early morning hours, while still maintaining acceptable levels of air contaminants.

Table 4
Effect of number of window glazings on annual energy use

Envelope	Electricity (MWh)	Reduction (%)	Cooling (GJ)	Reduction (%)	Heating (GJ)	Reduction (%)
Single-paned	12,031	−0.6	2523	−2.7	31,007	−5.8
Double-paned (existing)	11,962	0	2466	0	29,309	0
Triple-paned	11,960	0	2406	2.4	28,930	1.3

5.1. Window glazings

It is recognized that building envelope modifications are normally only cost effective in the design and construction phase. However, it was decided to examine one component, the number of glazings, since the building has a relatively large window surface area of a low thermal resistance compared to the other building envelope components.

Table 4 shows the effect of using single-glazed and triple-glazed windows compared to the installed double-glazed windows. No significant change in electrical energy use was observed other than a slight increase in the single-glazed case which could be attributed to a slight increase in pumping power to the perimeter baseboard heating system in winter. Cooling energy decreases with the number of glazings, likely because of the higher overall reflectance of solar energy when perimeter cooling is required. As would be expected, the heating energy requirements decrease with the number of glazings. However, the overall reduction in energy demand in going from the base case to a triple-glazed window was not that large, providing only a modest energy savings to finance the change. The peak energy demands did not vary significantly so were not presented [8]. Because of the thermal discomfort of occupants and potential condensation and frosting of the glazing, single glazing is impractical in a cold climate. This was not considered in the energy results presented in Table 4.

5.2. Occupancy sensors

Studies have shown that, in many cases, offices are not occupied for the majority of the working day, although lighting and air handling for those offices are maintained throughout. With the use of occupancy sensors, the energy associated with lighting and conditioning these offices during unoccupied periods could potentially be eliminated. The use of occupancy sensors to reduce air handling and lighting energy usage for only the office areas was simulated by multiplying the DOE-2 office occupancy schedule factors by 70%, 50% and 30% to represent these different occupancy levels. The effect of these occupancy factors on the electrical, cooling and heating energy consumption is shown in Table 5.

The reduction in energy use is approximately proportional to the amount of reduced occupancy in the offices. Reductions in peak demand were not considered, since it cannot be accurately predicted when offices will be occupied or unoccupied during normal working hours.

The use of occupancy sensors for reducing air handling and lighting energy results in very significant savings, but there is, of course, a capital and maintenance expenditure associated with implementing this measure. As well, there could be a reliability problem with these types

Table 5
Annual energy consumption for various office occupancy levels

Occupancy level	Electricity (MWh)	Reduction (%)	Cooling (GJ)	Reduction (%)	Heating (GJ)	Reduction (%)
Base case	11,962		2466		29,309	
70%	11,251	5.9	2170	12.0	28,468	2.9
50%	10,749	10.1	1937	21.4	27,302	6.8
30%	10,279	14.1	1730	29.8	27,076	7.7

of motion sensors, resulting from radio wave interference or too low a sensitivity to motion. These reliability problems can often be solved by using better quality sensors, but at an increased capital cost. However, even a substantial initial cost could be quickly offset by the large savings in energy that occupancy sensors provide.

Another issue that arises when using occupancy sensors to reduce air handling energy is the possibility of reduced comfort levels as occupants return to the unoccupied offices. Since the sensors would only affect the control of the air handling and not the baseboard heating, space temperatures would not drop to an uncomfortable level in the winter months. Without some space ventilation, there is a probability of decreased comfort in the summer months if the perimeter offices are unoccupied for long periods of time. More studies would have to be done on the transient effects of occupancy sensor air handling control of space temperatures to understand fully the implications of this type of strategy. Likely, some space ventilation would be required during periods of no occupancy.

5.3. Cold deck temperature set point reduction

A common way of reducing fan energy in dual duct systems is to reduce the set-point temperature of the cold deck which reduces the air quantity required to meet the space loads. This type of energy conservation measure was simulated for the agriculture building by reducing the cold deck set-point temperature in the DOE-2 model from 12.8°C to 10.0°C and 7.2°C. The reduction in the various types of annual energy consumption can be seen in Table 6 for these set-point temperatures.

Reduced air handling energy requirements account for the modest saving in electrical fan energy. For the cooling energy supplied by the chiller, the energy required to supply the colder

Table 6
Annual energy consumption for cold deck set point temperature reductions

CD Set-point temperature	Electricity (MWh)	Reduction (%)	Cooling (GJ)	Reduction (%)	Heating (GJ)	Reduction (%)
12.8°C Base case	11,962		2466		29,309	
10.0°C	11,774	1.6	2494	−1.1	29,107	0.7
7.2°C	11,645	2.7	2417	2.0	29,018	1.0

temperature can offset improvements in the coefficient of performance as the load is increased. A very small amount of heating energy is saved.

Reducing the set-point temperature of the cold deck may not require any capital expenditure and therefore the pay-back period of this operational modification could be immediate. However, there are some operational risks that must be considered before the cold deck temperatures could be substantially reduced. Low cold deck temperatures can result in discomfort for the occupants if the mixing boxes fail to provide good mixing of the cold and hot deck air. Also, low cold deck temperatures can result in excessive water vapour condensation on the cold deck ducting if it is not adequately insulated. Neither of these problems are expected to be a concern at 10.0°C but they could be at 7.2°C.

5.4. Ventilation air reduction

Outdoor air ventilation is required for all occupied spaces in a building in order to meet indoor air quality standards [9]. This ventilation rate depends on the number of occupants, their activity level and time duration in the space, the volume of the space, the rate of mixing in the space and the concentrations of non-human contaminants in the space. In many buildings, only human sources of air contaminants are significant. This is the case for the spaces served by the three main air handling systems in this building. In these situations, determining whether the CO_2 concentration level is less than 1000 ppm (0.1% by volume) is the best way to indicate whether ventilation requirements are being met. Using a constant ventilation rate per occupant for all hours of building operation generally results in an over design which forces the ventilation system to use extra electrical energy, as well as extra heating or cooling energy to condition the ventilation air. If fan energy could somehow be reduced, while still maintaining the CO_2 level below the acceptable level, then an energy saving opportunity could result.

The specific opportunity that was investigated for this project involved examining the transient effects of contaminant (CO_2) generation in occupied spaces. For example, for a single classroom with 30 students and 150 m^2 of floor area without any outdoor air ventilation or recirculation. On average, people who are sedentary or doing light activities will generate about 5 mL/s of CO_2. In this classroom, CO_2 is generated at a rate of approximately 2000 ppm/h, assuming the occupants arrive at the same time and no one leaves. This figure also assumes that the occupied zone only includes the bottom 1.8 m of the classroom, and the top portion is considered to be unoccupied. At this rate of CO_2 generation, the concentration will increase from 350 ppm (average atmospheric concentration) to 1000 ppm in 20 min. According to the standard, the steady state ventilation rate for this room would be a minimum of 0.225 m^3/s or 5.4 air changes per hour. Clearly, this room would require this amount of ventilation shortly after the students arrive, and no opportunity for reducing ventilation is present.

However, considering the whole building provides us the opportunity to recirculate air from the unoccupied spaces to reduce the amount of morning ventilation required without affecting the overall indoor air quality significantly. Based on 2250 m^2 of building classroom space and assuming that there are another 200 occupants sparsely distributed in other areas of the building yields a total required ventilation rate of 4.88 m^3/s. If no ventilation were to occur, it would take 2.8 h for the average CO_2 concentration in the building to reach 1000 ppm. For

Table 7
Annual energy consumption for ventilation air reduction

	Electricity (MWh)	Reduction (%)	Cooling (GJ)	Reduction (%)	Heating (GJ)	Reduction (%)
Base case	11,962		2466		29,309	
Reduced ventilation	11,326	5.3	2419	1.9	28,720	2.0

this strategy to work, of course, constant recirculation between occupied and unoccupied spaces must take place from the moment people arrive at the building. Presently, in the agricultural building, the main supply fans start at 7 a.m. to supply ventilation air to the building. If only the recirculation fans were to be started at this time, and the start up of the main ventilation fans was delayed until approximately 2.5 h after people arrived at the building, the CO_2 should not rise to an unacceptable level, with savings in fan energy.

This energy conservation measure was simulated using DOE-2 and the effect on annual energy consumption is presented in Table 7.

The reductions in energy consumption are significant, given that this energy conservation has no associated capital cost. The risk is also very low because the original operating schedule can be re-instituted if the expected savings do not occur of if indoor air quality becomes a problem.

Given that the building occupancy will drop rapidly at 4:30 p.m. most days, it may be practical to also reduce the ventilation rate from 4:30 p.m. to 11:00 p.m. when most of the fans are normally shut down. This could result in even more savings than the early morning procedure examined.

6. Conclusions

The DOE-2.1E computer simulation was found to agree with the monitored thermal performance to within generally acceptable accuracy for modeling of this type. The exception was the steam energy consumption which was attributed to inaccuracy in the monitoring device rather than the DOE-2 model.

Energy conservation alternatives were examined which included window glazings, occupancy sensors, cold deck temperatures set-point reduction and ventilation air reduction. Increasing the number of glazings above the base case (two) did not offer much potential energy savings and would require careful analysis, even for new construction. This reflects on other components of the building envelope as well. Increasing the thermal resistance of components, such as the insulated wall and roof, would not likely be justified, given their relatively high thermal resistance. The use of occupancy sensors in the office spaces to reduce lighting and air handling energy is attractive and could possibly be extended to laboratories and classrooms to further increase these savings. Reducing the cold deck temperature set point appears to be worth pursuing as an alternative. Reducing ventilation air in the morning hours is promising from an energy savings perspective, but may need more research on indoor air quality and air diffusion and recirculation before it could be implemented. If indoor air quality is not compromised, reducing peak electrical demands in the daytime, as well as reducing consumption towards the end of the day, may be further measures to be investigated. The last two measures have the advantage of no associated capital cost as well as ease of restoring the original schedules if problems arise.

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