R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 209–218. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

ENERGY PERFORMANCE MODELING OF AN OFFICE BUILDING AND ITS EVALUATION

Post-occupancy evaluation and energy efficiency of the building

Jihyun PARK, Azizan AZIZ, Kevin LI and Carl COVINGTON
Carnegie Mellon University, Pittsburgh, PA, United States
jihp@cmu.edu, azizan@cmu.edu, li.kevo@gmail.com,
ccovington83@gmail.com

Abstract. Energy performance modelling can provide insights into the efficiency and sustainability of commercial buildings, and also the achievement of certification standards such as USGBC LEED. However, the results from the modelling must be validated via a post-construction evaluation, which quantifies any discrepancies between the predicted energy usage and the actual energy consumed. In this study, an existing office building was examined to test how well the model predicts energy usage. The results from the model were compared with the actual usage of gas and electricity over two years (2010–2011). Our study showed a 123% higher gas usage, and a 36% lower electricity, compared with the simulation. This difference presents that occupant behaviour and building construction practices have significant impact on the energy usage of a building. For instance, the large discrepancy among gas usage is due to the office building's thermal envelope, which identifies the spots at which heat leaks out of the building, thereby forcing the heating unit to work more. Additionally, the post occupancy evaluation study identified that indoor environmental conditions impact on energy consumption of the building.

Keywords. Building performance evaluation; energy modelling; energy usage; user behaviour; post occupancy evaluation.

1. Introduction

1.1. ENERGY USE IN BUILIDNGS

Energy performance modeling provides an insight into understanding their efficiency and sustainability of the building. However, there is often a discrepancy between simulation and actual energy usage of buildings. The reasons for the differences are generally poorly understood and often have more to do with the role of human behavior than the building design.

Table 1. Main factors that influence building energy consumption (Yoshino, 2009).

Building-related factors	1) Climate 2) Building envelops 3) Building systems
User-related aspects	4) Operation and Maintains (O&M) 5) Occupant's Behavior 6) Indoor Environmental Quality (IEQ)

One of the major barriers for substantially improving energy efficiency in buildings is the lack of information about the factors determining the energy use of the building. In general, building energy consumption is mainly influenced by six factors shown in Table 1. One limitation of current research would be that it focuses mostly on building-related factors, such as climate, building envelope and HVAC systems rather than human related aspects (Yoshino, 2009). All of the factors, however, including building operation, occupants' activity and behavior, and indoor environmental quality, need to be analyzed using real measured energy consumption data (Effinger, 2012).

1.2. INDOOR ENVIRONMENTAL QUALITY AND ENERGY SAVINGS

Post occupancy evaluation (POE) is one of the most important efforts for energy consumption reduction while enhancing indoor environmental quality and occupant satisfaction. Raftery et al pointed out that user patterns would be a one of the important factors for total energy consumption modeling and adjustment of error (Raftery et al., 2009). Loftness et al pointed out that measured field data on IEQ, user satisfaction and the technical attributes of building systems (TABS) supports ongoing opportunities for energy conservation while meeting IEQ standards (Loftness et al., 2009). The Carnegie Mellon University (CMU) team has field findings for the General Services Administration (GSA) portfolio of offices that include 4% total energy savings by raising summer set points, 40% lighting energy savings by reducing ambient lighting and 25% reduction in lighting energy by daylight harvesting (Loftness et al., 2009; Aziz et al., 2012)

1.3. OBJECTIVES

The goal of this study is to better understand and strengthen the knowledge for effective total energy usage in buildings by analyzing energy usage and expenses, sustainable practices and materials during construction, and the indoor environment quality.

We highlight areas of efficient performance, as well as deficiencies within the building. Following our assessment, we provide strategies that can improve its energy efficiency, occupant comfort and the building's marketability through additional the U.S. Green Building Council (USGBC) Leadership in Energy and

Environmental Design (LEED) certification. These strategies will also factor in the cost of adopting the recommendations to provide the building owner with insights into the return from such investments, since not all benefits are quantifiable.

2. Methods

Our approach for assessing the overall performance of the TAI+LEE commercial building is to focus on three areas: thermal envelope, energy usage and indoor environment quality.

The energy usage comparison was conducted through the use of gas and electricity bills dating back to May 2010. This data was then compared to the energy simulation conducted using the eQUEST DOE-2 based simulation modelling tool. Energy consumption was normalized for the heating and cooling degree-days to determine how well the building was actually performing. The data from the energy bills were also inputted into the REM/Rate^{TM} software to provide a HERS rating, which also helped quantify our own recommended retrofit strategies.

To evaluate the thermal envelope, we used a thermo graphic camera to take pictures of the building exterior, work areas and the wall connections of the entire indoor space. This enabled us to identify areas of heat loss inside and outside the building. We also researched the materials of the building and their respective U-Values to compare with our actual findings from the pictures taken.

Lastly, indoor environmental quality field measurements were taken over two days in the TAI+LEE office building. The first measurements were taken on April 2nd, 2012, and the second set on April 17 and 18, 2012. Both were workdays with a number of employees present in the office.

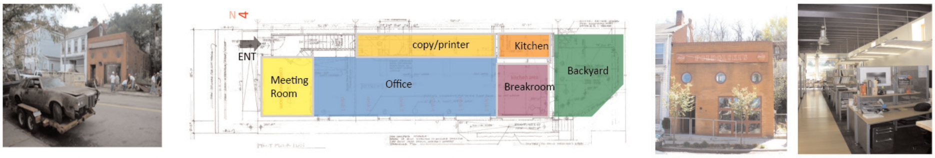
On the first day, thermo graphic pictures, digital photos, surveys and NEAT cart measurements were taken for all rooms and spaces, including the basement.

The subsequent days were used to capture additional thermo graphic and digital pictures, conduct interviews, distribute longer occupant surveys, and setup the 24-hour Airquity measuring system.

3. Analysis of Current Condition

3.1. BUILDING INFORMATION

The building in this case study is TAI + LEE Architects in Pittsburgh, PA and is owner occupied (Figure 1). It has 1 ½ floor plus a basement. The total floor area is 1,650 ft^2 (153 m^2) with a conditioned volume of 23,100 ft^3 (654 m^2). The total wall and window area is 2,716 ft^2 (252 m^2) and 182 ft^2 (27 m^2), respectively. When the TAI+LEE group took over the building it had to be completely reconstructed since there was no insulation, and the roof had caved in. Therefore, they had to start from scratch by reconstructing the floor, walls and roof.



Detached garage (Before renovation) Floor plan: 1st floor Exterior view Interior view

Figure 1. Floor plan, exterior, and interior photo.

3.2. BUILDING ATTRIBUTES AND CONTROLS

The radiant floor system serves as the primary heating unit for the building. It has a much smaller rated output of 42 kBTU/h versus 117 kBTU/h for the standard building. Its performance ratings are 96 for the EFF and 17 for the EER, compared to 80 and 8.9 for the traditional unit.

TAI+LEE also installed a supplemental air heat pump to heat and cool the building during extreme weather conditions. Although this system was installed to operate under the most extreme weather conditions, it is a high efficient system with a variable speed blower motor and is rarely used throughout the year.

The building is ventilated using two ERV systems, one in the basement (130cfm) and one on the first floor (200cfm) above the bathroom. The unit in the basement must be in constant operation to help control for humidity. However, the unit in the first floor is not used as often, since it is sufficient to manually ventilate the space by opening the windows on the north and south walls and the skylights.

Interviews conducted with the employees revealed that the indoor thermal controls were complicated to use, and most preferred to leave it alone. There are multiple devices for controlling various systems in the building. When the building was first finished, the central thermostat did not have an automated timer. This resulted in a significant time lag between when it was turned on and when the radiating floors would come into effect. A workaround for this was to turn on the heat pump while the radiating floor system took time to ramp up. Consequently, this resulted in higher electricity use until they installed an automated mechanism that set the temperature to 72°F (22.2°C) at 6 AM in the morning and 65°F (18.3°C) after 8 PM and on weekends.

The Mitsubishi controller is responsible for the ERV, AC and heater. Under normal conditions, passive techniques for ventilation are used, such as opening the skylights or front and rear windows. We noticed that the employees rarely used this control due to its multiple settings and the necessity to readjust once comfort level is reached. Although they prefer passive techniques, it has its own inconveniences, as occupants tend to stay focused on work until the thermal comfort levels were unbearable. When the ceiling fan was turned on, it made a significant positive impact for air circulation.

4. Energy Analysis and Results

4.1. COMPARISON OF SIMULATION AND ENERGY BILL

An energy simulation was conducted on TAI+LEE via eQUEST software and was compared against a reference case commercial building with the same floor area, volume and weather conditions (Pittsburgh, PA, USA). Table 2 shows the detailed

Table 2. Energy simulation comparison between baseline building and current building.

Description	Baseline Case	Current building
Weather file	PTTSBRGH.ET1	PTTSBRGH.ET1
Floor Area, ft^2	1650.0	1650.0
Surface Area, ft^2	6016.0	6016.0
Volume, ft^3	23100.0	23100.0
Total Conduction UA, Btu/h-F	484.1	307.2
Average U-value, Btu/hr-ft^2-F	0.080	0.051
Wall Construction	Code, R=9.7	triplebrick+foam, R=20.7
Roof Construction	R20polyiso, R=20.1	R30polyiso, R=29.5
Floor type, insulation	Crawl Space, Reff=24.0	Crawl Space, Reff=31.9
Window Construction	3026 wood code, U=0.35,etc	3070 wood kolbe, U=0.26,etc
Window Shading	None	None
Wall total gross area, ft^2	2716	2716
Roof total gross area, ft^2	1650	1650
Ground total gross area, ft^2	1650	1650
Window total gross area, ft^2	158	309
Windows (N/E/S/W:Roof)	9/0/12/0:0	11/0/8/5:3
Glazing name	codedouble, U=0.35	kolbe, U=0.26
Operating parameters:		
HVAC system	DX Cooling with Gas Furn	DX Cooling with Gas Furn
Rated Output (Ht/SC/TC),kBtu/h	117/48/64	42/28/37
Rated Air Flow/MOOA,cfm	1962/248	1873/120
Heating thermostat	72.0 °F, no setback	72.0 °F, setback to 67.0 °F
Cooling thermostat	76.0 °F, no setup	76.0 °F, setup to 81.0 °F
Heat/cool performance	eff=80,EER=8.9	eff=96,EER=17.0
Duct leaks total %	11/10	2/0
Peak Gains; IL,EL,HW,OT; W/ft^2	1.00/0.33/0.26/1.52	0.75/0.10/0.26/1.25
Added mass	none	none
Daylighting	no	no
Infiltration, in^2	ACH=1.0	ACH=0.3
Results:		
Energy cost	1.500$/Therm,0.100$/kWh	1.500$/Therm,0.100$/kWh
Simulation dates	01-Jan to 31-Dec	01-Jan to 31-Dec
Energy use, kBtu	306455	101184
Energy cost, $	$6153	$2558
Total Electric (**), kWh	27160	18405
Internal/External lights, kWh	5011/2226	3758/675
Heating/Cooling/Fan, kWh	0/3503/3135	0/1562/1485
Hot water/Other, kWh	0/13286	0/10926
Peak Electric, kW	11.8	5.7
Fuel, hw/heat/total, kBtu	6680/207098/213777	6680/31701/38380
Emissions, CO2/SO2/NOx, lbs	61750/238/139	29269/150/80

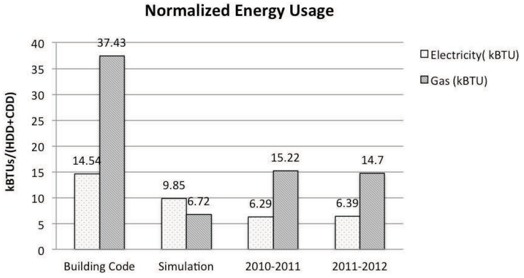


Figure 2. Normalized energy usage.

information of baseline data and current project. This building has a 36% lower average u-value for the entire building (0.051 btu/hr-ft2-f), with increased R-values coming from the roof, floor and windows construction. In addition, it employs a more efficient and smaller HVAC system due to the improved thermal envelope. In addition, it contained only 2% total duct leak, compared with the expected 11% for the reference commercial building. Therefore, TAI+LEE outperforms the reference case by 52% on cost and 32% on electricity use over the course of the year.

Although the simulation shows that the TAI+LEE building surpasses the reference commercial building, we wanted to compare the actual performance of the building to the simulated results. Based on the gas and electricity bills, TAI+LEE used a total of 130,807 and 103,171 kBTUs for the years 2010–2011 and 2011–2012, respectively. The simulation estimated a total energy usage of 101,184 kBTUs. However, the Heating degree day (HDD) and Cooling degree day (CDD) for 2008 may be different than those for which we analysed. Therefore, we normalized each year’s total energy usage by its respective HDD and CDD and separated it by electricity and gas use (Figure 2).

Comparing their EUI to the 2003 CBECS data for office buildings, TAI+LEE fell within the 25th percentile for electricity use (6.98 kWh/sq. ft.). However, their natural gas (47.09 cf/sq. ft.) put them in the 50–75th percentile range. This agrees with the findings above that they are using electricity efficiently, but gas use is suboptimal – possibly due to leaks within the thermal envelope.

4.2. ESTIMATION OF ENERGY CONSUMPTION

We performed REM/Rate simulation to estimate the current energy cost. Also adding a green roof can increase the performance of roof envelopment. Adding a green roof under their Photovoltaics (PV) panels, as well as filling out the rest of their roof space with both components would increase the efficiency at which PV panels perform, generate more electricity, and reduce the heating and cooling load of the building.

When we modelled the building in REMRate, the summation of all our recommendations amounted to an annual savings of $179, and improving our HERS index from 85 to 71. It is uncertain whether the REMRate model was able to capture benefits such as the reduction in heating and cooling load, but it also does not take into account the water runoff saved from employing a green roof. Because this renovation is capital intensive, TAI+LEE must perform a thorough investigation of its benefits before proceeding.

5. Building Envelope

5.1. THERMAL ENVELOP

The envelope of the building was constructed with high-quality, low U-Value materials. The Kolbe windows are double-paned argon filled gas, while the walls, roof and floor were constructed from low-waste wooden joists with Tripolymer foam insulation and minwool batt. Table 3 outlines the U-Value associated with each component of building.

One method to understand the large discrepancy among gas usage is to assess the office building’s thermal envelope. This helps to identify the spots at which heat leaks out of the building, thereby forcing the heating unit to work more. A thermo-graphic camera identified multiple spots of heat loss on the front sidewall of the building.

In 2008, a blower door test was performed for this building. The simulated infiltration was 0.3 ACH (Air exchange per hour), but the results from the test returned 0.4 ACH. The leaks, which were from the wire installations of the solar PV panels located on the second floor, were supposedly fixed shortly thereafter. However, Thermal graphic image shows some residual heat loss at the junction between the roof joist and the wall. Also, there are additional leaks in the conference room as seen in Figure 3. Overall, the majority of the leaks occur in the north wall/area of the building.

Table 3. U-Value of thermal envelope.

Components	U-Value
Windows: Double-pane argon filled gas	0.260
Roof: Wooden joists with Tripolymer foam insulation	0.028
Walls: Wooden joists with Tripolymer foam insulation	0.05
Basement Concrete Wall	0.630
Floor: MinWool Batt	0.072

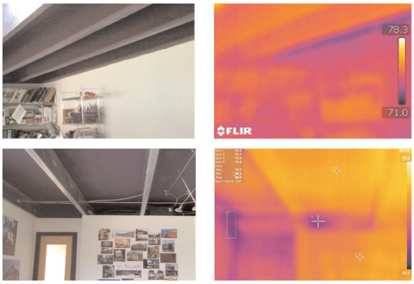


Figure 3. Thermal image of conference room.

5.2. IEQ EVALUATION: THERMAL QUALITY

In order to enhance the environmental profile of the work group beyond the descriptions possible with spot measurements, twenty-four hour continuous measurements were taken in one location of the office. An Aircuity Optima system is utilized to measure temperature, relative humidity, CO_2, CO, large and small particulates, TVOC, radon, and ozone. In this study, we are focused on thermal environmental qualities and findings. Table 4 shows the indices and user comfort standards for IEQ field measurement (ASHRAE, 2010).

Spot and 24 hour continuous air temperature measurements (1.1m, 0.6m, 0.1m) ranged between 68–78°F (20–25.6°C), average 73°F (22.8°C), comfortably within the seasonal comfort zone (Figure 4, Figure 5). Although all measurements fell

Table 4. The measurements taken at each workstation, as well as calculated variables.

Measures taken and units	**Standards**
Temperature at 1.1m, 0.6m, 0.1m (spot and 24 hour continuous)	ASHRAE 55-2010
Horizontal radiant temperature difference °C	ASHRAE 55-2010
Vertical radiant temperature difference °C	ASHRAE 55-2010
Relative humidity % (spot and 24 hour continuous)	ASHRAE 62-2010

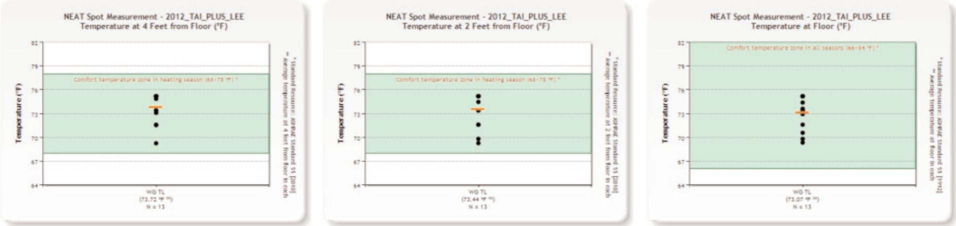
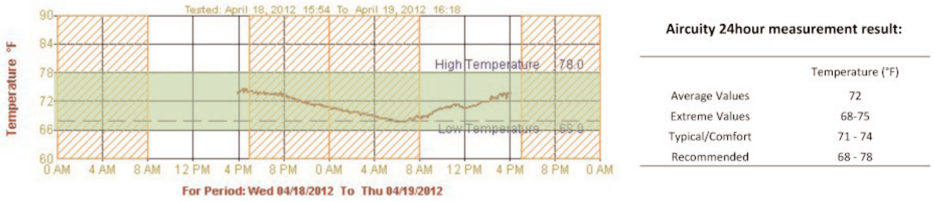


Figure 4. Spot measurement: air temperature at 1.1m, 0.6m and 0.1m from floor.



Aircuity 24hour measurement result:

	Temperature (°F)
Average Values	72
Extreme Values	68-75
Typical/Comfort	71 - 74
Recommended	68 - 78

Figure 5. 24-hour continuous measurement result: Air temperature.

within the comfort zone, we noticed the loft area was quite warmer than the first floor. The space is currently used only as a storage area.

6. Summary and Conclusion

The TAI+LEE commercial building was a well-thought out and executed retrofit on a dilapidated storage garage. Its use of high-quality, sustainable materials and selection of HVAC components are impressive. The electricity EUI was excellent as it fell within the 25th percentile of office buildings surveyed in the 2003 CBECS, and outperformed its energy simulation in 2008. In regards to the indoor environment quality, all measurements were within the comfort range and all employees enjoyed working in the building.

With that said, there were some areas that could have been improved. The natural gas EUI did not perform as well, since it fell within the 50-75th percentile of the 2003 (CBECS, 2003).

Comparative analyses showed that energy usage discrepancies between the predicted and actual usages were significant. Based on the gas and electricity bills, the building used a total of 130,807 and 103,171 kBTU for the years 2010-2011 and 2011–2012, respectively, whereas the simulation predicted a total energy usage of 101,184 kBTU.

Since the HDD and CDD may vary year by year, each year's total energy usage was normalized by its respective HDD and CDD and separated it by electricity and gas use. Although the simulation predicted the total energy use relatively well, larger discrepancies were found after differentiating between electricity (36% lower than actual) and gas use (123% higher than actual). In general a building simulation analysis is expected to predict the usage in less than 10% of error (Gundala, 2003). One method to understand the large discrepancy among gas usage is to assess the office building's thermal envelope. This helps to identify the spots at which heat leaks out of the building, thereby forcing the heating unit to work more. A thermo-graphic camera identified multiple spots of heat loss on the front sidewall of the building.

It infers that that occupant behavior and building construction practices may have significant impacts on the energy usage of a building. Accordingly, the design of a building needs to be incorporated with occupants' behaviors and interaction with their indoor environment. Additionally, it would be better that building codes and certification standards, such as USGBC LEED, include requirements for best practice at construction sites to ensure proper installation and storage of materials.

Acknowledgements

This material is based upon work supported by the Energy Efficient Buildings (EEB) Hub, an energy innovation hub sponsored by the Department of Energy under Award Number DE- EE0004261.

The authors gratefully acknowledge Erica Cochran, Dave Epley, Nina Baird, Shubha Mohunta, Yoko Tai, and Steve Lee for data collection, analyses, and reviewed our work.

References

ASHRAE: 2010, *Performance Measurement Protocols for Commercial Buildings*, American Society of Heating, Refrigerating and Air Conditioning Engineers.

Aziz, A., Park, J., et al.: 2012, Field measurement Protocols for Evaluating Indoor Environmental Quality and User Satisfaction in Relation to Energy Efficiency. U.S. DOE The Energy Efficient Buildings Hub, Department of Energy.

CBECS: 2003, 2003 Commercial Buildings Energy Consumption Survey (CBECS). Department of Energy, USA.

Gundala, S.: 2003, LEED Energy Performance Modeling and Evaluation of the S.T. Dana Building Renovations, Report No. CSS03-07, Center for Sustainable Systems, University of Michigan, Ann Arbor, MI.

Effinger, J., Effinger, M. and Kramer, H.: 2012, Overcoming Barriers to Whole Building M&V in Commercial Buildings, *2012 ACEEE Summer Study on Energy Efficiency in Buildings*, American Council for an Energy-Efficient Economy, Washington, DC.

Loftness, V., Aziz, A., Choi, J. H., Kampschroer, K., Powell, K., Atkinson, M. and Heerwagen J.: 2009, The value of post-occupancy evaluation for building occupants and facility managers, *Intelligent Buildings International*, **1**(4), 249–268.

Raftery, P., Keane M. and Costa, A.: 2009, Calibration of a detailed simulation model to energy monitoring system data: a methodology and case study, *Proceedings of the 11th IBPSA Conference*, Glasgow, UK.

Yoshino, H.: 2009, Total energy use in buildings: analysis and evaluation methods, ECBCS Project Factsheet, Annex 53, ECBCS, UK.