**Title**

Benchmarking and Equipment and Controls Assessment for a 'Big Box' Retail Chain

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# Benchmarking and Equipment and Controls Assessment for a 'Big Box' Retail Chain

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## ABSTRACT

The paper describes work to enable improved energy performance of existing and new retail stores belonging to a national chain and thereby also identify measures and tools that would improve the performance of 'big box' stores generally. A detailed energy simulation model of a standard store design was developed and used to:

- demonstrate the benefits of benchmarking the energy performance of retail stores of relatively standard design using baselines derived from simulation,
- identify cost-effective improvements in the efficiency of components to be incorporated in the next design cycle,
- use simulation to identify potential control strategy improvements that could be adopted in all stores, improving operational efficiency.

The core enabling task of the project was to develop an energy model of the current standard design using the EnergyPlus simulation program. For the purpose of verification of the model against actual utility bills, the model was reconfigured to represent twelve existing stores (seven relatively new stores and five older stores) in different US climates and simulations were performed using weather data obtained from the National Weather Service. The results of this exercise, which showed generally good agreement between predicted and measured total energy use, suggest that dynamic benchmarking based on energy simulation would be an effective tool for identifying operational problems that affect whole building energy use.

The models of the seven newer stores were then configured with manufacturers' performance data for the equipment specified in the current design and used to assess the energy and cost benefits of increasing the efficiency of selected HVAC, lighting and envelope components. The greatest potential for cost-effective energy savings appears to be a substantial increase in the efficiency of the blowers in the roof top units and improvements in the efficiency of the lighting. The energy benefits of economizers on the roof-top units were analyzed and found to be very sensitive to the operation of the exhaust fans used to control building pressurization.

## Introduction

The goal of the project that included the work reported here was to enable improved performance of existing and new retail stores belonging to a national chain by identifying beneficial new technology, tools and operating practices and demonstrating their benefits in selected stores. The objectives established at the beginning of the project included:

- demonstration of the benefits of benchmarking the energy performance of retail stores using baselines derived from simulation,
- identification of cost-effective improvements in the efficiency of components for the next design cycle, resulting in lower life-cycle costs,
- identification of potential control strategy improvements that could be adopted in all stores, improving operational efficiency.

The core enabling task of the project was to develop an energy model of the chain's dominant store design using the EnergyPlus simulation program developed and distributed by the US Department of Energy [Crawley *et al.* 2001]. The model was based on the design documentation for a specific, recently constructed store that adheres closely to the current standard store design. It is single-level building of approximately 125,000 ft$^2$ which includes a sales floor, stock/storage areas, and office/support space. The building includes a food service component and a small grocery component made up of enclosed refrigerated cases. Refrigeration is provided by independent compressor/condenser units located on roof. Modeled store hours are 8 am to 10 pm. The HVAC system is made up of individual commercial rooftop constant air volume DX cooling units with gas heat. Lighting is florescent on the sales floor, recessed in a suspended ceiling, and outside of the sales floor the lighting is typically controlled by motion sensors. Lighting is reduced and temperature is set back during overnight hours. Parking lot lighting is included in the energy model.

The production of the standard store model required some custom modifications to EnergyPlus, particularly for the heating, cooling and economizer controls, in order to more closely capture the controls sequences for the stores. Much effort went into modeling the rooftop units accurately, including the development of part-load efficiency curves for the units from catalog data from the manufacturers. Significant effort also went into the modeling of the refrigeration systems. In particular, the compressors for the medium temperature and low temperature refrigerated cases share a common condenser, since this configuration is not currently modeled explicitly by EnergyPlus, an equivalent system with separate condensers was designed and modeled, based on catalog data. Case credits were taken from manufacturers' data.

The standard store model served as a starting point for two different sets of models:

- a set of twelve models of existing stores, seven of which are in representative locations in seven US climate zones and were constructed within the last five years. The other five stores were built over twenty years ago and show significant variations in floor area and mechanical equipment.
- a set of seven models whose envelope characteristics and HVAC equipment sizing had been selected based on current design practice for the same seven representative locations

The next section presents the results of comparing the simulated electricity and gas consumption and the simulated peak electrical demand to utility bill data for the twelve existing stores, using weather and utility data for 2006. The two objectives of performing these comparisons were to verify the EnergyPlus model and to assess the potential of simulation-based benchmarking to identify degradation in energy performance at relatively low cost. Because of the latter objective, no explicit calibration of simulation models was performed. Systematic differences between measured and predicted performance that were common to all seven of the newer stores were used to prompt closer examination of the miscellaneous equipment installed in all stores. No changes were made to models of individual stores in order to reconcile measured and predicted performance, nor were any changes made to the generic store model that did not reflect design information or catalog data.

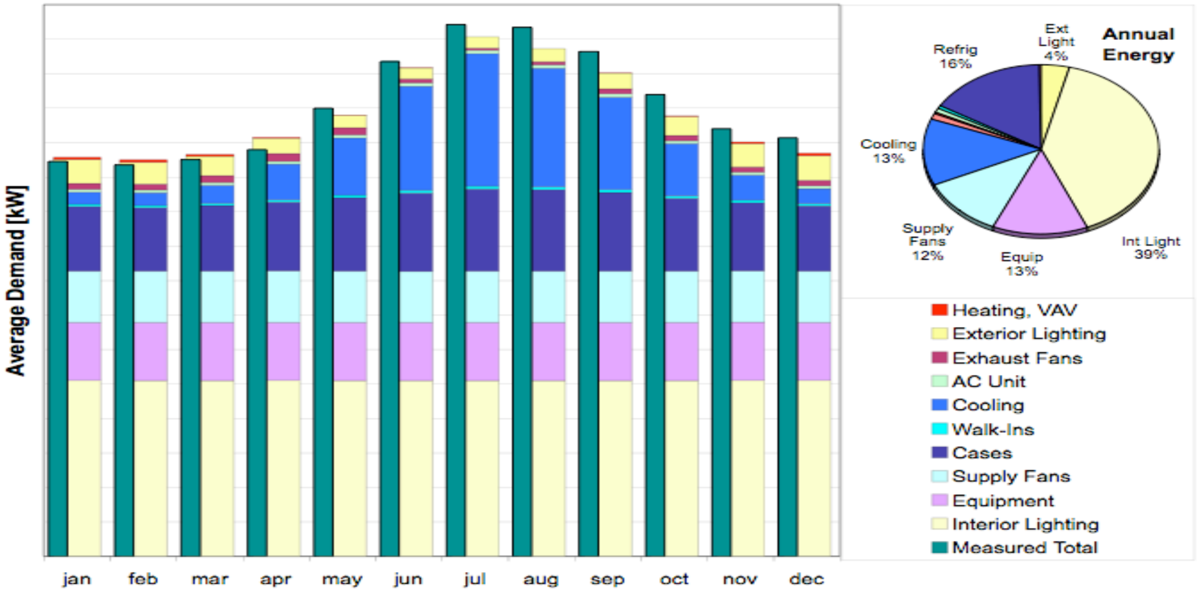
The remainder of the paper presents an analysis of the predicted benefits of improving the efficiency of selected HVAC, envelope and lighting components. The benefits of economizer operation are examined in some detail, with particular regard to the effect of the exhaust fans commonly used on roof top air-conditioning units.

## Model-Based Benchmarking

A comparison between the predictions of the EnergyPlus models of twelve stores and utility billing data was performed in order to provide a test of the model and as the first phase of the model-based benchmarking exercise. The initial model was reconfigured to represent twelve existing stores in different US climates, including the roof and wall insulation and the sizing and part load characteristics of the roof top units installed in those stores. Weather data were obtained from the National Weather Service (with total solar and the direct/diffuse split derived using the methods of Zhang and Huang [Zhang et al, 2002] and Watanabe [see Krarti and Seo, 2007]) and simulations were performed for twelve consecutive billing periods during the period 12/1/05 to 1/31/07. As indicated in Table 1b, the floor areas of some of the older stores differ from the floor area of the current stores. In comparing measured and predicted performance, it was assumed that all loads would scale with floor area, except for the conduction heat flow through the walls. The U-value of the walls in the model was adjusted so that the simulated heat flow would be proportional to the floor area rather than with the wall area.

Figure 1 shows the average measured and simulated electrical consumption for the seven newer stores, with the simulated consumption broken out by end use. Lighting is the largest electrical end use, and cooling, ventilation, plug loads and refrigeration split most of the remainder.

**Figure 1. Simulated End-Use Percentages for the Average of Seven Stores**



The annual results for electricity consumption and peak demand for the seven relatively new stores are summarized in Table 1a, and the five older stores in Table 1b. The measured consumptions and peak demands have been normalized to those of the Seattle store, since utility costs are sensitive information in the retail sector. In the case of the older stores, the normalization also includes the floor area. The general level of agreement between the simulated and measured is very good, particularly since the actual exterior lighting level at each store was unknown and a typical value was assumed for all stores. On average, for the newer stores, the predicted peak electricity demand exceeds the measured, while the predicted electricity use is less than the measured. This difference corresponds to the hours of use being underestimated in the model; however, there is no evidence that this is the actual cause of the difference and this trend is reversed in the older stores. End use monitoring in stores displaying this difference would be required to produce a definitive explanation. The designs of the newer stores are very similar to the current store design, but the older stores tend to differ from the current ones, not only with respect to their floor area, which has been corrected for, but in the miscellaneous equipment installed. It is to be expected that new stores would have a closer match to utility data than older stores.

**Table 1a. Simulation Results vs. Utility Data – Electricity, Newer Stores**

| | Electricity Consumption, Annual | | Peak Electric Demand, Annual | |
|---|---|---|---|---|
| Location | Normalized Measured | Simulated vs Measured | Normalized Measured | Simulated vs Measured |
| Chicago | 1.08 | 1.8% | 1.11 | 10.3% |
| Forth Worth | 1.34 | -1.0% | 1.50 | 1.6% |
| Phoenix | 1.43 | -6.6% | 1.44 | 1.3% |
| Seattle | 1 | 2.8% | 1 | 11.5% |
| Pasadena | 1.37 | -6.1% | 1.48 | -1.0% |
| New York | 1.09 | 2.0% | 1.17 | 5.5% |
| Tampa | 1.37 | 0.0% | 1.49 | -3.1% |
| *Average* | *1.24* | *-1.0%* | *1.31* | *3.7%* |

**Table 1b. Simulation Results vs. Utility Data – Electricity, Older Stores**

| | | Electricity, Annual [kWh] | | Peak Electric Demand, Annual [kW] | |
|---|---|---|---|---|---|
| Location | Floor Area rel. to Current | Normalized Measured | Simulated vs Measured | Normalized Measured | Simulated vs Measured |
| Denver | 93.6% | 1.27 | -17.3% | 1.06 | -11.7% |
| St Louis | 89.9% | 0.99 | 7.1% | 1.09 | -2.3% |
| Wyoming | 65.9% | 0.83 | -12.5% | 0.51 | -40.9% |
| Montana | 83.4% | 1.13 | -19.2% | 0.85 | -29.9% |
| Omaha | 90.7% | 1.18 | -12.7% | 1.05 | -11.9% |
| *Average* | *84.7%* | *1.08* | *-10.9%* | *0.91* | *-19.4%* |

The results for gas consumption are summarized in Table 2, which shows that while the fractional differences between the simulated and measured annual consumptions are much greater, the absolute differences are typically less than the differences in electricity consumption.

The ‘Total Source’ in this table was derived using a 3:1 site to source conversion for electricity relative to natural gas. Leaving aside the large positive difference for New York, which appears to be due to a billing problem, the range of differences (relative to the total source energy) is generally smaller than the range of differences in electricity consumption. The large fractional differences in gas consumption arise because the space heating load, which is the only gas load, is the relatively small difference between the ventilation and conduction heat loss rates and the internal heat gains. One source of uncertainty in the predictions of both the gas and the electricity consumptions is the actual minimum ventilation rates, which depend on the quality of the test and balancing performed when the roof top units were installed. However, if the minimum ventilation rates at a particular store were systematically high or low, the corresponding electricity consumption during the summer and gas consumption during the winter would both be high or low, respectively. This pattern is not seen in the annual data for the six stores (excluding New York), implying that variations in actual minimum ventilation rate, averaged over all the roof top units in the store, is not a major contributor to the difference between simulated and measured consumptions. However, it would be worth looking for this pattern in a larger sample of stores. Although the results suggest that the average minimum ventilation rate used in these simulations is appropriate, they do suggest particular cases where the simulated and actual rates may differ – e.g. the unexpected difference in measured gas consumption between Seattle and Chicago may be a result of minimum ventilation rates that differ from the simulated values.

**Table 2a. Simulation Results vs Utility Data – Gas, Annual [therms], Newer Stores**

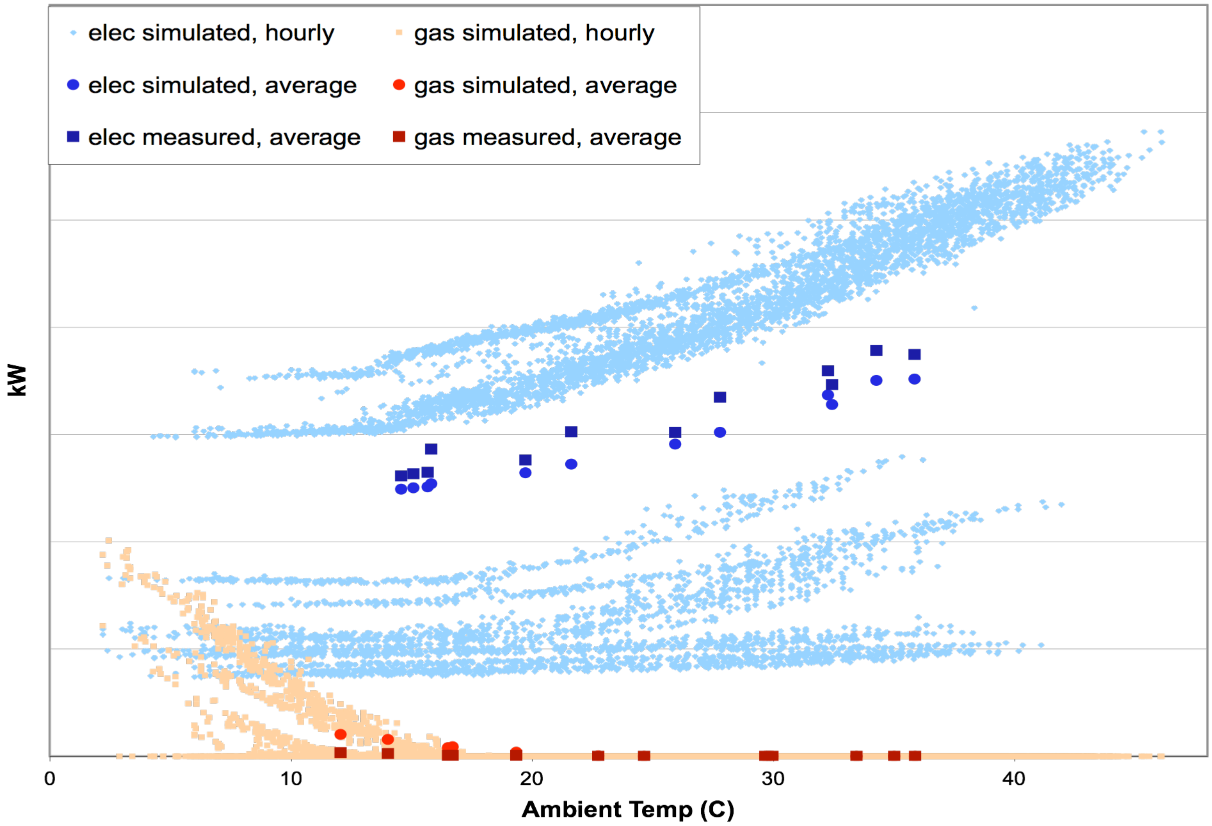
| Location | Normalized Measured | Simulated vs Measured | Difference rel. to Total Source Energy |
|---|---|---|---|
| Chicago | 0.73 | 50.0% | 2.29% |
| Forth Worth | 0.16 | 258.3% | 2.19% |
| Phoenix | 0.02 | 505.4% | 0.45% |
| Seattle | 1 | -0.7% | -0.05% |
| Pasadena | 0.25 | 87.1% | 1.09% |
| New York | 1.97 | -54.8% | -6.23% |
| Tampa | 0.01 | 264.5% | 0.14% |
| *Average* | *0.59* | *158.6%* | *-0.02%* |

**Table 2b. Simulation Results vs Utility Data – Gas, Annual [therms], Older Stores**

| Location | Floor Area rel. to Current | Normalized Measured | Simulated vs Measured | Difference rel. to Total Source Energy |
|---|---|---|---|---|
| Denver | 93.6% | 1.39 | -54.3% | -3.9% |
| St Louis | 89.9% | 1.17 | -21.4% | -1.7% |
| Wyoming | 65.9% | 1.65 | -39.3% | -4.9% |
| Montana | 83.4% | 1.17 | -39.3% | -2.7% |
| Omaha | 90.7% | 1.37 | -76.4% | -5.8% |
| *Average* | *84.7%* | *1.35* | *-46.2%* | *-3.8%* |

Figure 2 shows the variation of hourly electricity and gas consumption *vs.*outside air temperature for one store, located near Chicago. The darker points represent monthly averages of both the simulated and the measured consumption, and the lighter points represent the hourly simulation results. For the hourly electrical points, the upper band represents consumption during occupied hours, the lower bands correspond to periods when the lights are off but the HVAC is operating, and the almost horizontal band at the bottom corresponds to periods when only the refrigeration systems are operating. The upper band in the simulated hourly gas consumption represents consumption when the HVAC is operating but the lights are off and the lower band corresponds to periods when the lights are on. Hourly measured data for a full year are not yet available for any stores but the detail evident in the simulated hourly values suggests that a comparison of simulated and measured hourly values over a period of days to months could be a powerful aid to diagnosing energy performance problems.

**Figure 2. Energy Consumption, in arbitrary units, vs. Outside Air Temperature**



## Component Efficiency Studies

The EnergyPlus models of the seven newer stores used in the previous section were reconfigured to correspond to the new store designs. Sensitivity studies were then performed to assess the energy and utility cost benefits of selected improvements in component efficiencies. The efficiency improvements considered were:

- RTU compressor efficiency: +10% and +15%
- RTU supply fan efficiency: +15% and +30%
- RTU condenser fan efficiency: +15% and +30%
- Lighting power density: -10% and -20%
- Roof insulation: +R-4 and +R-8
- Wall insulation: +R-2 and +R-4

Average results for the seven stores are shown in Table 3. The predicted savings from improvements in lighting power density reflect the relative magnitude of the lighting. The much smaller efficiency gains predicted for insulation improvements reflect both the core-dominated nature of the loads and the diminishing returns from insulation. Of the efficiency improvements considered for the roof-top units, improvement of the supply fan efficiency is predicted to produce the most energy savings and is also likely to be the most cost-effective measure. The additional gas consumption results from a decrease in the heat produced by a more efficient fan.

**Table 3. Average Savings from Component Efficiency Improvements**

| | | Annual Energy Savings | | Estimated $ Savings |
|---|---|---|---|---|
| | | Electricity | Gas | Total |
| Compressor Efficiency | 10% | 1.00% | - | 0.98% |
| | 15% | 1.38% | - | 1.36% |
| Condenser Fan Efficiency | 15% | 0.11% | - | 0.11% |
| | 30% | 0.22% | - | 0.22% |
| Supply Fan Efficiency | 15% | 1.78% | -3.63% | 1.62% |
| | 30% | 3.15% | -6.51% | 2.86% |
| Lighting Power Density | -10% | 4.60% | -7.84% | 4.02% |
| | -20% | 9.19% | -16.22% | 8.01% |
| Roof Insulation | increase R-4 | 0.15% | 5.67% | 0.32% |
| | increase R-8 | 0.25% | 9.78% | 0.56% |
| Wall Insulation | increase R-2 | 0.05% | 3.35% | 0.13% |
| | increase R-4 | 0.07% | 5.24% | 0.20% |

Location-specific savings are shown for lighting power density in Table 4, and for supply fan efficiency in Table 5. The lighting savings are fairly constant across locations, with small variations due to the effects on heating and cooling loads. The greater regional variation of percentage savings with fan efficiency improvements is due both to the fan size differences and to the fact that the ventilation consumption is generally much smaller than the lighting consumption in these buildings.

**Table 4. Savings from a 20% Decrease in Lighting Power Density**

| Location | Annual Energy Savings | | Estimated $ Savings |
|---|---|---|---|
| | Electricity | Gas | Total |
| Chicago | 9.65% | -14.24% | 6.93% |
| Forth Worth | 8.77% | -13.86% | 8.36% |
| Phoenix | 8.92% | -17.70% | 8.56% |
| Seattle | 10.09% | -20.91% | 7.64% |
| Pasadena | 8.86% | -14.69% | 8.57% |
| New York | 9.59% | -17.28% | 6.63% |
| Tampa | 8.74% | -14.89% | 8.63% |
| *Average* | *9.19%* | *-16.22%* | *8.01%* |

**Table 5. Savings from a 30% Increase in Supply Fan Efficiency**

| Location | Annual Energy Savings | | Estimated $ Savings |
|---|---|---|---|
| | Electricity | Gas | Total |
| Chicago | 2.53% | -4.62% | 1.74% |
| Forth Worth | 3.21% | -6.41% | 3.04% |
| Phoenix | 3.30% | -11.64% | 3.10% |
| Seattle | 2.06% | -5.68% | 1.46% |
| Pasadena | 4.39% | -11.44% | 4.20% |
| New York | 2.69% | -6.07% | 1.70% |
| Tampa | 3.49% | -12.23% | 3.42% |
| *Average* | *3.15%* | *-6.51%* | *2.86%* |

## Control Strategy Improvements

### Zone Temperature Set-point Modifications

Table 6 shows the predicted savings from increasing the occupied cooling set-point by $2^{o}$F to $76^{o}$F and decreasing the occupied heating set-point by $2^{o}$F to $68^{o}$F. The annual savings are in the range of 1-3% of energy costs. The application of a similar $4^{o}$F modification (not shown here) resulted in savings in the range of 2-4% of energy costs. One possible source of some part of these savings could be a reduction in simultaneous heating and cooling due to a widening of the thermostat dead-band. However, analysis of the hourly heating coil and compressor energy consumptions for normal set-points in the Chicago store indicated negligible simultaneous heating and cooling between all of the sixteen RTU's, including reheat for the zones served by the VAV system. Since the Chicago climate spans a wide range of ambient temperatures, both high and low, this suggests that simultaneous heating and cooling is unlikely to be a significant problem in any climate and hence very little benefit would be likely to result from extending the RTU control strategy to inhibit simultaneous heating and cooling between adjacent units. This assumes that the combined thermostat calibration errors of adjacent units are less than the $4^{o}$F dead-band between heating and compressor cooling. If/when this is not the case, interzone mixing will give rise to substantial simultaneous heating and cooling.

**Table 6. Energy Savings with a 2°F zone temperature set-point modification**

| Location | Annual Energy Consumption | | Estimated $ Savings |
|---|---|---|---|
| | Electricity | Gas | Total |
| Chicago | 1.05% | 20.83% | 2.76% |
| Forth Worth | 1.84% | 29.76% | 1.95% |
| Phoenix | 1.54% | 46.84% | 1.62% |
| Seattle | 0.96% | 33.07% | 3.19% |
| Pasadena | 1.63% | 43.00% | 1.88% |
| New York | 1.02% | 25.62% | 2.43% |
| Tampa | 1.84% | 41.85% | 1.88% |
| *Average* | *1.44%* | *29.13%* | *2.26%* |

## Optimizing Minimum Outside Air Flow Rates

Table 7 provides an indication of the benefits expected from an engineered ventilation system if acceptable air quality can be maintained using 50% of the ventilation rate for the sales floor, relative to the design value of approximately 0.15 $cfm/ft^2$ (by floor area).

**Table 7. Energy Savings with a 50% reduction in outside air flow rates**

| Location | Annual Energy Consumption | | Estimated $ Savings |
|---|---|---|---|
| | Electricity | Gas | Total |
| Chicago | 0.52% | 58.43% | 5.67% |
| Forth Worth | 3.42% | 62.94% | 3.67% |
| Phoenix | 1.62% | 56.41% | 1.72% |
| Seattle | -0.04% | 59.05% | 4.10% |
| Pasadena | 0.35% | 66.94% | 0.77% |
| New York | 0.50% | 60.90% | 4.01% |
| Tampa | 2.29% | 49.25% | 2.34% |
| *Average* | *1.31%* | *60.42%* | *3.24%* |

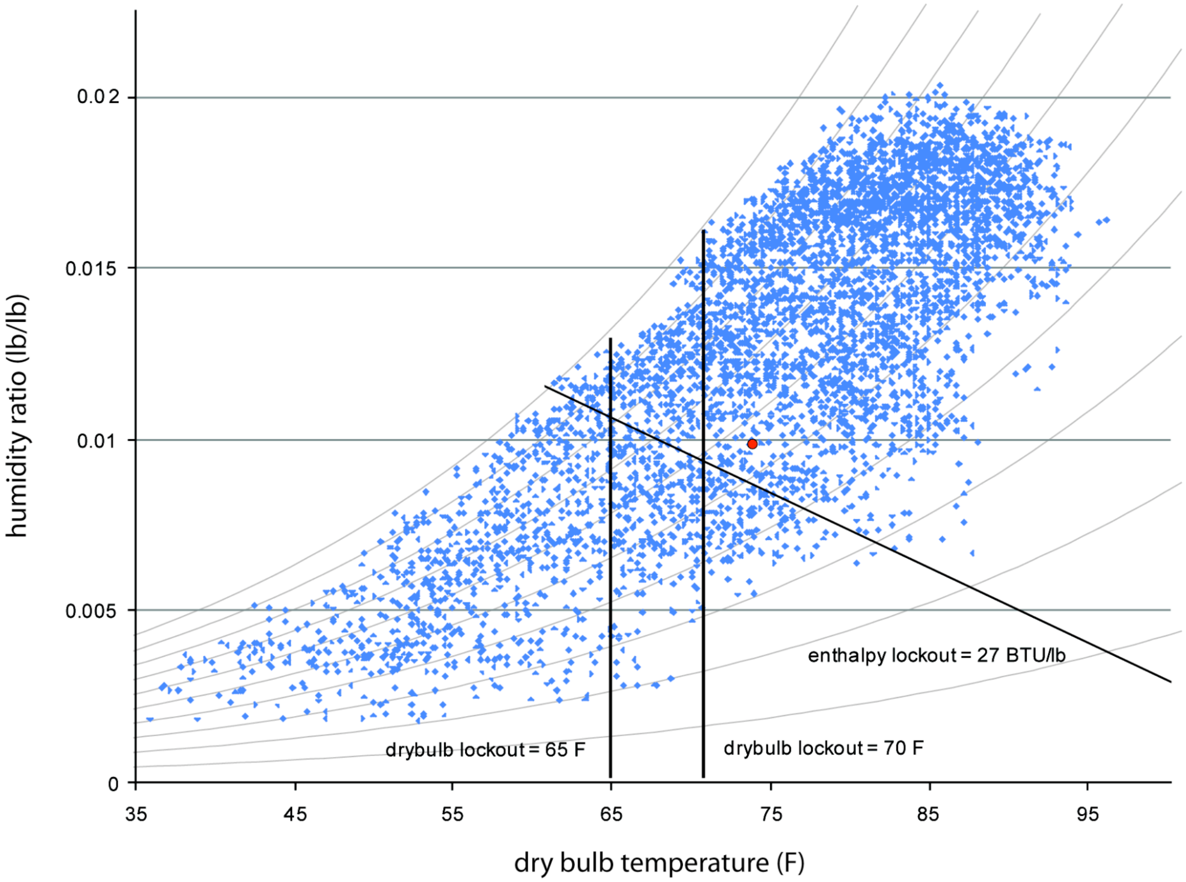
## Economizer Operations

Figure 3 shows the hourly weather data during occupied hours for Tampa, FL, selected for its humid climate, plotted on a psychrometric chart. The buildings are currently operating with an economizer lockout of 65°F. As suggested by Figure 3, increasing the lockout temperature to 70°F could capture many more hours of ‘free’ cooling. Note that the red dot in Figure 3 is the temperature and humidity set-point for the sales floor. The resulting savings are shown in Table 8. (The small increase in heating energy consumption is because of the lower temperature set-point with ‘free’ cooling – 72°F in ‘free’ cooling mode vs. 74°F in ‘pay’ cooling mode – which results in greater need for nighttime heating because of thermal storage, primarily in the floor slab. This difference in set-point is a consequence of the staged thermostat control used for the roof top units.)

**Table 8. Savings from Increasing the Economizer Lockout Temp from 65°F to 70°F**

| Location | Annual Energy Consumption | | Estimated $ Savings |
|---|---|---|---|
| | Electricity | Gas | Total |
| Chicago | 0.11% | -0.01% | 0.09% |
| Forth Worth | 0.13% | -0.04% | 0.13% |
| Phoenix | 0.26% | -0.45% | 0.25% |
| Seattle | 0.20% | -0.04% | 0.19% |
| Pasadena | 0.41% | -0.20% | 0.40% |
| New York | 0.13% | -0.01% | 0.13% |
| Tampa | 0.12% | -0.18% | 0.12% |
| *Average* | *0.20%* | *-0.06%* | *0.20%* |

**Figure 3. Economizer operation for Tampa Bay**



The savings are somewhat less than was expected, due in part to the operation of exhaust fans in the rooftop units. The exhaust fans run when the outside and exhaust air dampers are more than 50% open in order to avoid over-pressurization of the occupied space. As a result, the fan energy consumption increases with increasing economizer lockout temperature, partly offsetting the savings in cooling energy. Table 9 shows the breakdown of cooling savings and exhaust fan energy increases for the seven stores, with the 70°F economizer lockout. The 'savings relative to the base case end uses' (i.e. the percentage of the cooling end-use pie slice that is saved) show that this strategy can save a very significant portion of the cooling energy in some climates, and the 'savings relative to the base case total' show that approximately one half of the savings in cooling are offset by increased exhaust fan use.

**Table 9. Savings from Eliminating Exhaust Fan Energy Consumption**

| Location | Energy Savings (rel. to base case total) | | Energy Savings (rel. to base case end uses) | |
|---|---|---|---|---|
| | Cooling | Exhaust Fans | Cooling | Exhaust Fans |
| Chicago | 0.24% | -0.12% | 4.2% | -49.1% |
| Forth Worth | 0.27% | -0.12% | 2.0% | -15.7% |
| Phoenix | 0.50% | -0.24% | 3.3% | -102.0% |
| Seattle | 0.42% | -0.20% | 17.9% | -44.9% |
| Pasadena | 0.76% | -0.33% | 9.9% | -77.9% |
| New York | 0.31% | -0.14% | 5.4% | -52.4% |
| Tampa | 0.27% | -0.12% | 1.6% | -80.2% |
| *Average* | *0.39%* | *-0.18%* | *6.3%* | *-60.3%* |

## Conclusions

The good agreement between predicted and measured electricity consumption in the newer stores suggests that simulation models of standard store designs can be expected to provide a good basis for dynamic benchmarking of retail stores. Big box retail stores are particularly suitable for this application because their relatively small glazing areas make their simulated performance insensitive to errors in estimating insolation from National Weather Service measurements. Comparison of interval meter electricity data with time series simulation results should add to the diagnostic potential of the approach and is worth investigating. The significant differences in predicted and measured gas consumption, while explicable in terms of the uncertainties in the overall heat balance, given the relatively small heating loads, are worth further investigation to validate the model and better understand store operation.

The efficiency studies with this EnergyPlus model have also proven useful in the analysis of possible improvements in component efficiencies for future store designs. In particular, supply fan efficiency increases and lighting power density decreases were found to offer the greatest potential for cost-effective energy savings. The model has also been used in the investigation of control changes to the operational efficiency of both existing and future stores. In particular, it showed that exhaust fan operation has been offsetting much of the potential energy benefits of economizer operation and provides a tool for the analysis of possible changes to improve economizer operation, along with other aspects of building performance.

## Acknowledgements

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