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Air quality metrics and wireless technology to maximize the energy efficiency of HVAC in a working auditorium

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ABSTRACT

HVAC is the single largest consumer of energy in commercial and residential buildings. Reducing its energy consumption without compromising occupants' comfort would have environmental and financial benefits. A wireless testbed consisting of a retrofitted wireless Condensation Particle Counter (CPC), 25 wireless temperature sensors, 2 HVAC-embedded temperature and CO_2 sensors, and a webcam was deployed in a working auditorium, to monitor the air quality, temperature, and occupancy of the room. The main objectives were to identify particle sources using the retrofitted CPC, map the temperature variability of the room and select an optimal sensor location for HVAC control using clustering algorithms, and examine possible energy savings by operating the HVAC only during periods of occupancy using calendar-based scheduling and air quality indicators as proxies of occupancy. All air quality metrics increased with higher occupancy rates, although HVAC-modes changes were also identified as a source for particle numbers. Operating the HVAC using calendar-based scheduling resulted in energy savings of between 8 and 79%, increasing if occupancy events were scheduled close together. Finally, CO_2 was the strongest predictor of occupancy counts with an R^2 of 0.62 ($p < 0.001$) during simple regression analysis. Incorporating particle numbers and temperature improved estimates of occupancy only slightly ($R^2 = 0.67$), however incorporating a particle metric may enable the general air quality to be monitored, and identify when filters should be replaced.

1. Introduction

In 2010, the US primary energy consumption was 98 Quadrillion Btu, representing 19.2% of the world's energy consumption, second only to China [1]. Of this, 41.1% was consumed by the building sector – almost half by commercial buildings; and there is no slowdown in sight [2]. A large proportion of this energy was used on heating, ventilation and air conditioning (HVAC) [3]. Any HVAC system must operate within certain constraints overseen by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers [4] which states that HVAC must 1) be capable of ventilating at a rate of 5×10^{-4} m^3/s for every 9.3 m^2 of occupiable space or 3.6×10^{-3} m^3/s per occupant, and 2) maintain CO_2 concentrations at no more than 700 ppm above outside concentrations, or at an indoor concentration of less than 1000 ppm. While indoor air standards are becoming ever more stringent, reducing HVAC energy consumption is increasingly sought. Therefore improving HVAC efficiency without compromising indoor air quality or occupancy comfort could resolve these seemingly contradictory goals resulting in large energy and financial savings, as well as significant reductions in CO_2 emissions.

Occupants play an important role in indoor air quality, not only as a source of indoor particulates, heat and CO_2, but also as the constraint whose wellbeing and happiness must be satisfied through effective HVAC control [5]. Many HVAC systems operate using a schedule-based approach: switching between off- and on-modes at predetermined times, and delivering airflow based on a full-capacity scenario [6]. By failing to differentiate between a room that is occupied or unoccupied, and by assuming full-capacity, energy wastage is inevitable. Frequently the focus of many studies is on an occupancy-based HVAC control, delivering fresh air only when the room is occupied. Predicting times of occupancy can

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be accomplished in several ways. Numerous studies have proposed various CO_2-based demand controlled ventilation systems, in which occupancy is assumed based on an indoor CO_2 concentration, and ventilation air provided accordingly [7,8]. Other studies have used room temperature or occupants' temperature preferences in order to determine airflow [6]. Some studies have advocated a multi-agent control system with different combinations of, for example, environmental (CO_2, temperature) data, occupancy counts, and energy data [6,9,10], while several studies have assessed different HVAC scenarios for providing localized airflow, both ventilation and heat, to isolated zones within a larger space [11,12]. Energy savings of between 23% and 66% have been reported in these studies. One study took a different approach and tried to minimize occupant exposure by altering HVAC function to use less outdoor air during times of poor outdoor air quality [13]. By measuring indoor and outdoor $PM_{2.5}$ simultaneously they were also able to calculate filter efficiency. Incorporating sensing technology, and more specifically wireless sensors, enables efficient delivery of multiple data streams with which to inform HVAC function [14,15].

However, the majority of these studies focus on simulation modeling, and although indoor air quality is considered [13,16], few studies compare actual air quality measurement data, for example real-time particulate or CO_2 concentrations, with real-time occupancy counts. Nor do they assess whether the temperature sensors used for HVAC control are optimally placed and representative of the entire space the HVAC is servicing. The overall objective of this study was to monitor the indoor air quality of a university auditorium, and assess the energy-savings potential of its HVAC system through the implementation of a dense wireless sensor network incorporating real-time environmental data, whilst maintaining a healthy and comfortable environment. The first objective was to investigate the air quality of the auditorium using a Condensation Particle Counter (CPC), retrofitted to wirelessly transmit continuous particle measurements that could be logged remotely. The sources and sinks of particles were examined. The second objective was to assess the thermal environment of the auditorium, through the installation of a dense wireless network of temperature sensors. The optimal number and location of sensors needed to represent the thermal distribution across the entire room was investigated, and the optimal sensor location with which to control the HVAC identified. The final objective was to assess the benefits of using 1) a calendar-based schedule, and 2) air quality indicators, including particulates and CO_2, to determine occupancy and thus pinpoint the times at which HVAC should operate in on-mode, resulting in significant energy savings.

2. Methods

2.1. Building description

The test building is located on the northeast corner of Washington University in St Louis' Danforth campus, approximately 100 m from the intersection of 2 major roads and roughly.

300 m from the beginning of Forest Park, a 5 km^2 urban park. It was constructed as part of the university's commitment to greener buildings and received its Leadership in Energy and Environmental Design (LEED) certification for a new construction version 2.2 Gold in 2010 (WUStL, 2010). It is insulated with recycled blue jeans, has a high-albedo roof and a low-energy lighting system, and was constructed using only low-volatile organic compound (VOC) materials to promote good indoor air quality; indeed subsequent testing demonstrated negligible VOC emissions. A hi-tech digital control system displays real-time energy and water consumption using a touchscreen dashboard that is mounted in the foyer, and a high-efficiency HVAC system promotes the thermal comfort of workers [17,18].

2.2. Auditorium and HVAC function

The building's basement auditorium was the testbed for the project. It is a windowless multifunction conference room hosting seminars, classes, meetings and other unofficial events. Measuring 11 m in length, 12 m in width at the front and 16 m at the back, and 4–6 m in height from back to front, it can hold approximately 90 occupants, and is equipped with a computer, 2 projectors and lighting systems. Outside air enters an air handler unit that is equipped with 2 deep, minimum efficiency reporting value (MERV) 10 pre-filters followed by final filters with an MERV rating of 14. Here the chiller cools the air to 12.8 °C (or the boiler heats it to this required temperature). Recirculated air is warmed and mixes with this cooled air to obtain the required supply air temperature. This is the Supply Airflow (SAF), and is controlled by 4 Variable Air Volume (VAV) devices; when the room temperature drops to 21.6–0.6 °C, the VAV dampers open allowing additional warm air to enter the room. Conversely, when the room temperature increases to 21.6 + 0.6 °C, the VAV dampers close. Two temperature sensors, utilized to inform control decisions in the HVAC system, mounted on the walls on either side at the front of the auditorium (the stars in Fig. 1) control these VAVs. Additional SAF is allocated to the auditorium when CO_2 concentrations exceed 700 ppm.

The HVAC is currently programmed to switch from off-mode (unoccupied) to on-mode (occupied) at 6:00AM, and back to off-mode at 9:00PM. This schedule is repeated daily, including the weekend. A maintenance person cleans the room between 5 and 6:30AM each weekday morning. The HVAC-embedded temperature and CO_2 as well as airflow data are recorded and stored on a local server for 72 h at resolutions between 10 and 30 min before being stored permanently on a server external to the university. The HVAC data was downloaded every 24 h by logging into this server.

2.3. Experimental design

Measurements were collected between January 29th and April 29th, 2013. A wireless testbed consisting of a reconfigured wireless Condensation Particle Counter (CPC 3022A, TSI Inc, St Paul, MN), 39 wireless temperature sensors, and a webcam were deployed in the

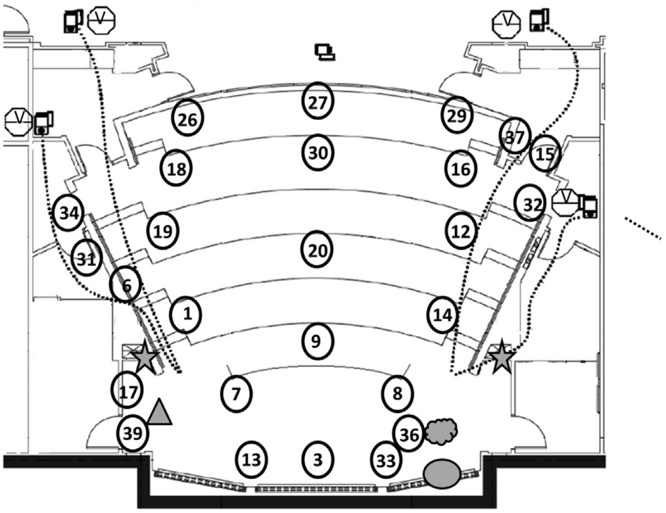

Fig. 1. A map of the auditorium depicting temperature sensor locations, CO_2 and thermostat sensors, wireless CPC, speaker podium and webcam.