ZonePAC: Zonal Power Estimation and Control via HVAC Metering and Occupant Feedback

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ABSTRACT

Heating Ventillation and Air Conditioning (HVAC) systems account for nearly 40% of primary energy consumption by commercial buildings. Yet, these systems by and large operate in an open-loop with the building occupants. While the monitoring and feedback of comfort conditions is by (much smaller) zones, the HVAC control systems operate on energy metering and monitoring at the scale of entire buildings. ZonePAC attempts to bridge this gap between metering, monitoring and control by providing an embedded sensing and information management architecture that provides for effective participation by the building occupants in zonal HVAC settings that directly affect the building scale HVAC control system. Our results from a deployment of 65 users spread across 51 zones in a 145,000 square feet commercial building demonstrate the viability and effectiveness of ZonePAC.

Categories and Subject Descriptors

H.3.5 [**Online Information Services**]: Web-based services; H.5.2 [**Information Interfaces and Presentation**]: User Interfaces—*User-centered design*; K.4.3 [**Organizational Impacts**]: Computer-supported collaborative work

General Terms

Measurement, Human Factors, Design

Keywords

HVAC, Thermostat, Energy Estimation, Variable Air Volume, User Interface

1. INTRODUCTION

HVAC systems contribute to 39.6% of the primary energy consumption in commercial buildings [2], and is one of the prime targets for improving building energy efficiency. Several studies have shown that providing relevant energy feedback to the occupants of a building can lead to significant energy savings [8, 22]. However, the energy feedback has been limited to electricity consumption [22]and has been designed for residential buildings [4, 8].

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ZonePAC bridges this gap between building operations and the experience by individual occupants. We do this by connecting zonal monitoring and estimation that incorporates participatory occupant sensing and occupant experiential feedback to be incorporated in the building scale HVAC system.

ZonePAC estimates the heating, cooling and electrical power consumption of each zone in a Variable Air Volume (VAV) type system using existing infrastructure sensors installed as part of the Building Management System (BMS). We provide the estimated zone power consumption as feedback to the occupants of the building over the web and on mobile devices along with other thermal comfort related measurements such as temperature and setpoint.

We have built ZonePAC on top of BuildingDepot [3], an open-source RESTful web service BMS. We have deployed ZonePAC on a 145,000 sqft university building with 237 zones and over 4700 BACnet data points for a period of 10 days. This paper primarily provides the results of our data collection and its analysis regarding distribution of energy consumption across zones. We identify anomalous behavior and provide possible causes behind energy inefficiency. Since the ZonePAC system also provides the occupant with the capability to change local HVAC control settings, we provide data on user experience and the results of such individual control settings collected for 65 occupants spread across 51 zones.

2. OUR BUILDING TESTBED

Our building testbed is the Computer Science and Engineering (CSE) building at University of California, San Diego (UCSD). Built in 2004, CSE building has 145,000 sqft of floor space with 466 rooms. The HVAC design of the building follows modern design practices and employs a VAV system which can be managed by a BMS using BACnet protocol.

Figure 1 shows the system design of the centralized part of the HVAC system. UCSD has a Central Utility Plant (CUP) that operates gas driven turbines with hot and chilled water by products. Chilled water is used for large scale energy storage that accounts for nearly 14% of daily energy use of the entire campus. As a result, we do not have chillers, cooling towers or boilers in the building normally associated with commercial HVAC systems. As the weather is temperate throughout the year in San Diego, the HVAC system was designed without any humidity control. Thus, we do not have any humidifiers or de-humidifiers found in buildings with harsher outdoor environment. The centralized part of the system supplies cold air and hot water to the VAV boxes for providing conditioned air to building spaces.

The cold water from CUP, supplied at $\sim 44\,^{\circ}\mathrm{F}$, is distributed to the rest of the system by four cold water pumps, two of which are dedicated for supplying water to the Computer Room Air Conditioning (CRAC) unit for the server room in CSE. The cold water is

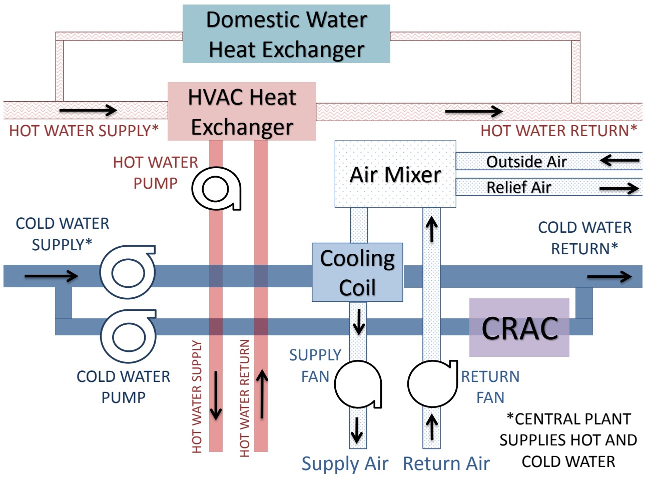

Figure 1: Centralized part of HVAC system showing details of air handler unit - cooling coils, heat exchanger, water pumps, supply/return fans, domestic water and CRAC units.

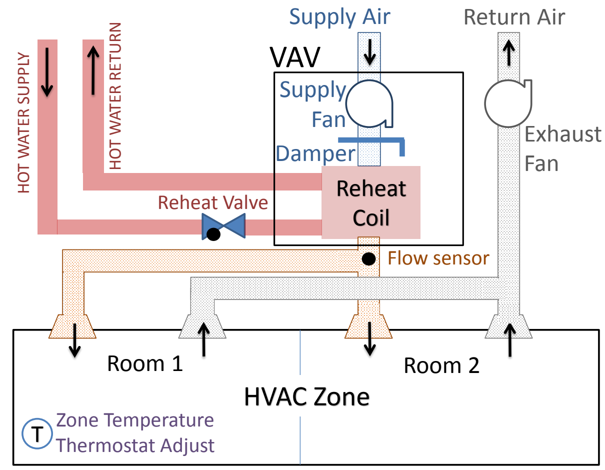

Figure 2: VAV with reheat system used for controlling the temperature of discharge air in each HVAC zone.

passed through cooling coils, which cool the mixture of outside and return air to the appropriate setpoint ($\sim 55\,^{\circ}$F) to provide supply air to all the zones in the building. The supply air is dispensed to the VAV boxes via ductwork using supply fans, and the flow of return air is facilitated using return fans. The air mixer uses economizers to increase the proportion of outside air if outdoor conditions are favourable for reducing energy usage.

The hot water from CUP, supplied in the form of pressurized steam at $\sim 325\,^{\circ}$F, passes through heat exchangers for heating up the hot water returned by the VAV boxes. Part of the hot water is used to heat the domestic water. The hot water from the HVAC heat exchanger is supplied via pipes to the VAV boxes using hot water pumps. All the pumps and the fans used in the centralized part of the system employ Variable Frequency Drives (VFDs). The CRAC units do not use the hot water, and have an electric reheat system for environment control.

Figure 2 shows the HVAC design of the VAV boxes in CSE. The amount of cold air supplied to each zone is modulated using a damper, and a flow sensor measures the airflow rate. The zonal temperature is controlled by modulating the amount of cold air and by using the hot water coil to reheat the air. The amount of hot water used in heating the air is modulated using an electronically controlled 2-way valve. Every zone has a thermostat which measures the current temperature, and acts as the feedback for the VAV control system. Occupants are allowed to change their temperature setpoints by $\pm 1\,^{\circ}$F using the thermostat dial.

The BMS operates the HVAC system on a weekly schedule. On weekdays, the HVAC system is put to "Occupied" from 6am to 6pm, then changed to "Standby" mode till 10pm, and switched to "Unoccupied" for the rest of the night. In the "Occupied" mode, a minimum amount of airflow is maintained for ventilation, and the minimum airflow setpoint for each zone is determined based on its maximum capacity. The temperature of the zone is maintained within $4\,^{\circ}$F range, and the exact range is determined by the temperature setpoint set by the BMS as well as the thermostat adjustment set by the occupant. In the "Standby" mode, the airflow is reduced to minimal amount, and the temperature range is increased to $8\,^{\circ}$F, and in the "Unoccupied" mode, the temperature range is further increased to $12\,^{\circ}$F. The HVAC system remains in the "Unoccupied" mode on weekends and holidays, and if an occupant were to use a zone during that time, she can express her occupancy by pressing a button on the thermostat. The basement student labs and public circulation area are an exception to the schedule, and are always set to "Occupied" mode.

As an experimental testbed, our building is also instrumented to allow us to measure the total cooling and heating thermal power, and electric power consumption of the entire HVAC system as well as the lighting, computer room and plug loads subsystems. This allows us to estimate and track zonal power use as discussed next.

3. ZONE POWER ESTIMATION

The goal of ZonePAC is to provide a real-time estimate of total power consumption of individual HVAC zones to the building occupants. We use the measurements from existing sensors, and apply first principles to estimate power consumption of an HVAC zone which consists of three parts - *cooling thermal*, *heating thermal* and *electrical*. The cooling thermal power is used for converting the warm mixed air to the cold supply air, the heating thermal power is used for reheating the cold supply air when the temperature setpoint of the zone is too high to be satisfied by reducing the supply air to minimum, and the electrical power is used by the fans and the pumps used for supplying cold air and hot water to the zones from the central HVAC equipments.

3.1 Cooling Thermal Power

We estimate cooling thermal power using the heat transfer equation:

$$Q_{cooling} = \rho * C * q * (T_{zone} - T_{supply}) \qquad (1)$$

where, ρ = density of air at $20\,^{\circ}$C, C = specific heat of air, q = rate of airflow, T_{zone} = zonal air temperature, T_{supply} = supply air temperature.

In the absence of sensors to directly measure the supply air temperature of each zone, we approximate it by the supply air temperature as measured by the central air handler unit (AHU) as it exits the cooling coils. This, of course, neglects the temperature loss due to imperfect insulation and leaks in the air ducts. Similarly, we estimate the return air temperature by the zonal temperature as measured by the thermostat in the zone. Finally, the airflow rate is measured directly by the flow sensor in the VAV box.

For HVAC systems which also provide humidity control, the power consumption estimate would also have to include the latent heat transfer. The corresponding sensors measuring the supply air

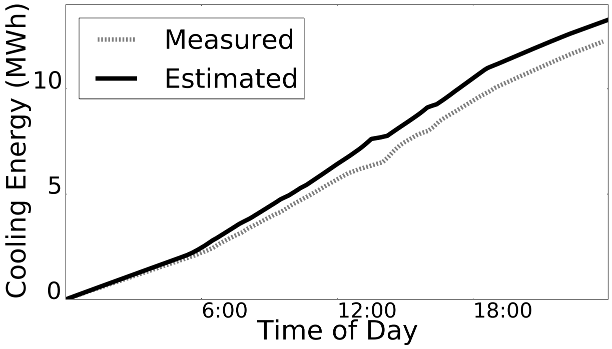

Figure 3: Comparison of aggregate cooling power estimated and measured cooling power from installed flow and measured sensors in the CSE building on July 30, 2013.

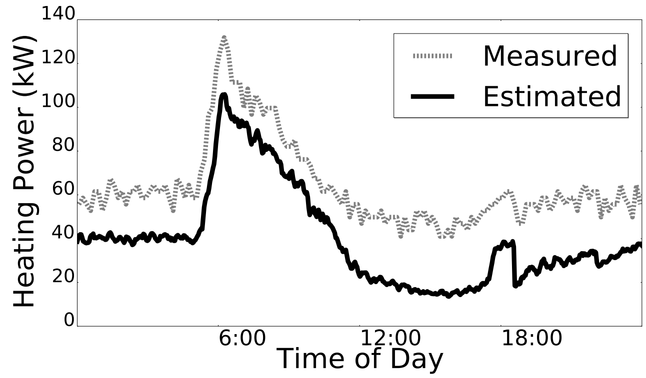

Figure 4: Comparison of estimated heating power and measured heating power from installed flow and measured sensors in the CSE building on August 14, 2013.

humidity and the return air humidity would be required for an accurate estimate.

We establish the accuracy of our estimate by comparing the total cooling power as measured by the building thermal power meter and the aggregate cooling power obtained by applying equation 1 to all the zones of the building. Due to implementation issues, we use an estimate of the power use by CRAC unit based on empirical measurements that showed an average use by the CRAC unit in a narrow range of 0.50 to 0.60 MMBTU/hour.

Figure 3 shows the comparison between cumulative estimated cooling power and the measured cooling power for July 30, 2013. The results show an average error of 12.8% across one week of measurements. We find that our estimates are accurate during the night time, but we frequently overestimate during the day. This overestimation is due to the fact that we do not have dedicated air ducts for return air, and it is directed through plenum space to the AHU. The leaks in return air reduces the air temperature when it reaches the AHU. Another reason for the overestimate is that we do not account for outside air mixed with the return air before cooling. After adjusting for both the return air losses and mixing of outdoor air using measured parameters, we found that the average error of our estimated cooling power improved to 5.1%.

3.2 Heating Thermal Power

The only sensor connected to BACnet related to the hot water system is the "Reheat Valve Command", which is the valve position command sent by the VAV digital control system. The reheat valve controls the amount of hot water through the heating coil, and the building plans show that our building uses a modulating 2-way electronic control valve. There are two types of modulating valves generally used in hot water coils - linear and equal percentage, and both the types of valves are designed to provide linear heat output with change in valve position. We obtain the maximum heat output of each VAV box from the building plans, and estimate the heating thermal power as:

$$Q_{heating} = H * Q_{max} \tag{2}$$

where, H = reheat valve command, Q_{max} = maximum heat output of heating coil.

To evaluate the accuracy of our estimation we compared the measured heating thermal power with the aggregate estimated heating power, similar to the methodology followed in Section 3.1. Figure 4 compares the estimated and measured heating power across one day (August 14, 2013). Although the estimation model captures the trends in power consumption appropriately, the gap between measured and estimated power is much larger with an average error of 26.7%. There are multiple reasons why this estimate could be so far from the actual power consumption. The "Reheat Valve Command" tag indicates the position of the valve as controlled by the VAV, but there is no sensor which measures the actual position of the valve. It is possible that the value is stuck at a position different from that indicated by the "Reheat Valve Command", and causes leakage of hot water. Another reason for underestimation is that the hot water pipes are not insulated, and there is heat loss even without usage of water. As hot water temperature is not available on a per zone basis, it is not possible for us to estimate this loss accurately.

3.3 Electrical Power

We have added power meters in the CSE building which measures the total mechanical power, and HVAC systems account for 13% to 46% of total electric power on a typical summer day. The electricity consumption depends on the air and water demand from the HVAC zones in the building, and thus, electric power consumption needs to be attributed to each zone. The fans and pumps used in CSE are Variable Frequency Drives (VFDs), and the speed of the motor is directly proportional to the amount of airflow pumped to the rest of the building. The power consumed by the VFDs is proportional to the cube of the fan speed. Thus, to estimate the electric power attributed to each zone, we use the following equation:

$$Q_{electric} = q^3 * Q_{totalelectric}/\Sigma q^3 \tag{3}$$

where, q = rate of airflow, $Q_{totalelectric}$ = total electrical power measured, Σq^3 = summation of cubic airflow through all zones.

Some of the VAV boxes are equipped with additional supply fans, to maintain the required air pressure in large zones. Also, some of the zones such as restrooms and kitchenettes have exhaust fans in them. We determine the status of these terminal fans using BACnet datapoints available, and we assume they operate at their rated power provided by manufacturer as there are no power measurements available. We subtract the contribution of the terminal fans from $Q_{totalelectric}$ in equation 3, and attribute their power to the corresponding HVAC zones directly. We ignore the contribution of some of the smaller equipments such as the air compressor used for operating pneumatic valves and hot water pumps, as we do not have their power measurements and their contribution to the total mechanical power is minimal.

4. IMPLEMENTATION

ZonePAC has been implemented on top of BuildingDepot [3], an open source RESTful API based building management web ser-

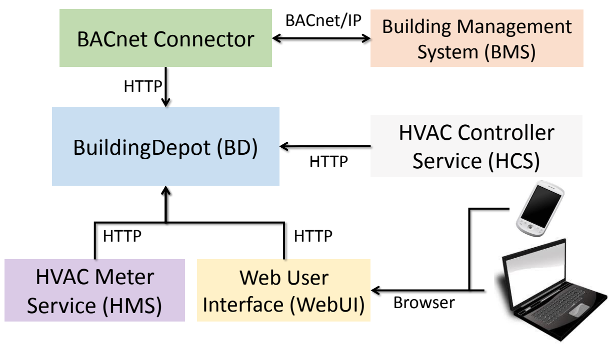

Figure 5: System Architecture of HVAC Meter

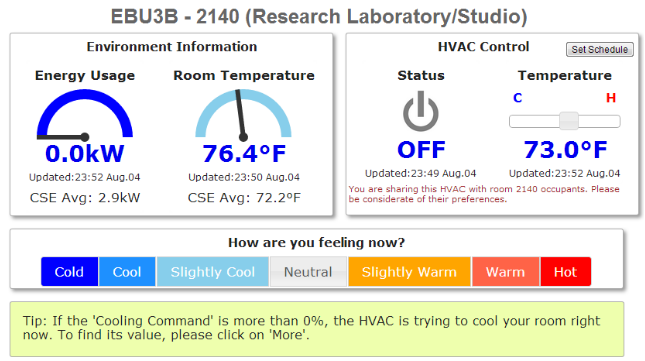

Figure 6: Screenshot of Web User Interface

vice. The data from BACnet sensors are collected using our BACnet connector, and the HVAC Meter Service estimates the power consumption of each zone as explained in Section 3. The Web User Interface (WebUI) reads the data from virtual power sensors created by ZonePAC, and presents it to the occupants. The interface also allows for change in control of HVAC zone settings. Figure 5 shows the software architecture of our system.

4.1 BuildingDepot

BuildingDepot (BD) is a web service based Building Management System (BMS) designed for next generation Smart Building applications [3]. The sensor data is stored in a timeseries database from different types of sensors in the building. The sensor data and metadata is organized in a uniform structure and exposed for access via a RESTful API. The API allows the sensors to be accessed by its context like location or sensor type, provides for creation of virtual sensors, and allows customized organization of data using sensorgroups.

The BACnet connector is a PC connected to the BACnet network as a Foreign Device. The connector continuously polls the data points from BACnet, and posts it to BD. The connector also writes to the BACnet points as indicated by BuildingDepot applications with appropriate permissions.

The HVAC Meter Service (HMS) subscribes to the relevant BACnet points needed for power estimation, and BD notifies HMS as new data is posted from BACnet via a notification url. HMS estimates the power as outlined in Section 3 and posts the computed power back to BD as virtual sensor data. HMS also computes related useful data such as aggregate heating and cooling power, zone power consumption per unit area, average zone temperature, etc.

4.2 Web User Interface

We implement an interactive webapp on top of BD which reads sensor data from both BACnet and ZonePAC. Interested occupants register their email address, and WebUI administrators provide permission to access the sensor information after manual verification. Access control among users is enforced by BD, and users are only provided information about zones to which they have physical access.

4.2.1 *Feedback Information*

The webapp has been designed for access from both desktop and mobile browsers. Figure 6 shows a snapshot of the desktop version. The most pertinent information such as the room temperature as measured by the thermostat, and the energy consumption as estimated by ZonePAC are displayed prominently. Users can provide feedback on their thermal comfort on a scale of -3 to +3, compliant with ASHRAE Standard 55 [1]. There are 17 different BACnet points related to each HVAC zone in CSE, and measurement from all the points are shown in the "Details" section. The user can also see the historical trend of each of the data points by clicking on the values being measured.

4.2.2 *Control Settings*

There are two types of control provided to the users - change in temperature setpoint, and change in HVAC occupancy status. For each of the zones, a common temperature setpoint is set by the BMS. The setpoint is typically set to 72 °F, and is modified if the occupants of the zone register a comfort complaint with the building manager. We allow the users of WebUI to change their temperature setpoint by $\pm 3\,^{\circ}$F from the preset setpoint. The setpoints are allowed to be changed once every 10 minutes per zone. A note at the bottom of the controls section informs the users of the neighbouring rooms with which they are sharing their zone. When there are conflicting thermal comfort requirements, we expect the occupants to resolve their differences by direct communication.

As explained in Section 2, there are three types of occupancy modes supported by the HVAC system in CSE: "Occupied", "Standby" and "Unoccupied". When a user turns OFF the HVAC using WebUI, the occupancy mode is changed to "Standby" during weekday (6am - 10pm), and is changed to "Unoccupied" on nights and weekends. We chose to use "Standby" mode during weekdays as the zone status is likely to be changed if occupants come in to the zone again, and the shallow setback temperature of "Standby" will reduce the thermal discomfort caused to the occupants. During the weekends, when the HVAC zone is turned ON, the zone status is changed to "Occupied" mode for two hours. The change in HVAC status is also restricted to once every 10 mins per zone.

The HVAC Controller Service (HCS) relays the commands provided by WebUI to the corresponding BACnet points. The HCS was designed such that the control service could be made unavailable to the users if needed without affecting the feedback services provided by WebUI.

4.2.3 *Energy Saving Suggestions*

In order to encourage the users of ZonePAC to save energy, we include a suggestion box which shows personalized energy saving recommendations. For example, if the VAV is cooling a zone excessively for over an hour, a suggestion is provided to increase the setpoint by 0.5 °F to save energy. The suggestion box also provides "tips" for using the WebUI to better control the HVAC system, and encourages the user to learn further about the sensor information provided. To provide a comparison with other zones, we display the average temperature and average zone power normalized by zone area as shown in Figure 6.

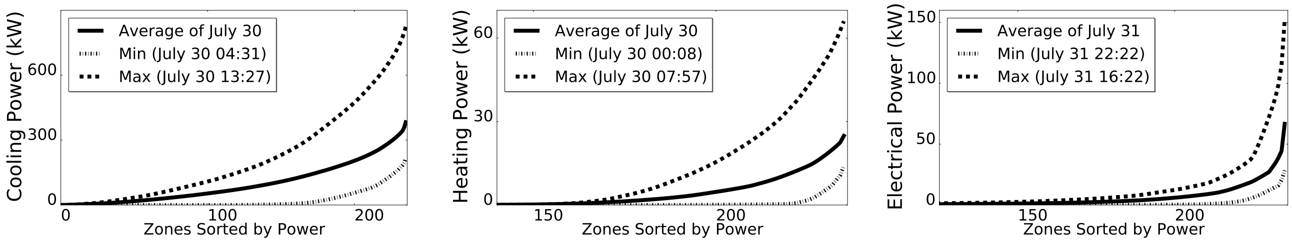

Figure 7: Power Distribution across HVAC Zones

5. RESULTS

The estimates on zone power using ZonePAC enables us to collect historical data and analyze the trends in energy consumption. We present our insights from observing ZonePAC data for 10 days across the 237 zones in CSE. Further, we deploy ZonePAC WebUI in CSE, and present the data collected for 65 registered building occupants.

5.1 Power Consumption Trends

In order to understand the distribution of HVAC power across the zones in the CSE building, we present the cumulative contribution of individual zones to the total power. Figure 7(a) shows the distribution for HVAC cooling for the average, the maximum and the minimum power consumption for July 30, 2013. The peak cooling power is more than double the average power consumption and which is the reason HVAC system is the dominant target for energy reduction during demand response events in our campus. On an average, 50% of the zones consume only 20% of the cooling power, and the remaining half of the zones account for 80% of the zones. Thus, with limited resources available, it will be prudent to target power intensive zones for aggressive energy saving strategies such as occupancy based HVAC control for maximum benefits. Similar trends can be observed in the distribution of heating and electrical power in Figures 7(b) and 7(c), with over 150 zones accounting for less than 2% of the total power.

Ironically, the most power intensive zones are the ones which house HVAC equipment and building substation. The equipment rooms are followed by basement computer labs. As there is no fixed schedule followed by the students, the labs are always kept conditioned. Further, as the minimum cooling air is determined by the maximum capacity of the labs, these zones are overcooled when fewer occupants are present causing them discomfort. An occupancy detection system would not only save energy by reducing the airflow ventilation with change in occupancy, but also provide better thermal comfort.

The thermostat adjust control in basement labs are often kept in their extreme positions, further exacerbating the effect of over cooling. As the labs are a shared space, no one takes responsibility for temperature control, and students are often unaware of the thermostat location. When the thermostat is set to decrease the temperature setpoint, there is excessive use of cooling power, and when it is set to increase the setpoint, heating coils are used with minimum cooling air. Thus, we find basement labs to be dominant in both heating and cooling power. We observed similar thermostat settings in several spaces which are shared - student lounge, conference rooms, lobby, kitchenette, etc. The sizes of the shared zones are large as they are designed for higher capacity, and hence, the minor changes in thermostat leads to large losses in energy. An ideal energy saving strategy would be to provide temperature control to occupants only when they are physically present in the shared space, and reset to energy efficient settings once the occupant leaves.

To examine energy inefficiency in smaller zones, we plot the trends in zone power consumption per unit area, as shown in Figure 8. We find that aberrant thermostat settings cause energy inefficiencies even in smaller zones. Although the thermostat could have been set according to occupant comfort preference, the feedback from our WebUI (Section 5.2) indicate that many occupants are unaware of the thermostat location and are uncomfortable with the current temperature settings. This is not unreasonable as a single zone can constitute multiple office rooms and the thermostat is located in only one of the rooms. By providing the WebUI, the occupants were both informed of the measured temperature, and could change their settings if they were not comfortable.

To further investigate the relation between thermostat setpoint and the zone power consumption, we manually inspect thermostats in the zones which required abnormally high heating. Although the facilities management mandates a range of $\pm 1\,^{\circ}\mathrm{F}$ from the predetermined setpoint, we found several thermostats allowed deviation of over $3\,^{\circ}\mathrm{F}$. Further, the change in the thermostat dial did not lead to a linear change in the temperature setpoint, and each thermostat had its unique mapping to actual changes in setpoint. For instance, the sensitivity of one of the thermostats was so high that a small change in the dial would change the setpoint by several degrees, and the midpoint of the analog adjust in another thermostat corresponded to an increase in setpoint by $3\,^{\circ}\mathrm{F}$. Such thermostat miscalibrations can lead to unintended temperature settings and cause both thermal discomfort and wastage of energy. We adjusted the thermostats for 8 of the zones to reduce the reheat required, which resulted in 50.7% savings in heating power. However, since our adjustments were not fine enough, it resulted in an increase in airflow rate which led to no savings in the total power.

Use of spaces for unintended purposes can also lead to unexpected effects on the HVAC system. For instance, one of the office rooms was repurposed to host computing equipment and the HVAC was requested to be always in "Occupied" mode and the thermostat was adjusted to its minimum position to satisfy the equipment cooling needs. However, as the "Occupied" mode has a narrow tolerance of $4\,^{\circ}\mathrm{F}$, the room was also heated at night when its cold outside. Facilities personnel informed us that such zones with high cooling demands can also cause the supply air temperature to be lowered as the maximum airflow rate is not enough to cool the zone. Reduction in supply air temperature leads to overcooling by all the areas served by the same air handler unit, and hence, such zones are installed with a special cooling unit to satisfy the additional cooling demands. However, the zones are difficult to locate unless the occupant directly contacts the facilities management.

We also found several faults on analyzing the data further. Several zones did not change the heating setpoint in the "Unoccupied" mode, and this led to use of heating coils on nights and weekends; some zones had missing BACnet points, leading to inappropriate control settings; airflow in some zones was high even when heating

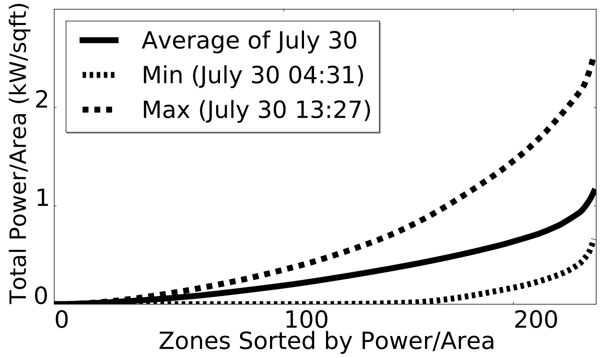

Figure 8: Distribution of HVAC Zones by Total Power per Unit Area

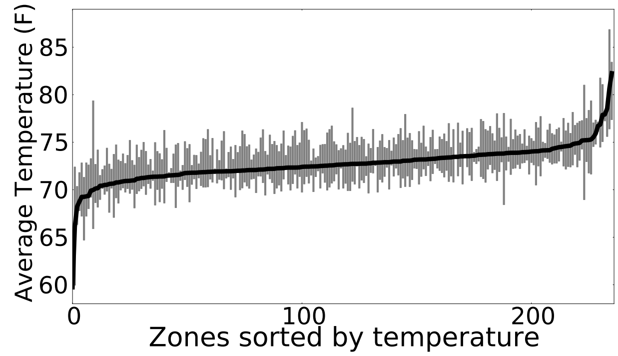

Figure 10: Distribution of average zone temperature with error bar for all the zones in the building

coils was in use or when the zone was in "Standby" or "Unoccupied" modes; and, several sensors were found to be miscalibrated or faulty.

5.2 Occupant Feedback

We deployed WebUI of ZonePAC for 10 weekdays at CSE, and report results obtained from 65 registered users across 51 zones. Participation was voluntary, and we did not provide any incentives to the occupants apart from providing feedback and control of HVAC system. We provided only the measurements from HVAC sensors on the first four days of deployment, then added the provision to change settings of the temperature setpoint and HVAC status. After two days of allowing control of settings, we added energy savings suggestions to the WebUI as explained in Section 4.2.3. We received over 140 feedback inputs on thermal comfort, and users changed their HVAC settings over 130 times during the course of the control period.

From the distribution of average zone temperature shown in Figure 10, we observe that most of the zones fall in the comfortable range of 70 °F to 75 °F. The zones which show large deviations from the ideal temperature are either anomalous or unoccupied, such as the server room (60 °F), an unused office space (82 °F)and a zone with a damaged damper (78 °F). The thermal comfort feedback we received from WebUI confirmed that most users were comfortable, as 60% of the feedback inputs indicated acceptable comfort levels as per ASHRAE Standard 55 [1], i.e., Slightly Cool, Neutral or Slightly Warm.

Before the control of HVAC settings were enabled, most of the comfort complaints were received when the HVAC system was either running in "Standby" or "Unoccupied" mode. This indicates that occupants were not aware that they could change the status by pushing the button on the thermostat. After the control was enabled, the majority of the complaints were from zones which failed to meet the setpoint despite the HVAC settings being correct. We found a number of zones in which occupants felt colder or warmer than the measured temperature, and a few zones which were slow to respond to the changes in zone temperature. The former problem indicates that in multi-office HVAC zones, a single temperature sensor does not represent the thermal environment of all the rooms in the zone, and a more granular temperature measurement is required for providing better thermal comfort to the occupants. The latter problem could be fixed by tuning the control system of the VAV box to respond faster to the changes in measured temperature.

Figures 9(b) and 9(c) show the distribution of control inputs from the users of WebUI across a week. With the flexibility to change HVAC status, many users put the zone to "Standby" mode if they were not currently in their office. The majority of the ON commands were all received during the period when HVAC would have been normally OFF (6pm - 6am). Some of the users also tried to duty cycle the HVAC system between ON and OFF to save energy. The changes in temperature setpoints do not follow any clear trends, as users changed the setpoint to whatever they felt comfortable with. Most users were content with their change in temperature settings in their first attempt, and only a few users would change their setpoint more than once a day.

Figure 11 shows the energy consumption of for six days of the deployment of ZonePAC for the 51 zones involved in the user study. We display the energy values only from 6am - 6pm as there was a bug in the WebUI which kept some of the zones in "Occupied" mode throughout the night on Monday, and there was an exception set to the regular schedule which set the HVAC zones to "Occupied" mode on Friday night. Apart from these exceptions, the energy consumption at night follow similar trends shown in Figure 11. On an average, we measure 5% energy savings after providing control over HVAC settings to the users. The energy consumption on Wednesday is unusually low due to a Demand Response(DR) event from the campus managers which put all the zones in the building to "Unoccupied" mode from 2pm to 4pm. We do not include Wednesday in our savings estimate. The difference between energy consumption on the days with and without energy saving suggestions were negligible.

The low energy savings obtained were expected as occupants are not responsible for the power bills in their offices and are not completely in control of the HVAC settings. However, absolute energy savings do not necessarily capture the motivation of the users to save energy. For example, if a zone is already being conditioned with the minimum amount of airflow possible, changes in setpoint can only increase the energy consumption of the zone. One of the users indicated in her feedback that she would prefer to be slightly cold to prevent reheat of the system and waste energy. However, significant energy savings could be obtained if the occupants were given more options that could save energy. For instance, we plan to allow users to set their schedule on the WebUI, and the HVAC system would be conditioned according to user specific schedule rather than a global schedule.

6. DISCUSSION

We have built ZonePAC for a modern building with VAV type HVAC system, and provide feedback to the occupants using a webapp. There are other types of HVAC systems used in commercial

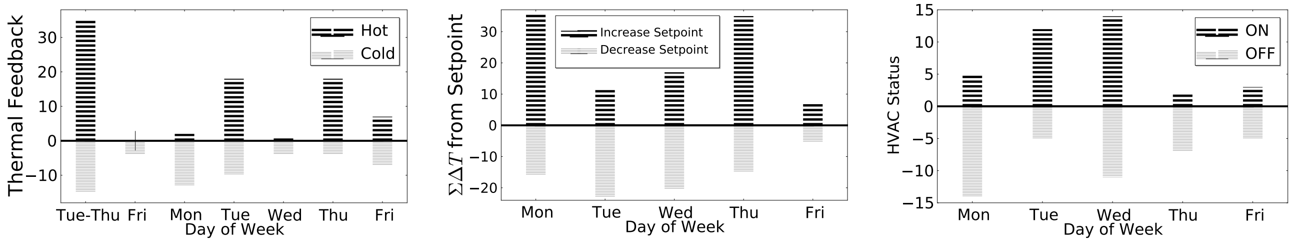

Figure 9: Feedback and Control using Web User Interface: Figure 9(a) shows the distribution of the thermal feedback received for 10 days of deployment, Figure 9(b) shows the change in setpoints selected by the users for one week of control, and Figure 9(c) shows the HVAC status commands sent by the users for the control week.

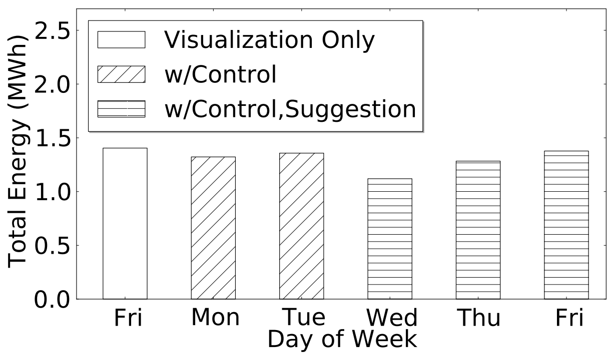

Figure 11: Average energy consumption of zones which were part of the feedback experiment

buildings which do not use a centralized plant and use humidity control equipments. From the general principles presented in this paper, it is possible to estimate zone power consumption in different types of HVAC systems using the measurement from installed sensors and modeling the heat transfer process.

Occupancy based HVAC control has been proposed for significant improvement in energy efficiency of buildings [10, 24]. ZonePAC provides insight into a variety of situations in which occupancy information would be useful for saving energy (Section 5.1). With power consumption information at the zone level, researchers would be able to design more optimized solutions that would exploit the inefficiencies in current HVAC systems.

Feedback from occupants using ZonePAC showed that they care about their energy footprint on the building (Section 5.2). Although our WebUI provides the information about HVAC and zone power consumption in a clear manner, it does not adopt sustainable HCI solutions such as use of social network [19] or providing comparison against other zones [22]. We hope ZonePAC acts as a stepping stone to develop better feedback interfaces so that occupants are incentivized to save energy.

Several parameters used for estimating HVAC zone power required careful study of building plans. Although the information from sensors installed in the building were readily available through BACnet, the details about the type of VAV box, the size of the air ducts and water pipes are not provided in a manner that could be easily used for developing applications such as ZonePAC. Automated methods to scan the existing building plans and extraction of relevant information to form a building model would significantly accelerate development of smart building applications.

7. RELATED WORK

HVAC power estimation is well understood, and detailed energy analysis can be done using established simulation engines such as EnergyPlus [7] and DOE-2 [12]. Building models are built using the simulation tools, and the HVAC system is tuned based on the results of such analyses. The methodology is followed for both design of new systems [5], as well as existing buildings [6].

Continuous commissioning [20] and automated Fault Diagnosis and Detection (FDD) [16] have been proposed for monitoring of HVAC systems using sensors and BMS. Mills et al. [20] report 16% median energy savings in existing buildings due to commissioning, and the savings were accrued due to faults corrected in all parts of HVAC system [21]. FDD methods have also advanced over the years from practical decision based rules [23], system models [18] to data driven approaches [9]. However, the commissioning and energy information systems developed are designed for domain experts, and no feedback is provided to the building occupants. Moreover, energy wastage due to behavorial faults such as anomalous thermostat settings remain unchecked. ZonePAC provides visibility into energy consumption of each zone, and the opportunity to detect behavioral faults using modern FDD methods. By providing feedback directly to occupants, ZonePAC also provides the opportunity for the behavorial faults to be self-corrected.

Prior work has shown that energy feedback can be effective in motivating users to save energy [4, 8]. In a energy conservation study, Peterson et al. show that motivated occupants saved 20% more energy when given feedback on energy consumption in a college dormitory [22]. Recognizing the importance of feedback, plug meters have been developed to provide feedback on appliance power consumption [15]. However, to the best of our knowledge, ZonePAC is the first attempt to provide feedback on HVAC energy consumption to building occupants.

Prior work has given web based feedback on HVAC system to the building occupants. Krioukov et al. [17] build a personalized control system, allowing occupants to view the current status of the system and change settings. Erickson et al. [11] and Jazizadeh et al. [13, 14] gather thermal comfort feedback from occupants, and change the HVAC settings to match their thermal needs. Unlike ZonePAC, none of the systems provide energy feedback to the occupants. Erickson et al. [11] do estimate zone energy consumption using heat transfer equation, but do not validate its accuracy and do not account for electrical power consumption. ZonePAC provides occupants with similar web based HVAC information and includes the estimated zone power consumption.

8. CONCLUSION

We have built ZonePAC, a real-time HVAC zone power estimation system, built on top of a RESTful web service. We present the trends in zone energy consumption, and provide insights into improving the energy efficiency of HVAC system. We find that the usage characteristics of a zone such as aberrant thermostat settings and presence of cooling demanding equipment can lead to significant wastage of energy. Further, we designed and deployed an interactive webapp which provides HVAC sensor information, zone power consumption and control of local HVAC settings to the occupants of the building. We present the data collected from the feedback study over a period of 10 days, and show that HVAC energy feedback to the occupants in commercial buildings could be used to motivate them to save energy.

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