ACHIEVING COMFORT: ENERGY MODEL VALIDATION OF A HISTORIC BUILDING RENOVATION

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ABSTRACT

Aging buildings and systems, occupant comfort, sustainability, and maintenance of historic buildings are some of the motivating factors for implementing existing building energy upgrades. Upgrades may include replacing fenestration, adding insulation/air seals, and replacing obsolete lighting and mechanical systems. Commercial and residential buildings represent approximately 40% of annual energy consumption and 46% of annual carbon dioxide emissions in the United States. The U.S. Department of Energy publishes data on construction dates for commercial buildings. The data shows that 54% of commercial buildings in the United States were built before the 1970s oil crises and the subsequent effort to construct buildings with higher energy efficiency and airtight enclosures.

This paper describes a case study of the St. Paul's School Schoolhouse in Concord, New Hampshire, which utilized energy simulation tools to predict future building performance for a 1936 masonry campus building renovation. Building energy simulations should account for all aspects of a building design and operation, including exterior enclosure construction, air leakage through the building enclosure, mechanical systems, lighting, occupancy and use, and the environment. Air leakage rates in existing buildings vary depending on architectural style, enclosure systems, and maintenance. The most accurate energy models include measured whole-building air leakage rates and are calibrated using site-specific weather files and submetered electric and mechanical system consumption data. This paper compares the predicted versus measured heating loads to understand simulation accuracy for the St. Paul's School Schoolhouse building.

BUILDING DESCRIPTION

The Schoolhouse building is located on the campus of St. Paul's School (SPS) and is a three-story brick-and-limestone-clad building designed by James Gamble Rogers Architects and constructed in 1936 (Photo 1). The building is primarily used for classrooms with limited office space. The exterior walls consist of solid brick masonry with limestone elements, primarily at window and door surrounds and copings. Roofing systems include steep-slope slate shingles, low-slope EPDM membrane, and copper. The original windows (over 500) were steel framed with leaded single-pane glazing with both fixed and operable sash.

Figure 1: Schoolhouse Building

The building is heated by forced hot-water fin-tube radiators at the building perimeter. Steam is supplied from October through May via a campus-wide Central Heating Plant to the Schoolhouse basement, where a heat exchanger converts the steam to hot water for heating. The building lacks air conditioning and is not mechanically ventilated with outdoor air. Bathrooms are exhausted through a common roof ridge vent.

OCCUPANT COMFORT AND BUILDING ENERGY USE

SPS engaged the authors' firm to conduct a building enclosure assessment and investigate the cause(s) of thermal discomfort and high energy usage for the building. Building occupants reported excessive air leakage through the existing windows and frequently covered the windows with clear plastic to reduce drafts during cold weather. Several occupants installed electric radiators to provide supplemental heating during winter, which increased electricity consumption. The building facilities personnel were unable to implement temperature setbacks at night or during the weekend because the existing heating system was unable to raise the interior temperatures to the setpoint in time for classes to start in the morning.

Figure 2: Original Steel Window Frames Lacked Gaskets at Operable Sash (Arrows)

The primary sources of air leakage through the windows included 1). through joints between lead cames and the glass, 2). around operable window sash lacking gaskets at metal-to-metal joints (Photo 2), and 3). through joints between the window frames and stone surrounds.

Field air leakage testing showed that the existing windows leaked approximately 2-1/2 to 10 times the current industry standard for a replacement window with gasketed joints at operable sash (Table 1).

Table 1: Comparison of Window Air Leakage Rates

Window Type	Air Leakage Rate (cfm/ft²) at 1.57 psf (75 Pa)
Existing Casement	0.748 to 2.93
AAMA 101-11 Standard (CW Windows)	0.30
Replacement Casement Window w/gaskets (field test)	0.33

Our data loggers in the perimeter classrooms and offices indicated that building's heating system was unable maintain the desired interior setpoint temperature during the winter and often required increasing the setpoint to compensate for cold interior conditions (Figure 3).

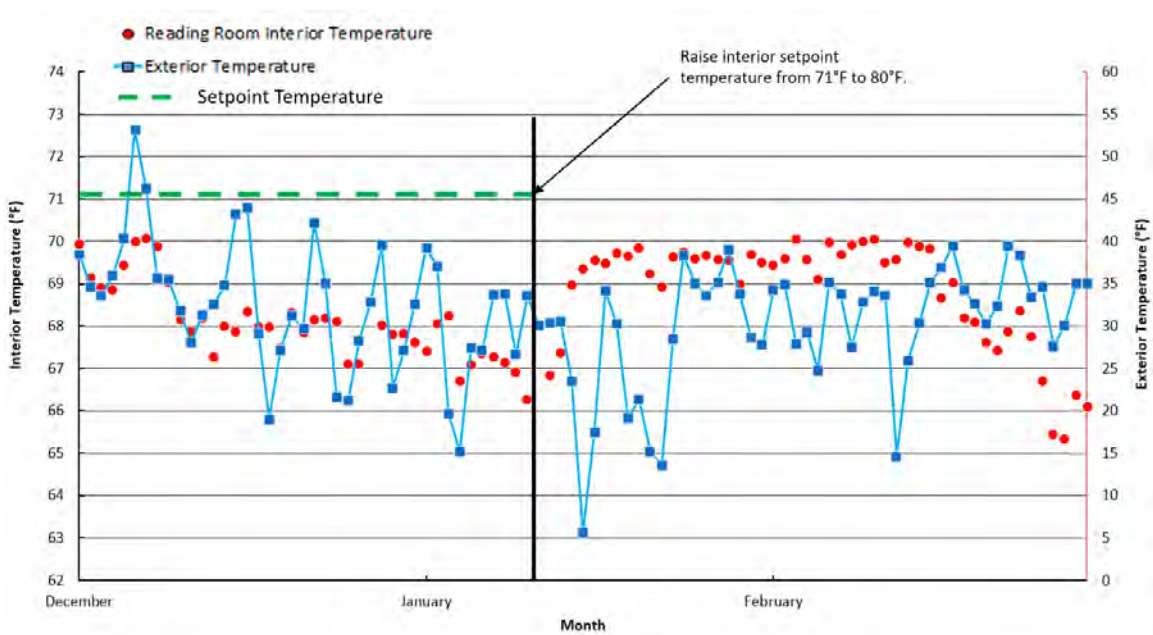

Figure 3: Interior versus Exterior Temperature (Existing Windows)

DATA LOGGING AND ENERGY MODELING

SPS elected to implement a building enclosure renovation project that included masonry repairs and window and roofing replacement. Replacement windows were also steel frames, but used single-lite insulating glass units with applied cames to simulate true divided lites. In addition, the operable sash included perimeter gaskets. The project was phased over two nonconsecutive summers with roofing replacement occuring during Phase 1 and window replacement and masonry repairs occuring during Phase 2. The project phasing allowed the authors' firm to complete a research project with SPS to generate energy models using data we collected at the project site and determine whether we could accurately predict building energy consuption using EnergyPlus™ modeling software before and after window replacement. The project included data

logging the interior temperature and relative humidity conditions, installing a rooftop weather station to record local weather conditions, and performing a whole-building air leakage test before and after window replacement. SPS submetered the daily steam and hourly electric consumption use for the building using a campus energy monitoring system.

We recorded the local weather and monitored the building prior to window replacement for one winter. In addition, we performed a whole-building air leakage test and measured an air leakage rate of 0.89 cfm/sq ft at 75 Pa pressure differential. We continued to monitor conditions after the window replacement project, repeated the whole-building air leakage test, and measured an air leakage rate of 0.63 cfm/sq ft at 75 Pa pressure differential.

Our simulation of the building geometry was developed to use a computational fluid dynamics (CFD) virtual wind tunnel (VWT) simulation developed by ODS Engineering (Lyon, E.G., et. al., August 2016). ODS Engineering uses Blender as a geometry platform and allows us to calculate the pressure coefficients on building surfaces for use in the EnergyPlus™ Airflow Network. The energy model utilized the local weather conditions recorded by the rooftop weather station.

MODEL CORRELATION AND BUILDING ENERGY REDUCTION

We plotted daily heating loads calculated by our energy models using local weather conditions against the metered usage provided by SPS before and after window replacement and noted the following trends:

- Existing Windows: Our predicted performance with the existing windows correlated poorly with the actual performance in the fall of 2011 and then dramatically improved in January 2012 during very cold winter weather (Figure 4). We speculate that the discrepancy in the fall was due to the exceptionally mild weather resulting in occupants leaving the windows open. SPS building maintenance personnel reported that they observed open windows throughout the fall.

- Replacement Windows: Our predicted performance with the new windows correlates well with actual performance during the fall of 2012 and winter of 2013 until the weather becomes mild enough for the occupants to open the windows near the end of the heating season, as open windows are the only source of cooling (Figure 5). The energy model under predicted the total heating load by 8%.

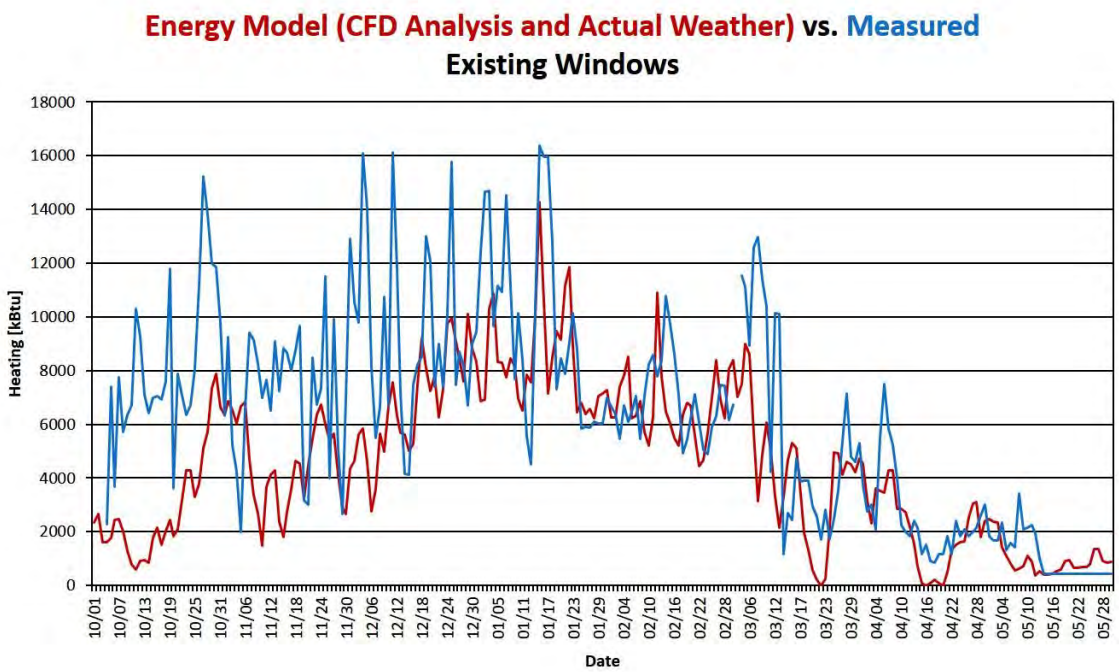

Figure 4: Heating Loads Calculated from Energy Model and Measured (Existing Windows)

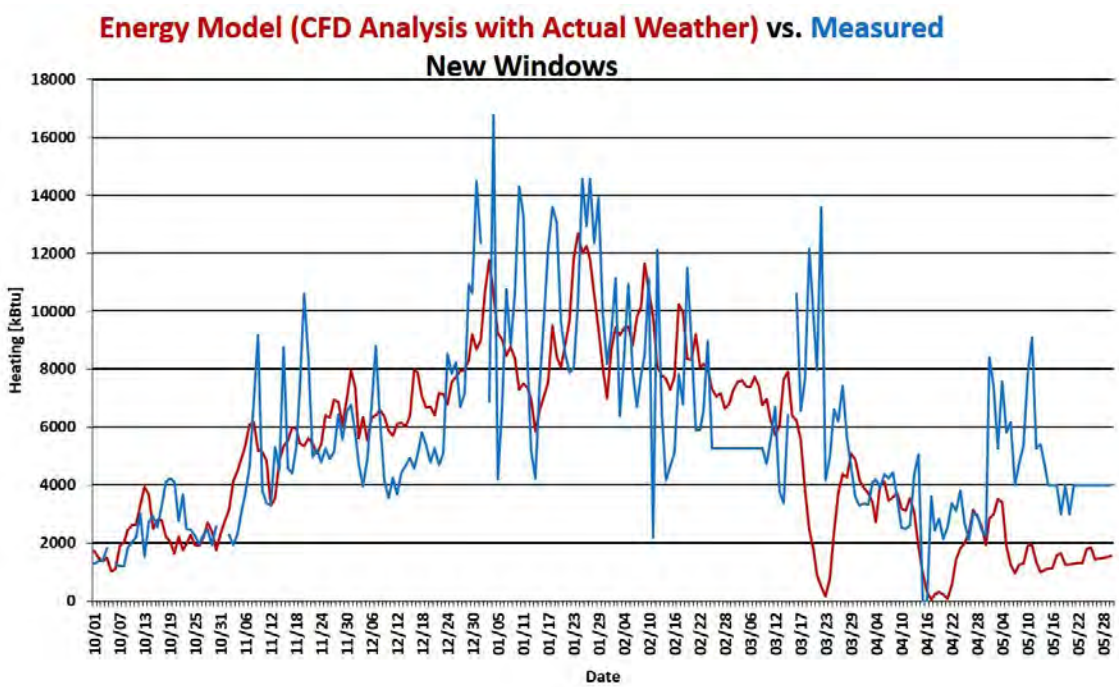

Figure 5: Heating Loads from Energy Model and Measured (New Windows)

Our review of the submetered data showed the following trends:

- Replacing the windows resulted in an 18% reduction in heating load after the window replacement project (normalized by heating degree day) with the average winter temperature of 42°F (pre-window replacement in 2011/2012) compared to 39°F (post-window replacement in 2012/2013). This was due to an overall reduction in uncontrolled air leakage through the building enclosure.

- The air leakage reduction improved thermal comfort for occupants and allowed the heating system to more closely control temperature setpoints, particularly during cold weather (Figure 6). SPS reported that occupants no longer requested clear plastic to cover their windows during the winter.
- Replacing the windows showed a 17% reduction in electrical consumption, primarily due to the discontinued use of supplemental electric radiators during the winter.

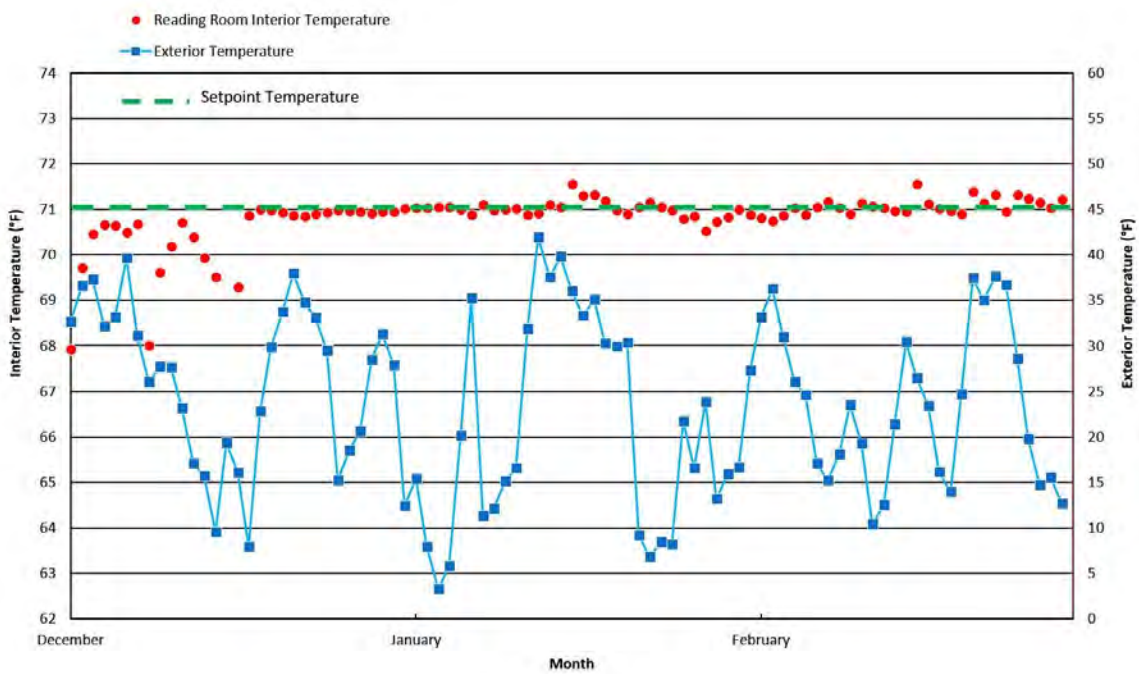

Figure 6: Interior versus Exterior Temperature (New Windows)

CONCLUSION

Our case study shows that whole-building energy models utilizing VWT, an EnergyPlus™ Airflow Network, and local weather files can be effective at predicting heating loads for a relatively simple building and mechanical system. Occupancy behavior impacted the accuracy of our simulations due to the operability of the windows. More simulation and correlation of energy models and existing buildings with measured airtightness is necessary, particularly for buildings with forced air heating and cooling systems and outdoor ventilation air, to understand the accuracy of the model predictions. The authors are currently conducting research on an 86,000 sq. ft. building located in the northeast United States that utilizes forced air heating and cooling systems in a building with eighty zones.

REFERENCES

Lyon, E.G., and Saldanha, C.M. 2016. Integrating whole building air leakage test data into EnergyPlus infiltration models. ASHRAE and IBPSA-USA SimBuilding 2016, Salt Lake City, Utah, 8–12 August 2016.