Do we supply adequate outdoor air to buildings occupancy?

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Abstract
This research aims to evaluate the adequacy of mechanical ventilation, in buildings with air handling unit-variable air volume (AHU-VAV) HVAC configuration, in maintaining acceptable indoor air quality (IAQ). Occupancy and ventilation data from an academic building in Ottawa, Canada were analyzed. Zone-level occupancy was estimated based on Wi-Fi device count and simultaneous CO2 and motion detector data. Concurrent zone-level ventilation rates were obtained from the building automation system (BAS). The data were analyzed and the per person ventilation rates were modelled. The results indicated that some zones experienced under-ventilation (less than 10 L/s-person) during 34% of occupied hours while other zones were over-ventilated for many of the occupied hours. The measured occupancy and corresponding ventilation issues shed new light on the importance of considering heterogeneous occupancy distributions during building design.

Key Innovations
In this paper the authors:

- Highlight fundamental issues with design and control current building multizone mechanical ventilation systems.
- Shed light on issues with IAQ that affects occupants’ health and wellbeing and can increase the spread of airborne infectious diseases.
- Provide insights and recommendations for building ventilation-related codes and standards.
- Introduce a new metric called building under-ventilation hours (BUH) that indicates the fraction of under-ventilated occupied hours.

Practical Implications
(1) This paper highlights an overlooked issue in designing multizone AHU-VAV systems. The issue is the inefficiency of outdoor air distribution at the zone-level.
(2) This paper is expected to inform IAQ specialists about the adequacy of current ventilation systems and provides insights on how to overcome the shortcomings of current AHU-VAV ventilation systems.
(3) This paper is expected to attract attention to the use of BAS data in controlling AHU-VAV systems in a way that saves energy and maintains IAQ.

Introduction
As people spend more than 90% of their time indoors (Ramos et al. 2017; Robinson & Nelson 1995), maintaining acceptable IAQ is a necessity for their health and wellbeing. Poor IAQ is caused by the accumulation of chemical and biological contaminants in the air from contamination sources and the absence of adequate ventilation (Brown 2019). A report by the World Health Organization has shown that poor IAQ led to 3.8 million fatalities worldwide in 2016 (World Health Organization 2018). Therefore, indoor air pollutants are classified among the top four environmental risks to public health (Hess-Kosa 2010; Pitarma et al. 2017).

Deploying an efficient ventilation system in buildings is considered a core strategy in maintaining acceptable IAQ (Bluyssen et al. 2011; Melikov 2016; Sultan 2007). The energy crisis in the 1970s resulted in substantial revisions to ventilation requirements (Mendell & Fine 1994; Mui et al. 2007). These changes were made in the pursuit for energy efficiency and reducing natural resource consumption (i.e., fossil fuels). As a result, required ventilation rates in buildings were reduced drastically (Jafari et al. 2015; Janssen 1999).

Supplying and distributing fresh outdoor air to multizone buildings is fundamental for the health and safety of occupants. Ventilation rates in buildings are regulated by building codes and standards such as the ASHRAE Standard 62.1 that require the supply of a minimum outdoor air regardless of the heating and cooling requirements (ASHRAE 2019; Laue 2018). Supplying outdoor air improves IAQ by diluting indoor contaminants to benign levels. For example, ASHRAE Standard 62.1 specifies a minimum supply 2.5 L/s-person in addition to 0.3 L/s-m² of outdoor air for office spaces that has ceiling supplied forced air AHU-VAV systems. Designers typically assume 20 m² per occupant in office settings (NRC 2017). Based on these assumptions, the person outdoor air flow rate (Rₚ), area outdoor air flow rate (Rₐ), and the AHU-VAV system efficiency of 0.8 can be combined to yield a typical combined outdoor air rate of 10 L/s per person in office buildings for IAQ purposes (ASHRAE 2019).

IAQ has been at the core of the efforts made to fight COVID-19 global pandemic, as it became evident that the...
SARS-CoV-2 virus that causes COVID-19 transmits through contagious aerosols (Center for Disease Control and Prevention 2020; World Health Organization 2020). Researchers have demonstrated that aerosolized droplets such as that carry SARS-CoV-2 from contagious individuals can stay suspended in the air for several hours (Bourouiba 2020; Chartier & Pessoa-Silva 2009). This airborne transmission of the virus can lead to infections even if safety measures, such as social distancing, are followed. Hence, ensuring that buildings are receiving adequate ventilation to mitigate and control the spread of COVID-19 has become the focus of professional entities, building owners/managers, and researchers (Public Health Ontario 2020; US EPA 2020). For instance, ASHRAE published recommendations for building operation that suggests maximizing the amount of outdoor air intake up to 100% if the system capacity permits (Schoen 2020).

Even though IAQ standards specify outdoor air requirements per space type, they do not enforce a mechanism that ensures the realization of these requirements. For example, during the design of AHU-VAV systems, equipment capacities, ducts sizes, air (including outdoor air) and water flow rates are determined based on an assumed full occupancy of building spaces as per relevant standards such as ASHRAE Standard 90.1 (2016). Despite the fact that the amount of outdoor air is calculated for the building at full occupancy, zone-level VAV systems are typically controlled based on thermal loads. Simply put, the spaces with high thermal loads (e.g., solar gains) have higher demands on ventilation, which is coupled with cooling (and sometimes heating) in AHU-VAV systems, and consequently will receive a larger fraction of the outdoor air, even if these spaces are under-populated (Liu & Brambley 2011; Stanke 2010). Conversely, spaces with low thermal loads will receive a smaller share of outdoor air even if they are densely populated. Additionally, occupants’ mobility between building zones can add another layer of complexity to this issue, which can contradict designers’ assumptions of homogeneously occupant distributions (Abuimara et al. 2020; Gilani et al. 2019; Peng et al. 2017; Schweiker et al. 2017; Wang et al. 2018). A careful observation of design and operation approaches of AHU-VAV systems underlines possible issues which can compromise IAQ (Chen & Demster 1996).

In the time of a pandemic such as COVID-19, when IAQ is a priority for safe operation of buildings, investigating these issues and proposing alternative solutions is critical. Therefore, a thorough evaluation of the way we design and operate buildings’ ventilation systems, especially AHU-VAV, is required. To this end, this study objective is to investigate the efficacy of the ventilation delivered by AHU-VAV systems to maintain acceptable IAQ. While the study is focused primarily on measured data, it demonstrates the importance to consider heterogeneous occupant densities in multi-zone buildings to assess ventilation adequacy.

**Literature review**

Numerous studies have tackled air distribution effectiveness of AHU-VAV systems. Anand et al. (2020) performed an investigation to assess the energy and IAQ implications of VAV terminals’ airflow rate control strategies. The research examined building operational data such as indoor air temperature, ventilation flow rates, and relative humidity of a university building. The research examined three alternative VAV air terminal control strategies: (1) the ventilation was set to meet the minimum ventilation requirements and to keep a constant indoor air temperature setpoint of 24°C, (2) the ventilation flow rate was minimized to maintain an indoor air temperature setpoint of 28°C if the space was unoccupied for 60-minutes to less than a day, and (3) the space was not ventilated if it is unoccupied for the entire day. The findings revealed that when the first VAV control strategy was implemented in building spaces such as classrooms, which are normally heavily occupied in the evenings, the minimum ventilation requirements were not met. Notably, no under-ventilation issues were noted when occupancy-based VAV air flow control was implemented. Yang et al. (2011) performed a simulation-based investigation that aimed at evaluating energy and IAQ implications of four alternative ventilation control strategies in a building with an AHU-VAV system. The four tested ventilation control strategies were: (1) using a constant outdoor air fraction of 0.3, (2) dynamic occupancy-based demand-controlled ventilation (DCV) (CO2 based-DCV), (3) supply air temperature reset based on occupants’ feedback and preferences, and (4) enthalpy-based economizer cycle and supply air temperature reset based on occupants’ feedback and preferences. Four different performance metrics were used in this study: energy use, indoor air temperature, predicted mean vote (PMV), and CO2 concentration. The results showed that employing the first strategy increased energy use, thermal comfort was acceptable, and CO2 concentrations were low. By implementing the second strategy, about 15% energy savings was achieved and thermal comfort was acceptable; however, CO2 concentrations were reported to be high. The implementation of the third strategy resulted in the most significant energy use savings of about 20% and CO2 concentration was reported to be low, but thermal comfort conditions were unacceptable. Implementing the fourth strategy resulted in 9.4% of energy use savings, and the CO2 concentrations were at their lowest of the four strategies during mild seasons.

The current literature on the topic of ventilation distribution across building spaces reveals that the focus of most studies has been on energy use savings; not enough consideration has been given to studying the effectiveness of AHU-VAV systems in distributing outdoor air to enhance IAQ. Thus, this paper aims to add to the existing literature by investigating control strategies of AHU-VAV systems with the objective of improving IAQ through operational data analysis.
Methodology

The objective of the study was approached through the analysis of design documents and real operational data from a floor of an institutional building in Ottawa, Canada. The data were collected from April up to and including December 2019. The following steps were taken in the data collection and analysis:

1. The study was initiated through studying the mechanical design drawings and details to identify thermal zones based on the associated AHUs and VAVs. The floor being investigated was found to have 14 thermal zones that are served by two different AHUs (Figure 1).

2. The geometric centroid of each room was computed using a scale drawing of the floor plate. The distances between the centroid of each room and each of the five Wi-Fi access point (AP) locations were calculated, and the rooms were subdivided into groups based on the closest associated Wi-Fi AP. The Wi-Fi data were available at hourly timesteps.

3. The collective occupancy of each subset of rooms was estimated using the hourly device count data from the associated Wi-Fi AP. Occupant-count estimation based on these data were performed following the regression model described in Hobson et al. (2019). Briefly, stagnant devices (i.e., printers, computers left on overnight, etc.) were discarded each day; a relationship of approximately 1.2 devices per person was used. Only device counts were monitored; no MAC addresses were monitored or stored over the course of this study per the institutions research ethics board. Further steps aim to subdivide the occupancy at the room level based on additional sensor data.

4. Presence data from passive infrared (PIR) sensors were used to remove unoccupied rooms from consideration at each hourly timestep. The PIR data were available at five-minute timesteps and were amalgamated to concurrent hourly timesteps to match the available Wi-Fi data; rooms were considered occupied if motion was observed within the hour-long timestep. Further, single occupant rooms (i.e., private offices) were treated as occupied by a lone occupant at timesteps when the sensors were triggered.

5. Hourly carbon dioxide (CO2) concentration data were used in tandem with the Wi-Fi based occupant-count estimates to estimate the occupancy of occupied multi-occupant rooms. An unmodified mass-balance approach that compares the indoor and outdoor CO2 concentration and ventilation rates was used (Zuraimi et al. 2017).

6. The outdoor air flow rate at the AHU level was estimated based on the outdoor air damper position using the relationship between the outdoor air fraction and the outdoor damper position established in Hobson et al. (2021) for these particular AHUs.

7. To calculate the per zone outdoor air flow rates, VAV terminal units’ air flow rates and corresponding AHUs’ outdoor air intake flow rates were obtained from the BAS.

8. Room-level occupancies were amalgamated to the zone-level. Each zone’s estimated occupancy was compared to the concurrent outdoor air flow rates calculated to determine the per person outdoor air flow rates for each zone.

9. The per person outdoor air flow rates were compared to ASHRAE Standard 62.1 requirements.

10. A new metric that measures the under-ventilation hours at the floor level was developed. The metric is called building under-ventilation hours (BUH) and it indicates the fraction of occupied hours when the ventilation requirements as per ASHRAE Standard 62.1 are not met in at least one zone.

Results and discussion

Overall, the calculated per person outdoor air in different building zones indicated that while some zones grossly exceeded the outdoor air requirements (i.e., are over-ventilated), other zones experienced under-ventilation during a large proportion of occupied hours. For example, Figure 2 provides an example of a zone (zone 2, recall Figure 1) that was over-ventilated; a significant portion of the occupied hours received ventilation that was over ten times the ASHRAE Standard 62.1 per person outdoor air requirements. Only 1.8% of the occupied hours did not meet ASHRAE Standard 62.1 outdoor air requirements.

Zone 2 comprises of four private offices that are barely occupied but facing south-west and have high window-to-wall ratios (WWRs) which makes it subject to overheating from high solar radiation, resulting in increased demand on cooling which is coupled with
ventilation in AHU-VAV systems. Even though VAV air terminals were able to sustain satisfactory IAQ for nearly all occupied hours in zone 2, there are still under-ventilated instances when minimum ventilation requirements were not met which can be considered a health threat during major events such as the spread of an airborne infectious disease.

In addition, the windows in zone 3 face north and northwest, which results in relatively low solar gains and consequently less solar-induced overheating. Hence, the cooling required by zone 3 was less than zone 2 (i.e., a zone with high solar gains) which resulted in insufficient amounts of outdoor air delivered to zone 3 for IAQ purposes (i.e., under-ventilation).

Figure 4 presents the findings of the calculated per person outdoor air flow rates in zone 4. The results of zone 4 demonstrate an extreme case of under-ventilation, where the per person ventilation rates were lower than ASHRAE Standard 62.1 requirements during 33.8% of occupied hours. Zone 4 is a north-facing zone (recall Figure 1) that receives low solar gains and was frequently densely populated as it is used as a classroom/computer lab.

On the contrary, Figure 3 demonstrates an example of zones (zone 3, recall Figure 1) that experienced under-ventilation. Observing the results from zone 3 shown in Figure 3 reveals that during 26.9% of the occupied hours ASHRAE Standard 62.1 requirements were not met. Zone 3 is serviced by the same AHU that serves zone 2; however, zone 3 is a shared room that hosts multiple occupants who are often present eight hours a day, five days a week. That is to say, this zone is often densely and sometimes over-occupied (i.e., exceeding design occupancy), as desks are shared by multiple occupants during peak hours.

This zone is served by two VAV terminal units which are supplied by the same AHU that serves other south and west-facing zones (i.e., zones 1, 2, 3, 6, and 7). These zones have high WWRs (50 to 60%) and are exposed to high solar gains, which increased demand on ventilation for cooling purposes to maintain temperature setpoints in these other zones. This combination of high occupancy and low solar gains in zone 3, along with the higher demand on ventilation for cooling purposes in many of the zones served by the same AHU, contributed to the frequently insufficient ventilation of zone 3.

Figure 5 provides an additional example that indicates inefficiency of AHU-VAV systems in distributing outdoor air across building zones. The histogram provides details about zone 5, where ventilation requirements as per ASHRAE Standard 62.1 during 17.9% of the occupied hours were not met. Zone 5 is located at the core of the buildings and hosts a computer lab. Zone 5 is served by the AHU that serves west and south-facing zones (i.e., zones 1 through 7) as shown in Figure 1. This further highlights the presence of under-ventilation as zones that have high thermal loads (i.e., the perimeter south and west-facing zones) are not served by the appropriate ventilation system.
west-facing zones) required higher ventilation rates (even when under-occupied or vacant) to cool their spaces, while zones that have low thermal loads and are densely populated (such as zone 5) suffered from under-ventilation over a comparatively significant portion of occupied hours.

![Histogram showing per-person ventilation rates for thermal zone 5 on the building floor](image)

Figure 5: A histogram showing the per-person ventilation rates for thermal zone 5 on the building floor shown in Figure 1.

Overall, even though some building zones experienced persistent under-ventilation, other zones were chronically over-ventilated. Although many of the zones have CO₂ sensors and motion detectors (PIR) installed, these sensor data were not used to inform or enhance the distribution of ventilation, as is the case in many buildings. This resulted in compromised IAQ in densely occupied zones (i.e., zones 3, 4, and 5), and increased energy use in instances where vacant or under-occupied zones were heavily ventilated (i.e., zone 2).

Over the course of the study period, at the floor level, there were 2520 occupied hours; during 1043 of these hours, the outdoor air requirements were not met in at least one zone. This corresponds to a BUH of approximately 41.4% which indicates significant violation of ventilation standards which can negatively impact IAQ.

Generally, the analysis of measured data revealed a major weakness in implementing ventilation-related codes and standards regarding outdoor air distribution in buildings with AHU-VAV systems. The present method of implementing relevant codes and standards is built upon flawed assumptions, such as the assumption that the outdoor air fraction at the AHU level is delivered equitably to each VAV terminal unit. This assumption neglects the way airflow at VAVs is controlled. Consequently, implementing ventilation-related codes and standards should be investigated and more effective approaches for implementation should be adopted. For instance, codes and standards such as ASHRAE Standard 62.1 should mandate new technologies and approaches that ensure proportional distribution of outdoor air based on building occupancy distribution. For example, deploying occupancy-based control of VAV air terminals can mitigate/eliminate under-ventilation as demonstrated in the study by Anand et al. (2019). Many buildings, especially recently constructed, have sensing infrastructure installed including CO₂ sensors and motion detectors. Additionally, decoupling ventilation from heating and cooling such as in systems such as dedicated outdoor air system (DOAS) can largely contribute in solving the under-ventilation issue.

**Conclusions**

In this paper, the effectiveness of multizone AHU-VAV systems in distributing outdoor air across building spaces was evaluated. Operational (occupancy and ventilation) data from a floor of an institutional building in Ottawa, Canada was used. The operational data included Wi-Fi device counts, PIR sensor data, CO₂ sensor data, and ventilation rates from the BAS. Room and zone-level occupancy was estimated based on Wi-Fi device counts, along with concurrent PIR sensor data and CO₂ sensor data. The simultaneous ventilation rates were obtained from the BAS. Then, per person outdoor air flow rates were calculated and instances of under-ventilation (i.e., less than 10 L/s-person) were identified for each zone based on ASHRAE Standard 62.1 requirements. The results highlighted that multiple building zones experienced under-ventilation while others were over-ventilated. One zone experienced under-ventilation for as much as 33.8% of occupied hours. At the floor level, the BUH was calculated to be 41.4% which indicates significant issues with AHU-VAV system effectiveness in distributing outdoor air across building spaces.

Overall, the study findings indicated that controlling AHU-VAV systems predominately based on zones’ thermal loads resulted in disproportionate distribution of outdoor air to under-occupied zones with high thermal demands compared to densely occupied zones with low thermal demands, which jeopardises IAQ. The following recommendations can be made based on the outcomes of this study:

1. The heterogeneous distributions of building occupants should be taken into account by HVAC designers. Accordingly, plans and technologies for accommodating variable occupancy should be incorporated early in the design phase for new construction. Additionally, designers can use building performance simulation (BPS) tools to test the impact of heterogeneous distribution of occupants on the effectiveness of the ventilation system. Such approaches could even be mandated by building codes, though care must be taken to balance ventilation and energy performance.

2. Existing data from sensing infrastructure available in existing buildings (such as CO₂ data) should considered for controlling zone-level ventilation wherever possible.
(3) Alternative HVAC DOAS should be considered in new designs. The use of DOAS can significantly improve IAQ while saving energy (Kim et al. 2016; Lim & Jeong 2018).

Although the findings of this study underscored a substantial IAQ issue that is caused by the way AHU-VAV systems are controlled, there are still limitations and unresolved issues that should be considered in future research. The limitations and suggestions for future research are as follows:

(1) This paper is focused on buildings with AHU-VAV HVAC configuration. Although AHU-VAV is a common HVAC configuration, there still many different HVAC systems that need to be evaluated in terms of outdoor air distribution effectiveness.

(2) The operational data used in the investigation represent an institutional building that has offices, classrooms, and labs. Data from buildings of different typologies and locations should be considered in future research in order to draw generalizable conclusions and highlight further issues.

(3) The findings of this study are limited to AHU-VAV systems with forced air distribution. Future investigations should include alternative air distribution types such as displacement ventilation and under floor air distribution.

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References


