Abstract—The ASHRAE standard requires that sufficient fresh air be provided to keep the CO$_2$ level below 1,000 ppm on buildings. However, surveys on buildings, classrooms, and houses found CO$_2$ concentrations at or above 1,000 and 2,500 ppm. To reduce CO$_2$ level in buildings, ventilation systems exchange air between indoor and outdoor. Meanwhile, according to occupants’ setting, heating or cooling system should also be turned on to keep the stable temperature in the building, which introduces energy cost. In this paper, we develop a system $E^2$Air to improve indoor air quality while reducing expense for compensation of heating or cooling. We deployed CO$_2$ and temperature sensors in buildings. Based on the CO$_2$ level, indoor and outdoor temperature, our design can automatically select the best time to turn on ventilation, heating and cooling systems to keep CO$_2$ and temperature within desired level. In addition, we also apply ventilation between rooms to reduce CO$_2$ level for a specific room to avoid turning on heating or cooling system of the whole house. Our experiments proved that our proposed design can improve air quality and offer valuable savings to buildings.

I. INTRODUCTION

High levels of Carbon Dioxide (CO$_2$) pose a threat to human health and prolonged exposure to high concentrations may eventually result in death from affixation [1]. Unfortunately, human beings have no natural way to detect this colorless and odorless gas. The ASHRAE standard [2] requires that sufficient fresh air be provided to keep CO$_2$ level below 1,000 ppm in buildings. However, many recent studies [3], [4] on buildings and classrooms found CO$_2$ concentrations at or above 1,000 and 2,500. More importantly, some studies have shown that working or studying at high levels of CO$_2$ concentrations would impair human health by inhibiting cognitive functions, as well as hampering decision-making [5].

Contemporary building practices exacerbate the problem of unhealthily high CO$_2$ levels. Such buildings are commonly constructed in a manner that attempts to achieve a completely airtightness envelope so as to prevent heat loss. This brings unfortunate consequence of preventing fresh-air from migrating into the building, and keeping CO$_2$ from migrating out of the building. To reduce the CO$_2$ level in a room, central heating systems (e.g., forced hot air systems) can be used to either reheat and re-circulate interior air. However, forced hot air system need to circulate air through all the rooms in the house, which introduces energy waste for unoccupied rooms. Another approach is to blow cold outside air into the room, and then utilize heating system to warm up the room. However, this approach also results in an unfortunate waste of energy because the heating system still needs to warm up the cold air from outdoor.

To the best of our knowledge, heating, ventilation, and air conditioning (HVAC) accounts for 38% of building energy consumption, and over 15% of all US energy usage. There already exist many works that propose different kinds of building applications for energy saving. Occupancy sensors are leveraged to perform energy efficient duty scheme for HVAC system [6] [7]. In [8], Human-Building-Computer interaction system is developed to optimize energy efficiency control in residential buildings. Energy sharing is proposed to minimize the electricity cost in a microgrid [19]. Building Application Stack [9] allows building applications to automatically adapt to differences in real-world settings. [10] retrofits a centralized HVAC system and enable room-level heating and cooling.

In this paper, we utilize the current infrastructure of the house for a new ventilation method by moving air between rooms of high CO$_2$ concentrations to rooms with low concentrations levels. Because CO$_2$ level increase is mainly caused by the persons in the room, if a room is not occupied, the CO$_2$ level in the room should be low. Then the unoccupied rooms can be used to lower CO$_2$ level of room with occupants. To move air between occupied rooms and unoccupied rooms, we deployed fans in rooms to blow air to the ducts. Then existing ducts can be used to route the air between rooms with little additional cost and minimally intrusive equipment. Besides that, our proposed design can be easily implemented as an auxiliary feature incorporated into existing energy efficient building applications.

The purpose of this project is aiming: i) to measure and analyze CO$_2$ concentrations in order to evaluate ventilation, and ii) to reduce the energy loss and expenses while introducing fresh air to control CO$_2$ level. In this paper, we deployed CO$_2$ and temperature sensors to monitor CO$_2$ levels and temperature in rooms. We also obtain outdoor temperature from National Weather Station (NWS). Then based on the historical data of CO$_2$ levels, occupancy and temperature, we propose an circulation scheduling algorithm that can meet the requirements of indoor air quality while minimizing energy loss.

The rest of the paper is organized as follows: background and overview of our design are introduced in §II; the detailed design of our air quality control system is described in §III; implementation and simulations are provided in §IV; related work is presented in §V finally, we conclude the paper in §VI.

II. BACKGROUND AND OVERVIEW

In this section, we give a brief description of ventilation system in a typical residential building and overview of our design.
A. Background

The architecture of home circulation in our experiment is shown in Figure 1. There are three rooms and the ventilation system locates in the basement. All rooms are typically connected to the furnace in series. Ventilation system would take the air from homes to outside through blue lines and take the air from outside to rooms through red lines. Because rooms are connected in series to the furnace, this means they are also connected to each other. And the air can be pushed or pulled between rooms without running the blower in the furnace.

To accomplish a transfer of air between rooms without the furnace’s blower motor, small “boost fans” can be attached to any given register (where the air comes into or out from a given room). These “boost fans” are in fact commonly available in building supply stores, and are employed as a way to increase hot air flow into a room. With the “boost fans”, the air from a room with a high concentration of CO₂ can be exchanged with air from a room with lower concentration of CO₂ through ducts.

B. Overview of Design

The overview of our design is shown in Figure 2. It mainly contains three components: CO₂ model, temperature model and circulation scheduling.

CO₂ model. The current and historical indoor CO₂ level is used to predict future CO₂ level. Because CO₂ level increases fast when the room is occupied and decreases slowly when the room is not occupied, current and future occupancy results for each room can be predicted based on the change of CO₂ level.

Temperature model. The current and historical indoor temperature data is used to predict future indoor temperature for each room. Specifically, we apply Exponentially Weighted Moving Average (EWMA) [11] for temperature prediction. The current and future outdoor temperature is obtained from NWS.

Circulation Scheduling. The predicted future indoor temperature, outdoor temperature, CO₂ level and occupancy result is then used for circulation scheduling algorithm to decide when and how long we do indoor circulation and outdoor circulation.

III. Design

In this section, we describe the details of occupancy, CO₂ and temperature prediction. Then we propose a circulation scheduling algorithm to decide how to conduct circulation to reduce energy consumption while maintaining good air quality.

A. CO₂ Model

To decide whether we need to conduct circulation, we first need to predict future occupancy and CO₂ level in the room. 

Occupancy detection. Because the CO₂ level in the room is mainly determined by the number of occupants when there is no circulation, we can detect occupancy based on historical CO₂ trend. For example, if the increasing speed of CO₂ level in a room is faster than the increasing speed of CO₂ level when one person is in the room during experiment, then the room is detected as occupied. Otherwise, the room is detected as unoccupied.

Occupancy prediction. For predicting the future occupancy in the specific room, we use historical occupancy detection results. In this approach we collect data for one month. Each day is divided into 15 minutes time slots. We mark the time slot as occupied if the given time slot is occupied for more than or equal to 10 minutes. Then next step is to find out if for the required day what the occupancy was in the room for last 4 days. If the room was occupied for the last four Mondays for specific time slot then we will consider the time slot of next Monday as the occupied and condition the air in that room at that specific time slot.

CO₂ level prediction. We utilize both historical CO₂ level and occupancy prediction results to predict future CO₂ level. Let \( L_i(n) \) denote the CO₂ level of room \( i \) at time \( n \), \( \hat{L}_i(n+1) \) denote the predicted CO₂ level of room \( i \) at time \( n+1 \) and \( C_i(n+1) \) denote predicted occupancy at time \( n+1 \). We predict future CO₂ level as:

\[
\hat{L}_i(n+1) = 2L_i(n) - L_i(n-1) + (\hat{C}_i(n+1) - C_i(n)) \cdot \Delta L \tag{1}
\]

where \( 2L_i(n) - L_i(n-1) \) is the prediction based on historical CO₂ level and \( (\hat{C}_i(n+1) - C_i(n)) \cdot \Delta L \) is the CO₂ change caused by occupancy change. \( \Delta L \) is the CO₂ level change caused by occupancy change.
B. Temperature Model

To predict the room’s temperature, we use a simple model based on an Exponentially Weighted Moving Average (EWMA). The EWMA exploits the diurnal nature of room temperature, while it also adapts to variations. On a typical day, we expect the room temperature to be similar to the room temperature of previous days with slight deviations in weather and daily activities.

Let $T_i(n)$ denote the temperature of room $i$ at time $n$ and $\hat{T}_i(n + 1)$ denote the predicted temperature of room $i$ at time $n + 1$, which is given by:

$$\hat{T}_i(n + 1) = \alpha \cdot \hat{T}_i(n) + (1 - \alpha) \cdot T_i(n)$$

(2)

More sophisticated models that consider weather conditions and other information are also possible applied to our design.

C. Circulation Scheduling

In this system we not only provide good air quality but also consider the energy consumption for heating/cooling the home. Thus, we propose an circulation scheduling algorithm to schedule indoor and outdoor circulation based on current and future status of the house. To reduce CO$_2$ level in a room, there are three approaches: i) turn on fans in the room to exchange air with a room with lower CO$_2$ level; ii) turn on forced air cycling system; and iii) outdoor circulation by opening the door or windows in the room. Based on our experiment results, outdoor circulation can reduce CO$_2$ fastest and needs most energy for warming up the room. And using fans to exchange air between two rooms reduce CO$_2$ slowest but needs least energy for turning on the fans. In the proposed system, air circulation takes place only when occupancy is detected in the room. To reduce energy consumption, we turn on fans when CO$_2$ level is only a little higher than threshold; turn on forced air system when CO$_2$ level is relatively high; and start outdoor circulation when CO$_2$ level is very high. Another consideration of our design is that we only reduce CO$_2$ level when the room is detected as occupied.

The detailed circulation scheduling algorithm is shown in Figure 1. $t_{out}$, $t_{in}$, $t_{fan}$ are the time for turning on outdoor circulation, forced air circulation and fans to reduce CO$_2$ level under the threshold respectively. These three values can be calculated based on speed of CO$_2$ reduction of three approaches in the experiments. We first check if current CO$_2$ level and occupancy of room $i$ (Lines 1-2). If CO$_2$ level is higher than threshold and the room is occupied, we immediately start outdoor circulation to reduce the CO$_2$ and calculate the time for CO$_2$ level of room $i$ to be lower than threshold (Line 3). Then we check if turning on the fans is enough to keep CO$_2$ level under threshold (Lines 4-5). If yes, we then turn off outdoor circulation and turn on the fans (Line 6). Otherwise, we turn on the forced air cycling system (Lines 7-9). If current CO$_2$ level is lower than threshold or there is no occupant in the room, we check if we need to conduct circulation for future (Line 10). If predicted future CO$_2$ level is higher than threshold and the room is predicted to be occupied, we then calculate the time for turning on the fans or forced air cycling system to reduce CO$_2$ level in future (Line 11). If turning on the fans or forced air cycling system can reduce CO$_2$ level under the threshold, we turn on the fans or forced air cycling system (Lines 12-15). Otherwise, we calculate the time to turn on outdoor circulation based on outdoor temperature forecast from NWS (Lines 16-20).

![Algorithm 1 Circulation Scheduling Algorithm](image)

IV. IMPLEMENTATION AND EVALUATIONS

To evaluate our design, we deployed CO$_2$ and temperature sensors in a residential building (shown in Figure 3(a)). The sensors then send out collected data to a server through gateway (shown in Figure 3(b)). The server then make the decision to control fans or ventilation system through a transceiver model (shown in Figure 3(c)). We also deployed gas meter and eGauge meter to measure the gas and electricity consumption (shown in Figure 3(d) and 3(e)). The detailed data collection of electricity consumption can be found in [18]. All our experiments can be summarized into two different phases. The first phase is to obtain basic pattern of how CO$_2$ level changes according to natural ventilation, and how temperatures change alongside CO$_2$ level increases and decreases. The second phase is apply our design in the residential building to control the fans and ventilation system.

CO$_2$ Accumulation. Figure 4 shows experiments on basic CO$_2$ accumulation behavior. Several experiments were run with similar results, depending on occupancy. Here we show typical real results. We conjecture that the curves can be imitated by using polynomial functions. In other words, functions...
may be used which use several variables, such as size or the room and number of occupants, to closely imitate the natural curves. By using such functions, actual CO₂ readings might rapidly indicate useful information, allowing an algorithm to decide how to handle air flows to dissipate current or predicted CO₂ levels.

**CO₂ Dissipation.** Figure 5 shows experiments on basic CO₂ dissipation behavior. Note that we only have limited time for the experiments, we do not select the time with same CO₂ level as the beginning of the experiments. However, the curve of dissipation rate in different scenarios can be observed in Figure 5. The top curve shows a room exhibiting “natural dissipation” in an empty house, in an empty room, after CO₂ had accumulated. This scenario is much like a home-owner going to work in the morning, leaving her house empty. The door was left closed, and the heating system was disabled. This would be the worst-case scenario without further CO₂ being generated. The best scenario is the smallest, steepest, shortest, fastest curve. This curve shows when the door is simply left open to the hallway in a completely empty house (after the CO₂ level had built up in the room). The middle curves show various other scenarios, as indicated in the graph. For an occupied room, the best scenario for CO₂ removal/dissipation is to employ a typical forced hot air furnace system. The graph also shows that the CO₂ Routing solution can imitate the running of the furnace, but without the cost of heating.

**CO₂ Control.** Observations in Figure 6 show one day of the our design running. At hour 6, CO₂ level reaches the threshold of CO₂ level (1200 ppm). However, because at that time, the outdoor temperature is relatively low, thus we only turn on the fans to conduct indoor circulation. At hour 13, the outdoor temperature is high enough, then we start outdoor circulation to quickly reduce the CO₂ level. During the night, as the individual was generating CO₂, the algorithm behaved like a “room respirator”, cycling on and off in order to maintain a minimally healthful CO₂ concentration. This shows up as a “bouncing effect” in the CO₂ levels near those thresholds.

We also show the energy consumption of our design and traditional HVAC circulation in Figure 7. Overall, the energy consumption of our design (3.6 kWh) is much lower than HVAC (4.9 kWh) in 24 hours. Combined with Figure 6, at hour 13, the temperature of outdoor is relative high, then our design allows outdoor circulation to quickly reduce the CO₂ level. Thus, the energy consumption of our design surpass the
energy consumption of HVAC at that time. However, because the CO$_2$ is lower after outdoor circulation, then our design needs much less energy after that.

V. RELATED WORK

Many studies contributed to use indoor CO$_2$ concentration to evaluate IAQ and ventilation. To investigate the relationship between indoor CO$_2$ levels and air change rates, Nabinger et al. monitored ventilation rates with the tracer gas decay technique and indoor CO$_2$ levels in an office building for two years [12]. However, the assessment was done for a whole building and not for individual rooms. Another study used parameter estimation methods to estimate CO$_2$ source generations; airflow rate and overall room ventilation effectiveness from simulated data and applied the best performed method to the field area [13]. The goal was to evaluate cost savings for demand-controlled ventilation (DCV) system for commercial buildings. Also, it has been proposed a transient ventilation model based on occupant load using optimization method to determine model parameters for energy savings from a year-round occupant load survey [14]. Besides HVAC, there are other works on energy and economic efficient design in residential buildings [16] [17].

VI. CONCLUSION

High levels of Carbon Dioxide (CO$_2$), pose a threat to human health. The ASHRAE standard requires that sufficient fresh air be provided to keep the level below 1,000 ppm on buildings. However, surveys on buildings, classrooms and houses found CO$_2$ concentrations at or above 1,000 and 2,500 ppm. In this paper we attempt to improve indoor air quality, and subsequently human health, while reducing expense. We introduced a new method of detecting indoor temperatures and CO$_2$ levels using sensors and establish a decision making model based on real data from these sensors. In addition to the predictive algorithm, we also designed a new ventilation system to improve air quality in a room by reducing CO$_2$ levels while minimizing energy consumption by avoiding heat loss through several different methods. Our experiments proved that our final design can offer valuable savings to and independent household.

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REFERENCES