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DEVELOPMENT OF A HIGH-PERFORMANCE OFFICE BUILDING SIMULATION MODEL FOR A HOT AND HUMID CLIMATE

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ABSTRACT

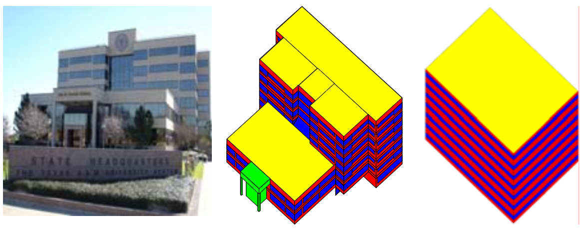
This paper presents the results of implementing 14 high-performance measures in a prototypical office building in a hot and humid climate using the DOE-2 simulation program. The objectives of this research were to discover high-performance measures applicable to office buildings in hot and humid climates and to develop a high-performance (maximum energy-efficient) building model that only uses technologies readily available in the contemporary market. The high-performance model showed 48% total energy savings above the ASHRAE 90.1-1999 code and 61% savings when compared to the calibrated simulation model of the case-study building. The results show that substantial energy savings can be achieved only by using common technologies.

INTRODUCTION

This study is based on the calibrated simulation model for an existing office building, the John B. Connally (JBC) building in College Station, Texas. This model was developed using the DOE-2 simulation program and calibrated to the field measured data and was presented in the previous publication (Cho and Haberl, 2008a). The calibrated simulation model was further extended to an ASHRAE 90.1 code-compliant model, which was used as the baseline model for the development of a high-performance (energy-efficient) model.

However, the code-compliant model did not use the as-built building geometry of the JBC building; rather, it used a simplified geometry. The simplified-geometry, code-compliant simulation model was developed using the eCALC program, which is a web-based emissions and energy calculator developed by the Energy Systems Laboratory (ESL) at Texas A&M University (Haberl et al., 2004). eCALC is a compilation of several legacy programs including: the DOE-2 program for building energy simulation analysis; the F-Chart program for solar thermal analysis; the PV F-Chart program for solar photovoltaic analysis; and ASHRAE's Inverse Model Toolkit (IMT) (Kissock et al., 2002) for monthly utility billing analysis, traffic light, street light, water, waste water, and wind energy analysis. The DOE-2 model inside the eCALC program, which uses simplified building geometries, was modified to represent the JBC building's systems characteristics. The results were compared between the as-built geometry simulation and simplified-geometry (eCALC) simulation. The error was within 2% between the two simulations. This comparison study was also presented in the previous publication (Cho and Haberl, 2008b).

Using the simplified-geometry, code-compliant (ASHRAE 90.1-1999) simulation model, a total of fourteen high-performance measures were applied both individually and cumulatively to see the impacts of the measures. These high-performance measures were identified from the previous survey on the high-performance buildings and systems in the U.S. (Cho and Haberl, 2006). In this study, the eCALC DOE-2 simulation model, which is the ASHRAE 90.1-1999 code compliant model having a simplified geometry, was used as the baseline for the calculation of the energy savings that were achieved from implementing high-performance measures. Figure 1 shows a pictorial explanation for the baseline model development (a) the case study building, (b) as-built geometry DOE-2 simulation model, and (c) simplified geometry eCALC DOE-2 simulation model, which is the baseline model for this study.



(a) (b) (c)

Figure 1 (a) case study building, (b) as-built geometry model, and (c) simplified geometry model

CASE STUDY BUILDING

(1) Building description: The John B. Connally (JBC) building is one of the Texas A&M University facilities in College Station, Texas. This building consists of 11,520 square meters of conditioned space with seven stories and a thermal plant, which is detached from the building. This building is used for offices and conference rooms. The JBC building has a window-to-wall ratio of 40%.

(2) HVAC systems: There are a total of nineteen (19) Air Handling Units (AHUs) of which seventeen are Single-Duct, Variable Air Volume (SDVAV) AHUs with Variable Frequency Drives (VFDs). Two (2) AHUs are SDVAV outside AHUs, which provide 100% of the outside air to the seventeen (17) SDVAV AHUs. The SDVAVs, as shown in Figure 2, are equipped with a cooling coil and a draw-through supply air fan.

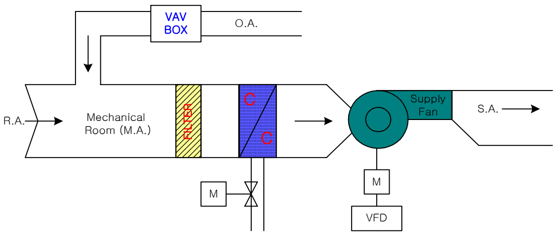


Figure 2 AHU systems diagram in the JBC building

(3) Thermal Plant: The thermal plant has two chillers providing chilled water for space cooling, two boilers providing hot water for space heating, and one water heater for service water heating. The two centrifugal chillers have a capacity of 280-ton each. The JBC building only needs one 280-ton chiller to meet the building's maximum cooling loads during occupied hours. The chillers are sequenced to allow both to run equal amounts each year. Two cooling towers are located next to the thermal plant, which have a condensing water flow of 53 litre per second (3,180 litre pre minute) each. The plant also contains two hot water boilers, which are gas-fired (80% efficiency) boilers with an input capacity of 586 MJ/sec each.

BASELINE MODEL AND 14 MEASURES

Before the 14 high-performance measures were applied, the baseline model (ASHRAE 90.1-1999 code compliant model) was developed and compared to the as-built, calibrated simulation model to verify the energy consumption changes. Figure 3 compares the energy uses by category and by total as well. The ASHRAE 90.1 model consumed total energy of 2,145 MJ/yr, which is 25% less than that of the as-built model. The savings were achieved mainly from the lights and space cooling. The detailed calibration simulation and the development of the ASHRAE 90.1-1999 code compliant model for this case study building (JBC building) were presented in previous publications (Cho and Haberl, 2008a; Cho and Haberl, 2008b).

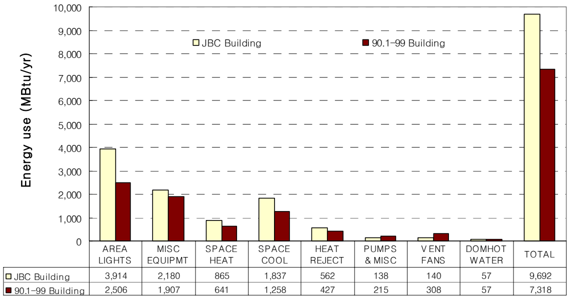


Figure 3 Energy consumption comparison: JBC building vs. ASHRAE 90.1-1999 compliant building

Table 1 shows the ASHRAE 90.1-1999 code requirements for this building and compares theses parameters with 14 high-performance measures. However, there were some parameters that were not available from the code such as window-to-wall ratio and light control. In such cases, other sources were used and notated in the next column in the table.

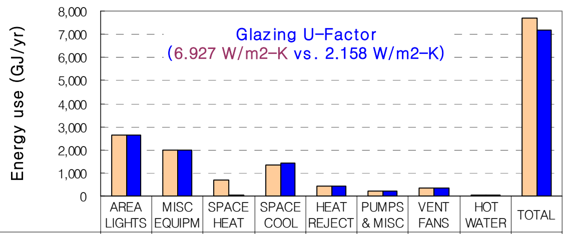
Table 1 The 14 High-performance measures compared to the ASHRAE 90.1-1999 code compliant parameters

No.	Items	Base-Case (ASHRAE 90.1-1999)		High-Performance Measures	
		Values	Remarks	Values	Remarks
1	Glazing U-Factor	6.927 W/m^2-K	ASHRAE 90.1-1999 Table B-5 (11.4.2(c)), (p.95)	2.158 W/m^2-K	Hawaii Commercial Building Guidelines for Energy Efficiency
2	Window-To-Wall Ratio	50%	Average WWR (Huang & Franconi, 1999, p.31)	35%	ASHRAE Advanced Energy Design Guide (AEDG)
3	Lighting Load	0.1208 W/m^2	ASHRAE 90.1-1999 Table 9.3.1.1, (p.51)	0.0836 W/m^2	ASHRAE AEDG (Climate Zone 2 Table)
4	Light Control	ASHRAE RP-1093 Schedule	Abushakra et al., 2001 (ASHRAE RP-1093, p.61)	Occupancy Sensor	ASHRAE AEDG (Climate Zone 2 Table)
5	Shading	None	No shading	75 Cm	ASHRAE AEDG (Proj. Factor=0.5)
6	Cold Deck Reset	Constant	100% Constant speed	Reset	Typical reset schedule from Texas A&M Univ. (TAMU) campus buildings
7	Supply Fan Total Pressure	623 Pa	Conventional value used	374 Pa	Information by CC^{TM} engineers
8	Economizer	None	No economizer	Temperature	Temperature Economizer
9	Chiller Coefficient of Performance (COP)	COP5.55	ASHRAE 90.1-1999 Table 6.2.1C, (p.29)	COP7.5	Hongkong Institute of Engineers
10	Boiler Efficiency (Thermal)	75%	ASHRAE 90.1-1999 Table 6.2.1F, (p.31)	95%	Cost Estimating (RSMeans, 2008)
11	Service Hot Water (SHW) Heater Efficiency (Thermal)	80%	ASHRAE 90.1-1999 Table 7.2.2, (p.47)	85%	ASHRAE AEDG (Climate Zone 2 Table)
12	Chilled Water Pump Control	Constant	Constant speed	VSD	Variable speed
13	Hot Water Pump Control	Constant	Constant speed	VSD	Variable speed
14	Chiller Staging	One Chiller	One 280-ton chiller	Three Chillers	Three 93.3-ton Chillers

More specifics were addressed in the following sections showing the simulation results from the 14 individual high-performance measures.

SIMULATION RESULTS

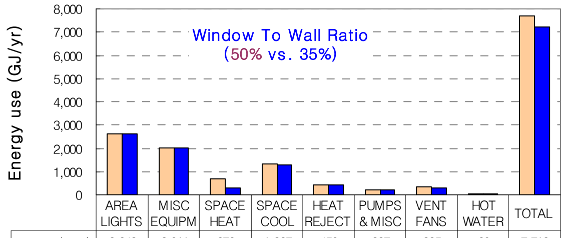
(1) Improved glazing U-factor (2.158 from 6.927 W/m²-K): In the code, the U-factor of windows in buildings was set at 6.927 W/m^2-K. The SHGC of the building was set at 0.44 for the north orientation and 0.17 for the other orientations. Window shadings or overhangs were not used. To improve the glazing performance, the U-factor was reduced to 2.158 W/m^2-K. The selection of this lower U-factor was to minimize the winter heat loss using available commercial glazing products. The SHGC of the base-case building remained the same. Figure 4 shows the simulation results. This measure: 1) reduced the total energy consumption to 7,174 GJ/yr from 7,721 GJ/yr, which is 7.1% lower than the base-case; 2) reduced the space heating energy consumption to 46 GJ/yr from 676 GJ/yr, which is 93.1% lower than the base-case. The improved glazing U-factor significantly reduced the heat transfer between inside and outside the building, especially in the winter period. The main heating loads are from the exterior zones and the walls of the exterior zones consist of 50% windows. The heating loads were significantly reduced by reducing the U-factor of the windows; and 3) increased the space cooling energy consumption to 1,427 MJ/yr from 1,327 MJ/yr, which is 7.5% higher than the base-case.



	AREA LIGHTS	MISC EQUIPM	SPACE HEAT	SPACE COOL	HEAT REJECT	PUMPS & MISC	VENT FANS	HOT WATER	TOTAL
U-Factor (6.93)	2,643	2,011	676	1,327	450	227	325	60	7,718
U-Factor (2.16)	2,643	2,011	46	1,427	451	196	339	60	7,171

Figure 4 Energy consumption comparison: baseline vs. simulation with improved glazing U-factor

(2) Reduced window-to-wall ratio (35% from 50%): This window-to-wall ratio was reduced from 50% to 35% based in the ASHRAE's Advanced Energy Design Guide (AEDG) (ASHRAE, 2004). ASHRAE's AEDG recommends a reduced window-to-wall ratio for this climate zone in which the case-study building is located, namely a 20%-40% window-to-wall ratio. As a high-performance measure in this study, the 35% window-to-wall ratio was chosen and simulated. Figure 5 shows the simulation results. This measure: 1) reduced the total energy consumption to 7.243 GJ/yr from 7,721 GJ/yr, which is 6.2% lower than the base-case; 2) reduced the space heating energy consumption to 294 GJ/yr from 676 MJ/yr, which is 56.5% lower than the base-case; and 3) reduced the space cooling energy consumption to 1,286 GJ/yr from 1,327 GJ/yr, which is 3.1% lower than the base-case.



	AREA LIGHTS	MISC EQUIPM	SPACE HEAT	SPACE COOL	HEAT REJECT	PUMPS & MISC	VENT FANS	HOT WATER	TOTAL
WWR (50%)	2,643	2,011	676	1,327	450	227	325	60	7,718
WWR (35%)	2,643	2,011	294	1,286	450	198	299	60	7,240

Figure 5 Energy consumption comparison: baseline vs. simulation with reduced window-to-wall ratio

(3) Reduced lighting power density (0.0836 from 0.1208 W/m²): Figure 6 shows the lighting profile adopted from the ASHRAE's diversity factor toolkit (Abushakra et al., 2001). The impact of energy-efficient lighting was determined by reducing the Lighting Power Density (LPD) from 0.1208 W/m^2 to 0.0836 W/m^2. The reduced lighting power density of 0.0836 W/m^2 is a recommended value by the ASHRAE AEDG. Figure 7 shows the simulation results.

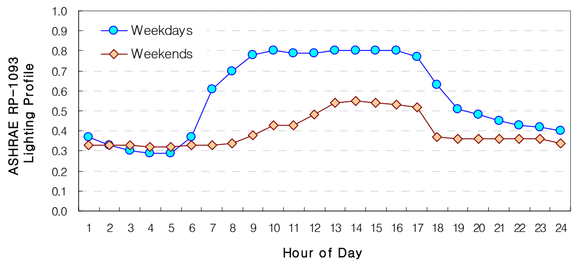
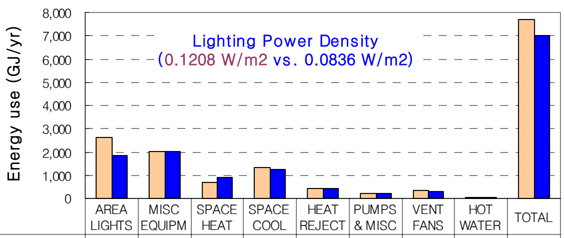


Figure 6 Base-case lighting profile adopted from the ASHRAE RP-1093 (large office)



	AREA LIGHTS	MISC EQUIPM	SPACE HEAT	SPACE COOL	HEAT REJECT	PUMPS & MISC	VENT FANS	HOT WATER	TOTAL
LPD (0.1208)	2,643	2,011	676	1,327	450	227	325	60	7,718
LPD (0.0836)	1,830	2,011	890	1,243	449	223	304	60	7,010

Figure 7 Energy consumption comparison: baseline vs. simulation with reduced lighting power density

This measure: 1) reduced the total energy consumption to 7,013 GJ/yr from 7,721 GJ/yr, which is 9.2% lower than the base-case; 2) increased the space heating energy consumption to 890 GJ/yr from 676 GJ/yr, which is 3.2% higher than the base-case; and 3) reduced the space cooling energy consumption to 1,242 GJ/yr from 1,327 GJ/yr, which is 6.4% lower than the base-case. In contrast to the space heating case, the reduction of internal heat gain by reducing the lighting power density resulted in a lower cooling load than the base-case.

(4) Occupancy sensors for lighting control: To apply the occupancy sensors to the lighting profile, Figure 6, the occupancy profile from the ASHRAE 90.1-1989, as shown in Figure 8, was utilized and modified.

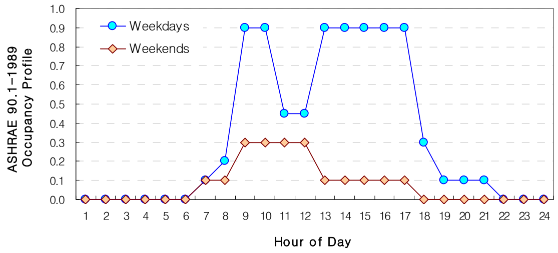


Figure 8 Occupancy profile adopted from the ASHRAE 90.1-1989 standard

Figure 9 shows the modified occupancy schedule for the occupancy sensors implementation. There are two modifications in Figure 9 (lighting profile) compared to Figure 8 (occupancy profile). First, the minimum lighting power (5%) is maintained in the night time for emergency. Second, the weekdays' profile is maintained lower than the occupancy profile for the hours of 9am, 10am, and 1-5pm. This is because the lighting profile of ASHRAE RP-1093 is lower than the occupancy profile of the ASHRAE 90.1-1989 Standard for these hours. The modified lighting schedule was developed not to exceed the lighting level for each hour of day.

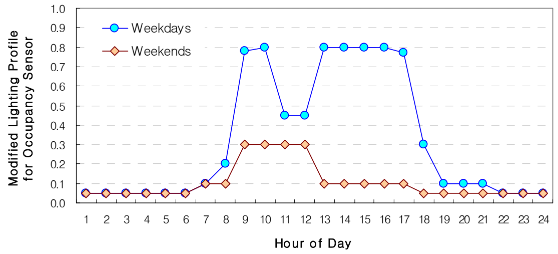
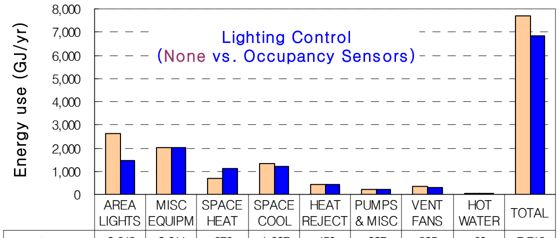


Figure 9 Modified lighting profile for occupancy sensors application

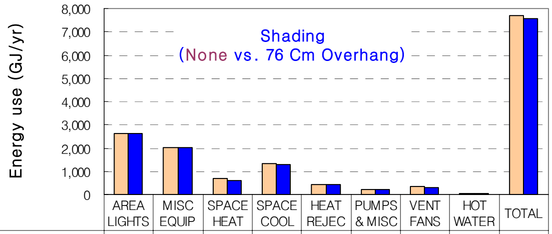
This measure: 1) reduced the total energy consumption to 6,855 GJ/yr from 7,721 GJ/yr, which is 11.2% lower than the base-case; 2) increased the space heating energy consumption to 1,136 GJ/yr from 676 GJ/yr, which is 68.0% higher than the base-case. The reduced lighting heat gain from the occupancy sensors resulted in lower internal heat gain, so the space heating load was increased; and 3) reduced the space cooling energy consumption to 1,210 GJ/yr from 1,327 GJ/yr, which is 8.8% lower than the base-case. The space cooling energy was supposed to be reduced as the internal heat gain was reduced by this measure.



	AREA LIGHTS	MISC EQUIPM	SPACE HEAT	SPACE COOL	HEAT REJECT	PUMPS & MISC	VENT FANS	HOT WATER	TOTAL
No Sensor	2,643	2,011	676	1,327	450	227	325	60	7,718
Occ. Sensor	1,454	2,011	1,136	1,209	449	228	305	60	6,852

Figure 10 Energy consumption comparison: baseline vs. simulation with occupancy sensors application

(5) Adding a shading device (76 Cm overhangs): The impact of window shades was considered. The ASHRAE AEDG recommends window overhangs on the windows, using a projection factor of 0.5. Since the windows used in the base-case simulation were set to heights of 5 feet, this implementation resulted in shades that projected 76 cm from the top of the windows. Also, these 76 cm overhangs were applied to all windows except windows in the walls that faced north. Figure 11 shows the simulation results.



	AREA LIGHTS	MISC EQUIP	SPACE HEAT	SPACE COOL	HEAT REJEC	PUMPS & MISC	VENT FANS	HOT WATER	TOTAL
No Shading	2,643	2,011	676	1,327	450	227	325	60	7,718
Overhang (76 Cm)	2,643	2,011	591	1,285	450	214	305	60	7,558

Figure 11 Energy consumption comparison: baseline vs. simulation with shading devices (overhangs)

This measure: 1) reduced the total energy consumption to 7,562 GJ/yr from 7,721 GJ/yr, which is 2.1% lower than the base-case; 2) reduced the space heating energy consumption to 591 GJ/yr from 676 GJ/yr, which is 12.6% lower than the base-case; and 3) reduced the space cooling energy consumption to 1,286 GJ/yr from 1,327 GJ/yr, which is 3.1% lower than the base-case.

(6) Supply air temperature reset: The supply air temperature was changed from a constant 12.8 ºC to a schedule as shown in Figure 12.

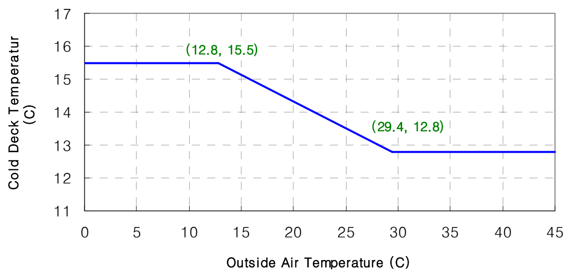
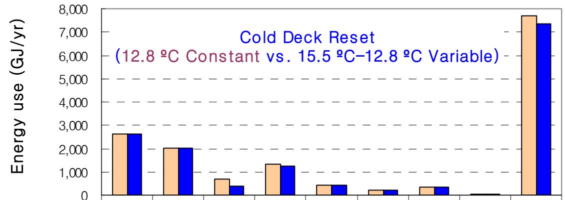


Figure 12 Cold deck temperature reset schedule based on the outdoor air dry-bulb temperature

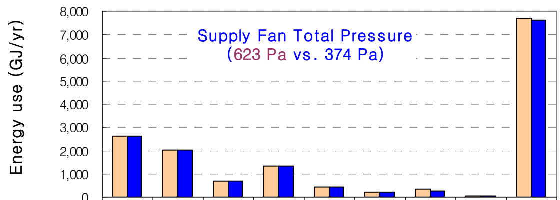
The cold deck air temperature is set at 15.5 ºC when the outdoor temperature is 12.8 ºC or lower and at 12.8 ºC when the outdoor temperature is 29.4 ºC or higher. The cold deck temperature decreases linearly from 15.5 ºC to 12.8 ºC as the outdoor temperature increases from 12.8 ºC to 29.4 ºC. Figure 13 shows the simulation results. This measure: 1) reduced the total energy consumption to 7,347 GJ/yr from 7,721 GJ/yr, which is 4.8% lower than the base-case; 2) reduced the space heating energy consumption to 384 GJ/yr from 676 GJ/yr, which is 43.2% lower than the base-case; and 3) reduced the space cooling energy consumption to 1,238 GJ/yr from 1,327 GJ/yr, which is 6.8% lower than the base-case.



	AREA LIGHTS	MISC EQUIPM	SPACE HEAT	SPACE COOL	HEAT REJECT	PUMPS & MISC	VENT FANS	HOT WATER	TOTAL
Const (12.8)	2,643	2,011	676	1,327	450	227	325	60	7,718
Vari (15.5-12.8)	2,643	2,011	384	1,237	450	227	333	60	7,345

Figure 13 Energy consumption comparison: baseline vs. simulation with cold deck reset schedule

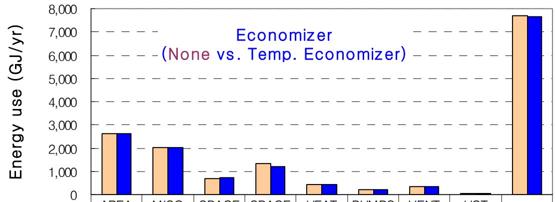
(7) Reduced supply air static pressure (374 from 623 Pa): The base-case building model had a supply air total static pressure of 623 Pa. This value was obtained from a survey through CC(R) engineers at the ESL. It represents an average value from the Texas A&M University campus buildings. The total supply fan static pressure was reduced from 623 Pa to 374 Pa, which was the value recommended by the CC(R) engineers at the ESL. This measure: 1) reduced the total energy consumption to 7,638 GJ/yr from 7,721 GJ/yr, which is 1.1% lower than the base-case; 2) increased the space heating energy consumption slightly, which is 0.4 GJ/yr, compared to the base-case, which is 676 GJ/yr. The percent increase of the heating energy was 0.06%; 3) reduced the space cooling energy consumption to 1,317 GJ/yr from 1,327 GJ/yr, which is 0.8% lower than the base-case; and 4) reduced the fan energy use to 255 GJ/yr from 325 GJ/yr, which is 21% lower than the base-case.



	AREA LIGHTS	MISC EQUIP	SPACE HEAT	SPACE COOL	HEAT REJECT	PUMPS & MISC	VENT FANS	HOT WATER	TOTAL
Fan SP (623 Pa)	2,643	2,011	676	1,327	450	227	325	60	7,718
Fan SP (374 Pa)	2,643	2,011	676	1,316	450	224	255	60	7,634

Figure 14 Energy consumption comparison: baseline vs. simulation with reduced static pressure

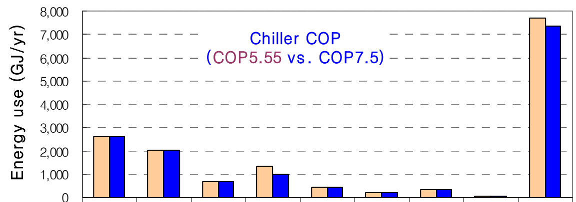
(8) Economizer control (temperature-based): A temperature-based economizer is a way to utilize free cooling when the outside air temperature is cool enough to be used for space cooling. An enthalpy-based economizer is a better option for humid climates due to the humidity; however, there are also drawbacks in the system, such as difficulties on maintenance. In this study, a temperature-based economizer was applied. Figure 15 shows the simulation results. This measure: 1) reduced the total energy consumption to 7,649 GJ/yr from 7,721 GJ/yr, which is 0.9% lower than the base-case; 2) increased the space heating energy consumption to 729 GJ/yr from 676 GJ/yr, which is 7.8% higher than the base-case. This is due to the lower mixed air temperature coming into the heating coil when the outside air dry-bulb temperature is 18.3 ºC or lower; and 3) reduced the space cooling energy consumption to 1,202 GJ/yr from 1,327 GJ/yr, which is 9.5% lower than the base-case.



	AREA LIGHTS	MISC EQUIPM	SPACE HEAT	SPACE COOL	HEAT REJECT	PUMPS & MISC	VENT FANS	HOT WATER	TOTAL
No Econo.	2,643	2,011	676	1,327	450	227	325	60	7,718
Temp. Econo.	2,643	2,011	729	1,201	450	228	325	60	7,646

Figure 15 Energy consumption comparison: baseline vs. simulation with economizer

(9) High efficiency chiller (COP 7.5 from 5.55): The base-case building has a 280-ton (985 kJ/sec) centrifugal chiller installed with a COP of 5.55, which is the minimum code requirement. This minimum efficiency of the centrifugal chiller was changed to a higher COP of 7.50. Figure 16 shows the simulation results.



	AREA LIGHTS	MISC EQUIPM	SPACE HEAT	SPACE COOL	HEAT REJECT	PUMPS & MISC	VENT FANS	HOT WATER	TOTAL
COP5.55	2,643	2,011	676	1,327	450	227	325	60	7,718
COP7.50	2,643	2,011	676	982	450	227	325	60	7,374

Figure 16 Energy consumption comparison: baseline vs. simulation with high efficiency chiller

This measure: 1) reduced the total energy consumption to 7,377 GJ/yr from 7,721 GJ/yr, which is 4.5% lower than the base-case; 2) maintained the space heating energy consumption the same as the base-case building, which was 676 GJ/yr, since the chiller efficiency change did not impact any space heating energy consumption; and 3) reduced the space cooling energy consumption to 982 GJ/yr from 1,327 GJ/yr, which is 26.0% lower than the base-case.

(10) High efficiency boiler (Et 95% from 75%): The base-case building model has two hot water gas boilers, which have 139 kJ/sec capacities each. The code requires a minimum boiler thermal efficiency of 75%. The building's heating system efficiency was improved by increasing the natural gas boiler efficiency to 95% (condensing boiler) from 75% (conventional boiler), which was set for the base-case simulation. Figure 17 shows the simulation results. This measure: 1) reduced the total energy consumption to 7,583 GJ/yr from 7,721 GJ/yr, which is 1.8% lower than the base-case; 2) reduced the space heating energy consumption to 538 GJ/yr from 676 GJ/yr, which is 20.4% lower than the base-case; and 3) maintained the space cooling energy consumption the same with the base-case building's consumption, which was 1,327 GJ/yr.

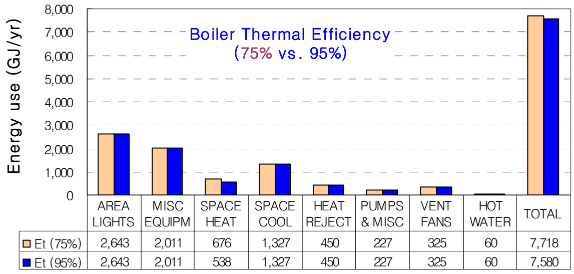


Figure 17 Energy consumption comparison: baseline vs. simulation with high efficiency boiler

(11) High efficiency water heater (Et 85% from 80%): The code minimum thermal efficiency requirement for the service water heater is 80%. This minimum efficiency was improved to the thermal efficiency of 85%. The impact of this measure to the total energy consumption was relatively small since the service water heating energy is small compared to the base-case building's electric use, space heating energy, or space cooling energy. Figure 18 shows the simulation results.

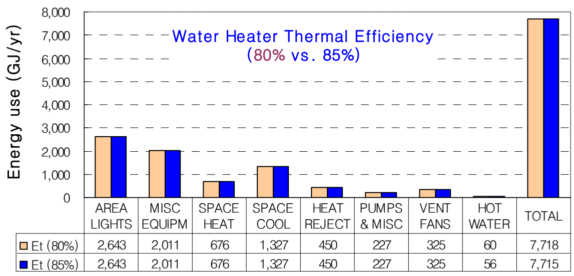


Figure 18 Energy consumption comparison: baseline vs. simulation with high efficiency water heater

This measure: 1) reduced the total energy consumption to 7,718 GJ/yr from 7,721 GJ/yr, which is less than 0.1% lower than the base-case; 2) reduced only the service water heating energy to 56 GJ/yr from 60 GJ/yr, which is 7.0% lower than the base-case.

(12) Chilled water pump control (VSD from constant): The base-case building model has a chilled water pump with a constant speed control. To improve the performance of the cooling system, the constant speed chilled water pump was replaced with a variable speed chilled water pump. Figure 19 shows the simulation results.

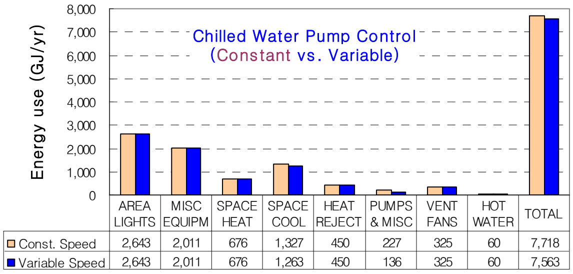


Figure 19 Energy consumption comparison: baseline vs. simulation with variable speed chiller pumps

This measure: 1) reduced the total energy consumption to 7,567 GJ/yr from 7,721 GJ/yr, which is 2.0% lower than the base-case; 2) did not change the space heating energy consumption of 676 GJ/yr; 3) reduced the space cooling energy consumption to 1,263 GJ/yr from 1,327 GJ/yr, which is 4.8% lower than the base-case; and 4) reduced the pump energy use to 136 GJ/yr from 227 GJ/yr, which is 40% lower than the base-case.

(13) Hot water pump control (VSD from constant): The base-case building model also has a hot water pump with a constant speed control. To improve the performance of the heating system, the constant speed hot water pump was replaced with a variable speed hot water pump. Figure 20 shows the simulation results.

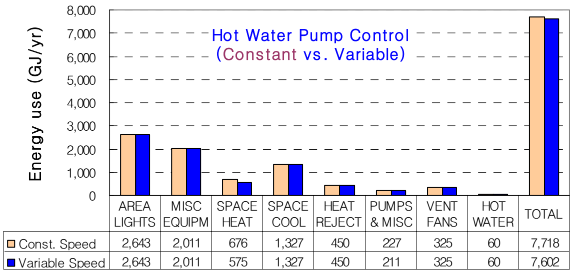
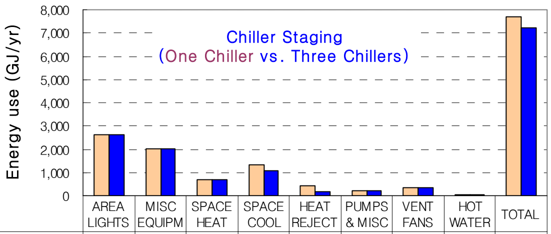


Figure 20 Energy consumption comparison: baseline vs. simulation with variable speed boiler pumps

This measure: 1) reduced the total energy consumption to 7,605 GJ/yr from 7,721 GJ/yr, which is 1.5% lower than the base-case; 2) reduced the space heating energy consumption to 576 GJ/yr from 676 GJ/yr, which is 14.8% lower than the base-case.

This was mainly due to the reduction in hot water consumption, consequently resulting in less N.G. use; 3) did not change the space cooling energy consumption of 1,327 GJ/yr; and 4) reduced the pump energy use to 211 GJ/yr from 227 GJ/yr, which is 7% less than the base-case.

(14) Chiller staging: For most chillers, the chiller efficiency increases as the load ratio increases from 40% to 80%. However, when the load ratio is either lower than 40% or at maximum load, the chiller efficiency is reduced. Running chillers in the efficient load ranges can reduce the electric energy use for chillers. To optimize the chiller performance, chiller staging is an option, using more than one chiller rather than using one large chiller. The 280-ton chiller used in the base-case model was replaced with three small chillers having 93.3 tons each. Figure 21 shows the simulation results. This measure: 1) reduced the total energy consumption to 7,724 GJ/yr from 7,721 GJ/yr, which is 6.4% lower than the base-case; 2) did not change the space heating energy consumption of 676 GJ/yr; 3) reduced the space cooling energy consumption to 1,094 GJ/yr from 1,327 GJ/yr, which is 17.6% lower than the base-case; and 4) reduced the heat rejection energy use to 187 GJ/yr from 451 GJ/yr, which is 58.5% less than the base-case.



	AREA LIGHTS	MISC EQUIPM	SPACE HEAT	SPACE COOL	HEAT REJECT	PUMPS & MISC	VENT FANS	HOT WATER	TOTAL
One Chiller	2,643	2,011	676	1,327	450	227	325	60	7,718
Three Chillers	2,643	2,011	676	1,093	187	227	325	60	7,221

Figure 21 Energy consumption comparison: baseline vs. simulation with chiller staging

SUMMARY

(1) Individual savings of 14 measures: The base-case building model simulation was performed using the ASHRAE 90.1-1999 minimum code requirements. This base-case model consumed a total of 7,721 GJ/yr. As shown in Figure 22, the implementation of occupancy sensors impacted the energy consumption the most, saving 11.2% of the total energy consumption. By this measure, indoor lights were shut off when spaces were not occupied, while keeping the emergency lights on, which required the minimum lighting power density of 5%. This reduced the lighting energy substantially by 50%, while the space heating energy increased by 68%. The percent change is larger in the space heating energy; however, the heating energy consumption was only about one fourth of the lighting energy use. As a result, the total energy reduction from the lighting was more substantial. The space cooling energy savings were 8.8% due to lower internal heat gains. The second largest energy savings were achieved also in the measure related to the lighting. The lighting power density change from 0.1208 W/m^2 to 0.0836 W/m^2 achieved the total energy savings of 9.2%. This measure also increased the space heating energy by 31.7%. The third largest energy savings were achieved by changing the glazing U-factor to 2.158 W/m^2-K from 6.927 W/m^2-K. The total energy savings were 7.1%. In this measure, the space heating energy saving was the most substantial of 14 measures. After the U-factor measure implemented, the space heating energy reduced to 46 GJ/yr from the base-case model's space heating energy use 676 GJ/yr, which is 93% consumption reduction. In terms of space cooling energy savings, the change of chiller COP to 7.5 from 5.55 had the most impact of 14 measures, saving the space cooling energy 26%.

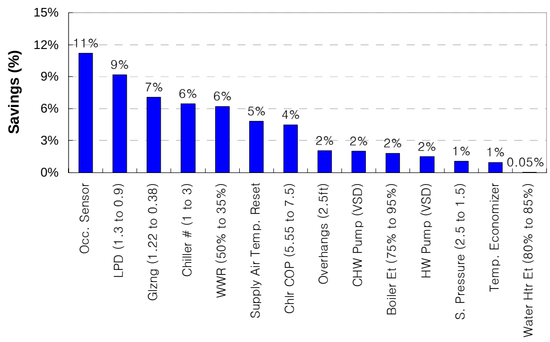
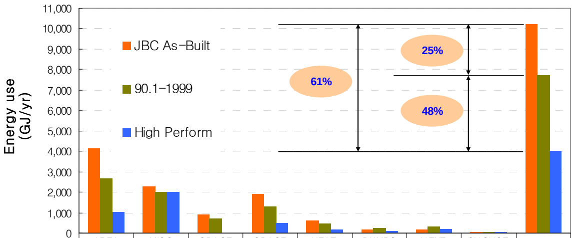


Figure 22 Savings summary of 14 high-performance measures

The least energy savings occurred in the hot water heater thermal efficiency change from 80% to 85%. Although the hot water savings achieved from the measure was about 6%, the energy reduction was only 3.5 GJ/yr, which was relatively too small compared to the total energy use of 7,721 GJ/yr for the building.

(2) Cumulative savings of 14 measures: When the individual 14 high-performance measures are added together, the total savings are calculated as 64.8%. However, the savings of 64.8% may or may not be the case when the 14 measures are applied at the same time, since each individual measure affects the other when combined. The combined 14 measures could achieve a more or less total energy savings. After all the 14 high-performance measures were combined, the simulation results showed the total combined savings of 48.1%, which is 16.7% lower than the simply added individual savings of 64.8%. The combined total savings of 48.1% is above the ASHRAE 90.1-1999 building energy code, which is substantial. As noted earlier, the ASHRAE 90.1-1999 code compliant building model consumed 25% less energy than the as-built JBC building did. The high-performance building model used 48% less than the ASHRAE 90.1-1999 code compliant model. When compared to the as-built JBC building, the high-performance building model consumed 60.8% less energy, as shown in Figure 22.



	AREA LIGHTS	MISC EQUIPMT	SPACE HEAT	SPACE COOL	HEAT REJECT	PUMPS & MISC	VENT FANS	SVCHOT WATER	TOTAL
JBC As-Built	4,128	2,299	912	1,937	593	145	148	60	10,221
90.1-1999	2,643	2,011	676	1,327	450	227	325	60	7,718
High Perform	1,007	2,011	5	496	162	75	192	56	4,004

Figure 22 Energy savings comparison: as-built vs. code compliant model vs. high-performance model

CONCLUSIONS

(1) Substantial energy savings available from common technologies: This study showed substantial energy savings, 48% above ASHRAE 90.1-1999, by implementing 14 high-performance measures. As listed, these measures are not high-tech skills, such as Under Floor Air Distribution (UFAD) and double skin façade, but are readily available technologies in this era. It indicates that there are already numerous opportunities to design high-performance buildings in terms of energy efficiency using widespread energy efficiency measures.

(2) Energy savings efforts needed on the "equipment" electricity use: Figure 23 shows cumulative energy savings by 14 high-performance measures. In this figure, highlighted with yellow is the equipment electricity use not changed by any measures. For the base-case model, the first bar from the left, the electricity use by equipment is 26% (2,012 GJ/yr) of the total energy use. However, this same usage of 2,012 GJ/yr becomes 50% of the total energy use after the 14 high-performance measures were implemented, as shown in the last bar. This is a substantial amount remaining. Therefore, it is necessary to come up with ideas and measures to reduce electric energy from the equipment use.

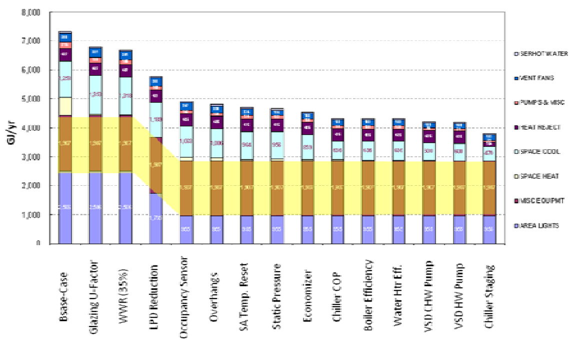


Figure 23 Energy savings by individual measures and equipment electricity use highlighted with yellow

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