The Pennsylvania State University
The Graduate School
Architectural Engineering Department

COMPARISON OF PART LOAD MODEL PREDICTION OF COMMERCIAL OFFICE
SUBSYSTEM ENERGY CONSUMPTION WITH SUB-METERED DATA

A Thesis in
Architectural Engineering
by
Parichehr Salimifard

© 2014 Parichehr Salimifard

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

August 2014
The thesis of Parichehr Salimifard was reviewed and approved* by the following:

James D. Freihaut  
Professor of Architectural Engineering  
Thesis Advisor

Stephen Treado  
Associate Professor of Architectural Engineering

Seth Blumsack  
Associate Professor of Energy and Mineral Engineering

Chimay J. Anumba  
Professor of Architectural Engineering  
Head of the Department of Architectural Engineering

*Signatures are on file in the Graduate School
ABSTRACT

Among the three primary energy use sectors (buildings, industry, and transportation), building sector with about 40% of total U.S. primary energy used in 2011 has the highest energy consumption. Given the fact that buildings have had the least improvement in energy efficiency compared to the other energy use sectors in the past 50 years, there is a lot of potential to reduce primary energy consumption by attempting to make building sector more energy efficient.

A good understanding of each end use energy consumption in the building is a prerequisite for identification of potential Energy Conservation Measures (ECMs). Energy modeling packages use part load equations as a base line to estimate the energy use associated with different end uses in the building. Since equipment is selected on a design day basis, but operates mainly in part load status, the accurate simulation of part load energy use is an important aspect of accurate energy simulation predictions of a building operation. Accuracy of each end use energy consumption estimation by forward modeling packages is essentially dependent on how well these equations represent the actual performance of equipment at part load. This thesis investigates how well each end use energy consumption is predicted by these part load curves.
# TABLE OF CONTENTS

LIST OF FIGURES .................................................................................................................. vi

LIST OF TABLES ...................................................................................................................... ix

ACKNOWLEDGEMENTS .......................................................................................................... x

Chapter 1 Introduction ........................................................................................................... 1

  Problem Statement .............................................................................................................. 1

Chapter 2 Literature Review .................................................................................................. 5

  Background .......................................................................................................................... 5

Chapter 3 Case Study ............................................................................................................. 9

  3.1 Case Study 1: Building 101 .......................................................................................... 9
  3.2 Case Study 2: Building 2 ............................................................................................... 10

Chapter 4 Using ANCOVA to Evaluate the Energy Retrofit Effectiveness ....................... 11

  4.1 Method .......................................................................................................................... 11
  4.2 Results ........................................................................................................................... 13
  4.3 Summary ....................................................................................................................... 18

Chapter 5 Comparison of Part load Models Energy Use Prediction with Sub-metered Data for Each End Use ........................................................................................................ 19

  5.1 Interior Lighting ............................................................................................................ 19
    5.1.1 Suite 210 Interior Lighting ..................................................................................... 22
    5.1.2 Building 101 Interior Lighting ............................................................................. 31
    5.1.3 Summary .............................................................................................................. 34
  5.2 Plug Load ....................................................................................................................... 35
    5.2.1 Suite 210 Plug Load ............................................................................................. 36
    5.2.2 Building 101 Plug Load ....................................................................................... 38
    5.2.3 Summary .............................................................................................................. 39
  5.3 Ventilation ...................................................................................................................... 40
    5.4.1 Summary .............................................................................................................. 51
  5.4 Space Cooling ................................................................................................................. 52
    5.4.1 Building 101 Cooling Load ................................................................................... 52
    5.4.2 Summary .............................................................................................................. 60
  5.5 Space Heating ................................................................................................................. 61
    5.5.1 Summary .............................................................................................................. 65

Chapter 6 Conclusions, Future Work, and Recommendations ............................................. 66
6.1 Conclusions........................................................................................................66
6.2 Future Work .........................................................................................................68
6.3 Recommendations................................................................................................68

Bibliography ..............................................................................................................70
LIST OF FIGURES

Figure 1-1. Primary Energy Used by Different Sectors in US, 2011 Data extracted from Energy Information Administration website (www.EIA.gov) ................................................. 2

Figure 3-1. East (left) and west (right) view of Building 101 (Xu 2012) ........................................ 9

Figure 4-1. Scatter plot of building energy use (kW) vs. relative humidity (％) ..................... 13

Figure 4-2. Scatter plot of building energy use (kW) vs. outside air temperature (F) .......... 14

Figure 4-3. Scatter plot of building energy use (kW) vs. occupancy (number of people in the building) ............................................................................................................. 14

Figure 4-4. Residual Plots ............................................................................................................. 15

Figure 4-5. Means of building energy use before and after the change in building management system, Tukey comparison with the 5% significance level ...................... 17

Figure 5-1. DOE Reference Buildings lighting schedules ................................................................. 21

Figure 5-2. WL2PAC panel power use in each minute, May 2013 .............................................. 23

Figure 5-3. WL2PBA panel power use in each minute, May 2013 .............................................. 24

Figure 5-4. WL2PBA panel power use in each minute (filetered 1 < WL2PBA < 2), May 2013 ......................................................................................................................... 25

Figure 5-5. WL2PBA panel power use in each minute, July 2013 ............................................... 26

Figure 5-6. WL2PBA panel power use in each minute, August 2013 ............................................. 26

Figure 5-7. WL2PAA panel power use in each minute, July, 2013 ............................................. 27

Figure 5-8. WL2PAB panel power use in each minute, May, 2013 ............................................. 28

Figure 5-9. WL2PBC panel power use in each minute, May, 2013 ............................................. 29

Figure 5-10. Track Lighting panel power use in each minute, June 2013 ................................. 30

Figure 5-11. Suite 210 interior lighting power use for each minute, June 2013 ....................... 30

Figure 5-12. Error in predicted interior lighting power use in each minute, June, 2013 ........ 31
Figure 5-13. Building 101 interior lighting load profile, Jun 2013 ........................................32

Figure 5-14. Building 101 interior lighting load profile for a typical weekend, 6/1/2013 (Saturday) ........................................................................................................................................................32

Figure 5-15. Building 101 interior lighting load profile for a typical working day, 6/3/2013 (Monday) ........................................................................................................................................................................33

Figure 5-16. DOE Reference Buildings plug load schedules .................................................................................36

Figure 5-17. Suite 210 plug load power use in each minute, June 2013 .................................................................37

Figure 5-18. Error in Suite 210 predicted plug load power use in each minute, June 2013 ..........................37

Figure 5-19. Building 101 plug load power use in each minute, June 2013 .........................................................38

Figure 5-20. Error in Building 101 plug load power predicted by DOE Ref. Bldgs., June 2013 ............................................................... ...............................................................................................................39

Figure 5-21. ASHRAE 90.1 standard and DOE Reference Buildings suggested part load fan curves .........................................................................................................................42

Figure 5-22. AHU1 supply air fan efficiency in June 2013 before applying minimum kW filter, Bldg. 1 ........................................................................................................................................................................43

Figure 5-23. AHU1 supply air fan efficiency in June 2013 after applying kW filter (min 500 W), Bldg. 1 ........................................................................................................................................................................43

Figure 5-24. Normalized air flow vs. normalized power. June 2013, Bldg. 1 .................................................................46

Figure 5-25. Normalized air flow vs. normalized power. January 2014, Bldg. 1 .......................................................46

Figure 5-26. Normalized air flow vs. normalized power. June 2013, Bldg. 2 ...............................................................47

Figure 5-27. Normalized air flow vs. normalized power. January 2014, Bldg. 2 ............................................................47

Figure 5-28. Error in predicted power use by ASHRAE 90.1-standard and DOE Reference Buildings. Building 1, January 2014 ......................................................................................................................................................50

Figure 5-29. Error in predicted power use by ASHRAE 90.1-standard and DOE Reference Buildings. Bldg.2, January 2014 .............................................................................................................................................50

Figure 5-33. Difference between air temperature before and after heating coil versus supply air fan speed, July 2013 ..............................................................................................................................................53

Figure 5-34. Difference between air temperature before and after AHU3 heating coil versus supply air fan speed, July 2013 .............................................................................................................................................53
Figure 5-35. Wet bulb temperature of air flow entering AHU3 cooling coil, July 2013 .......................... 54
Figure 5-36. Wet bulb temperature of air flow leaving AHU3 cooling coil, July 2013 .......................... 55
Figure 5-37. Cooling load provided by DX cooling coil in AHU3, Jul 2013 ........................................ 56
Figure 5-38. Cooling power vs. PLR, July 2013 ................................................................................. 58
Figure 5-39. Normalized power vs. normalized cooling capacity, July 2013 ...................................... 59
Figure 5-40. Error in predicted power use by DOE-2 suggested part load equation, July 2013 .............. 60
Figure 5-42. Metered and predicted boiler fuel consumption, January 2014 ........................................ 64
Figure 5-43. Error in predicted boiler fuel consumption, January 2014 .............................................. 64
LIST OF TABLES

Table 5-1: Inaccuracy percentages of lighting power use predicted by DOE for different months ................................................................. 35

Table 5-2. Inaccuracy percentages of plug load power use predicted by DOE for different month ................................................................. 40

Table 5-3. Sensor specifications ................................................................................................................................. 41

Table 5-4. Design air flow and power of fans ................................................................................................................. 44

Table 5-5. Inaccuracy Percentage of Power Use Predicted by Fan Models, Building 1 ............................. 48

Table 5-6. Inaccuracy Percentage of Power Use Predicted by Fan Models, Building 2 ............................. 49

Table 5-7. Design properties of the air flow entering and leaving the direct expansion (DX) cooling coil .................................................................................................................. 54

Table 5-8. Condensing units ............................................................................................................................................. 56

Table 5-9. DX coil part load performance equation coefficients ......................................................................................... 58

Table 5-10. Inaccuracy percentages of cooling load power use predicted by DOE-2 part load equation for different months ........................................................................................................ 60

Table 5-11. Boiler design conditions ............................................................................................................................ 61

Table 5-12. Heating coil design conditions ...................................................................................................................... 62

Table 5-13. Hot water pumps (pump 1 and 2) design conditions ....................................................................................... 62

Table 5-14. Inaccuracy percentages of boiler fuel use consumption predicted by part load equation .......................................................................................................................... 65
ACKNOWLEDGEMENTS

I am grateful of my thesis adviser, Dr. James Freihaut, for his generous guidance and support throughout this research study. I have been very fortunate to have Dr. Freihaut as my adviser; a great scientist with a greater personality who tries to make world a better place with his research endeavors. He has been a true inspiration and made me more passionate to my research. I am also thankful of my committee members, Dr. Stephen Treado and Dr. Seth Blumsack, for their guidance and support.

I would like to thank Dr. Mohammad Heidarinejad who has not only been a good friend but also a great mentor. He generously contributed his time to help out me and other graduate students whenever he was asked. His advice and support has been a great help to my master studies and this thesis research.

I would like to extend my appreciation to Dr. Payam Delgoshaei and other researchers in the Energy Efficient Buildings Hub (EEB Hub) who helped me with getting the data about the case studies and cooperated with me in this research. I also thank all the faculty members, nice and friendly staff, and my friends in the Architectural Engineering department.

My sincere thanks goes to all my friends here, especially Atefeh and Peyman, who have made it easier to bear with the distance of family and friends and all I miss in Iran by their presence, and to my husband, Mahdad Talebpour, for his endless love and support.

Last but not the least; I would like to thank all my family and friends in Iran especially my dear friend ,Maryam, my brother, Ashkan, my sisters, Paria and Parnian, my mother and father for all their love and support that has kept me going forward.
Chapter 1
Introduction

Problem Statement

There is a variety of research being done to establish ways to design environmentally friendly, green, and sustainable systems. Basically two different approaches are being followed. One approach is to use renewable energy – biomass, solar, wind, hydropower, and geothermal energy instead of producing energy by combustion of traditional fossil fuels. A second approach is to reduce primary energy use, it is from renewable or non-renewable, by increasing the energy efficiency of the operating system. In general, from life-cycle-cost analysis points of view the states-of-the-art in renewable energy technologies have not reached the level which can justify their frequent application. In other words, the amount of energy that is spent in producing and maintaining renewable energy equipment and emissions associated with their production is more than energy and emission savings realized by using the renewable energy produced during the life cycle of the equipment. Therefore, following the second approach, which is trying to increase the efficiencies of energy production and use, provides us not only with a more sustainable way to decrease emissions, but also results in more cost savings.

Primary energy consumption is divided into three different sectors; industry, transportation, and buildings (see Figure 1-1). During the last 50 years, the building
sector accounts for almost half of the United States annual energy consumption. In 2011, residential and commercial buildings combined accounted for 40% of the U.S. total energy consumption (Energy Information Administration 2012) The amount of energy consumed in buildings worldwide exceeds even the U.S. level of energy use (Pérez-Lombard, Ortiz, and Pout 2008). Moreover, buildings have had the least improvement in energy efficiency compared with the two other sectors (Foley et al. 2011). Therefore, even a slight increase in energy efficiency for a big energy consumer sector like buildings would result in a significant energy savings.

![Primary energy Use By Sector](image)

Figure 1-1. Primary Energy Used by Different Sectors in US, 2011
Data extracted from Energy Information Administration website (www.EIA.gov)

Two main inefficiency sources in buildings should be addressed:

1) Inefficiencies in the delivered energy to the buildings (inefficiencies in the way energy is transmitted to the building), and
2) Operational inefficiencies of different end uses in buildings (inefficiencies in the utilization of energy).

The first inefficiency source mentioned above is the energy losses that occur during the electricity generation in power plants and then during its transmission and distribution through the grid to the buildings. In power plants, about 44-68% of primary energy put into the generator is lost in the form of the exhaust heat, with 60% loss being typical. After that, on average, 8% of the electrical energy produced in the power plant is lost during the transmission and distribution processes (Deru and Torcellini 2007). Finally the overall efficiency of these processes is 31-51%, with 33% being the most commonly used overall efficiency number for electricity generation and site distribution. It means that consumers will receive only 33 units of energy for every 100 units of primary energy put into the power plants (U.S. Environmental Protection Agency Combined Heat and Power Partnership 2008). One way to address this inefficiency source is using distributed energy or on-site power plants, e.g. Combined Heat and Power (CHP). Every building needs thermal energy in addition to electricity. The idea behind CHP is to generate the needed electricity at the site and use the exhaust heat to meet the thermal needs of the building. Following this approach, a substantial fraction of heat produced during the electricity generation process is recovered, but also transmission and distribution losses associated with central power plant electrical distribution are avoided.

After addressing inefficiencies in providing energy to the building, inefficiencies in the way the building uses the delivered energy should be addressed. To do so various Energy Conservation Measures (ECMs) can be identified for different end uses in an existing building. These ECMs can vary from turning off extra lightings and sealing air
leaks to using thermal and electrical energy storages for peak shaving purposes and avoiding part load inefficiencies.

Solutions for both inefficiency problems above have one requirement in common; the need for a good understanding of the deconvoluted energy use profiles of a building. To be able to propose any rational and accurate ECM one should understand how each end use subsystem of a building is performing. Not only does designing an on-site power plant need exact thermal and electrical energy use profiles of the building, and one needs this data to confirm the feasibility of such on-site energy production plans in the first place. In conclusion, one either wants to reduce energy use of the building by proposing ECMs for specific end uses or deliver a primary energy more efficiently by proposing an on-site or district energy system for the building. In either case it is necessary to characterize the energy profile of each end use subsystem in the building.

In general there is not that common to have sufficient data about energy end use and performance of buildings of various types. There are only a few buildings metering and monitoring their energy end use. Most buildings have simply the total electricity and gas use in specific time intervals and this is generally not enough. The more detailed sub-metering being done in a building, the more precisely and certainly energy efficient retrofits could be planned. On the other hand, the cost of sensors and their installation and continuous monitoring is a barrier. This thesis tries to calculate the inaccuracy that predicted energy used by each end use would have if only a forward energy model is used without being calibrated by sub-metered data. Metered energy consumption data related to each end use in a case study will be compared to that of predicted by part load curves used in forward energy modeling software.
Chapter 2

Literature Review

Background

ASHRAE Handbook of Fundamentals (2009) classifies building energy use analysis methods into two categories; forward (classical) modeling and data driven (inverse) modeling. Forward modeling approach is suitable for energy analysis of new buildings. This approach needs physical geometry, heat transfer coefficient of the building envelope, characteristic and efficiency of the equipment in different systems, and many other physical details as input. Blast, DOE-2, TRYNSYS, and EnergyPlus are examples of computer software programs for forward modeling. Forward modeling tries to estimate the energy use of the building by building its physical model, whereas inverse modeling tries to analyze the building energy use by developing its mathematical model. This mathematical model is created with available data from the building e.g. utility bills, and data from sensors installed in the building (ASHRAE 2009).

Inverse modeling (data driven) energy analysis is being used with three different approaches; empirical or “Black Box”, calibrated simulation, Grey Box.

- In the Black Box model, the relationship between building energy use (or any other response variable the researcher is interested in) and the independent variable (usually climatic variables e.g. outside air temperature) is described with a regression model (Kissock, Haberl, and Claridge 2002).
• In calibrated simulation, the researcher tries to adjust the inputs of a forward model with the results of the inverse model so that the forward model energy use predictions match with the building energy use as is.

• In Gray Box approach, first a physical model is defined by formulas that describe the structural and physical configuration of the building and different systems in the building. Then, using these formulas and statistical analysis, specific key parameters and overall physical characteristics of the building would be identified.

Inverse modeling (data driven) methods are suitable for existing buildings, especially those which are candidates for energy efficiency retrofit. Inverse modeling can be applied for identifying more accurate ECMs and planning more successful energy retrofits as well as enabling operational analysis, real time control, and fault detection. Clearly, the more detailed metering and monitoring in a building, meaning the more available data from the building, would enable engineers to achieve more accountable and accurate results from any type of data driven modeling approach being followed. However, installing sensors and monitoring is expensive and it is a significant barrier in the way of achieving effective energy retrofits. Two options are available to address the problem of monitoring cost:

1. Reduce the monitoring time period

2. Reduce the number of installed sensors

First proposed solution to address the cost of monitoring is to reduce the monitoring time period. There has been studies on trying to reduce the time period in which the monitoring before and after the retrofit should be done in a building and yet be
able to verify energy savings independently caused by the retrofit. When less than a year of data is available, normalized energy use inverse models are used (Reddy and Claridge 2000). Researchers have investigated the impact of data resolution, monitoring time period, and also the time of the year monitoring is done on the accuracy of the estimated energy savings (Haberl, Reddy, and Elleson 1997; Katipamula, Reddy, and Claridge 1995; Katipamula, Reddy, and Claridge 1994; Kissock et al. 1993; Montgomery 1991; Reddy and Claridge 2000). (J. Effinger, Effinger, and Kramer 2012; J. Effinger, Effinger, and Friedman 2011; M. Effinger, Anthony, and Webster 2009) have done several case studies to investigate:

- the effects of post-installation monitoring period duration on accuracy of annualized estimated savings,
- the impact of data resolution on the inverse model quality and accuracy, and
- The optimal timeframe for monitoring durations of less than one year.

Second proposed solution for metering cost barrier is to reduce the number of installed sensors by identifying the minimum required measured variables that can lead to a detailed and informative inverse model. This approach can lead to a low cost available data for forward and inverse energy analysis (Heidarinejad 2014). Besides, having an ongoing monitoring in the building can make operational analysis, real time control, fault identification and future energy retrofit planning possible. One missing components in the identification of the minimum required measured variables for the deployment in inverse and forward models is consideration of the part load curves. Most of the existing studies consider the typical part load curves defaulted in the energy models. This research study investigates the reliability of uncalibrated forward energy modeling through
calculating the inaccuracy percentages of predicted energy use caused by using part load curves due to unavailability of sub-metered data.
Chapter 3

Case Study

3.1 Case Study 1: Building 101

The effectiveness of the proposed strategy, will be evaluated using a case study of Building 101, (4747 South Broad Street, Philadelphia, PA, 19112), located in the Philadelphia Navy Yard. This building was originally built in 1910s as a Marine barrack, and experienced a major renovation in 1999. This brick building has three floors above ground, plus an attic floor and a basement (Figure 3-1). It has been instrumented for sub-metering.

![Figure 3-1. East (left) and west (right) view of Building 101 (Xu 2012)](image)

Building 101 is a mid-size office building in a climatic region with many similar old buildings requiring energy retrofits, which, if implemented, could results in
significant energy savings in the regional building stock. All these features make it a unique building and the best candidate for this case study.

The measurements in building 101 are being done to set both energy, and indoor air quality and indoor environment baselines for the building. Over 1,500 data points are being measured and stored on a minute-by-minute basis.

There are sufficient data points collected in this building to quantify the electricity and natural gas energy used in each of the five end-uses (interior lighting, plug load, ventilation, space cooling, and space heating) in each minute.

In addition to measurements for overall understanding of the building, more detailed and comprehensive sub-metering is being done in one of the suites of Building 101; Suite 210 on the north end of the second floor (“EEB Hub” 2013).

3.2 Case Study 2: Building 2

Besides Building 101, another case study has been analyzed to investigate the accuracy of part load models that are being used to calculate ventilation power use. In this document this building will be recalled as Building 2. Case Study Building 2 is a ten-story office building with 215,000 square feet located in Norristown, PA. It has been constructed in 1973. In 2004, building has undergone a retrofit; some of the HVAC equipment has been changed with new systems. Two large air handling units with VAV supply air fans are serving this building. This building has been instrumented for sub-metering and the data are recorded in 15-minute intervals.
Chapter 4

Using ANCOVA to Evaluate the Energy Retrofit Effectiveness

The building management system (controls system) of building 101 was changed in early 2013 in the hope of making this building more energy efficient. This chapter examines the effectiveness of this energy retrofit in reducing the building electricity use using analysis of covariance (ANCOVA). The hypothesis of this ANCOVA is that the performed energy retrofit has been effective and therefore building 101 is consuming less energy after the change in its controls system. Also, effect of different independent variables like occupancy, outside air temperature, and relative humidity on building energy use variation is investigated.

4.1 Method

In order to check whether an energy retrofit has been successful in making the building more energy efficient, building energy use before and after the retrofit is compared. However, other factors playing a role in the energy use such as weather-related variables and occupancy can be the cause of building energy use variation as well. To be able to draw any conclusion on the effectiveness of the any energy retrofit it should be tried to look at energy use variation solely caused by the retrofit. Analysis of Covariance (ANCOVA) is a proper statistical method to so. By putting other influential independent variables in the model as covariates, the energy use variation cause by these factors can be put aside and the change in energy use due to application of the energy retrofit can be studied.
Since many of these factors like outside air temperature and occupancy cannot be controlled during the study, it is an observational study. Here the treatment of the ANCOVA is the change in building management system. Building energy use in the summer (cooling season) before and after the change in building management system is compared here. However, the same strategy can be used to investigate the effect of energy retrofit on each end use and also building energy use can be analyzed from various aspects and many more factors can be included in the analysis. Outside air temperature, relative humidity, and building occupancy are the independent variables considered as covariates in this study. So this ANCOVA study has the following features:

- Total building electrical power use as response
- Installation of a new building management system as treatment
- Outside air temperature (OAT) as covariate
- Outside air relative humidity (RH) as covariate
- Building occupancy as covariate.

The month of June is selected as a representative of cooling season, so June 2012 represents the energy use before the energy retrofit, and June 2013 is the representative of energy use after the energy retrofit. Minute-interval data provides a huge data set with a large number of data points. In order to make the number of data points smaller (to have lower degrees of freedom and avoid pseudo replication) the data are converted into hourly intervals. The preliminary data analysis and visualization is done by MATLAB and Minitab is used for statistical analysis.

In statistical terms, the null and alternative hypotheses are:

\( H_0 \): The mean of building energy use before and after applying the treatment (change in controls system) is not significantly different.

\( H_a \): The mean of building energy use after applying the treatment (change in controls system) is significantly lower than before.
4.2 Results

Figures 4-1, Figure 4-2, and Figure 4-3 show the scatter plots of the building electrical power use versus covariates before and after the retrofit. Building electrical power use shows little change as RH is increasing, whereas it shows slightly higher change as OAT varies. Scatter plot of building power use versus occupancy shows a significant correlation between these two. Just by looking at the scatter plots it is expected that occupancy has a higher effect on the response of ANCOVA compared to the other covariates.

Figure 4-1. Scatter plot of building energy use (kW) vs. relative humidity (%)
Figure 4-2. Scatter plot of building energy use (kW) vs. outside air temperature (F)

Figure 4-3. Scatter plot of building energy use (kW) vs. occupancy (number of people in the building)
Figure 4-4. Residual Plots

Figure 4-4 shows the residual plots indicating that all required assumptions of ANCOVA are met. The residuals are randomly distributed, have a mean of zero, are independent, and are equally distributed among treatment levels.

ANCOVA Result from Minitab Software:

General Linear Model: Whole Bldg Power(kW) versus trt

Factor Type Levels Values
trt fixed 2 After, Before

Analysis of Variance for Whole Bldg Power(kW), using Adjusted SS for Tests

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq SS</th>
<th>Adj SS</th>
<th>Adj MS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupancy(ave. no. people)</td>
<td>1</td>
<td>5596778005</td>
<td>4747481157</td>
<td>4747481157</td>
</tr>
<tr>
<td>OAT (F)</td>
<td>1</td>
<td>1099518892</td>
<td>1083217243</td>
<td>1083217243</td>
</tr>
<tr>
<td>RH_(%)</td>
<td>1</td>
<td>2905288</td>
<td>78931204</td>
<td>78931204</td>
</tr>
<tr>
<td>trt</td>
<td>1</td>
<td>2569650350</td>
<td>2569650350</td>
<td>2569650350</td>
</tr>
<tr>
<td>Error</td>
<td>1205</td>
<td>5548947101</td>
<td>5548947101</td>
<td>4604935</td>
</tr>
<tr>
<td>Total</td>
<td>1209</td>
<td>14817799636</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source                  | F   | P    |
-------------------------|-----|------|
Occupancy(ave. no. people) | 1030.96 | 0.000 |
OAT (F)                  | 235.23 | 0.000 |
RH_(%)                   | 17.14  | 0.000 |
### Expected Mean Squares, using Adjusted SS

<table>
<thead>
<tr>
<th>Source</th>
<th>Expected Mean Square for Each Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Occupancy(ave. no. of people)</td>
<td>$(S) + Q[1]$</td>
</tr>
<tr>
<td>2 OAT (F)</td>
<td>$(S) + Q[2]$</td>
</tr>
<tr>
<td>3 RH_(%)</td>
<td>$(S) + Q[3]$</td>
</tr>
<tr>
<td>4 trt</td>
<td>$(S) + Q[4]$</td>
</tr>
<tr>
<td>5 Error</td>
<td>$(S)$</td>
</tr>
</tbody>
</table>

### Error Terms for Tests, using Adjusted SS

<table>
<thead>
<tr>
<th>Source</th>
<th>Error DF</th>
<th>Error MS</th>
<th>Synthesis of Error MS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Occupancy(ave. no. of people)</td>
<td>1205.00</td>
<td>4604935</td>
<td>$(S)$</td>
</tr>
<tr>
<td>2 OAT (F)</td>
<td>1205.00</td>
<td>4604935</td>
<td>$(S)$</td>
</tr>
<tr>
<td>3 RH_(%)</td>
<td>1205.00</td>
<td>4604935</td>
<td>$(S)$</td>
</tr>
<tr>
<td>4 trt</td>
<td>1205.00</td>
<td>4604935</td>
<td>$(S)$</td>
</tr>
</tbody>
</table>

### Variance Components, using Adjusted SS

<table>
<thead>
<tr>
<th>Source</th>
<th>Estimated Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error</td>
<td>4604935</td>
</tr>
</tbody>
</table>

### Means for Covariates

<table>
<thead>
<tr>
<th>Covariate</th>
<th>Mean</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupancy(ave. no. of people)</td>
<td>24.53</td>
<td>35.129</td>
</tr>
<tr>
<td>OAT (F)</td>
<td>73.70</td>
<td>8.563</td>
</tr>
<tr>
<td>RH_(%)</td>
<td>63.56</td>
<td>18.625</td>
</tr>
</tbody>
</table>

### Least Squares Means for Whole Bldg Power(kW)

<table>
<thead>
<tr>
<th>trt</th>
<th>Mean</th>
<th>SE Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>After</td>
<td>6168</td>
<td>85.48</td>
</tr>
<tr>
<td>Before</td>
<td>9162</td>
<td>91.48</td>
</tr>
</tbody>
</table>

### Grouping Information Using Tukey Method and 95.0% Confidence

<table>
<thead>
<tr>
<th>trt</th>
<th>N</th>
<th>Mean</th>
<th>Grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>565</td>
<td>9162</td>
<td>A</td>
</tr>
<tr>
<td>After</td>
<td>645</td>
<td>6168</td>
<td>B</td>
</tr>
</tbody>
</table>

Means that do not share a letter are significantly different.

P-values for all terms in the general linear model are less than level of significance (0.05), so they are all significant. Since it is an observational study cause-and-effect statements cannot be made. However by putting as many possible significant covariates in the model it is tried to account for the variability caused by other factors not controlled in this study.
Occupancy has the highest adjusted sum of squares (Adj. SS) in the ANCOVA model meaning that it is accountable for the highest amount of variability in the response. Treatment (trt) has the second highest Adj. SS. OAT and RH have smaller Adj. SS values, so they play little part in variability of the electrical power use.

Tuckey Method is used to compare the mean of power use before and after the energy retrofit. Figure 4-5 shows the bar chart of the mean of building power use before and after the change in building management system. Means that do not share the same letter are significantly different. By using Tukey means comparison, with the 5% significance level, means of building energy use before and after the energy retrofit are significantly different. So we can reject the null hypothesis and conclude that the building is using less electrical energy after the retrofit has been done.

![Bar chart showing mean building energy use before and after change in building management system.](chart.png)

Figure 4-5. Means of building energy use before and after the change in building management system, Tukey comparison with the 5% significance level
4.3 Summary

This observational study investigates the effect of the energy retrofit done in this case study, building 101. The measured variables included in the ANCOVA model are:

- **Response**: Building energy use (kW), continuous quantitative variable
- **Treatment**: change in building management system, categorical, two levels (before and after)
- **Covariate**: building occupancy (number of people in the building), discrete quantitative variable
- **Covariate**: outside air temperature (Fahrenheit), continuous quantitative variable
- **Covariate**: outside air relative humidity (%), continuous quantitative variable

All the factors in the ANCOVA are significant (with p-values of zero). The result of Tukey mean comparison shows that with 95% of confidence mean of building electrical energy use after the energy retrofit is significantly lower than before the retrofit.

Occupancy is responsible for the most of variability in the electrical energy use in this building. Effect of occupancy variable on this building energy use is so much higher than weather related variables like OAT and RH. It points out the significant effect of occupancy in building energy use. Accordingly, it is tried to analyze each end use part load energy use from the occupancy perspective as well.
Chapter 5

Comparison of Part load Models Energy Use Prediction with Sub-metered Data for Each End Use

5.1 Interior Lighting

U.S. Energy Information Administration reports that the total energy consumption of commercial buildings sector in 2011 was 18.1 quads Btu and lighting end use with 2.95 quads Btu accounted for 16.3% of the total energy consumed by commercial sector. Among commercial building types, office buildings with 20.2% held the first rank in electricity consumption and lighting end use was accountable for more than 39% of the total electricity used in office buildings in 2003 (Energy Information Administration 2012). Thus making this end use more energy efficient in the office buildings would significantly improve the overall energy efficiency of the commercial building sector. The first step toward identification of ECMs related to lighting end use is to understand the lighting load profile of the building. This chapter analyzes the lighting energy used in Building 101 and compares the lighting load profiles developed using sub-metered data versus default load profiles used in energy modeling software which are proposed by standards.

ASHRAE 90.1 states that buildings shall comply with either of the two proposed prescriptive requirements; Building Area Method or Space-by-Space Method. The Building Area Method of calculating interior lighting power allowance has the following steps:

- First, the appropriate building area type and its associated Lighting Power Density (LPD) (watts per unit area) should be determined. A table of various building types and their LPD values are given by standard 90.1. LPD for office buildings is 0.9 W/ft².
• Gross lighted floor area (ft$^2$) should be determined.

• $\sum$ Gross lighted floor areas of building type(s) $\times$ LPD is the interior lighting power allowance of the building.

The alternative of the Building Area Method is the Space-by-Space compliance path. In this method the building area is divided into different area types, and the interior lighting power allowance is calculated for each area type. DOE Reference buildings for mid-size office buildings uses the Building Area method and proposes the LPD of 1 W/ft$^2$.

Building 101 covers 61700 ft$^2$ over four floors, basement to third floor. So interior lighting power is calculated with ASHRAE 90.1 standard and DOE commercial buildings suggested LPD values.

• ASHRAE standard 90.1
  
  o Building 101: $0.9 \left(\frac{W}{R^2}\right) \times 61700 \text{ (ft}^2\text{)} = 55,530(W)$
  
  o Suite 210: $0.9 \left(\frac{W}{R^2}\right) \times 6342 \text{ (ft}^2\text{)} = 5,707.8(W)$

• DOE Reference Buildings
  
  o Building 101: $1 \left(\frac{W}{R^2}\right) \times 61700 \text{ (ft}^2\text{)} = 61,700(W)$
  
  o Suite 210: $1 \left(\frac{W}{R^2}\right) \times 6342 \text{ (ft}^2\text{)} = 6,342(W)$

The values above show the maximum interior lighting power used in the building. However, the lighting power use in the building is not constantly at peak value. Various lighting schedules are proposed for different building types. DOE Reference Buildings suggests three different office building lighting schedules for working days, Saturdays, and Sundays or other holidays. These schedules are shown in Figure 5-1. To obtain the lighting power use in each hour,
the fraction of power use (diversity factor) suggested by the appropriate lighting schedule should be multiplied by the lighting density and area of the building.

\[
\text{Lighting power use (W) } = \text{diversity factor} \times \text{LPD} \left( \frac{W}{1} \right) \times \text{area (ft}^2) \quad (5-1)
\]

Figure 5-1. DOE Reference Buildings lighting schedules

The exterior lighting fixtures are generally controlled by astronomical clock. Knowing the number of exterior lighting fixtures (exterior lighting density) of the building should lead to an acceptable estimation of exterior lighting energy use. Hence, only the interior lighting load profile of building 101 and its difference with DOE Reference Buildings interior lighting load profile are analyzed here.
5.1.1 Suite 210 Interior Lighting

The power used by interior lighting fixtures in suite 210 is the sum of power used by different panels serving lighting fixtures in various parts of this suite.

Suite 210 Interior lighting power (kW) = WL2PAC + WLP2BA + WLP2AA + WLP2AB + WLP2BC + Track Lighting  

(5-2)

Where WL2PAC, WLP2BA, WLP2AA, WLP2AB, WLP2BC, and Track Lighting are variables representing the power used by each panel serving suite 210 lighting fixtures.

5.1.1.1 WLP2AC

WL2PAC represents the kW used by the panel that is serving two lighting fixtures in mechanical/electrical closet, center light in second floor, one night light fixture in telepresence room, and four night light fixtures in the office area. To separate the night light fixtures power consumption from the total power used by this panel, WL2PAC for several months has been analyzed. Since the night light is always on, it should be the base load of this variable. Figure 5-2 shows the one-minute interval metered power used by this panel in May 2013. Minimum kW is 1.55 and maximum is 1.72. Median and the mode are equal to 1.6 kW and the mean with the value of 1.601 kW is very close to the median. The data shows a normal distribution with standard deviation of 0.023 kW. So we can conclude that the night light fixtures are using 1.6 kW per minute. It can also be verified by multiplication of the number of night light fixtures and their power consumption.

# of Night Light fixtures: 5; 4 fixtures in the office area and 1 fixture in the telepresence room

Each fixture has eight 40W T-5 bi-axis fluorescent lamps.

kW of each fixture:
Night Light Power:

\[
5 \times 320(W) = 1600(W) = 1.6 (kW)
\]

Figure 5-2. WL2PAC panel power use in each minute, May 2013

5.1.1.2 WLP2BA

WLP2BA represents the kW used by the panel that is serving 8 lighting fixtures; two lighting fixtures in conference room 201 and six lighting fixtures in the open office south. Conference room 201 is not part of suite 210 so it should be excluded from suite 210 calculations.

WLP2BA for May 2013 is visualized in Figure 5-3. WLP2BA has four different power consumption levels;

- Level 1: all lighting fixtures are off (min=0 kW),
- Level 2: only the two fixtures of conference room are on,
- Level 3: only the six lighting fixture of open office south are on,
- Level 4: all lighting fixtures are on (max= 2.65 kW).
In order to find the power level 2 which is part of suite 210, the data has been filtered and only the data points with the following condition has been kept.

\[ 1 < WL2PBA < 2 \]

Filtered data points are shown in Figure 5-4 with minimum and maximum values of 1.26 and 1.94 kW. Mode and median of the filtered data are equal to 1.84 kW. Mean (1.85 kW) is pretty close to median and mode and standard deviation is 0.05 kW. It can be concluded that open office south lighting fixtures are using 1.84 kW per minute. Sum of the kW of the lamps in these fixtures is 1.92 kW.

Nominal power of the open office south lighting fixtures:

\[ 6 \times 320(W) = 1920(W) = 1.92 \text{ (kW)} \]
There was a change in the BMS lighting control in July 2013. Lighting switches became automatic; subsequently occupants had no control over the lights. It neglects the occupancy behavior effect of a typical office building. As it is shown in Figure 5-5, on July 11th we the four levels of power use for this panel don’t exist anymore. There are only two power levels in the following months (August 2013); either all the lighting fixtures are off or all of them are on simultaneously (See Figure 5-6).
Figure 5-5. WL2PBA panel power use in each minute, July 2013

Figure 5-6. WL2PBA panel power use in each minute, August 2013
5.1.1.3 WLP2AA

WLP2AA represents the kW used by the 12 lighting fixtures in the office area (cubicals).

Figure 5-7 shows the power used by these fixtures in each minute in July 2013.

Nominal power of the lighting fixtures in the office area:

\[ 12 \times 320(W) = 3840(W) = 3.84 \text{ (kW)} \]

![Figure 5-7. WL2PAA panel power use in each minute, July, 2013](image)

5.1.1.4 WLP2AB

WLP2AB represents the kW used by the 10 lighting fixtures in the ICON Lab and 3 lighting fixtures in the telepresence room. Figure 5-8 shows 4 different levels of power usage;

- when all the lighting fixtures are off (0 kW),
- when all the lighting fixtures are on (\( 13 \times 0.32(kW) = 4.16 \text{ (kW)} \)),
- only telepresence room lighting fixtures are on (\( 3 \times 0.32(kW) = 0.96 \text{ (kW)} \)).
only ICON Lab lighting fixtures are on ( 10 * 0.32(kW) = 3.2 (kW) ).

Figure 5-8. WL2PAB panel power use in each minute, May, 2013

5.1.1.5 WLP2BC

WLP2AB represents the kW used by the 4 lighting fixtures in the northern open office area and 2 lighting fixtures in the lounge area. Figure 5-9 shows 4 different levels of power usage;

- when all the lighting fixtures are off (0 kW),
- when all the lighting fixtures are on ( 6 * 0.32(kW) = 1.92 (kW) ),
- just lighting fixtures in the lounge area are on (2 * 0.32(kW) = 0.64 (kW) ),
- just northern open office area lighting fixtures are on ( 4 * 0.32(kW) = 1.28 (kW) ).
Figure 5-9. WL2PBC panel power use in each minute, May, 2013

5.1.1.6 Track Lighting

Track lighting represents the open office area track lights, ICON Lab track lights, and ICON Lab overhead lights. The power used by these lighting fixtures in each minute of July 2013 is shown in Figure 5-10.
5.1.1.7 Overall Suite 210 Interior Lighting

Figure 5-11 shows the interior lighting power used in suite 210 versus the interior lighting power predicted by DOE Reference Buildings for each minute in July 2013. Suite 210 is using much more interior lighting energy than DOE Reference Buildings predicted for a typical office building. The difference in power use predicted by DOE Reference Buildings and actual power use metered in suite 210 is defined as error. Figure 5-12 shows the error of predicted power use in each minute of July 2013.

Figure 5-11. Suite 210 interior lighting power use for each minute, June 2013
5.1.2 Building 101 Interior Lighting

But Based on the assumption that building 101 is consuming energy in each end use in a homogenous way, total power used by interior lighting end use in the building is calculated by extrapolation of suite 210 power use. It is assumed that all floors in the building are fully occupied and has the same load profile as suite 210. So building 101 interior lighting load profile is calculated by multiplication of area factor and suite 210 power use in each minute.

Building 101 lighting power use (kW) = \left( \frac{61700 \text{ ft}^2}{6342 \text{ ft}^2} \right) \times \text{Suite 210 lighting power use (kW)}
Figure 5-13. Building 101 interior lighting load profile, Jun 2013

Figure 5-14. Building 101 interior lighting load profile for a typical weekend, 6/1/2013 (Saturday)
Figure 5-15: Building 101 interior lighting load profile for a typical working day, 6/3/2013 (Monday)

Figure 5-13 shows the Building 101 interior lighting load profile in June 2013. Figures 5-14 and Figure 5-15 show the building 101 interior lighting load profiles for a typical weekend and working day respectively. Although DOE load profile is close to metered data in Figure 5-15, it cannot be considered as a fair prediction of lighting load profile. It should be remembered that building 101 is not fully occupied and not a good representative of a typical office building at this state. Thus DOE lighting load profile should be compared with the suite 210 extrapolated load profile.

Building 101 metered interior lighting load profile shares the same pattern with the load profile extrapolated from suite 210 interior lighting. Thus it can be concluded that the whole building has the same trend of lighting energy use as suite 210 except for the fact it is using less lighting energy per square feet due to being unoccupied in parts of the building. As it was expected, total Building 101 metered lighting power use is significantly lower than Suite 210 extrapolated load.
profile. It points out the effect of occupancy in the building load profile. Since Suite 210 is fully occupied it has higher lighting density than the half occupied Building 101.

DOE load profile is significantly lower than suite 210 extrapolated load profile. Based on DOE this building should have an interior lighting base load of 3.1 kW whereas this building actually has a base load of 10.5 kW and if it was fully occupied it would have had a base load of about 15.5 kW. In the peak interior lighting energy use, building 101 is using about 50 kW per minute while DOE predicts the peak lighting energy use to be 55.5 kW. If the building was fully occupied the peak interior lighting power would have been as high as around 113 kW.

5.1.3 Summary

Inaccuracy of the predicted power use is calculated by dividing the sum of errors by sum of measured power use.

\[
\text{error (kW)} = \frac{\text{Suite 210 interior lighting power (kW)}}{\text{interior lighting power predicted by DOE Ref. Bldgs. (kW)}}
\]

5-3

\[
\% \text{ of inaccuracy} = \frac{\text{sum of error}}{\text{sum of measured power use}} \times 100
\]

5-4

Where,

\[
\text{sum of error (kW)} = \sum \text{error (kW)}
\]

\[
\text{sum of measured power use (kW)} = \sum \text{Suite 210 interior lighting power (kW)}
\]

Using equations 5-3 and 5-4, the inaccuracy percentage of lighting power use predicted by DOE Ref. Buildings is calculated for each month (Table 5-1). Positive values show overestimation of lighting power use and negative values show underestimation.
Table 5-1: Inaccuracy percentages of lighting power use predicted by DOE for different months

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Suite 210 – DOE Ref. Bldgs.</td>
<td>-57.8</td>
<td>-56.3</td>
<td>-53.1</td>
<td>-55.7</td>
<td>-47.7</td>
<td>-44.8</td>
<td>-59.4</td>
<td>-57.5</td>
<td>-58.4</td>
<td>-55.6</td>
<td>-56.4</td>
<td>-56.6</td>
</tr>
</tbody>
</table>

Inaccuracy percentages of interior Suite 210 lighting power use predicted by DOE ranges from -44.8% to -59.4%. For whole building, it ranges from -6.9% to -31.9%. Both Suite 210 and Bldg. 101 power use load profiles are being underestimated all the time.

5.2 Plug Load

Energy used by end uses other than space heating, space cooling, ventilation, and lighting is usually defined as plug load. Based on the U.S. Energy Review published in 2012, plug load end use accounted for 32.4% of total electricity used in office buildings with the following breakdown; 4.5% for office equipment, 10.3% for computers, 4.9% for refrigeration, 1% for cooking, and 12.7% for other end uses (Energy Information Administration 2012). Forward energy models’ accuracy in predicting plug load energy use would be at risk if not calibrated based on influential variables like occupancy and schedule (Heidarinejad et al. 2013).

Similar to lighting, energy modeling software calculate plug load end use using power density and equipment schedule. DOE Reference Buildings for mid-size office buildings suggests the power density of 1 \( \frac{W}{ft^2} \). There are different equipment schedules suggested by DOE Reference Buildings for working days, Saturdays, and Sunday and
holidays are shown in Figure 5-16. The methodology and calculation process used in developing plug load profiles is the same as lighting.

Figure 5-16. DOE Reference Buildings plug load schedules

5.2.1 Suite 210 Plug Load

Building 101 has been instrumented for sub-metering power used by each panel. Delgoshaei et al. (2013) have studied the power use profile of each equipment in Suite 210 and have developed hourly plug load profiles for this suite. Similar to most buildings, different end uses in Building 101 have not been assigned to different electricity panels. Consequently, developing the load profile of different electricity end users is much more difficult than if there were separate electrical panels for different end users. With help of circuit finder tool, Delgoshaei et al. have identified the electrical panels that are supplying equipment in Suite 210. There are some circuits that serve both Suite 210 and the conference room next to this suite. Those circuits have been blocked and are not used in Suite 210 anymore in order to avoid the any potential overlap. There is a very small chance that one of the circuits in Suite 210 is serving another room in another level (either first floor or third floor). They have been checked with circuit finder tool
as well and no outlet has been found that is served by any of the Suite 210 circuits. Figure 5-17 shows the sum of power used by all equipment in Suite 210 that fall under plug load end use category in each minute interval of June 2013 versus the plug load power use predicted by DOE. The difference between the metered plug load power use in Suite 210 and that of predicted by DOE is defined as error. Figure 5-18 shows the error for each minute interval in June 2013.

Figure 5-17. Suite 210 plug load power use in each minute, June 2013

Figure 5-18. Error in Suite 210 predicted plug load power use in each minute, June 2013
5.2.2 Building 101 Plug Load

But with the same assumptions and methodology explained in the lighting chapter, Building 101 plug load profile has been developed from Suite 210 load profile extrapolation. Figure 5-19 shows the Building 101 plug load profile from actual total power used in whole building versus load profiles developed from Suite 210 extrapolation and suggested by DOE. Despite the fact that Building 101 is not fully occupied and it was expected to have plug load profile with lower base and peak load than Suite 210 extrapolated load profile, they don’t seem to be very different. It might be because some of the occupied suites in the building are much more plug load energy intense than a typical office building and their plug load energy usage is compensating for the unoccupied ones. Figure 5-20 shows the error in Building 101 plug load power predicted by DOE Reference Buildings in each minute interval in June 2013.

![Figure 5-19. Building 101 plug load power use in each minute, June 2013](image-url)
5.2.3 Summary

The inaccuracy percentage of the plug load power use estimated by DOE for each month is reported in Table 5-2. Suite 210 inaccuracy percentages range from 21% to 37.9%. Bldg. 101 inaccuracy percentages range from 1.1% to -26.8%. DOE Ref. Bldgs. Plug load part load model is representing Bldg. 101 load profile better than Suite 210. Difference between Suite 210 extrapolated load profile and whole bldg. metered data is not as high as lighting end use. Although some suites in the building are not occupied and there is no lighting or plug load power use associated to those parts of the building, unlike lighting end use, plug load power use does not have a homogenous distribution in the building. Some suites are more plug load energy intensive than Suite 210 and are compensating for the unoccupied suites. As a result, Building 101 plug load profile is being underestimated by DOE Reference Buildings while Suite 210 is being overestimated.
5.3 Ventilation

Energy use associated with fans in HVAC systems account for a significant portion of total building energy use. About 20% of total US primary energy use is consumed by commercial buildings and 32.5% of total electricity used in commercial buildings was related to ventilation end use in 2006 (Energy Information Administration 2012). Forward modeling packages use fan part load energy use equations as a base line to estimate the energy use associated with fans in a building. Since equipment is selected on a design day basis, but operates mainly in part load status, the accurate simulation of part load energy use is an important aspect of accurate energy simulation predictions of a building operation. Accuracy of ventilation energy use estimation by forward modeling packages is essentially dependent on how well these equations represent the actual performance of fans at part load.

In an effort to alleviate the limitations in DOE-2 (York and Tucker 1980) and ASHRAE Secondary Toolkit (Brandemuehl, Gabel, and Andresen 1993; Clark 1985) fan models, Stein and Hydeman (2004) developed a grey box model of fan efficiency as a function of air flow and fan
static pressure. However the basic assumptions made in laboratory investigations to develop characteristic curves for fans are generally quite different from the field conditions.

This chapter investigates how accurate the commonly used part load fan models predict the ventilation energy use of case study building 1 (Building 101) and case study Building 2. This is one of the end-uses that require careful consideration of the part load curves based on the onsite measurements (Salimifard et al. 2014). All major HVAC facilities are equipped with Variable Speed Drives (VSDs) and their energy uses are currently sub-metered. Both buildings are using the same types of sensors for air flow and power measurements (Table 5-3). Installed sensors collect one minute interval data in case study building 1 and 15-minute interval data in Building 2.

Table 5-3. Sensor specifications

<table>
<thead>
<tr>
<th>Reading (Units)</th>
<th>Accuracy</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Air Flow (cfm)</td>
<td>± 2% of reading, ±0.25% repeatability</td>
<td>0 to 5,000 fpm (0 to 25.4 m/s)</td>
</tr>
<tr>
<td>Fan Power (kW)</td>
<td>0.5% nominal</td>
<td>Electrical Operating Voltage Range: 80% - 115% of nominal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Power Line Frequency Range: 50 to 60 Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Environmental -30°C to +55°C (-22°F to 131°F)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Humidity: 5 to 90% RH (noncondensing)</td>
</tr>
</tbody>
</table>

ASHRAE 90.1 standard-2010 (See Figure 5-21) suggests the following formula to calculate the energy use of VAV Fan Systems at part load:

\[
P_{\text{fan}} = 0.0013 + 0.1470X + 0.9506X^2 - 0.0998X^3 \quad (5-5)
\]

Where,

\( P_{\text{fan}} \) = fraction of full – load power, and

\( X \) = Part load ratio of fan operation (actual cfm / design cfm) (ASHRAE 2010).
On the other hand the input part load equation for EnergyPlus suggested by DOE Commercial Reference Buildings for office buildings (the default equation of OpenStudio) is (Michael Deru et al. 2011; Field, Deru, and Studer 2010):

\[ P_{\text{fan}} = 0.040759894 + 0.08804497X + 0.0729612X^2 + 0.943739823X^3 \]  

(5-6).

Figure 5-21. ASHRAE 90.1 standard and DOE Reference Buildings suggested part load fan curves
Figure 5-22: AHU1 supply air fan efficiency in June 2013 before applying minimum kW filter, Bldg. 1

Figure 5-23: AHU1 supply air fan efficiency in June 2013 after applying kW filter (min 500 W), Bldg. 1
Before conducting the analysis, the data is checked for invalid readings. E.g. when the fan is not working (kW reading is almost zero), but there may be a small air flow measured in the ducts, resulting in fan efficiency value being over 100% or more. If the air handler unit and, subsequently its supply air fan is off, analyzing its performance would be meaningless. These associated data points are filtered. Figures Figure 5-22 and Figure 5-23 show the efficiency of AHU1 supply air fan in building 101 before and after filtering the data.

Supply fan performance collected data is visualized by plotting the normalized power use (NPU) vs. normalized air flow (NAF) for different months in different working seasons against part load curves suggested by AHRAE standard 90.1, 2010 and DOE Reference Buildings. These plots allow us to compare the performance of Building 1 and 2 fans against an ideal fan law curve and the part load curves suggested by ASHRAE 90.1 standard and DOE Reference Buildings. Table 5-4 summarizes the design air flow and power of supply fans. The design air flow and power are the measured values at maximum fan speed in building.

\[
\text{NAF} = \frac{\text{actual air flow (cfm)}}{\text{design air flow (cfm)}}
\]

\[
\text{NPU} = \frac{\text{actual power use (kW)}}{\text{design power use (kW)}}
\]

Table 5-4. Design air flow and power of fans

<table>
<thead>
<tr>
<th>Bldg. 1, AHU1</th>
<th>Design Power (kW)</th>
<th>Design Air Flow (cfm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bldg. 1, AHU2</td>
<td>10.5</td>
<td>15486</td>
</tr>
<tr>
<td>Bldg. 1, AHU3</td>
<td>18.3</td>
<td>19150</td>
</tr>
<tr>
<td>Bldg. 1, AHU3</td>
<td>18.6</td>
<td>21031</td>
</tr>
<tr>
<td>Bldg. 2, AHU1</td>
<td>79.1</td>
<td>62156</td>
</tr>
<tr>
<td>Bldg. 2, AHU2</td>
<td>45.3</td>
<td>38289</td>
</tr>
</tbody>
</table>

Inserting the normalized air flow (X) into the ASHRAE 90.1 standard and DOE Reference Buildings part load equations, energy use predicted by these curves for each data point
is calculated. Subsequently difference between predicted power use by these curves and the actual fan power use measured by installed sensors is calculated.

$$\text{error}_{\text{model}} = P_{\text{design}} \times (P_{\text{model}} - \text{NPU})$$  \hspace{1cm} (5-9)

Finally, the percentage of over/under estimation of energy use by the aforementioned curves will be calculated:

$$\% \text{ of inaccuracy} = \frac{\text{sum of error}}{\text{sum of measured energy use}} \times 100$$  \hspace{1cm} (5-10)

$$\text{sum of error}_{\text{model}} = \sum P_{\text{design}} \times (P_{\text{model}} - \text{NPU})$$  \hspace{1cm} (5-11)

Where $P_{\text{design}}$ is the design fan power use, the fan power use measured at maximum air flow, and model refers to ASHRAE and DOE Reference Buildings part load equations.

Figures 5-24 to Figure 5-27 show the normalized air flow versus normalized power of supply air fans of case study Building 1 and 2 respectively, plotted against ASHRAE 90.1 standard and DOE Reference Buildings part load fan curves. AHUs of both buildings are working with fans with variable frequency drive. While the Building 1 fan data shows acceptable performance of VFD controls, Building 2 fans don’t seem to follow proper VFD control behavior. It seems to be operating more like a multiple speed fan rather than a fan with VFD control. Such fault detections in controls would not easily be found if fan metered data was not available.
Figure 5-24. Normalized air flow vs. normalized power. June 2013, Bldg. 1

Figure 5-25: Normalized air flow vs. normalized power. January 2014, Bldg. 1
Figure 5-26: Normalized air flow vs. normalized power. June 2013, Bldg. 2

Figure 5-27: Normalized air flow vs. normalized power. January 2014, Bldg. 2
The percentage of over/under estimation of energy use by fan part load equations proposed by ASHRAE 90.1 standard and DOE Reference Building EnergyPlus Models have been calculated for the two case studies over the course of one year. Tables Table 5-5 and Table 5-6 and summarize the results. Positive values show overestimation and negative values are a sign of underestimation by the part load equations. These “standard” fan models over or under predict fan energy use significantly most of the time. Moreover, they don’t show consistent errors across the two buildings. Although both systems are variable air volume systems in the same climate, the inconsistency could be due to different performance of fan systems in the two buildings and variations in system pressure drops at different flow conditions in each building system.

Table 5-5. Inaccuracy Percentage of Power Use Predicted by Fan Models, Building 1

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>AHU1 - ASHRAE</td>
<td>43.8</td>
<td>41.7</td>
<td>26.8</td>
<td>30.6</td>
<td>49.8</td>
<td>46.5</td>
<td>31.6</td>
<td>31.6</td>
<td>41.0</td>
<td>38.0</td>
<td>44.7</td>
<td>47.6</td>
</tr>
<tr>
<td>AHU2 - ASHRAE</td>
<td>-7.9</td>
<td>-10.9</td>
<td>1.7</td>
<td>21.4</td>
<td>16.8</td>
<td>16.2</td>
<td>3.2</td>
<td>2.5</td>
<td>7.0</td>
<td>7.4</td>
<td>-1.7</td>
<td>-3.9</td>
</tr>
<tr>
<td>AHU3 - ASHRAE</td>
<td>54.9</td>
<td>47.4</td>
<td>36.0</td>
<td>43.1</td>
<td>67.5</td>
<td>62.9</td>
<td>34.4</td>
<td>51.9</td>
<td>52.3</td>
<td>52.7</td>
<td>74.0</td>
<td>88.4</td>
</tr>
<tr>
<td>Total - ASHRAE</td>
<td>23.4</td>
<td>19.9</td>
<td>19.1</td>
<td>31.5</td>
<td>39.1</td>
<td>35.2</td>
<td>16.6</td>
<td>25.2</td>
<td>28.1</td>
<td>28.6</td>
<td>30.9</td>
<td>34.1</td>
</tr>
<tr>
<td>AHU1 - DOE</td>
<td>2.7</td>
<td>-0.9</td>
<td>-1.7</td>
<td>0.1</td>
<td>11.7</td>
<td>10.8</td>
<td>4.2</td>
<td>8.7</td>
<td>4.4</td>
<td>6.5</td>
<td>7.1</td>
<td>3.7</td>
</tr>
<tr>
<td>AHU2 - DOE</td>
<td>-39.2</td>
<td>-37.9</td>
<td>-27.7</td>
<td>-14.0</td>
<td>-11.9</td>
<td>-11.8</td>
<td>-14.4</td>
<td>-24.1</td>
<td>-23.1</td>
<td>-21.4</td>
<td>-34.6</td>
<td>-38.4</td>
</tr>
<tr>
<td>AHU3 - DOE</td>
<td>6.8</td>
<td>4.3</td>
<td>-3.9</td>
<td>5.6</td>
<td>16.8</td>
<td>13.5</td>
<td>1.5</td>
<td>7.8</td>
<td>4.7</td>
<td>3.4</td>
<td>12.4</td>
<td>26.4</td>
</tr>
<tr>
<td>Total - DOE</td>
<td>-15.2</td>
<td>-15.9</td>
<td>-13.3</td>
<td>-3.2</td>
<td>1.8</td>
<td>-0.2</td>
<td>-6.9</td>
<td>-7.6</td>
<td>-8.0</td>
<td>-8.1</td>
<td>-11.2</td>
<td>-8.8</td>
</tr>
</tbody>
</table>
Table 5-6. Inaccuracy Percentage of Power Use Predicted by Fan Models, Building 2

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>AHU1 - ASHRAE</td>
<td>5.7</td>
<td>5.3</td>
<td>10.6</td>
<td>22.1</td>
<td>-3.2</td>
<td>-14.2</td>
<td>-9.5</td>
<td>11.1</td>
<td>14.0</td>
<td>21.5</td>
<td>25.6</td>
<td>18.4</td>
</tr>
<tr>
<td>AHU2 - ASHRAE</td>
<td>-9.5</td>
<td>-8.8</td>
<td>-8.6</td>
<td>-12.7</td>
<td>-16</td>
<td>-21.4</td>
<td>-21.5</td>
<td>-14.7</td>
<td>-12.5</td>
<td>-6.0</td>
<td>-1.8</td>
<td>-5.2</td>
</tr>
<tr>
<td>total - ASHRAE</td>
<td>-0.3</td>
<td>0.4</td>
<td>4.1</td>
<td>10.3</td>
<td>-7.8</td>
<td>-16.9</td>
<td>-14.1</td>
<td>1.3</td>
<td>4.4</td>
<td>11.0</td>
<td>13.8</td>
<td>7.6</td>
</tr>
<tr>
<td>AHU1 - DOE</td>
<td>-0.5</td>
<td>9.0</td>
<td>18.6</td>
<td>41.4</td>
<td>-3.8</td>
<td>-24.5</td>
<td>-19.2</td>
<td>6.1</td>
<td>12.9</td>
<td>24.4</td>
<td>12.1</td>
<td>-2.4</td>
</tr>
<tr>
<td>AHU2 - DOE</td>
<td>-18.5</td>
<td>-17.1</td>
<td>-16.7</td>
<td>-21.7</td>
<td>-25.2</td>
<td>-33.5</td>
<td>-34.5</td>
<td>-26.9</td>
<td>-26.5</td>
<td>-14.2</td>
<td>-10.0</td>
<td>-13.0</td>
</tr>
<tr>
<td>total - DOE</td>
<td>-7.5</td>
<td>0.0</td>
<td>6.7</td>
<td>19.9</td>
<td>-11.6</td>
<td>-27.9</td>
<td>-25.1</td>
<td>-6.5</td>
<td>-1.4</td>
<td>9.7</td>
<td>2.5</td>
<td>-7.3</td>
</tr>
</tbody>
</table>

Figures Figure 5-28 and Figure 5-29 display the errors of predicted energy use for each data point of January 2014 in Buildings 1 and 2 fan energy use prediction respectively. The trend of error as air flow increases is consistent in Building 1, but Building 2 clearly shows different linear error lines as the fan is staging into each speed stage. The error in predicted energy use is due to problem in VFD controls. Although AHUs are using VFD supply fans, the fans are not working in a VFD manner, as noted above in the power use data. They are working as if they are using multiple frequency drives. As the air flow increases, the error increases. Using the part load curves, we expect to see an increase in fan energy use by increase in air flow. But the data and analysis indicate the fan energy use remains constant for different intervals of air flow, explaining the increase in error when air flow increases. As the air flow reaches the threshold of next stage the error drops to negative values, indicating that energy use is being underestimated.

Different operational seasons show different inaccuracy percentages in energy use predicted by fan part load equations. Since different building operational schedules would affect the fan part load profiles, developing separate periodically part load equations would improve the ventilation energy use prediction.
Figure 5-28. Error in predicted power use by ASHRAE 90.1-standard and DOE Reference Buildings. Building 1, January 2014

Figure 5-29. Error in predicted power use by ASHRAE 90.1-standard and DOE Reference Buildings. Bldg.2, January 2014
5.4.1 Summary

For Building 1, DOE Reference Building part load fan equation gives better predictions of supply air fans energy use at part load fan conditions than the equation suggested by ASHRAE 90.1 standard.

In Building 1 ASHRAE 90.1 standard part load equation total inaccuracy percentages in energy use predicted for different months ranges from 16% to as high as almost 40%. Although ASHRAE 90.1 standard and DOE fan part load equations have an acceptable range of error in predicting the overall energy use of all supply air fans of Building 2, the error rate for different fans varies significantly. Despite the fact that Building 2 supply fans are not following VAV controls, energy use predicted for Building 2 supply fans by both equations show smaller error percentages. It appears that the load profile of any specific fan cannot be predicted with certainty without having its performance data while working in the building available. And if the supply air fans within a specific building cannot be successfully modeled with these “typical” part load fan curves, then there is no guarantee that any one specific, “standard” part load fan equation can be used to model fans in different buildings. Apparently no other existing model would have succeeded in doing so without having fan performance field data available, which also revealed the problem in VFD control operation.

Using the actual part load fan curve as the input for a forward modeling package should result in more accurate estimation of ventilation energy use of the building.

Using given “standard” or “typical” part load expressions for a variety of equipment types selected on design performance specifications introduces appreciable uncertainly in the energy simulations. It is not apparent how this issues can be systematically addressed without introducing more sub-metering in building subsystem and key HVAC components.
5.4 Space Cooling

Based on the U.S. Energy Review published in 2012, cooling end use accounted for 13.5% of the total electricity used in commercial buildings and 14.0% of total electricity used in office buildings in 2003 (Energy Information Administration 2012). After lighting, cooling end use holds the second highest electricity energy consumption use in commercial buildings.

5.4.1 Building 101 Cooling Load

Air handling units (AHUs) in building 101 are instrumented for measuring various variables including air flow volumetric flow rate, dry-bulb temperature, and relative humidity. With the dry bulb temperature and relative humidity readings for each point in the AHUs, other psychrometric properties like enthalpy, humidity ratio, and wet bulb temperature are calculated using EES software. There is no relative humidity sensor between heating and cooling coils. In summer (cooling season) heating valve is closed and there is no heat transfer between heating coil and mixed air passing through them. Hence, the humidity ratio of the air flow before and after the heating coil can be assumed equal. Likewise, in winter the humidity ratio before and after cooling coils can be assumed equal. Figure 5-30 shows the dry bulb temperature difference of air flow before and after heating coil. The mode of the temperature difference is 0.11°F, meaning that most of the time the temperature difference is very close to zero. There are some data points showing that this temperature difference ranges from below -5°F to above +20°F. The reason can be found out from Figure 5-31. It can be seen that when the supply air fan is working (fan speed is above zero), the temperature difference is close to zero.
To validate these directly metered and virtually calculated properties of air flow in the air handling unit ducts, they have been compared against the values provided in the design documents. Table 5-7 summarizes the design properties of the air flow entering and leaving the direct expansion (DX) cooling coil in the air handling units. Figures Figure 5-32 and Figure 5-33
show an example of this validation. Figure 5-32 shows the wet bulb temperature of air flow entering the DX cooling coil with mode of 62.3°F which is very close to the design entering wet bulb temperature of 63.3°F. Figure 5-33 shows the wet bulb temperature of air flow leaving the DX cooling coil with mode of 51.59°F which is very close to the design entering wet bulb temperature of 51.3°F.

Figure 5-32. Wet bulb temperature of air flow entering AHU3 cooling coil, July 2013

Table 5-7. Design properties of the air flow entering and leaving the direct expansion (DX) cooling coil

<table>
<thead>
<tr>
<th></th>
<th>Entering air dry bulb temp. (°F)</th>
<th>Entering air wet bulb temp. (°F)</th>
<th>Leaving air dry bulb temp. (°F)</th>
<th>Leaving air wet bulb temp. (°F)</th>
<th>Cooling Capacity (MBH)</th>
<th>Refrigerant</th>
</tr>
</thead>
<tbody>
<tr>
<td>DX Cooling coil 1</td>
<td>80.9</td>
<td>64.8</td>
<td>51.6</td>
<td>50.8</td>
<td>436</td>
<td>R-22</td>
</tr>
<tr>
<td>DX Cooling coil 2</td>
<td>79.5</td>
<td>63.3</td>
<td>52.1</td>
<td>51.3</td>
<td>716</td>
<td>R-22</td>
</tr>
<tr>
<td>DX Cooling coil 3</td>
<td>79.5</td>
<td>63.3</td>
<td>52.1</td>
<td>51.3</td>
<td>696</td>
<td>R-22</td>
</tr>
</tbody>
</table>
Cooling load provided by each DX cooling coil is calculated using the following formula.

\[
Q \left( \frac{\text{Btu}}{\text{hr}} \right) = 4.5 \times \text{cfm} \times (h_{\text{leaving air}} - h_{\text{entering air}})
\]  

(5-12)

Where \(h_{\text{entering air}}\) and \(h_{\text{leaving air}}\) are the enthalpies of air flow entering and leaving the cooling coil respectively. Figure 5-34 shows the cooling load provided by AHU3 for each minute of July 2013. The cooling load reaches as high as high 627.4 MBtu/hr which is still smaller than the design capacity of condensing unit 3 (696.3 MBtu/hr). The design capacities of condensing units and their rated power usage and efficiencies are summarized in Table 5-8.
Figure 5-34. Cooling load provided by DX cooling coil in AHU3, Jul 2013

Table 5-8. Condensing units

<table>
<thead>
<tr>
<th></th>
<th>Nominal capacity (MBtu/hr – Ton - kW)</th>
<th>Power input (kW)</th>
<th>Efficiency (EER)</th>
<th>Saturated suction temp. (°F)</th>
<th>Ambient air (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CU1</td>
<td>444 – 37 – 130.124</td>
<td>44.2</td>
<td>10</td>
<td>38</td>
<td>95</td>
</tr>
<tr>
<td>CU2</td>
<td>728 – 60.67 – 213.356</td>
<td>63.1</td>
<td>11.537</td>
<td>43.5</td>
<td>95</td>
</tr>
<tr>
<td>CU3</td>
<td>696.3 – 58.025 – 204.065</td>
<td>62</td>
<td>11.23</td>
<td>41</td>
<td>95</td>
</tr>
</tbody>
</table>

ASHRAE classifies building HVAC equipment as primary and secondary. Primary equipment are those that convert the given electricity or fuel to the desired forms of energy like cooling and heating energy. Secondary equipment are responsible for transferring the converted energy to different zones in the building. Chiller, boiler, and cogeneration plants are examples of primary equipment and heat exchangers and fans are examples of secondary equipment.

Most simulation programs assume that primary equipment have the following part load energy consumption (ASHRAE 2009):

\[ P = \text{PIR} \times \text{Load} \quad (5-13) \]

\[ \text{PIR} = \text{PIR}_{\text{nom}} \times f_1(t_a, t_b, \ldots) \times f_2(\text{PLR}) \quad (5-14) \]

\[ C_{\text{avail}} = C_{\text{nom}} \times f_3(t_a, t_b, \ldots) \quad (5-15) \]
PLR = \frac{\text{Load}}{C_{\text{avail}}} \quad (5-16)

Where,

P = \text{equipment power, kW}

PIR = \text{power input ratio}

PIR_{\text{nom}} = \text{power input ratio under nominal full-load conditions}

Load = \text{power delivered to load, kW}

C_{\text{avail}} = \text{available equipment capacity}

C_{\text{nom}} = \text{nominal equipment capacity, kW}

f_1 = \text{function relating full-load power at off-design conditions (t_a, t_b, ...)}\text{ to full-load power at design conditions}

f_2 = \text{fraction full-load power function, relating part load power to full-load power}

f_3 = \text{function relating available capacity at off-design conditions (t_a, t_b, ...)}\text{ to nominal capacity}

t_a, t_b = \text{various operating temperatures that affect power}

PLR = \text{part load ratio.}

The nominal rated performance of a DX rooftop unit is generally given at the design outside air dry-bulb temperature and wet-bulb temperature of air entering the cooling coil. The efficiency adjustment curves for DX are usually functions of these two variables (Equations 5-17 and 5-18).

\begin{align*}
f_1(t_{wb,ent}, t_{oa}) &= a_0 + a_1 t_{wb,ent} + a_2 t_{wb,ent}^2 + a_3 t_{oa} + a_4 t_{oa}^2 + a_3 t_{wb,ent} t_{oa} \quad (5-17) \\
f_3(t_{wb,ent}, t_{oa}) &= c_0 + c_1 t_{wb,ent} + c_2 t_{wb,ent}^2 + c_3 t_{oa} + c_4 t_{oa}^2 + c_3 t_{wb,ent} t_{oa} \quad (5-18) \\
f_2(PLR) &= b_0 + b_1 PLR + b_2 PLR^2 + b_3 PLR^3 \quad (5-19)
\end{align*}

DOE-2.1 building energy simulation program uses Equations 5-17 to 5-19 with coefficients in Table 5-9. The power used by each DX system has been calculated using
these equations. Figure 5-35 shows the predicted power use for DX unit 3 versus part load ratio for each minute in July 2013. The metered power use by the condensing unit in order to provide cooling load for DX cooling coil has also been shown. Figure 5-36 shows the normalized power use versus normalized capacity.

\[
\text{normalized power use} = \frac{\text{current power use (kW)}}{\text{nominal power (kW)}} \quad (5-20)
\]

\[
\text{normalized capacity} = \frac{\text{current cooling load (kW)}}{\text{design cooling load (kW)}} \quad (5-21)
\]

Table 5-9. DX coil part load performance equation coefficients

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_1 )</td>
<td>-1.063931</td>
<td>0.0306584</td>
<td>0.0001269</td>
<td>0.0154213</td>
<td>0.0000497</td>
<td>0.0002096</td>
</tr>
<tr>
<td>( f_2 )</td>
<td>0.201230</td>
<td>-0.031218</td>
<td>1.950498</td>
<td>-1.120511</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( f_3 )</td>
<td>0.8740302</td>
<td>0.0011416</td>
<td>0.0001711</td>
<td>-0.002957</td>
<td>0.0000102</td>
<td>0.0000592</td>
</tr>
</tbody>
</table>

Figure 5-35. Cooling power vs. PLR, July 2013
Figure 5-36. Normalized power vs. normalized cooling capacity, July 2013

The difference between predicted power use and metered power use is defined as error.

Figure 5-37 shows the error in DX unit 3 predicted power use for each minute in July 2013.

error (kW) = metered condensing unit power (kW) – power predicted by DOE – 2 part load model (kW) \hspace{1cm} (5-22)

\[
\% \text{ of inaccuracy} = \frac{\sum \text{error (kW)}}{\sum \text{measured power use (kW)}} \times 100 \hspace{1cm} (5-23)
\]

Where,

\[
\sum \text{error (kW)} = \sum \text{error (kW)}
\]

\[
\sum \text{measured power use (kW)} = \sum \text{metered condensing unit power (kW)}
\]
5.4.2 Summary

The inaccuracy percentages for each condensing DX unit and also for total cooling load provided by all DX units are calculated (Table 5-10). AHU1 DX unit has the highest inaccuracy percentage. The part load equation is underestimating the DX unit 1 and 3 power use in July 2013 by about 29% and 20% respectively. DX unit 2 power use is estimated with an acceptable inaccuracy percentage (below 5%). The overall power use by all three DX units in this month is underestimated by 12%. Here DX units can be better modeled with a stepwise function.

Table 5-10. Inaccuracy percentages of cooling load power use predicted by DOE-2 part load equation for different months

<table>
<thead>
<tr>
<th>Inaccuracy Percentage (%)</th>
<th>Jun-13</th>
<th>Jul-13</th>
<th>Aug-13</th>
</tr>
</thead>
<tbody>
<tr>
<td>DX cooling coil unit 2</td>
<td>19.25</td>
<td>2.80</td>
<td>3.20</td>
</tr>
<tr>
<td>DX cooling coil unit 3</td>
<td>3.01</td>
<td>-19.96</td>
<td>-9.78</td>
</tr>
<tr>
<td>Total cooling load</td>
<td>7.81</td>
<td>-11.97</td>
<td>-11.18</td>
</tr>
</tbody>
</table>
5.5 Space Heating

Based on EIA data, 23.7% of total delivered energy to commercial buildings in 2011 has been used for space heating end use. Space heating end use also accounted for 13.3% of total primary energy consumed by commercial buildings (Energy Information Administration 2014). With this being said and the fact that heating end use has a high chance of becoming more energy efficient if proper related ECMs are identified. Understanding the heating energy consumption in the building is a prerequisite for any attempt to identify related ECMs. As an example, feasibility of on-site combined heat and power generation would not be determined unless heating end use is accurately calculated. This chapter investigates the amount of inaccuracy the space heating end use would face once the sub-metered data is not available. For this purpose building 101 space heating end use metered data is compared to that of predicted by default formula used in forward modeling packages.

Space heating for building 101 conditioned zones is mostly provided by heating coils in the air handling units. Hot water from gas fired boiler circulates in the heating coils and increases the enthalpy of the air passing through heating coils. Hot water from boiler also serves the VAV boxes reheat coils and hot water radiators in the building. Design specifications of the boiler, heating coils and hot water pumps are given in Tables Table 5-11,

Table 5-12, and Table 5-13 respectively.

Table 5-11. Boiler design conditions

<table>
<thead>
<tr>
<th>Leaving water temp. (°F)</th>
<th>Entering water temp. (°F)</th>
<th>Gas Input (MBH)</th>
<th>Gross output (MBH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>140</td>
<td>2050</td>
<td>1632</td>
</tr>
</tbody>
</table>
Table 5-12. Heating coil design conditions

<table>
<thead>
<tr>
<th></th>
<th>Air flow (cfm)</th>
<th>Entering air dry bulb temp. (°F)</th>
<th>Entering air wet bulb temp. (°F)</th>
<th>Hot water flow (gpm)</th>
<th>Heating capacity (MBH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>heating coil 1</td>
<td>11340</td>
<td>42</td>
<td>180</td>
<td>5.0</td>
<td>100.6</td>
</tr>
<tr>
<td>heating coil 2</td>
<td>21400</td>
<td>53</td>
<td>180</td>
<td>5.4</td>
<td>109.4</td>
</tr>
<tr>
<td>heating coil 3</td>
<td>20500</td>
<td>53</td>
<td>180</td>
<td>5.4</td>
<td>109.4</td>
</tr>
</tbody>
</table>

Table 5-13. Hot water pumps (pump 1 and 2) design conditions

<table>
<thead>
<tr>
<th></th>
<th>water flow (gpm)</th>
<th>Pump head (ft. water)</th>
<th>Pump motor power (HP)</th>
<th>Motor rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>69</td>
<td>40</td>
<td>1.5</td>
<td>1750</td>
</tr>
</tbody>
</table>

Hot water from the two storage type water heaters is used for DHW purposes and also for attic space heating. To investigate the reliability of space heating end use energy predicted by forward energy modeling software, the required fuel energy calculated by default boiler part load equation used in forward modeling is compared to metered boiler fuel consumption.

Commercial Buildings Energy Modeling Guidelines and Procedures (MGP) by Commercial Energy Services Network (COMNET) states that energy modeler should use the following boiler part load performance curve unless she/he can provide supporting documentation for the alternative curve used. However the software uses the default equation to calculate the building baseline heating use (COMNET 2010).

\[
\text{Fuel}_{\text{part load}} = \text{Fuel}_{\text{design}} \times \text{FHeatPLC}(Q_{\text{part load}}, Q_{\text{rated}}) \tag{5-24}
\]

\[
\text{FHeatPLC} = a + b \times \frac{Q_{\text{part load}}}{Q_{\text{rated}}} + c \times \left(\frac{Q_{\text{part load}}}{Q_{\text{rated}}}ight)^2 \tag{5-25}
\]

Where,

FHeatPLC : The Fuel Heating Part Load Efficiency Curve
Fuel_{\text{partload}} : The fuel consumption at part load conditions (Btu/hr)

Fuel_{\text{design}} : The fuel consumption at design conditions (Btu/hr)

Q_{\text{partload}} : The boiler capacity at part load conditions (Btu/hr)

Q_{\text{rated}} : The boiler capacity at design conditions (Btu/hr)

a: constant, 0.082597

b: constant, 0.996764

c: constant, -0.079361.

Using equation 5-24 the fuel used by boiler for each minute is calculated. The fuel used by boiler is measured by a natural gas flow meter. Figure 5-38 shows the metered and predicted boiler fuel use for January 2014. The discrepancy of these two is defined as error. The error for each minute in January 2014 is shown in Figure 5-39.

\[
\text{error} \left( \frac{\text{MBtu}}{\text{hr}} \right) = \text{metered boiler fuel consumption} \left( \frac{\text{MBtu}}{\text{hr}} \right) - \text{fuel consumption predicted by partload equation} \left( \frac{\text{MBtu}}{\text{hr}} \right)
\]

\[
\% \text{ of inaccuracy} = \frac{\text{sum of error}}{\text{sum of metered fuel consumption}} \times 100 \tag{5-27}
\]

Where,

\[
\text{sum of error} \left( \frac{\text{MBtu}}{\text{hr}} \right) = \sum \text{error} \left( \frac{\text{MBtu}}{\text{hr}} \right)
\]

\[
\text{sum of metered fuel consumption} \left( \frac{\text{MBtu}}{\text{hr}} \right) = \sum \text{metered boiler fuel consumption} \left( \frac{\text{MBtu}}{\text{hr}} \right).
\]
Figure 5-38. Metered and predicted boiler fuel consumption, January 2014

Figure 5-39. Error in predicted boiler fuel consumption, January 2014
5.5.1 Summary

The inaccuracy percentage of fuel consumption predicted by part load equation is calculated using equation 5-27 and the results for different months are given in Table 5-14. January 2014 which had many days close to cooling design day has the lowest inaccuracy percentage (-46%). In November 2013 that is representative of shoulder season, the boiler fuel consumption is underestimated by 92%. It can be seen that part load equation has higher underestimation percentage when it is further from design conditions.

Table 5-14. Inaccuracy percentages of boiler fuel use consumption predicted by part load equation

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Inaccuracy</td>
<td>-91.8</td>
<td>-61.5</td>
<td>-46.0</td>
<td>-47.2</td>
<td>-50.5</td>
<td>-80.2</td>
</tr>
</tbody>
</table>
Chapter 6

Conclusions, Future Work, and Recommendations

6.1 Conclusions

Energy use consumption in each end use is different from that of predicted by part load curves used by forward modeling packages such as EnergyPlus and DOE-2. In this research study energy used by each end use in the case study was compared with the energy predicted by part load curves suggested by standards and defaults used in the forward modeling software.

As part of the preliminary analysis, ANCOVA analysis was done to investigate the effectiveness of the change in building management system performed in Building 101. ANCOVA results showed how much of the change in building energy use was due to the energy retrofit after putting aside that of caused by other independent variables. Among the independent variables used as covariates in the model, occupancy was the accountable for the largest portion of variability (33.8%) in the building energy use. Since Building 101 is not fully occupied, based on the ANCOVA findings it was expected to observe a difference in energy use intensity in Suite 210 (a fully occupied suite in the building that is being sub-metered) and the whole building.

Overall, the effectiveness of the part load models for five end uses, including interior lighting, plug load, ventilation, space cooling, and space heating, are analyzed. The results for the end uses show:

- Comparing the Building 101 interior lighting load profiles and the building load profile extrapolated from Suite 210 confirmed the ANCOVA results. Suite 210 extrapolated
interior lighting load profile had higher base line (15.7 kW) and peak energy use (about 110 kW than Building 101 (with base and peak load of about 10.12 and 50 kW).

- The highest discrepancy between the metered energy use and the predicted energy use was observed in space heating end use in shoulder seasons when the heating energy demand was further from its design value (-46% to -80%).
- Lighting and plug load end uses had the second and third highest rates of difference from predicted energy use (-6.9% to 59.4%).
- Third highest is plug load end use (1.1% to 37.9%)
- Ventilation inaccuracy for individual fans was up to 88.4%.
- Space cooling end use had the lowest rates of inaccuracy percentages compared to other end uses (each DX unit: -2.8% to 27.6%, total: 7.8% to -12%)

In addition to building 101, another case study was analyzed for the ventilation end use. Ventilation end use metered power use for all five supply air fans in both buildings were compared against the fan power use predicted by ASHRAE 90.1 standard suggested part load equation and OpenStudio default equation which is suggested by DOE Reference Buildings. Each supply fan showed different inaccuracy rates when compared with these two part load equations. Overall, the building 101 supply fans power use were better modeled with OpenStudio default equation, whereas second case study supply fans part load power use were better represented with ASHRAE 90.1 equation.

It would be difficult to use forward models alone to prioritize ECMs in a specific building. This suggests the need of using inverse and forward models to benefit from the onsite data collections for better predictions of the ECMs.

Overall, among the analyzed end uses lighting and plug load end uses are more dependent on the accurate predictions of the occupancy and power densities. However, the results indicate the
ventilation, space cooling, and heating are more function of the controllers of the HVAC systems. In both Building 101 cooling coil DX units and boiler load profiles different plateau levels were observed. Therefore, use of the steady state part load models for the prediction of these three end uses cannot provide the dynamic variation observed in the measured data.

6.2 Future Work

This study calculated the energy use prediction inaccuracies in for different months. Performing the same analysis in daily periods would be beneficial to control purposes and improving schedules.

Modeling each end use energy consumption from the occupancy perspective is also recommended. Applying the same principle used in lighting and plug load chapters would lead to clearer conclusion about how good each system in this building is performing. It is also interesting to run the comparison again after normalizing each end use based on occupancy.

Creating a calibrated forward model with detailed information about each end use acquired from inverse modeling would be a good complement to this study.

Cost analysis of sub-metering compared to potential energy savings for each end use would also be beneficial to encourage building managers to stakeholders to do sub-metering in the building.

6.3 Recommendations

Forward modeling packages like EnergyPlus have specific default function types as inputs for each equipment part load curve. For example, a fan part load equation in EnergyPlus
can only be given as a polynomial. As it was observed in case study 2 discussed for the ventilation end use, although supply air fans are supposed to work in a VAV manner, a step-wise function could be a better representative of fan part load performance.

Sometimes part load performance of the HVAC equipment cannot be well represented with an equation. If energy simulation software had the capability to accept real sub-metered data or time-series as input it would improve the calibrated energy model accuracy in predicting each end use contribution to whole building energy consumption.

The results of the ANCOVA analysis in this study showed how much of the variation in the building energy use can be caused other factors like occupancy and weather related variables like outside air temperature. Comparing the energy use of different buildings or even judging the effectiveness of a retrofit in one building would be unfair should the effect of variation in these independent factors be ignored. ANCOVA is a proper statistical tool to account for such variations and is recommended for such purposes.
Bibliography


Effinger, Joan, Mark Effinger, and Hannah Kramer. 2012. “Overcoming Barriers to Whole Building M&V in Commercial Buildings.” In PECI.

Effinger, Mark, James Anthony, and Lia Webster. 2009. “CASE STUDIES IN USING WHOLE BUILDING INTERVAL DATA TO DETERMINE ANNUALIZED ELECTRICAL SAVINGS.” In PECI.


