COMPARATIVE SIMULATION OF A HIGH PERFORMANCE BUILDING WITH EE4-DOE2.1E AND ENERGYPLUS

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ABSTRACT

The University of Calgary's Child Development Center (CDC) is a 12,000m^2 new LEED Platinum building, for which building energy performance in the "very cold" climate was a key design consideration. A Natural Resources Canada (NRCan) incentive program required that energy modeling be done with NRCan's EE4 user interface (DOE2.1E simulation engine) and following NRCan procedures. As DOE2.1E lacks specific features to simulate advanced systems such as radiant cooling that were included in the CDC, an EnergyPlus model was later developed to further evaluate these systems. The EE4-DOE2.1E model was used for quality control in EnergyPlus model development. While there were large differences for some components, the whole building energy use estimates were similar with regard to systems for which DOE2.1E had specific simulation features. Advanced energy systems were added to the EnergyPlus model, but the difference in estimated total annual energy use was very small (photovoltaic generated electricity not included). The comparative process revealed numerous input errors in EnergyPlus model and is recommended until a more straightforward EnergyPlus interface is available.

INTRODUCTION

The University of Calgary's Child Development Center (CDC) was officially opened in October, 2007. It is an all-new four-story, 12,000 m^2 building hosting office, medical and child care spaces.

The CDC was designed and constructed as a high-performance building with an (achieved) Leadership in Energy and Environmental Design (LEED) Platinum target. It is the highest scoring LEED building in Canada with 57 earned points under the LEED Canada New Construction (NC) 1.0 rating system, which is slightly more stringent than the USGBC's LEED NC 2.2. The CDC was awarded 2007 "Photovoltaic Project of the Year" by the Canadian Solar Industries Association for its building integrated photovoltaic system (CanSIA 2007).

The green features of the CDC encompass site, water efficiency, energy efficiency, material and resource, and indoor environmental quality measures. This paper focuses on the CDC energy systems and the simulation of those systems.

The energy systems used in the CDC form an integrated response to factors such as local climate, construction and operation costs, indoor environmental quality, and occupant wellness. A design annual energy cost reduction of 71% was predicted relative to Model National Energy Code for Buildings (MNECB) baseline (NRCan. 1997), through measures that included: 1) a well-insulated building envelope which is about 25% better than the MNECB baseline, 2) window-to-wall ratio of about 0.21 compared with the MNECB reference limit of 0.40 (NRCan. 1997), 3) an efficient lighting system (lighting power density of 7.3 W/m^2 excluding control credits), 4) displacement ventilation for the level 1 educational spaces, 5) under-floor air distribution for the office-type spaces on the other three levels, 6) radiant cooling panels in perimeter spaces, 7) exhaust air heat recovery, 8) air-side and water-side water economizers, 9) high efficiency plant equipment, and 10) a building-integrated photovoltaic system that shades south-facing windows.

Figure 1 provides a perspective view of the Child Development Center.

THE CHILD DEVELOPMENT CENTER

Calgary is at 51^{o} north latitude with a climate classified as "very cold" (Briggs *et al.* 2002) with mean annual temperature of around 4 ^{o}C. The 99% heating design temperature is -27 ^{o}C. The 1% cooling design temperatures (dry bulb/wet bulb) are 26 ^{o}C/15 ^{o}C. The region is semi-arid with skies that are rarely overcast and often very clear.

The energy systems design approach was to 1) minimize loads and 2) use low energy systems and very efficient components to meet them, seeking to use systems that would also enhance environmental conditions in terms of factors such as ventilation effectiveness. A construction manager worked with the University to solicit bids on systems and components as the project proceeded.

Heat gains from people, lights and equipment generate year-round cooling requirements in core spaces. These loads generate perimeter net daytime cooling loads to temperatures in the vicinity of –10 ^{o}C, and to lower temperatures in zones receiving direct solar radiation. With night-time decline of interior gains, perimeter areas require heating (the outdoor temperature is below 18 ^{o}C 90% of yearly hours). Perimeter cooling peaks and heating loads typically increase with window to wall ratio.

Building envelope

The wall (RSI-2 effective), roof (RSI-5 effective) and window (U-value about 2 $W/m^2.K$) thermal properties yield an envelope about 25% better than the MNECB (NRCan. 1997) reference (details in Tables 1 and 2). The building also has a relatively small window-to-wall ratio (WWR) of 0.21 which is intended to reduce the heat gains and losses through windows. Due to pressures of an overheated construction market, only one (very high) bid was received for triple-glazed windows, so double-glazed windows were used. These account for 14% of envelope area, but 40% of the overall average envelope heat transfer coefficient.

Lighting systems

Roughly 50% of the building area is core space, due to 1) pressures from the leasing authorities to allow more flexible interiors and 2) site constraints such as height limitations due to the air ambulance flight path to the nearby children's hospital. An average connected load of 7.3 W/m^2 (dominated by 3 floors of office space designed for 7.5 W/m^2) was achieved with premium efficiency luminaires, ballasts and lamps. Occupancy sensors were used extensively, and on-off daylight controls were used in perimeter public areas for an effective load of about 5.2 W/m^2.

A field study by Galasiu *et al.* (2007) found that individual dimming contributed an 11% reduction in perimeter workstation lighting energy use for a building near Calgary's latitude. For a 10 m^2 workstation with lighting scheduled on 10 hour/day, this would translate to a lighting energy use reduction of 18 kWh per year. The energy cost savings for a decade at \$0.10 per kWh would be \$18. Given that the premium for a dimming ballast was about \$60, a dimming daylight-responsive control system had a very long estimated payback.

In Calgary's "very cold" climate, the utility peak loads typically occur in November to February at about 16:00-20:00, after sunset in those months and precluding a reduction from daylight-responsive control of electric lighting. The EE4-DOE2.1E peak demand estimate ranges from a low of about 140 kW in midwinter to a high of about 160 kW in midsummer. Lighting contributes around 58 kW, of which about 29 kW would be in the roughly 50% of spaces that are perimeter. Using the 11% reduction from dimming daylight-responsive control reported by Galasiu *et al.* (2007) would reduce the summer peak by about only 2%.

HVAC systems

The CDC was designed with two air handling systems, based on the differing outdoor air requirements of the level 1 education spaces and the upper office spaces. Level 1 is served by a displacement ventilation system with low side-wall diffusers. An under-floor air distribution system provides ventilation and cooling to office-type spaces on floors 2-4 (Figure 2). Both air supply systems are variable air volume (VAV), may recirculate air, and have air-side economizers. As noted above, metal radiant cooling panels were installed in south and west perimeter spaces to help offset solar gains (Figure 3).

Space heating in perimeter spaces is provided through baseboard heating sized to allow use of low return water temperatures, which enhances boiler operating efficiency. Hot and chilled water are provided by two high efficiency boilers (efficiency 0.96) and one two-stage centrifugal chiller (COP=6.5) with a cooling tower. The cooling loop includes a water-side economizer to bypass the chiller when the outdoor dry bulb temperature is below about 10 ^{o}C.

SIMULATION OF THE CDC

Methods

The CDC was first modeled using EE4 with DOE2.1E simulation engine (NRCan 2006a), because of requirements of a federal energy efficiency incentive program. However, EE4-DOE2.1E lacks specific features to simulate some systems used in the CDC such as radiant cooling and displacement ventilation. EnergyPlus v2.0, which has specific features to model unconventional systems such as radiant cooling and displacement ventilation (DOE 2007a), was used to further study the CDC energy systems design. The building and system design parameters and information were collected from design documents. The EE4-DOE2.1E model had many fewer input parameters and was much easier to build than the EnergyPlus model (for example, the air distribution system). It was used to fine tune the EnergyPlus model in the absence of measured energy data.

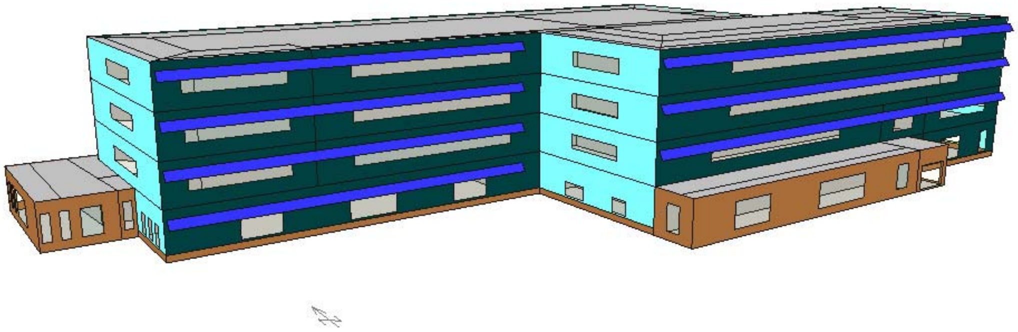

Figure 1: Child Development Center (generated with Ecotect); the long façade faces due south.

Table 1: Main wall and roof constructions and thermal properties

Type	Description of Layers	Thickness	Thermal Conductivity	Density	Specific Heat	Thermal Resistance	Overall Effective U value
	(from outside to inside)	(m)	(W/m.K)	(kg/m^3)	(J/kg.K)	(m^2.K/W)	(W/m^2.K)
W3 Wall	Siding Alum w Sheathing	0.01	0.0934	1600	1210		0.45
	Air Space					0.15	
	Insulation Roxul w framing	0.06	0.0345	240	710		
	Gypsum Sheathing	0.03	0.161	800	1090		
W5 Wall	Steel Sheathing	0.022	0.52	1120	880		0.41
	Air Space					0.15	
	Insulation Roxul w framing	0.06	0.0345	240	710		
	Gypsum Sheathing	0.012	0.161	800	1090		
	Air Space					0.15	
	Fiber Board Sheathing	0.016	0.0546	290	1300		
W6 Brick Wall	Brick Face	0.09	1.25	2080	790		0.27
	Air Space					0.15	
	Insulation Roxul	0.1	0.0345	240	710		
	Gypsum Sheathing	0.012	0.161	800	1090		
	Air Space					0.15	
	Fiber Board Sheathing	0.016	0.0546	290	1300		
R3 Roof	Roofing Built up	0.01	0.1724	1100	1460		0.17
	Fiber Board Sheathing	0.013	0.0546	290	1300		
	Insulation Polyisocyanurate	0.107	0.02	32	920		
	Gypsum Sheathing	0.013	0.161	800	1090		

Table 2: Window thermal properties and WWR

Construction	Type	Category	Effective U value (W/m^2.K)	SHGC
Window	Win-A	Fixed	1.94	0.32
Window	Win-B	Operable	2.3	0.32
Direction	**North**	**East**	**South**	**West**
WWR (%)	25.8	20	24.1	13.3

The modeling steps were:

1. Build the CDC EE4-DOE2.1E energy model, excluding radiant cooling and water-side free cooling, displacement ventilation, under-floor air distribution, and BIPV.
2. Create the CDC geometry in Ecotect (Marsh 2006) and export it to EnergyPlus (due to the lack of a graphical user interface in EnergyPlus). The “basic” EnergyPlus model zoning, building envelope, HVAC system and internal loads were consistent with the EE4-DOE2.1E model. Simulation results were compared and discrepancies rectified as identified.
3. Add the features beyond the scope of DOE2.1E to the “basic” EnergyPlus model to create an “advanced” model and obtain the predicted building energy performance with the additional energy efficiency measures and renewable energy systems.

Figure 2: Under-floor air distribution in CDC

SIMULATION RESULTS COMPARISON

Whole building energy end uses

In a nutshell, there was no major difference between the results from the EE4-DOE2.1E and the “basic” EnergyPlus 2.0 models, once data entry and similar errors were corrected (Table 3). The biggest relative difference was in cooling tower energy use (heat rejection). This is due to differences between DOE2.1E and EnergyPlus definitions of “heat rejection”. In DOE2.1E, “heat rejection” energy use includes both cooling tower fan energy use and condenser water circulation pump energy use, while in EnergyPlus “heat rejection” includes only cooling tower fan energy use. The simulated condenser water pump energy use in DOE2.1E is about 16 GJ.

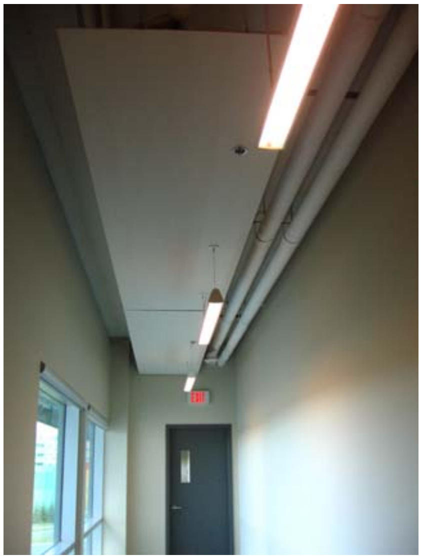

Figure 3: Radiant cooling panel in CDC (daylighting controls commissioning still in progress)

Both simulation results show temperatures exceeding the cooling setpoint (24 °C) in perimeter spaces in summer because the models lacked supplementary radiant cooling included in the CDC design. DOE2.1E is limited to a single system per zone except for baseboard heating (Hirsch 2003). In addition, the sequential structure without feedback from HVAC systems to load calculations causes inaccurate prediction of indoor temperature in DOE2.1E, especially when the transient load cannot be met as in this situation (Drury *et al.* 2001).

Coil and baseboard energy use

The EnergyPlus estimates of energy use in preheating, heating and cooling coils for air handling units (AHU) 1 and 2, as well as baseboard heating in associated zones are similar to those from EE4-DOE2.1E, except for the AHU-1 preheat coil (Table 4). In EE4-DOE2.1E, the preheat coil for air systems is located after the heat recovery unit and mixing box (NRCan 2006b), contrary to normal placement of the preheat coil upstream of the heat recovery unit to limit frosting with outdoor air temperatures below 0 °C.

In the CDC, the minimum temperature of air leaving the preheat coil was set to 0 °C. In the EE4-DOE2.1E model, the energy use in the preheat coil is zero because the air temperature entering the preheat coil from the mixing box is above 0 °C. EnergyPlus allows the preheat coil to be placed upstream of the heat recovery and mixing box, as in the CDC design.

Table 3: Simulated building energy end uses

Program	**EE4-DOE2.1E**	
Energy (GJ)	Electricity	Natural Gas
Lighting	632	/
Equipment	800	/
Heating	/	2418
Cooling	47	/
Heat Reject	17	/
Pump	30	/
Fan	298	/
DHW	/	656
TOTAL	1824	3074
Program	**EnergyPlus V2.0**	
Energy (GJ)	Electricity	Natural Gas
Lighting	622	/
Equipment	828	/
Heating	/	2330
Cooling	41	/
Heat Reject	2.3	/
Pump	31	/
Fan	295	/
DHW	/	658
TOTAL	1819	2988

Table 4: Coil and baseboard energy use

Energy (GJ)	**Equipment**	**EE4-DOE2.1E**	**EnergyPlus V 2.0**
AHU1	Preheat coil	0	183
	Cooling coil	120	91
	Baseboard	556	538
AHU2	Cooling coil	182	167
	Heating coil	717	872
	Baseboard	1034	915

Fan energy use

Fan energy use estimates are similar for the two models (Table 5). DOE-2.1E allows return fans with smaller air flow rates than supply fans, while EnergyPlus 2.0 requires that return air flow rates equal supply air flow rates, except for flows through zone exhaust fans (Witte 2006). The return fan energy use is the result of adjusting the return fan efficiency or pressure drop to represent smaller air flow rates as per the systems design.

Table 5: Fan energy use

Energy (GJ)	**Equipment**	**EE4-DOE2.1E**	**EnergyPlus V2.0**
AHU1	Supply fan 1	112	108
	Return fan 1	71	69
AHU2	Supply fan 2	78	81
	Return fan 2	38	36

Pump energy use

The simulated chilled water pump energy from EnergyPlus 2.0 is lower than that from EE4-DOE2.1E. In EE4-DOE2.1E (Table 6), pumps are assumed to run continuously (NRCan 2006a), while the CDC pumps were designed to operate on demand. The pump control is modeled as "intermittent" in EnergyPlus. Further investigation of the difference in chilled water pump energy use is required to clarify this discrepancy.

Table 6: Pump energy use

Equipment Energy (GJ)	**EE4-DOE2.1E**	**EnergyPlus V2.0**
Hot water pump	14	15
Chilled water pump	16	4
Condenser water pump	16	12

Modeling inter-zone surfaces

In EE4-DOE2.1E, interior walls between two conditioned spaces are generally omitted from the model. In EnergyPlus, interior walls between perimeter spaces and core spaces may affect predicted indoor temperatures. When heat transfer through interior walls adjacent to perimeter spaces is taken into account, the EnergyPlus simulation results show that, in winter, the indoor temperature of core zones may be about 2 ^{o}C lower than when these interior walls are set as adiabatic, although the simulated energy uses are similar. This is because the perimeter spaces have night temperature setback to 18 ^{o}C and thus will affect adjacent core spaces. This indicates that it may be necessary to model interior walls as "heat transfer surfaces" to more accurately predict indoor temperatures, especially in cold climates when night-time temperature setback control is applied.

MODELING ADVANCED FEATURES

Features beyond the scope of DOE-2.1 were then added to the EnergyPlus model (results in Table 7). The additional energy efficiency measures modeled in EnergyPlus were: 1) water-side free cooling to bypass the chiller with outdoor temperatures below 10 ^{o}C (with the “heat exchange:hydronic: free cooling” module); 2) radiant cooling panels installed in west and south perimeter spaces to provide cooling for transient heat gains (with the “low temperature radiant system:hydronic” module); 3) side-wall displacement ventilation for the first floor; and 4) underfloor air distribution for floors 2-4 (with the “UCSD UFAD” modules).

The simulation results indicated that there was a slight increase in natural gas energy use for heating with reduced fan energy use. Cooling energy increased with added radiant cooling panels.

Table 7: Simulated energy end use with energy efficiency measures

Program	**EnergyPlus V2.0**	
Energy (GJ)	Electricity	Natural Gas
Lighting	622	/
Equipment	828	/
Heating	/	2476
Cooling	58	/
Heat Reject	3	/
Pump	29	/
Fan	276	/
DHW	/	658
TOTAL	1816	3074

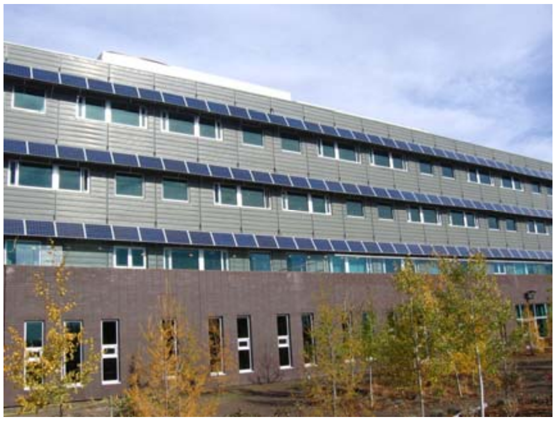

Figure 4: CDC BIPV system on south façade

The CDC has a photovoltaic system installed on the south façade with maximum power output of 43 kWp (Figure 4), simulated with the EnergyPlus “generator:PV:effective one-diode” module. The simulation results indicate the photovoltaic system may provide roughly 14% of annual electricity use (Table 8). EnergyPlus lacks an inverter model, so the results are an upper end estimate than an accurate prediction of the generated electricity (DOE 2007b).

Table 8: Building electricity load and generated power

Electric Sources	**Electricity**	**Percent**
	(GJ)	(%)
Photovoltaic Power	249	14
Electricity From Utility	1599	88
Surplus Electricity To Utility	32	2
Net Electricity From Utility	1567	86
Total On-Site and Utility Electricity	1816	100

DISCUSSION

The EE4 user interface simplifies DOE2.1E modeling, in terms of the building shell and control systems, at the cost of limited access to DOE2.1E parameters. For example, only single plant component type (i.e., one type of boiler, chiller, and cooling tower) can be created in one model. All surfaces are placed at 0, 0, 0, unlike other DOE2.1E interfaces that create a representative 3D model of the building. One the other hand, the EE4 interface automatically generates the MNECB baseline energy model in just a few seconds.

Third-party programs such as Ecotect have significantly expedited building geometry input for EnergyPlus modeling. The “Compact HVAC” module in EnergyPlus has also greatly reduced data entry for “node connection” in EnergyPlus. However, extensive input efforts may still be necessary when modeling unconventional HVAC systems and when revising the simulation model to reflect changes in building design. For example, to add a water-side economizer (free cooling) to conventional HVAC systems in an EnergyPlus model, program users have to setup several types of parameters in several parts of the EnergyPlus model, including schedules, plant-condenser loops, set point managers, condenser equipment, node-branch management and plant-condenser flow control. This complexity may lead to data entry errors, especially when in the case of new users.

In the EE4-DOE2.1E and “basic” EnergyPlus simulation models, lighting, plug loads (equipment), heating and domestic water heating account for about 94% of annual energy use. Reduced energy use with some advanced features (e.g., reduced air flow and fan power with displacement ventilation and underfloor air distribution) are largely accounted for in these models. Meanwhile, it should be noted that the EE4-DOE2.1E and “basic” EnergyPlus models could not be used to predict the indoor temperature trends due to the supplementary radiant cooling system was not modeled.

Radiant cooling contributes to some reduction in fan and pump energy use in the “advanced” EnergyPlus model relative to the “basic” EnergyPlus model, but fan and pump energy use account for only about 7% of annual energy use. This accounts for the small difference between whole building estimates for the “basic” and “advanced” EnergyPlus models. It is likely that the difference would be greater in more moderate and cooling-dominated climates.

Configuration differences between the two programs may cause differences in results. For example, in EE4-DOE2.1E, the preheat coil is located downstream of the mixing box while within EnergyPlus it can be placed upstream of heat recovery and the mixing box, which represents the arrangement used in cold climates.

FUTURE WORK

To further investigate the CDC energy performance, measurement and verification will be carried out following the “calibrated simulation” approach (IPMVP 2002) with weather data monitored at the nearby university weather station. The CDC has been equipped with an extensive array of instruments. For example, plug and lighting circuits are wired to separate power panels on each floor with dedicated transducers. The CDC will be a research platform and further research will be conducted:

- actual system operation control parameters will be investigated to fine tune the simulation model;
- indoor thermal conditions will be measured, including temperature, humidity, air velocity as well as secondary thermal parameters such as draft rate and vertical air temperature stratification;
- ventilation effectiveness will be investigated to study the possible improvement of air quality with displacement ventilation and under-floor air distribution systems.
- the photovoltaic system output will be monitored.

CONCLUSIONS

This paper reports an energy simulation study of a high performance building. During design, the building was modelled using the EE4-DOE2.1E software suite. This precluded simulation of some advanced features such as radiant cooling but was done to meet the requirements of a government incentive program..

Then the building was modeled in EnergyPlus v2.0 with the same conventional HVAC systems (“basic” EnergyPlus model). The EE4-DOE2 model was useful in quality assurance verification of Energy Plus inputs, increasing confidence in results. The dual EE4-DOE2.1E and EnergyPlus results allowed comparison of both the whole building energy end uses and specific equipment energy performance. The simulation results indicate general agreement between building energy end uses and specific equipment energy data estimates provided by the two programs. The differences in simulation results for specific components are discussed.

In the third stage, the energy efficiency measures beyond the capability of EE4-DOE2.1E were modeled in EnergyPlus (“advanced” EnergyPlus model), including radiant cooling, water-side economizer, displacement ventilation as well as under-floor air distribution systems. The building integrated photovoltaic system was also modeled in the EnergyPlus program.

The initial EnergyPlus simulation results differed widely from the EE4-DOE2.1E model results due to input errors related to the many parameters and complexity of the EnergyPlus model. Comparison of the energy end uses and specific equipment (e.g., fan, pump) energy uses in the two simulation models helped identify these errors. The extra time required is justified by the quality improvement and is recommended at least until a more straightforward interface is available for EnergyPlus.

Future monitoring of building energy use will aid in evaluating the simulation results and process.

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