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Airflow Based Model to Estimate Commercial Building HVAC Energy Use: Analysis to determine principal factors for different climate zones

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ABSTRACT

This paper presents an airflow based modeling method to estimate HVAC energy consumption in large commercial office buildings. The model was developed by analyzing operational data from building automation system, relating load profiles and efficiency of key HVAC equipment, based on economizer control policies that determine outside and return airflow rates. The model predicts annual energy use for buildings HVAC loads based on hourly climate data (temperature and relative humidity), and building airflow requirements. The model determines HVAC energy use in terms of building airflow rates for systems utilizing central air handler units with economizers, and identifies the key consumption drivers. Some parts of the model (economizer performance and fan energy use) were based on data collected from the building automation system, relating major component energy use in terms of airflow rates and control laws. Data was obtained for three commercial scale office-lab buildings at Boston University. Results are given in terms of major contributors to HVAC energy use and cost in terms of heating, cooling, and fan motor power for 4 different US cities. A comparison to the building HVAC model used to disaggregate CBECs data is presented.

1. INTRODUCTION

In medium to large commercial office buildings heating, ventilation and air conditioning (HVAC) systems typically accounts for a large portion of the building energy usage of which typically a third goes to driving the ventilation fans. Historically in the United States this category of buildings have been designed with high minimum air-flow rate set-points that are greater than that needed for ventilation. Among CBECS ((EIA, 2012)) building stock for offices over 100,000 sq.ft. there are 18,541 buildings (0.3% of total number of buildings) with total building area of 5.33 billion sq.ft. (7.4% of total building stock sq.ft.) which means improving efficiency of few buildings can have a relatively large impact in terms of energy savings. It is important to reveal how much actual energy is invested in this class of buildings and identify the key consumption drivers.

Pushing air through buildings round-the-clock turns out to be a major contributor and it is not only related to the fan energy required to transport the air but also the required energy to condition (heat and/or cool). An essential part of studying this phenomena is to be able to, for a particular building or project, predict the energy usage. For example when considering airflow rate reductions the prediction model has to be able to assess the energy requirements of each cubic feet of air that needs to be transported through the building. Consequently a model centered around airflow rates has the potential to be more simple and more suitable than a model based on the whole building energy balances. Additionally it makes it possible to quantify where the major cost drivers for HVAC systems in commercial buildings come from.

From an engineering point of view what determines HVAC energy use is 1) airflow rate 2) equipment efficiency 3) how the air is being used (conditioning). Many of the detailed prediction methods available in literature focus on building energy balances to realize the heating and cooling needs while assuming ventilation requirements proposed by standards. This makes them not suitable to estimate savings based on actual airflows rates. Many of the statistical regression models have the potential to base their equipment sub-models fully or partly on measured operating data but typically do not. These consideration were the main motivation to develop an airflow-driven model that could predict energy consumption of HVAC systems. The model methodology is restricted to modern buildings with AHU, central heating/cooling and can accommodate an economizer. This fits with some medium sized and most large sized commercial buildings. The method should give a conservative estimate of the energy use since it ignores energy losses from air infiltration and external heat gain (people, lights, equipment, solar, etc.). For this reason the level of accuracy should be highest in larger buildings where energy consumed for conditioning air flow is much higher than the buildings losses and external loads.

Zhao and Magoules (Zhao & Magoules, 2012) present an extensive review of different models and distinguish between engineering methods, statistical methods and artificial intelligence methods. The methods in the first group have in common that they are based on physical principles to calculate thermal dynamics and resulting energy usage for the whole building and many have the option to do a breakdown to sub-level components. Sometimes the detailed simulation are only used as benchmarks or complimented by model calibration (see (Yik, Burnett, & Prescott, 2001) (Pan, Huang, Wu, & Chen, 2008) and (Fumo, Mago, & Luck, 2010)). Using these methods typically requires an extensive knowledge of the building being studied, both structurally but also the type and rated performance of installed equipment.

Statistical regression models are based on correlating the output (energy consumption, cooling requirement, etc.) with a set of selected influencing variables (see (Chirarattananon & Taveekun, 2004) and (Catalina, Virgone, & Blanco, 2008)). Some of the variables are constant for a particular building but also historical data is essential which includes at least the relevant climate information. A balance between model complexity (number of variables) and model accuracy has to be selected based on level of usage. The most extensive statistical regression surveys related to commercial building energy usage in the U.S. is the Commercial Buildings Energy Consumption Survey (CBECS). CBECS is a national survey that collects information of commercial buildings, including energy-related building characteristics and energy use. The first survey was done in 1979 and the tenth and most recent in 2013 (for calendar year 2012). As part of the 2003 survey ((EIA, 2012)) an end-use energy consumption (EUC) regression models were developed ((KEMA, 2012)). Eight submodels, each covering different part of the building, are either analyzed independently or added to get estimates of the total building energy consumption. The model data are made available to the public through tables, reports and data files.

The third group includes high level learning algorithms (such as artificial neural networks (ANN) or support vector machines (SVM)) which based on historical data try to ”learn” the dynamical behavior of the desired output such as (Neto & Fiorelli, 2008).

Among CBECS 2012 building stock 35% of building sized over 100,000 sq.ft. have central HVAC systems in place. Central systems typically use chilled water as cooling medium and has three major components: air-handling unit(s) (AHU), chilled water plant (chiller) and a boiler plant. The AHU conditions and supplies air to the conditioned building space and can be equipped with or without an airside economizer. By measuring climate conditions and applying a control policy an economizer allows the ventilation system to reduce or eliminate needed cooling when weather is mild and cold. Figure 1 shows the main components of an economizer based AHU where return air mixes with outside air before it is conditioned using heating and/or cooling coils. The hot and cold water flowing inside the coils comes from the chillers and boilers, respectively. End-use estimates from CBECS 2003 indicate that 38% of total energy use in large (> 100k) office buildings is related to HVAC which is equivalent to 33.2 mBtu per each sq.ft. of building space.

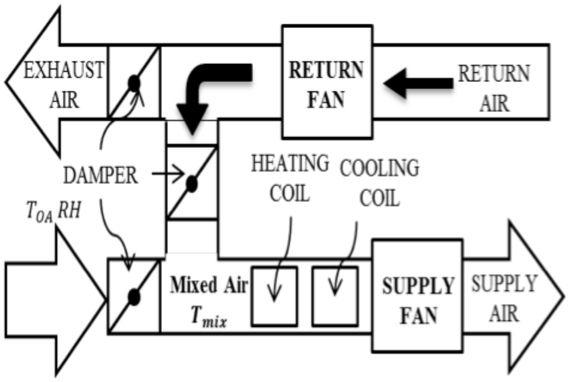


Figure 1: AHU with airside economizers main compoenents

To model the energy consumption and related costs we determine how a buildings total annual HVAC energy use is driven by: a) outside air condition (both temperature and relative humidity) b) the amount of air used c) the economizer control policy (determining the mix of return air in a building with outside air) d) the energy as a function of cubic-feet-per-minute (CFM) of airflow models for fans, chillers and boilers. Based on the climate data and the building CFM demand the economizer control policy determines the amount of outside air (OA) needed. Knowing the mixing temperature set-point allows for the estimation of heating and cooling requirements for the two airstreams. Component models to transform cooling, heating and airflow demand to actual energy consumption are obtained by correlating physical information with measured data from the building automation system (BAS). Data collection from airflow experiments were done on three commercial scale office-lab buildings at Boston University to verify the model.

2. HVAC BUILDING ENERGY MODEL

Based on climate data the economizer control policy sets the heating/cooling requirements as well as the necessary airflow outside air ratio. These results are inputted into the three demand component models for 1) fans 2) cooling plant 3) boiler plant. Each of these models were developed based on data obtained from detailed BAS logging and provide predictions of daily energy use. This ensures that the models are firmly based on operational data and not just equipment specifications. This is important in buildings since part load conditions are common for many of the different equipment and the performance is normally not well documented from the equipment manufacturers. The energy component models were developed for electricity use by AHU and chillers, and natural gas use for boilers. The fan component model receives special attention since it turns out that half of the total yearly HVAC cost is related to running the fans. This stems from the fact that the fans are always on but heating and cooling is only necessary for parts of the year.

2.1 Climate Data and Airflow Energy Content

As mentioned the AHU conditions and supplies air to the building by either using air from outside or from within the building through the return system. What determines the ratio of outside air to return air and level of conditioning is the outside temperature. The energy content of air has a sensible and a latent part. The sensible part (h_s) is only based on temperature and defines the required amount (BTU/hr) of heating or cooling of air:

$$h_s = 1.08Q\Delta T \tag{1}$$

where Q is the air volume flow in cubic feet per minute (CFM) and ΔT is the temperature difference in degrees Fahrenheit. The latent part represents the required energy to condensate the added moisture defined by the relative humidity. The relationship between latent energy content, temperature and relative humidity can be found from psychometric charts or empirical models.

Figure 2 shows how significant the amount of the latent heat energy required is by normalizing the amount of energy required to condensate moisture above a 50% threshold over the sensible heat required to cool from the climate temperature to the HVAC set point (usually $55°F$). For example at 60% humidity and $90°F$ the latent energy is two times that of the sensible heat at that temperature difference.

Figure 3 shows local climate data for Boston in 2010 on a yearly basis. Three switching temperatures, explained further next section, are shown in the figure as horizontal red lines which correspond to the temperatures that the economizer switches and varies the ratios of outside and return air to minimize to chiller energy usage.

It is apparent that relative humidity has a large range of variation over all seasons which indicates that substantial latent heat energy does not necessarily have to be related to the hottest summer days. These variations make it hard to estimate the total daily energy content without having hourly measurements of both variables. As an example of this nonlinearity climate data for a single day (July 21) is presented in Figure 4. It shows how the relative humidity is high overnight and drops as soon as the temperature starts to rise in the morning. If, for this particular day, we were to use daily average temperature and relative humidity to estimate the energy content in the airstream we would overestimate it by 40%. In contrast the CBECS 2003 end-use estimates ((KEMA, 2012)) for cooling accounts for the latent heat by using a multiplication factor (1.70) which is directly proportional to the total cooling energy end-use. These three observations motivated the decision to base the model on hourly climate data and accurate latent heat energy calculations.

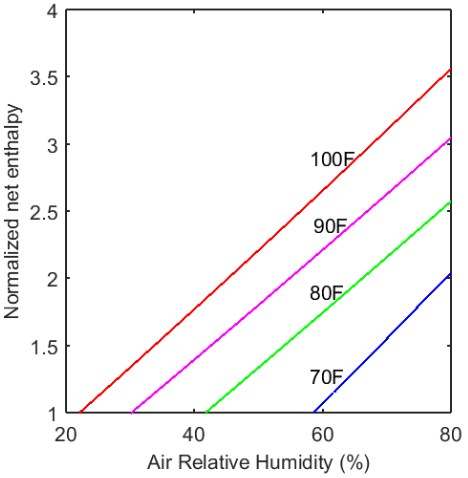


Figure 2: Ratio of relative latent heat and sensible heat change to reach HVAC setpoint (55°F and 100%RH) normalized by sensible heat change as a function of relative humidity.

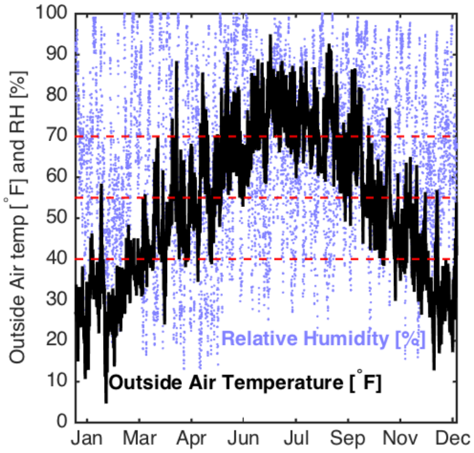


Figure 3: Temperature and relative humidity in Boston for year 2010

2.2 Airside Economizer Model

The economizer model 1) determines, based on outside air temperature, the ratio of outside air versus return air to meet conditioning and ventilation requirements 2) calculates the mixed air temperature which determines the level of conditioning needed. The mixed air temperature set-point, as implemented in the building control policy, is 55°F in the buildings studied (also called the activation temperature) and ensures that the internal building relative humidity objectives are achieved throughout the year. Figure 5 shows how the economizer control policy is implemented as a function of outside air temperature. When outside air temperature is less than the mixed air set-point (55°F) heating is required and we want to use as much of return air as possible so the outside air ratio is set at minimum (here the minimum outside air policy is 50% opening). The outside air temperature break-point where no more heating is required (saturation limit) is based on two factors: 1) the ratio of return air to supply air (based on measured BAS data, this was close to 50% on a yearly basis for the 3 buildings studied, see histogram in Figure 6), and 2) the return air temperature which is observed to be 70°F on a yearly basis.

The model is equipped having return air temperatures as an hourly based dataset which greatly benefits the analysis in buildings where it varies through the year. For outside air ratio of 0.5 and return air temperature of 70°F the break-point

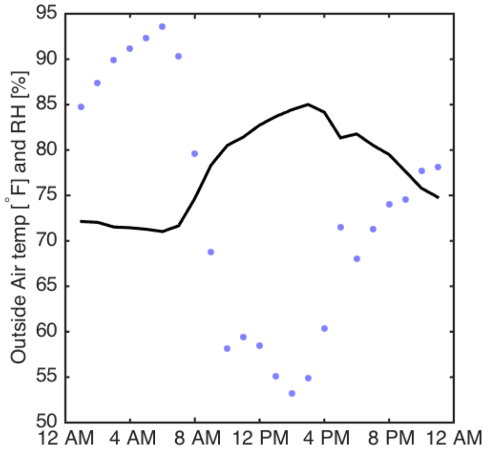


Figure 4: Temperature and relative humidity in Boston on July 21st, 2010

is at 40°F outside air. Between 40°F and 55°F the outside air ratio is increased linearly to accommodate the available free-cooling and is 100% at 55°F all the way to 70°F. When outside air temperatures reach the return air temperature set-point the level of outside air ratio is set to the minimum again. For reference, Figure 3 shows how the switching temperatures 40°F, 55°F and 70°F (red lines) map onto Boston climate data where one can realize for which periods each operating zone is dominant.

Between climate zones the activation temperature should be selected according to the economizer control mode 1) temperature based control 2) enthalpy based control and the variation on outside air temperature and humidity. There is a activation set-point that maximizes energy savings related to the economizer efficiency but currently and in the past it has been selected rather arbitrary. Zhou et. al. (Zhou, Wei, Turner, & Claridge, 2006) discuss common misconceptions related to airside economizer control and explain how to select the "best" activation temperature. As discussed the model being presented here is especially targeted to estimate the benefit of different control strategies and activation temperatures so they can be applied to the building being optimized.

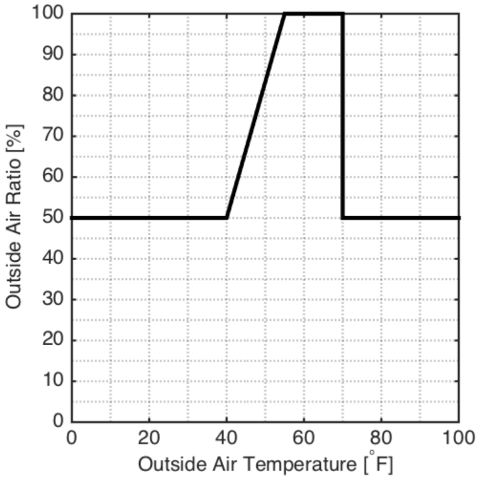


Figure 5: Outside air damper switching curve

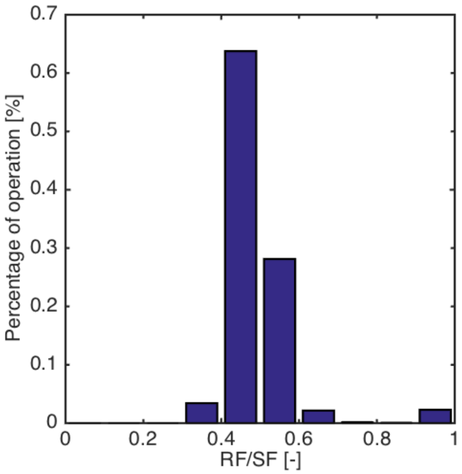


Figure 6: Frequency of return over supply flow ratio for AHU4 in PHO for Mar-Sep 2014

2.3 Energy Demand Model for HVAC Components

Detailed energy models for each of the major HVAC components were developed based on data obtained from detailed BAS logging throughout a full year. This ensures that the model is firmly based on actual operational data and few assumptions. Data based analysis is particularly important since many pieces of equipment operate differently at part load, as well as the overall HVAC system operates differently due to different design practices and control implementation.

Demand models were developed for electricity use by air handlers and chillers, and natural gas use for boilers. All energy demand models were developed as a function of the buildings actual supply airflow rate and are designed to handle hourly input data for the most accurate estimate. This is especially important in buildings were un-occupied mode has been implemented and large changes in airflow are apparent. For others assuming an average constant airflow rate throughout the year will give sufficient results.

Fan Model: Fan energy use depends on 1) fan air power (product of airflow and pressure head across fan 2) fan efficiency 3) motor and drive efficiencies. All of these are non-constant for building HVAC systems where pressures and flows can be varied. This means that the ”system curve” is constantly changing and this detailed mapping of the fan performance is seldom available from the fan manufacturer.

Fan energy models were developed as a function of air flow rate (specified in terms of cubic feet per minute (cfm)) for each particular building. They are based on actual fan hourly electricity use data, operating at full and part load conditions throughout the year. The complete models were checked against actual electrical and natural gas bill and sub-metering, and show to estimate HVAC energy use within 10% of actual demand for an entire year. Both supply and return fans are included in the analysis. To develop the relation of motor power consumption (in kilowatts electricity) as a function of airflow rate (in cfm), data form the Building Automation System (BAS) was recorded, and verified by manually comparing data from the fan’s variable frequency drives.

These results were also confirmed for airflow reduction by explicitly reducing VAV minimum set-points for a large part of the rooms in the buildings. For example, Figure 7 shows the overall correlation between fan power and supply flow rate for one of three buildings studied. The Photonics Building has identical AHU’s which leads to a less complex correlation than for the School of Management Building which has many different sized AHU’s. Variations about the correlation functions (shown as black lines), are due to variations in the supply fan pressure set point, which varies due to changes in net duct resistance as VAV boxes open and close.

As a comparison the CBECS submodel (KEMA, 2012) for ventilation requirements uses the regulatory required outside air volume for the building size and assumes 100% outside air for labs and 30% for offices. Using CBECS estimates the amount of return air is assumed to be 35% (0.7 times ratio of static pressure drop for return air over static pressure drop for supply air) compared to the 50% seen from the actual operational data.

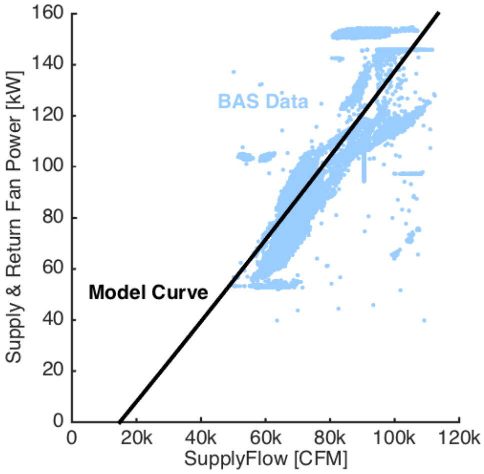


Figure 7: Fan Model Curve (for supply and return fans) for Photonics Center. Data from all 4 identical AHU's is used for the fit yields 1.29 KW/1000 CFM.

Heating and Cooling Model: Cooling and heating (apart from re-heat) is modulated at the AHU level where control valves determine the chilled or hot water flow through two separate heat exchanger coils (see Figure 1). The total supply airflow flows over the coils which makes it a suitable dependent variable. The model estimates the heating and cooling need based on the climate enthalpy and and control policy presented in section **??**. Reheat is assumed to be needed all year to increase the temperature from the mixing set-point at the AHU level to the supply temperature at the VAV-boxes ($55°F$ to $65°F$). Boiler and chiller efficiencies were selected based on specification from manufactures that were adjusted based on actual air reduction experiments. With more experimental data it would have been possible to map the operational profile of both the boiler-plant and chiller-plant for an even more realistic estimate.

3. ANALYSIS OF ANNUAL HVAC ENERGY CONSUMPTION IN 3 BUILDINGS

The 3 Boston University buildings used in this study were chosen due to their different sizes, different HVAC architectures, and different uses. Two of the buildings are large buildings - the School of Management (SMG) building, which is primarily offices (325,000 sq.ft., built in 1996, 1057 rooms, 8 AHU's, 495 VAV-boxes and several dining/cooking areas) and the Photonics Center (PHO), which is a mixed office, classroom, and laboratory space (243,000 sq.ft. built in 1997, 667 rooms, 4 AHU's, 443 VAV-boxes, and 33 fume hoods). The smaller building, Engineering Manufacturing Building (EMB), consists of 2 floors, 50,000 sq.ft. with 2 AHU's, 50 VAV-boxes, and mixed office, research lab, and manufacturing space, constructed in 1997.

First the supply and return airflow trends were analyzed. If a complete set of hourly BAS data is available (without any gaps or missing data) that can be used directly but if not, the airflow characteristics of the building has to be identified. Figure 8 shows a histogram of the total supply flow from one of the buildings revealing constant flow throughout the year (and clearly does not have an un-occupied mode).

Based on the model, we predict the daily energy used to both heat and cool the air for an entire year. The results are presented for PHO in Figure 9. The outside air heating (in red) reflects the economizer dispatch when the maximum amount of return air is used, while the reheat portion (in purple) reflects the use throughout the year to bring the mixed air temperature up to the $65°F$ at the VAV boxes. Cooling energy (in blue) reflects where chillers are needed to provide a $55°F$ mixed air temperature, which is determined by the outside air and relative humidity plots. The total heating load throughout the year per CFM of airflow is 104 kBtu/CFM, while the total demand for cooling is 57.5 kBTU/CFM (averaged over the year). The figure shows how these loads are distributed over the calendar year where cooling loads are depicted on the positive y-axis in terms of But per hour per CFM and heating and reheat are summarized and depicted on the negative half of the y-axis in terms of BTU per hour per CFM . These BTU loads are then converted to therms of natural gas assuming a boiler efficiency of 85%, and the stated efficiency of the chillers (.7kW/Ton). Power

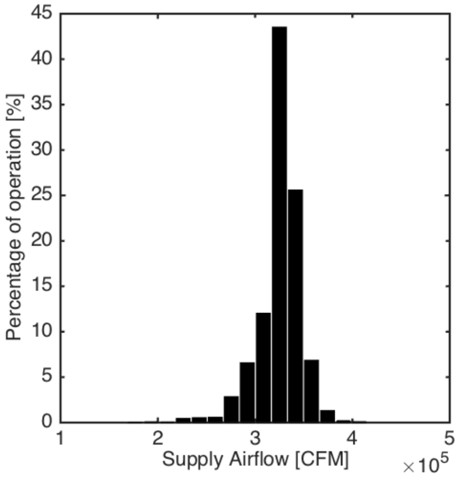


Figure 8: Histogram of Total Supply Airflow (4 AHU's) for Photonics Building (2014).

consumed by AHU's per CFM delivered for each of the three buildings comes from actual fan model curves taking into account supply and return fans and accounting for un-occupied mode where appropriate.

A prediction of heating, cooling and fan energy use for all three buildings is summarized in Table 1. There heating and cooling demands per CFM are identical between the three buildings since they orginate only from the same climate data and economizer control policy. The fan demand per CFM is related to the actual operational fan curves and therefore are buildings specific. PHO and SMG have similarly efficient fans while the smaller capacity equipment in EMB is less efficient. The HVAC energy model is based on current commercial utility rates in Boston ($0.15/kWh and $1.16/Therm), reflecting the reduction of natural gas prices over the past several years. This analysis indicates that these buildings currently operate at an HVAC energy cost of $4.44 - 4.64 per CFM/year, which corresponds to an average of $3.00/sq.ft. of buildings space per annum. Overall it is striking, that the cost of running the fans is for all buildings is at or just above 50% of the total HVAC operating cost.

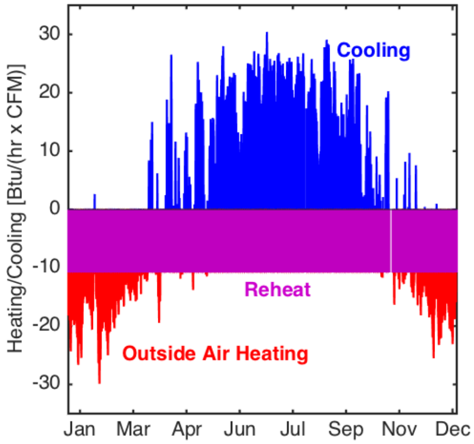
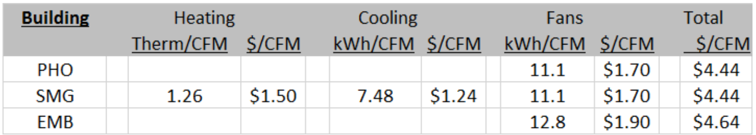


Figure 9: Building HVAC daily heating and cooling energy use per CFM of airflow, model prediction (Boston, 2010.)

Table 1: Model analysis of HVAC Energy consumption per CFM for heating, cooling and fans for the three buildings studied.

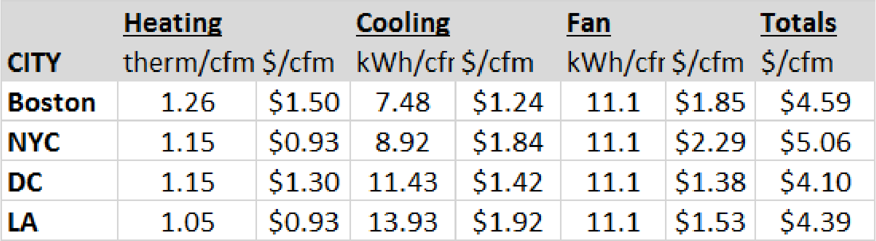


Building	Heating		Cooling		Fans		Total
	Therm/CFM	$/CFM	kWh/CFM	$/CFM	kWh/CFM	$/CFM	$/CFM
PHO					11.1	$1.70	$4.44
SMG	1.26	$1.50	7.48	$1.24	11.1	$1.70	$4.44
EMB					12.8	$1.90	$4.64

4. DISCUSSION

Available hourly climate data from three other climate zones (other than Boston) allows for a model comparison of HVAC energy and cost requirements. Keeping all other factors constant (i.e. estimating the consumption of the ”same” building in all zones) leads to an enlightening comparison. Table 2 shows the heating, cooling and fan energy estimates of three different metropolitan areas along with Boston. These are New York City, Washington DC and Los Angeles. Local costs of energy (per Therm and per kWh) have been used to populate the table.

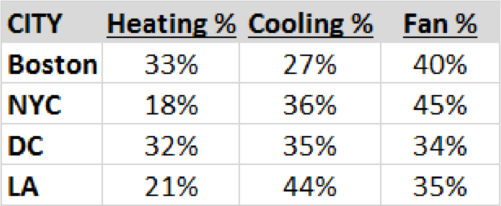
Table 2: HVAC energy consumption and cost estimates for heating, cooling and fans for different cities.



	Heating		Cooling		Fan		Totals
CITY	therm/cfm	$/cfm	kWh/cfr	$/cfm	kWh/cfr	$/cfm	$/cfm
Boston	1.26	$1.50	7.48	$1.24	11.1	$1.85	$4.59
NYC	1.15	$0.93	8.92	$1.84	11.1	$2.29	$5.06
DC	1.15	$1.30	11.43	$1.42	11.1	$1.38	$4.10
LA	1.05	$0.93	13.93	$1.92	11.1	$1.53	$4.39

As expected cooling costs are highest in LA and heating cost are highest in Boston and each contribute to a high total HVAC cost per CFM which is slightly higher than the other two cities. Table 3 shows the percentage breakdown for heating, cooling and fans per city. What is striking is the high percentage of the cost that goes into driving the supply and return fans. The percentage cost is lowest for DC at 43% and highest for NY at 55%. This shows that the amount of air that is required to be pushed through the building is the real cost driver for HVAC systems.

Table 3: Percentage cost breakdown for heating, cooling and fans by city.



CITY	Heating %	Cooling %	Fan %
Boston	33%	27%	40%
NYC	18%	36%	45%
DC	32%	35%	34%
LA	21%	44%	35%

We have also compared our results to those of the CBECS end-use energy estimates presented in (KEMA, 2012), which is the basis for breaking out the HVAC energy & cost breakouts presented in CBECS data tables. Our model should be considered to be lower bound estimate since it does not consider air infiltration, heat gain because of people and equipment and heat losses (through windows, open doors, etc.). Looking at the actual building operation in terms of fan energy in the three buildings studied and comparing with the CBECS ventilation estimates shows that on a per CFM basis, both are consistent in terms of the energy required for both the supply and return fan electricity consumption). However, they two models differ significantly in terms of the assumed air flow. In terms of both buildings studied, the CBECS model uses only 55% of the actual air used in the SMG building, and 32% of the Photonics laboratory building. Thus, the CBECS HVAC cost estimates will similarly be understated by 45 to 68% relative to the actual HVAC costs and energy attributable in the study buildings. This large difference is due to the fact that the CBECS model is based on ASHRAE 62.1 airflow design specifications, but many if not most buildings were designed and built with much higher minimum airflow rates. For example, several studies have found that many VAV systems are implemented where the minimum VAV airflow setting is set at 30 to 50% of the maximum flow rate (Arens, Zhang, & Holt, 2015) (Gallagher, Gunnsteinsson, Morse, & Gevelber, 2015).

Historically in the United States this category of buildings have been designed with high minimum air-flow rate setpoints that are greater than that needed for ventilation. If supply airflow rates can be reduced for a building not only is less energy required to transport the air but also to condition (heat and/or cool) it. An essential part of studying this phenomena is to be able to, for a particular building or project, predict the energy savings. When considering airflow rate reductions the prediction model has to be able to assess the energy requirements of each cubic feet of air that needs to be transported through the building which is one of the key component of this model presented.

5. SUMMARY

A model to estimate HVAC energy consumption in large commercial office buildings has been developed based primarily on analysis of building airflow rates. The model is based on analysis of three commercial buildings in terms of operational data from building automation system, mapping of load profiles and efficiency of key HVAC equipment, investigating building airflow control policies and deriving buildings loads using hourly climate data. The model reveals how much actual energy is consumed by the HVAC systems in these buildings and to identify the key consumption drivers. In particular, the model analysis reveals that roughly 40% of HVAC energy cost is associated with running supply and return fans. As such, these results indicate that minimizing airflow rates in buildings while meeting required outside air requirements provides a significant opportunity to improve building energy efficiency.

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