Zone-Level Control Algorithms Based on Occupancy Information for Energy Efficient Buildings

Siddharth Goyal, Herbert A. Ingley and Prabir Barooah

***Abstract*— We examine the problem of how to use occupancy information of various fidelity to reduce the energy consumed in maintaining desired levels of thermal comfort and indoor air quality (IAQ) in commercial buildings. We focus on the zone-level control, where the control inputs to be decided are the supply air (SA) flow rate and the amount of reheat. We propose three control algorithms with varying information requirements: (i) *POBOC*, that requires long-horizon accurate prediction of occupancy and a model of the hygrothermal dynamics of the zone, (ii) *OMBOC*, that requires only occupancy measurement and a dynamic model, and (iii) *Z-DCV*, that requires only occupancy measurement. The first two strategies use a model predictive control framework to compute the optimal control inputs, while the third one is a pure feedback-based control strategy. Simulations with a calibrated model show that significant energy savings over a baseline controller, the kind usually used in existing buildings, is possible with the last two strategies, that is, even without occupancy prediction. Trade-offs between complexity and performance of the control algorithms are discussed.**

I. INTRODUCTION

Buildings are one of the primary energy consumers worldwide. In the United States, they consume about 40% of the total energy consumption. Inefficiencies in the building's HVAC (Heating Ventilation and Air-Conditioning) operation, which are mostly due to the sensing and control strategies used, cause a large fraction of energy uses to be wasted.

A common configuration of HVAC systems used in modern buildings is the so-called variable-air-volume (VAV) system, where a building is divided into a number of "zones". The flow rate of air supplied to a zone is controlled through dampers in the "VAV box" of the respective zones. Most commercial buildings in the United States maintain temperatures at certain pre-specified desired values (set points) almost all the time, even when they are unoccupied. Moreover, a minimum amount of air is always supplied to the zone. These minimum flow requirements come from IAQ standards set by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers), which dictate that the air supplied to a zone should be at least $30-40\%$ of the designed maximum at all times, unless the zone's occupancy, i.e., number of occupants, is known. Since occupancy information is usually not available, a large amount of air is supplied even in unoccupied times. High flow rate causes high consumption in fan, AHU (Air Handling Unit) and reheating energy.

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As a concrete example, data collected from a zone in a building at the University of Florida campus is shown in Figure 1. During the entire 24 hour period, the mass flow rate of supply air is rarely below $290\ cfm$. The AHU supplies air at around $55°$F, while the measured supply air (SA) temperature is almost always higher than that, meaning the reheating is performed continually. The zone temperature is maintained around the set point $72°$F, no matter if the zone is occupied or not. Unlike residential buildings, in this case increasing the temperature set point in the summer will in fact increase energy consumption since even more reheating will have to be performed.

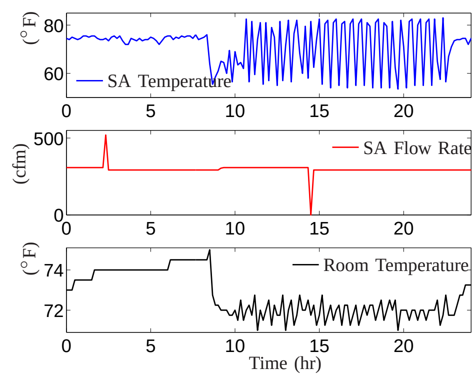


Fig. 1. Measured supply air (SA) temperature, mass flow rate and zone temperature in a building (Pugh Hall) at the University of Florida, Gainesville, Fl during July 29, 2011, where 0 represents midnight.

The main function of the HVAC system is to ensure health and comfort of the occupants. When the building or a zone is not occupied, there is no need to maintain temperature or provide large amount of ventilation air. We conjecture that there is room for substantial energy savings *by not supplying air or maintaining comfortable temperatures when it is not needed to do so*. To implement such a strategy, occupancy information needs to be incorporated in the operation/control of the building. Moreover, if the focus is on energy conservation while satisfying constraints on thermal comfort and IAQ etc., then the proper framework is to use optimal control methods. A number of papers that have studied optimal control methods for energy efficient building controls [1], [2], [3], [4], [5].

In this paper, we examine how much energy can be saved by using information on occupancy and system dynamics, and how the savings depend on the fidelity of the information. As more fine-grained information is available, we may be able to save more, but the control algorithm may become more complex. We focus on the zone level control, where two control inputs are to be decided: the mass flow rate and

SA temperature.

To apply optimal control methods, one needs a model of the system's dynamics, as well as predictions of the exogenous inputs such as occupancy and weather forecasts. When both occupancy and weather information are known a-priori, one can apply MPC (model predictive control) to compute the control inputs. We develop a control algorithm, called *POBOC* (Predicted Occupancy Based Optimal Control), that uses occupancy prediction, weather forecasts, and a model of the hygrothermal (temperature and humidity) dynamics of the zone to compute the control inputs. IAQ dynamics is not modeled, instead constraints are posed on the air flow rate so that IAQ is assured.

Obtaining occupancy prediction, especially for long time horizons, is quite challenging. Therefore, we next develop a controller for the case when occupancy forecasts are not available. Instead, we assume that only occupancy measurement is available. It uses the measured occupancy as a prediction for short time horizons to solve an optimization problem. The resulting controller is called the *OMBOC* (Occupancy Measurement Based Optimal Control).

Finally, we examine the case when predictive models for either hygrothermal dynamics or occupancy are not available, but occupancy measurements are available. In this case, we develop a feedback control scheme to decide on the flow rate based on the measured occupancy. Temperature control is performed as it is done currently in existing buildings, which we call the baseline controller. The resulting control algorithm is called the *Z-DCV* (Zone-level Demand Controlled Ventilation) controller due to its similarity with DCV (demand control ventilation), which is currently used in a small but growing fraction of commercial buildings [6].

There has been a growing interest in developing energy efficient control strategies [3], [4], [5]. These papers do not take humidity into account in their problem formulation, while humidity is as important in ensuring thermal comfort of the occupants. The paper [2] seeks to reduce energy use by varying the temperature set point of the zone. The papers [7], [2] examine the energy efficient control problem from an optimal control viewpoint as well. The objective function minimized in these papers contains Predicted Mean Vote. A stochastic MPC solution was proposed in [1] that explicitly accounted for the uncertainties in weather forecasts. None of these papers, however, addresses the problem we do - examine the trade-off between efficiency achieved and the information requirements/complexity of the control algorithm.

The rest of paper is organized as follows. The common control logics used in the buildings are described in Section II. Section III describes the model of a building thermal dynamics and power consumption. Section IV describes three proposed control strategies mentioned above. Simulation results with the proposed controllers are shown in Section V. Section VI concludes the paper and discusses future work.

II. Current Practice in Zone Control

A schematic of a single-zone building with a VAV box is shown in Figure 2, where T^{in}, W^{in} and m^{in} represent the temperature, humidity ratio and flow rate of SA entering the zone, respectively. Temperatures of conditioned air and outside air are represented by T^{AHU} and T_0, and occupancy (number of people) is denoted by n^p. The heat gain Q depends on the occupants, solar radiation entering the zone and the heat generated by equipments, lights, etc. The temperature and humidity ratio of the air in the zone are represented by T_1 and W, respectively.

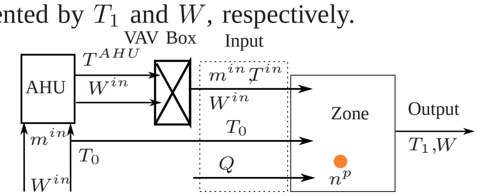


Fig. 2. A schematic of a single-zone HVAC system with an AHU and a VAV box.

A common control logic used at the VAV boxes to maintain IAQ and temperature in a zone is the so-called "Single Maximum" control [8], which we call *baseline controller* in this paper. In this scheme, the control logic is divided into three modes based on the zone temperature: (i) Reheating (ii) Dead Band and (iii) Cooling, which are shown schematically in Figure 3. If the zone temperature stays below the "Heating Set Point (HTG)" for more than 10 minutes, the reheating mode is turned on. Similarly, if the zone temperature remains above the "Cooling Set Point (CLG)" for more than 10 minutes, the cooling mode is turned on. If the zone temperature stays between HTG and CLG for more than 10 minutes, the dead band mode is turned on. In the reheating mode, air flow rate is set to the minimum allowed value and the SA is reheated by using the reheat coils in the VAV box. In the dead band mode, no reheating is performed (i.e. $T^{in} = T^{AHU}$), and SA flow rate is set to the minimum allowed value. In the cooling mode, no reheating is performed, but the SA flow rate is varied to maintain the desired temperature in the zone.

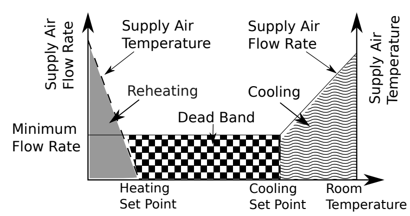


Fig. 3. Schematic representation of the baseline control strategy ("single maximum") used at the VAV terminal boxes of commercial buildings.

III. Hygrothermal dynamics and power model

In this section, we describe a model of the hygrothermal dynamics of a single zone, along with models of the power consumed in conditioning and reheating the supplied air. These models will be used by two of the control algorithms proposed later in Section IV to compute the optimal control signals. We do not model the dynamics of IAQ, which is determined mostly by concentrations of CO_2, VOCs (volatile organic compounds), which are extremely difficult to model.

For the sake of simplicity, we ignore dynamic interactions among zones, and assume that one AHU supplies air to only one zone. The output variables of the model are zone temperature T_1 and humidity ratio W. The vector u of controllable input signals and v of measured exogenous inputs to the model are:

$$u = [m^{in}, T^{in}],\ v = [W^{in}, Q, T_0]^T, \tag{1}$$

The model is a set of nonlinear coupled ODEs

$$\dot{X} = f(X, u, v), \tag{2}$$

where the state vector $X = [T^T \quad W]^T$ consists a vector of temperatures, T, which consists of zone temperature (T_1) and the temperatures interior to the walls; see [9] for details.

Power consumption can be divided into three parts: (i) power consumed in conditioning the air at the AHU, which we call "conditioning power" P_U, (ii) power consumed by the fan(s) (P_F) to push the air through the zone, and (iii) power consumed in reheating the air at the VAV box, which we call P_R. The conditioning power can be written as

$$P_U = m^{in}(h^{AHU} - h^{out}), \tag{3}$$

where $h^{out} = C_{pa}T_0$, and $h^{AHU} = C_{pa}T^{AHU}$ are the enthalpy of outside air and conditioned air, C_{pa} is specific heat capacity of air at constant pressure. Usually, enthalpy equation contains an additional humidity term. We ignore this term for the sake of simplicity since the resulting error is a small constant. The power consumed by the fan (P_F) is: $P_F = \alpha m^{in}$, where α is a system dependent constant. The reheating power (P_R) at the VAV box is

$$P_R = m^{in}(h^{in} - h^{AHU}), \quad h^{in} = C_{pa}T^{in} \tag{4}$$

where h^{in} is the enthalpy of the air supplied to the zone after the reheat coil. Since the VAV box can only perform reheating, $T^{in} \geq T^{AHU}$, and the humidity ratio of air does not change from AHU to the VAV box. We call "total power" as the sum of fan, reheating and conditioning power.

IV. Control Algorithms for Energy Efficiency

In this section, we describe the three proposed control algorithms, *Z-DCV*, *OMBOC* and *POBOC*.

A. *Zone-level Demand Controlled Ventilation (*Z-DCV*)*

The *Z-DCV* control strategy is almost the same as the baseline controller described in Section II, except that the minimum flow rate of SA to the zone is determined based on the measured occupancy as follows:

$$\max(m_p^{in} n^p(t), m_{low}^{in}) \leq m^{in}(t) \leq m_{high}^{in}$$

where $n^p(t)$ and $m^{in}(t)$ are the occupancy and supply flow rate, respectively, at time t. A non-zero minimum flow rate of air (m_{low}^{in}) is supplied to the zone even when it is unoccupied, which is done to maintain IAQ. The parameter m_p^{in} is the flow rate of air required per person that is decided by the ASHRAE ventilation standards [10]. This controller requires only temperature and occupancy measurements. This controller is not computationally expensive because the control inputs are computed using a PID logic, instead of using any other computationally expensive control strategies such as MPC that solves an optimization problem at each time step.

B. OMBOC *(Occupancy Measurement Based Optimal Control)*

The *OMBOC* algorithm seeks to reduce energy consumption by maintaining temperature and IAQ only *when needed* based on the prediction of heat gains and dynamic response of the zone. It lets the temperature float in predefined ranges, the range being dependent on whether the zone is occupied or not. If occupied, the temperature is required to be in a "comfortable range" of temperatures. In unoccupied times, the temperature is allowed to float in a much larger range. Predictions from the dynamic model of the zone (described in Section III) is used to compute the optimal control inputs so that the energy consumption over a time period is minimized while maintaining temperature within the allowable ranges. A MPC formulation is adopted. Time is now measured with a discrete index $k = 0, 1, \ldots$, where the time period between k and $k+1$ is denoted by m. At every time k, we compute the optimal control over a time horizon of, say, length K, and execute only the first of those K controls. At $k+1$, the whole process is repeated.

To perform this optimization, we need predictions of the exogenous input vector $v = [W^{in}, Q, T_0]^T$ over the time horizon of optimization. Prediction of the outside temperature T_0 is assumed available from weather forecasts. The supply air humidity ratio W^{in} is usually constant over time. The heat gain Q is crucially dependent on occupancy, so one needs occupancy prediction to obtain prediction of v. Another reason occupancy prediction is required to compute the optimal controls is that the range in which the temperature is allowed to stay depends on whether the zone is occupied or not. However, we only have occupancy measurements. Therefore, we assume that the occupancy evolves according to the following first order dynamics: $n^p(k+1) = n^p(k) + \epsilon(k)$, where $n^p(k)$ is the occupancy at time k and $\epsilon(k)$ is a zero mean i.i.d. process. The optimal linear prediction for $n^p(k+i)\ i \geq 1$, given the measured occupancy $n^p(k)$ at time k, is simply the measured occupancy at time k. This controller therefore takes the measured occupancy at k as the prediction for $k+i$, $i \geq 1$.

In the proposed method, the control logic is divided into two modes: (i) Unoccupied, and (ii) Occupied, which are explained below in detail.

1) Unoccupied Mode: If the measured occupancy at time index k, i.e., at the beginning of the k-th time period, is observed to be 0, then the controller turns on the unoccupied mode. The optimal control inputs for the next K time indices are obtained by solving the following optimization problem:

$$arg \min_{m^{in}, T^{in} \in \mathbb{R}^K} J_{unocc}(m^{in}, T^{in}) \tag{5}$$

where $J_{unocc} := \sum_{i=k}^{k+K} (W_F P_F(i)^2 + W_R P_R(i)^2 + W_U P_U(i)^2)$, subject to the following constraints:

$$\left.\begin{array}{r} T_{low}^{unocc} \leq T(i) \leq T_{high}^{unocc} \\ m_{low}^{in} \leq m^{in}(i) \leq m_{high}^{in} \\ T^{AHU} \leq T^{in}(i) \leq T_{high}^{in} \\ W_{low}^{unocc} \leq W(i) \leq W_{high}^{unocc} \end{array}\right\} \forall i = k, \ldots, k+K \tag{6}$$

where the objective function J_{unocc} is a weighted average of fan power, and reheating power and conditioned power, with corresponding weights W_F, W_R and W_U, and the constraints are explained below.

The first constraint means that the zone temperature is allowed to vary anywhere in a range [T_{low}^{unocc}, T_{high}^{unocc}], where T_{low}^{unocc} and T_{high}^{unocc} are design variables. Since the zone is unoccupied, T_{low}^{unocc} and T_{high}^{unocc} need not be close to a comfortable temperature. However, it is not advisable to let the temperature deviate too far from a comfortable value either. Otherwise, when the zone becomes occupied, it will take a long time to bring the temperature back to the comfortable range. This will cause discomfort to the occupants. The closer the values of T_{low}^{unocc} and T_{high}^{unocc} are to a comfortable range, more quickly the zone can be brought back to comfortable conditions when occupancy changes. However, this will not result in large energy savings, so a trade-off between energy savings and fast response time has to be made in choosing these parameters.

The second constraint means that a minimum airflow (equal to m_{low}^{in}) is supplied even though the zone is predicted to remain unoccupied. This is done to take care of contaminants and humidity, so that IAQ is maintained even during the unoccupied mode. It is not possible to include IAQ in the cost function J_{unocc} since we do not have a model of contaminant dynamics. Another reason is to make the resulting IAQ robust to errors in occupancy measurements. By ensuring IAQ even during times when the zone is predicted to be unoccupied (whether correctly or not), we eliminate the problem of predicting the effect of control inputs on IAQ. The upper bound m_{high}^{in} reflects the maximum capacity of the VAV box.

The third constraint is simply to take into account actuator capabilities, which is an upper bound on the amount by which the reheat coil can increase the temperature of SA.

The fourth constraint means that the zone humidity is allowed to vary in a predefined humidity range [W_{low}^{unocc}, W_{high}^{unocc}], where W_{low}^{unocc} and W_{high}^{unocc} are design variables, which should not be too far from the comfortable range.

Note that in solving the optimization problem over the time horizon K, the exogenous input signal Q is computed based on forecasts of solar radiation alone; the heat addition due to occupants and lighting etc is set identically to 0, which corresponds to 0 occupancy.

2) Occupied Mode: The occupied mode is turned on if the measured occupancy of the zone is at least 1 at the k-th time index. In this mode, the occupancy for the next K time indices is same as the measured occupancy at the beginning of the k-th time period. The optimal control inputs for the next K time indices are obtained by solving the following optimization problem.

$$arg \min_{m^{in}, T^{in} \in \mathbb{R}^K} J_{occ}(m^{in}, T^{in}) \tag{7}$$

where $J_{occ} := \sum_{i=k}^{k+K} (W_R P_R(i)^2 + W_U P_U(i)^2 + W_F P_F(i)^2 + W_e (T_1(i) - T^{set}(i))^2)$, subject to the following constraints:

$$\left.\begin{array}{c} T_{low}^{occ} \leq T(i) \leq T_{high}^{occ} \\ T^{AHU} \leq T^{in}(i) \leq T_{high}^{in} \\ m_p^{in} n^p(i) \leq m^{in}(i) \leq m_{high}^{in} \\ (W(i), T(i)) \in \mathbb{S} \end{array}\right\} \forall i = k, \dots, k+K \tag{8}$$

where the objective function J_{occ} now has an additional term (over J_{unocc}) penalizing the temperature tracking error $(T_1(i) - T^{set}(i))^2$), where T^{set} is the desired temperature, with $W_e \geq 0$ being the corresponding weight. The constraints are explained below:

The first constraint means that the zone temperature is allowed to vary anywhere in a range [T_{low}^{occ}, T_{high}^{occ}]⊆[T_{low}^{unocc} T_{high}^{unocc}], where T_{low}^{occ} and T_{high}^{occ} are design variables. Since the zone is occupied, T_{low}^{occ} and T_{high}^{occ} should be close to the comfortable value of temperature. If the range [T_{low}^{occ}, T_{high}^{occ}] is chosen high, more energy can be saved. However, this makes occupants uncomfortable because the zone temperature deviates from the desired set point. If the temperature preferred by the occupants is known, that can be assigned as the desired temperature T^{set} and a penalty on the deviation $T_1(i) - T^{set}(i)$ being part of the cost.

The second constraint is the same as mentioned in the unoccupied mode. ASHRAE standards [11] require a minimum amount of air per person (m_p^{in}) should be supplied when the zone is occupied.

The fourth constraint means that the pair (T_1, W) should lie in a set $\mathbb{S}$ which defines a *comfort envelope*. The envelope $\mathbb{S}$ is described in [12]; we omit the details due to space limit.

Prediction the exogenous input signal v for the optimization is similar to that in the *OMBOC* algorithm, except that the contribution to Q due to occupants and lighting etc. is taken as a scalar multiple of the measured occupancy.

C. POBOC *(Predicted Occupancy Based Optimal Control)*

This control algorithm is very similar to the *OMBOC* algorithm, the only difference is that now we assume that prediction of occupancy over an arbitrarily long time horizon is available. As in the *OMBOC* algorithm, the control inputs during the occupied times are obtained by minimizing the cost function J_{occ} with associated constraints as described in Section IV-B.2. The occupied times are known ahead of time since occupancy predictions are available. During the unoccupied mode, the objective function J_{unocc} in (5) is minimized without any constraints.

V. Simulation Results

Simulations are carried out for a model of a zone from the second floor in a building (Pugh Hall) at the University of Florida campus, Gainesville, FL, which is shown in Figure 4. The calibrated model is used to compare the performance of the baseline, *Z-DCV*, *OMBOC* and *POBOC* controllers.

A. Model Calibration and Validation

The model is calibrated by changing the total thermal resistance per unit area of the walls. The thermal capacitance

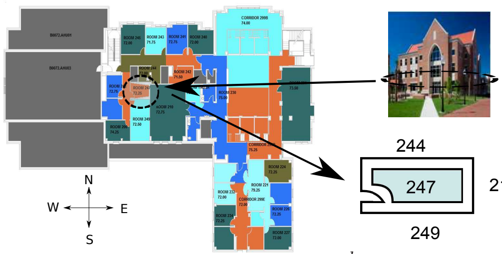
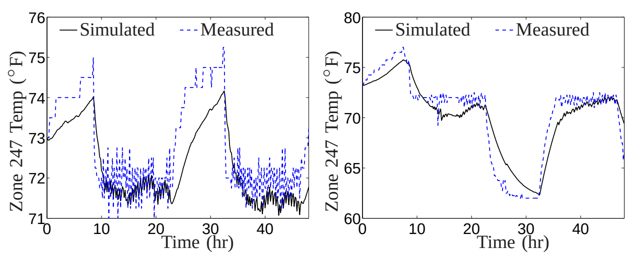


Fig. 4. Layout of the zone 247 on the 2^{nd} floor in Pugh Hall at the University of Florida, Gainesville, FL.

per unit area of the walls obtained from the Carrier's Hourly Analysis Program (HAP)[13] is 27.7 $KJ/(m^2K)$. Measurements of the zone temperatures, supply air temperatures and flow rates are obtained from the Building Automation System at 10-minute intervals. The total thermal resistance per unit area of the walls is tuned to minimize the error between the measured temperature and the predicted temperature of the zone. Data for a 48 hour long period (Jan 29-Jan 30, 2011) is used to calibrate the model. Since this time corresponds to a weekend, it is assumed that there are no occupants during this time. Since zone is an interior room, no solar radiation enters the zone. The comparison between the measured and predicted temperatures with the calibrated model are shown in Figure 5(a)-Figure 5(b). The validation data set (midnight Feb 5th through midnight of Feb 6th, 2011) also is from a weekend.



(a) Calibration (b) Validation

Fig. 5. Comparison of predicted and measured temperature in zone 247 when the model is calibrated and validated

B. Controller performance comparison

In this section, the building thermal model described in (2), and calibrated to mimic the zone 247, is simulated with the baseline, *Z-DCV*, *OMBOC* and *POBOC* algorithms as described in Section IV. Note that the baseline and *Z-DCV* controllers are implemented in continuous time because they are purely feedback-based algorithms. The *OMBOC* and *POBOC* controllers are simulated with discretized model with a 150 second time step, which leads to predictions close to that of the continuous-time model.

It is assumed that the zone temperature is exposed to constant outside temperature of 65°F, and m_{in}^p is chosen as 25 cfm following ASHRAE standards. The occupancy profile in the zone 247 is shown in Figure 6(c)-(d).

The design parameters T_{low}^{in} and T_{high}^{in} are chosen as 55°F and 86°F, T_{low}^{occ}, T_{high}^{occ}, T_{low}^{unocc} and T_{high}^{unocc} are chosen as 71°F, 73°F, 69°F and 75°F respectively. Weights W_U, W_R, W_e, W_F are chosen as 1, 1, 1 and 20 respectively. The time horizon of length K, m and T are chosen as 30, 10 and 30 minutes, respectively. The desired zone temperature (T^{set}), HTG and CLG are set as 72°F, 71°F and 73°F respectively. For the baseline controller, the minimum flow rate is chosen as 290 cfm, which is currently being used in zone 247. For the *Z-DCV* and *OMBOC* controllers, m_{low}^{in} and m_{min}^p are chosen as 95 cfm and 48 cfm; these choices will be explained in Section V-C. However, m_{low}^{in} and m_{min}^p are chosen as 0 and 25 cfm for *POBOC* controller as per ASHRAE standards.

Figure 6(a) and (b) show the temperature and humidity predictions, respectively, for all the control strategies mentioned above with a specific occupancy profile, which is shown in Figure 6(c)-(d). Since the outside temperature is lower than the zone temperature, it saves energy if the temperature is allowed to become low, which eliminates the need for reheating. Both *OMBOC* and *POBOC* controllers let the temperature drop to the minimum allowable values for each controllers, while the baseline and *Z-DCV* controllers maintain temperature around 71°F through reheating. This also results in oscillating humidity ratio with the baseline and *Z-DCV* controller. However, humidity ratio predictions with the *OMBOC* and *POBOC* controller are less oscillatory. The humidity ratio for all the control algorithms stays in the comfortable envelope $\mathbb{S}$, which is described in ASHRAE standards [12].

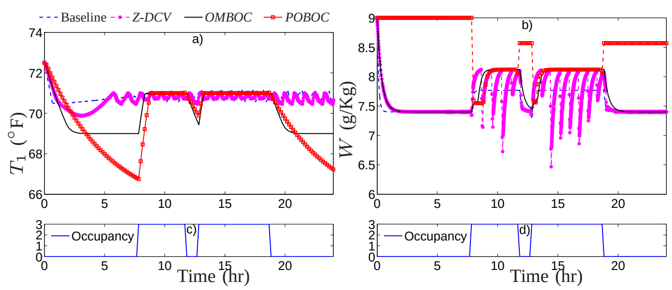


Fig. 6. The output of the system: T_1 (zone temperature) and W (humidity ratio) in zone 247 for a 24 hr time period with a specific occupancy profile.

Figure 7 shows the SA temperature and flow rates for all the controllers mentioned above. Since the minimum supply flow rate is quite high in case of the baseline controller, it switches between reheating and cooling mode quite frequently. Similar trend is seen in the other feedback based scheme: *Z-DCV*. The flow rate and SA temperature shows much less oscillatory behavior in the *OMBOC* and *POBOC* controllers. Since power is a function of the flow rate and SA temperature, the total power consumption trends for all the controllers are similar as the flow rates.

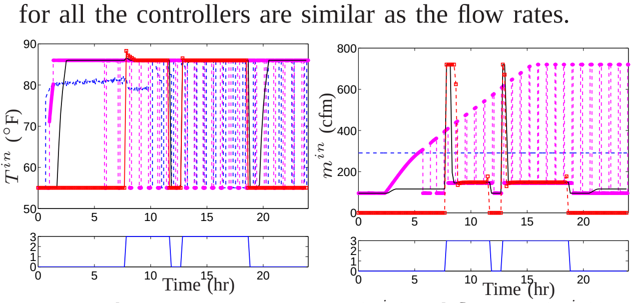


Fig. 7. The inputs: SA temperature (T^{in}) and flow rate (m^{in}) in zone 247 for a 24 hr time period with a specific occupancy profile.

The total energy consumption by all the controllers over the 24 hour period simulated is shown in Table I. A savings of 30% is achieved with the *Z-DCV* controller over the baseline controller. An additional savings of 27% is achieved with *OMBOC* controller over *Z-DCV* controller. Further 37% savings are possible if occupancy prediction is available and *POBOC* controller is used over *OMBOC* controller.

TABLE I
ENERGY CONSUMPTION OVER A 24-HOUR PERIOD, AND INCREMENTAL SAVINGS WITH VARIOUS CONTROLLERS.

Controller	Energy Consumption (MJ)	Incremental Savings (%)
Baseline	1074	-
Z-DCV	757	30
OMBOC	552	27
POBOC	355	37

C. Robustness to occupancy measurement errors

Occupancy measurements are likely to suffer from measurement error. Incorrect measurements, especially when occupancy is measured to be 0 while in fact the zone is occupied, can have a large detrimental effect on IAQ. A minimum flow rate (m_{low}^{in}) is supplied by the occupancy measurement based controllers in unoccupied times to guard against such an eventuality. We now discuss the trade offs involved in choosing m_{low}^{in}. Figure 8 shows the effect of minimum flow rate (m_{low}^{in}) on the total energy consumption for the *OMBOC* algorithm. It is clear from the figure that energy consumption increases quickly beyond $95\ cfm$. We therefore adopt a conservative approach by choosing the minimum flow rate as $95\ cfm$ during the unoccupied time and $144\ cfm$ during occupied time in the zone for *Z-DCV* and *OMBOC* control algorithm, which will tolerate an error of 3 in occupancy measurements. As per ASHRAE standards, zone 247 requires a minimum airflow of $75\ cfm$ for 3 people during occupied times.

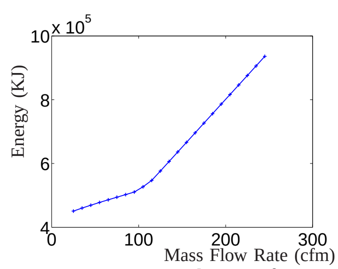


Fig. 8. Total energy consumption in a day as a function of m_{low}^{in} with the *OMBOC* controller.

VI. CONCLUSION/FUTURE WORK

We examined complexity vs. performance trade-offs in control algorithm development, where the control goal is to reduce energy use while maintaining thermal comfort and IAQ in commercial buildings. We proposes new control strategies, *Z-DCV*, *OMBOC* and *POBOC*, that require varying fidelity of information, and correspondingly vary in their performance. The *Z-DCV* control algorithm requires only occupancy and zone temperature measurement, the *OMBOC* control algorithm requires a hygrothermal dynamic model in addition to occupancy measurements, while the *POBOC* controller requires - in addition to the dynamics model - occupancy prediction. The *Z-DCV* controller is the simplest and most readily implementable in a building, while the other two require predictive model and are also computationally intensive. The *POBOC* controller is the most complex since it requires occupancy prediction.

The main conclusion from the simulations are that (i) even with simple feedback-based algorithm, significant energy savings can be obtained with occupancy measurements, (ii) with additional prediction capability (of dynamics or occupancy), large additional savings in energy consumption can be realized, and (iii) MPC-based control with occupancy measurement being used in place of prediction can result in substantial savings over not only the baseline controller but also occupancy measurement based pure feedback control.

The avenues for the future are to i) study the effect of design parameters used in the optimization on the control algorithms, ii) study the effect of outside weather on controllers performance, and iii) include the inter-zone interactions. In this paper we examined the problem from a deterministic viewpoint. In the future, we plan to investigate the problem from a stochastic viewpoint as in [1], in which uncertainties in the forecasts of exogenous inputs and model predictions will be incorporated.

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