Zonal Air Handling in Commercial Buildings

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ABSTRACT

Commercial buildings and multi-unit residential buildings provide a setting for prolonged human-to-human contacts that contribute to the spread of infectious diseases. Central air handling by commercial HVAC systems in these buildings is considered a contributory factor to the spread of the current pandemic caused by the SARS-CoV-2 virus (that causes COVID-19 disease). The emerging view is that the indoor environment and indoor gathering present a spreading risk as virus-laden aerosol lingers in indoor air for hours at high concentration rather than being quickly dispersed and destroyed through UV (sun)light outside. Accumulated exposure to viral load over time is an important risk determinant for an individual to be infected. The central building management systems could provide a potential means to monitor, reduce, and control such spread. Closed-loop circulation systems in these buildings provide longitudinal monitoring mechanisms for ascribing disease spread to local events. Through a case study with the implementation of such monitoring and control in a real-life commercial building – EBU3b for CSE, we describe how recent advances in metadata modeling and application programs in buildings can be applied to achieve a new capability for *zonal* air handling and thus reach a higher air quality guarantees expressed in terms of air change rates than currently possible in building-level air control. Based on these experiments, we discuss challenges and opportunities in indoor-climate control as a three-way tradeoff between safety, occupant comfort, and energy costs.

KEYWORDS

Smart buildings, air handling, safety, energy efficiency

1 INTRODUCTION

Since the 1970s, scientists have observed diseases spread such as legionella and humidifier fever due to indoor microbial contamination [6]. In the context of the current pandemic caused by the spreading SARS-CoV-2 virus that causes COVID-19 disease, a number of efforts are underway to control its spread in order for the public health-care system to maintain its capacity and keep fatalities low. These efforts include testing, tracing and tracking individuals across social connections, geographic locations to ensure a localized spreading event is controlled as early as possible. This control strategy is informed by our evolving understanding of the viral transmission that supports a much granular means by which the disease spreads. Key findings among these are the role of individual 'super-spreaders' and exposure to viral loads via aerosols and droplets over time in indoor environments [1, 2, 4, 10, 12, 14–17]. These two observations have a direct implication on our testing/tracing protocols and how indoor facilities are organized and operated to minimize the environmental risk of contracting the disease. Thus, the risk is associated with the environment, specifically, places such as classrooms and corridors. This risk is estimated as a function of the volume of the room, the number of persons, their aerosol emission (i.e. activity level and type), temperature/humidity, and air flow (room layout, vent locations, thermal circulations, etc). As an engineered system, a room serves as a continuous reactor or open system, where the contaminant is added through occupants and removed through HVAC. The operation of the HVAC system provides a critical means to reduce the likelihood of spreading events.

Traditional research and practice for building control are focused on optimizing energy efficiency and thermal comfort [5, 9, 13]. When adding a third "objective" of safety into the optimization equation, existing optimization methods and solutions to air handling do not well suit the need with many unknowns remaining. For example, one of the recommended measures is to increase the air circulation rate (measured by air changes per hour (ACH), i.e., the air volume added to or removed from a space divided by the volume of the space). However, there are many practical challenges and considerations in achieving a higher ACH, and to name a few, how to know whether a target room/space can reach the desired ACH rate which requires knowing the installed terminal unit's limit and room dimension to calculate; how to know whether the Air Handler Units (AHUs) in a building can still satisfy the air flow and cooling demands at increased ACH rate when operating with 100% outside air; if increasing ACH requires AHUs to operate under increased supply air temperature (to avoid over-cooling), how to satisfy the varied cooling demands from the spaces in a building considering special-purpose spaces exist such as server rooms; even if the equipment supports these needs, how to quickly and flexibly implement new building operation protocols at scale.

In this study, we demonstrate how to realize increased air circulation in a building, empirically study the impact of such operation on the building, and discuss implications of increased air handling by zones on overall building operating conditions.

2 BACKGROUND AND RELATED WORK

2.1 Background

Guidelines on Building Operation. Various guidelines have been issued by ASHRAE[1], CDC[2], and the European union REHVA[3] on building operation to ensure safety of the occupants during the COVID-19 pandemic. These guidelines provide detailed recommendations regarding multiple aspects of building operation and share much in common, including, but not limited to, use of high-rating Minimum Efficiency Reporting Value (MERV) filters and/or UV-C lighting to treat the return air, 24/7 HVAC operation, no use of recirculated air (i.e. use 100% outside air), increased air change (ACH) rate during occupancy. While comprehensive, these recommendations are difficult to implement altogether, if not completely impossible. The effects of these measures and their implications on the building systems with respect to energy consumption and occupants' thermal comfort still largely remain unclear to practitioners and residents. As computer scientists and systems researchers, in this study, we particularly focus on demonstrating how increased ACH rate can be programmatically and systematically achieved and on examining how such operations would impact buildings.

HVAC and Operation. In a typical commercial building with a centralized HVAC system, an AHU (Figure 1) feeds fresh, temperature-controlled air to terminal units and the terminal units supply the air to their dedicated zone. The return air will be either returned to an economizer mixing it with fresh outside air or exhausted to outside the building. The economizer's (or sometimes called mixer) policy determines the proportion of fresh and recirculating air and how fresh the indoor air will be. AHUs provide a central place for any measures—such as UVC scrubbing—that need to work on aggregate air for the entire building, or a substantial portion of it.

The majority of commercial building uses two types of terminal units: Variable Air Volume units (VAVs) and Fan Coil Units (FCUs). VAVs receive temperature-controlled air (chilled air) from an AHU, reheat the air if necessary, and mainly control the air flow rate into the zone. FCUs use cold and hot water to fine-tune the temperature of fresh air provided by an AHU. In both VAVs and FCUs, multiple terminal units are connected to an AHU, forming an air loop.

[1]https://tinyurl.com/yy8f5faq
[2]https://tinyurl.com/y9lczbwp
[3]https://tinyurl.com/yy8nzlmj

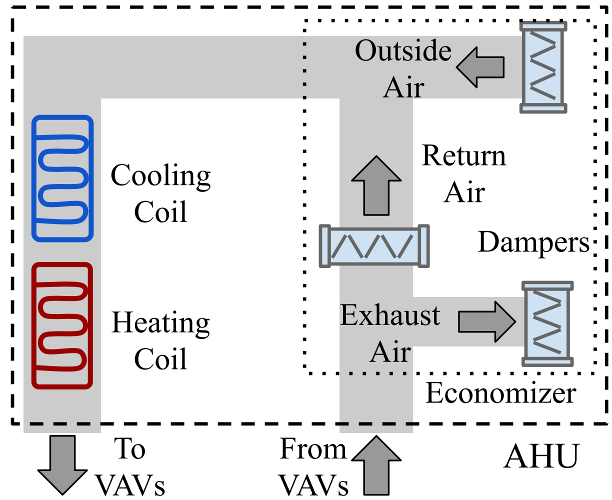


Figure 1: An AHU with an economizer that determines recirculation of air from VAVs, reducing virus transmission.

2.2 Related Work

Building Control and Operation for Air Quality. Researchers have devised strategies to maintain the desired CO_2 level [7, 11]. While studies have thoroughly examined the effects of various treatment measures such as filtration on reducing pollutants [8, 18], the ongoing pandemic presents a challenge with a virus being much smaller in size than the traditional particles (PM 2.5) in focus. Thus, evidence is needed to validate these measures against the spread of COVID-19 disease, and more importantly, their impacts on thermal comfort and energy consumption.

Building Resource Management and Programming. Building resources (equipment, sensors, and actuators, etc.) are manufactured and instrumented by different vendors. Contextual information about these resources (e.g., sensor types and their relations) is usually encoded as "metadata" that is often vendor dependent. Programming over building resources via such metadata is hard. Thus, numerous tools have emerged that organize, manage, and analyze metadata information so as to enable applications relatively quickly without referring to the architecture and specifics of individual buildings and their HVAC systems. These tools and services form the emerging "Building Operating Systems (BOS)" as shown in Figure 2. In this context, Brick provides a uniform way to represent the heterogeneous resources using a standardized symbolic representation of resources that models the types of entities (e.g., `Zone`, `Sensor`) and their possible relations (e.g., `hasLocation`, `feeds`) [3]. In effect, Brick serves as an "assembly language" to access building resources for a new class of "building applications".

3 EXPERIMENT AND RESULTS

3.1 Building in Case Study

The CSE building for our experiment has a central AHU serving around 200 VAVs, each serving a dedicated zone. We have a BOS running upon the resources in buildings and it supports various applications from data trending to customized control (e.g., one for reducing the spread of SARS-CoV-2 virus). As illustrated in Figure 2, the BOS comprises two key components: 1) a BACnet Connector that polls data from and issues control commands to the BACnet controllers in a building; 2) an API endpoint with operational components that manage requests from different applications of resources and retrieve resources based on their metadata in the Brick format. For example, to realize changes to a VAV supply airflow, one would implement so in a control program that issues "write commands" to the right resource located based on its metadata.

3.2 Experiment Protocol

We focus on measures to increase air circulations[4] by real-time control of air flow across various zones and how that would impact the thermal comfort and energy consumption:

- Control variables: supply air temperature (SAT) of AHU, economizer of AHU, air flow of VAV in individual rooms
- Control plan: SAT at 60F and 65F for AHU, economizer set to use 100% outside air, max air flow for VAVs per their limit
- Types of zones for experiment: classrooms, student labs, and conference room; seven in total
- Observables: temperature and CO_2 , humidity (when available) in each room, the total energy consumption of the building.

3.3 Results and Discussions

In the first set of experiments, we examine the impact of supply air temperatures (SATs) on thermal comfort conditions and impact on HVAC equipment. Specifically, for a classroom we picked three two-hour intervals in the day when we set the VAV supply airflow to the maximum and observed the response of several phenomena as illustrated in Figure 3. In the remaining time, the default control logic was used. We conducted this experiment on two different days with similar weather (outside air temperature, solar radiance level, etc) and used different SATs at the central AHU. Results establish the baseline control where room temperature changes according to SAT settings. We also see that the CO_2 concentration was always at a stable level regardless of ventilation at distinct airflow rates – this corroborates our observations that CO_2 level is not an effective indicator of sufficient air circulation at high target ACH levels. More importantly, regarding the achievable ACH rate, the default HVAC control strategy provides a maximum ACH rate at 5 that falls short of the target rate for offices[5]. Ideally, we would seek substantially higher ACH rates for classrooms (e.g., ACH 12 for infection isolation in hospitals). Such a target can not be achieved for an entire building but a viability in the case of zonal air flows. We also present in Figure 5 the power consumption of the classroom on these two days, along with an uncontrolled baseline day. We see that increased airflow rate leads to higher energy consumption, so did using cooler air (SAT=60F vs SAT=65F).

There are several limitations to increasing ACH rates in a building beyond current ratings (typically ACH 2-3). While the room temperature still remained in the desired range (refer to the upper and lower limits in Figure 3), increasing the SAT to 65F (as opposed to the default setting of 60F) could result in overheated spaces such as server rooms which generate excessive heat and require lower SAT. Also, the building in the experiment is located in a temperate climate where using complete outside air (i.e., return air from each zone is exhausted to outside the building) does not stretch the limit of the central AHU. This may not be feasible in hotter regions. In addition, these experiments were conducted with *no* occupancy (due to ongoing closure of buildings to normal occupancy). It remains a question whether our hypothesis and observations would still hold when the building sees actual occupants.

We also examined interior rooms without windows. In particular, we controlled airflow in two adjacent rooms of similar size – one was subject to the three two-hour experiments, the other one was not. Results are presented in Figure 4. In the controlled room, the temperature dropped below the allowed lower limit multiple times under increased ACH during the experiment, resulting in not only reheating of the air but also potential discomfort.

3.4 Planned Deployment using Brick Schema

Based on our verification of safety-aware control, we plan to deploy additional application logic across multiple buildings using Brick to standardize discovery, access, and control of resources. We exemplify the use of Brick for implementing a safety-aware control app where a user wants to maximize

[4]https://tinyurl.com/y2pbcojj

[5]https://tinyurl.com/y2pbcojj

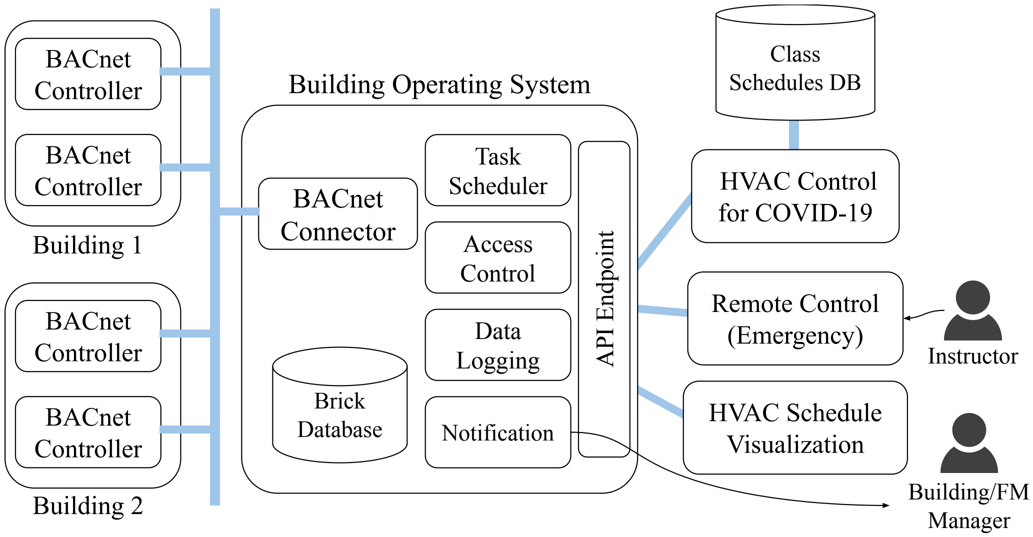


Figure 2: Overview of a building operating system that supports applications on top of resources managed with standardized metadata.

a zone's airflow rate on demand in a centralized HVAC configuration (e.g., AHUs and VAVs). The algorithm proceeds as follows:

(1) A user designates a target zone (e.g., Room-101);
(2) Calculate the remaining capacity of AHU (such as air flow and cooling);
(3) Identify the maximum mechanical air flow limit of the terminal unit of the zone;
(4) Identify the air flow setpoint of the target zone;
(5) Change the setpoint value in the controller.

While Brick standardizes the resource discovery process for all the steps above, calculating the remaining capacity of AHU involves more complex relations across different entities, which we detail more. As we discussed in Section 2.1, it is recommended to maximize airflow rate during occupancy to reduce the risk of virus transmission. To maximize the air flow rate while not damaging the equipment, we need to know the percentage of AHU's capacity used, which requires to understand the relation among a target zone, its associated AHU, and all the VAVs associated with the AHU. To do so, we use the standard SPARQL[6] query in Brick to find such relations, as shown in Listing 1.

Listing 1: A SPARQL Query for Calculating AHU's Current Capacity

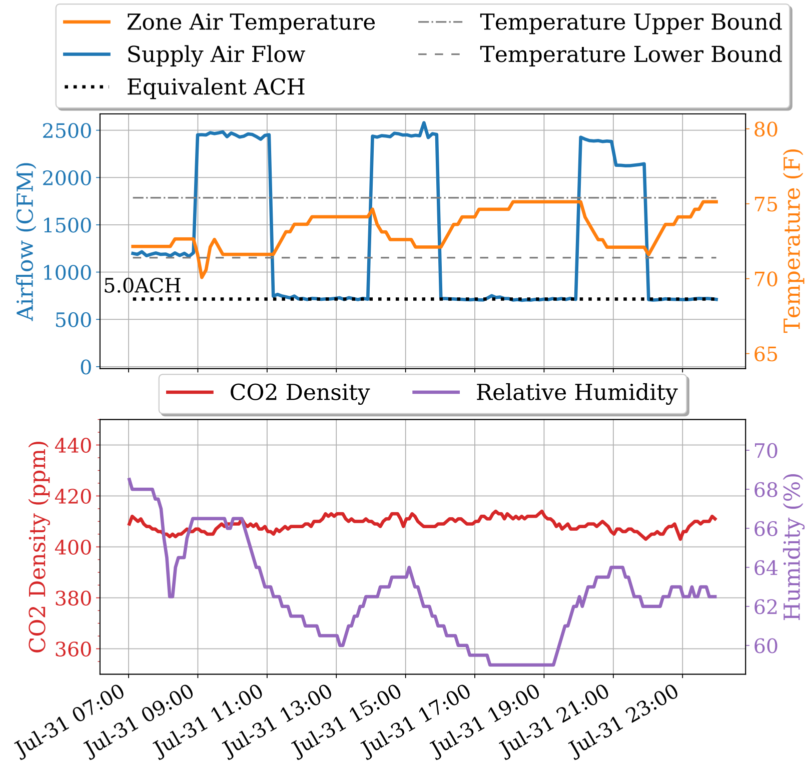
```
prefix brick: <https://brickschema.org/schema/1.1/Brick#>
prefix brick-ext: <https://brickschema.org/schema/1.1/BrickExtension#>

select ?ahu ?ahu_limit ?vav_saf ?vav_limit where {
  BIND (<ZONE_ID> AS ?zone )       # [1]
  ?ahu  a             brick:AHU.   # [2-1]
  ?ahu  brick:feeds+  ?zone.       # [2-2]
  ?ahu  brick:feeds+  ?vav.        # [3-1]
  ?vav  a             brick:VAV.   # [3-2]

  # An extension of Brick for representing properties of devices.
  ?vav  brick-ext:mechanicalairflowLimit  ?vav_limit.  #[4-1]
  ?ahu  brick-ext:mechanicalairflowLimit  ?ahu_limit.  #[4-2]
}
```

[6]SPARQL 1.1 Query Language, https://www.w3.org/TR/sparql11-overview

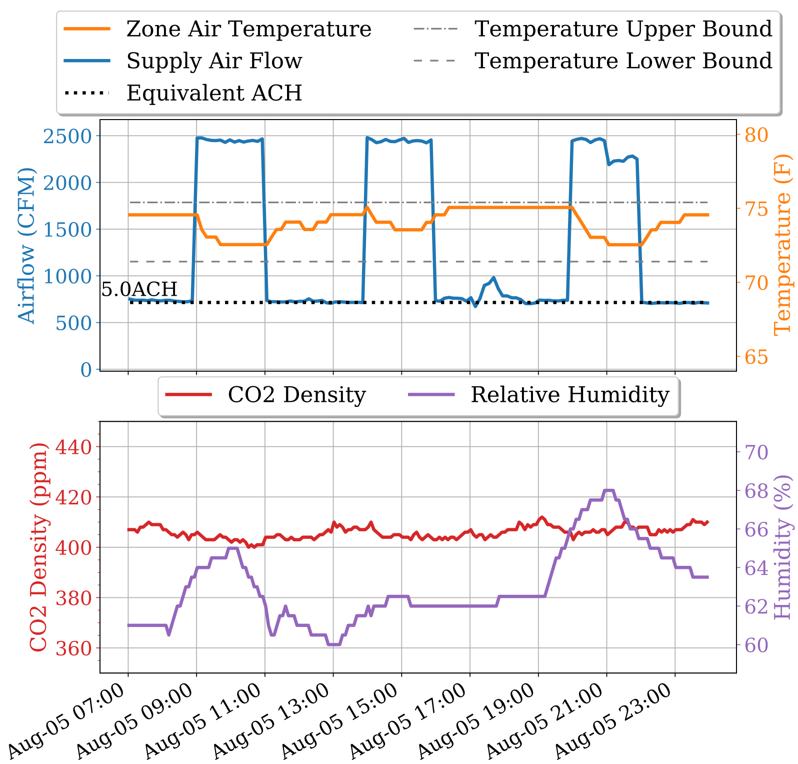
Given a target zone as specified in [1], SPARQL's transitive pattern (*) can flexibly describe which AHU ([2-1]) feeds air into the zone without knowing intermediate components ([2-2]). Then, we are also interested in other VAVs ([3-1]) associated with the AHU ([3-2]). While Brick currently focuses on modeling entities and their relations, devices' properties such as their mechanical limit are highly useful for standardizing app logic. Thus, we add those numeric properties of devices ([4-1], [4-2]), augmenting existing Brick's scope, to enable the same logic over multiple buildings.

4 CONCLUSION AND FUTURE WORK

Existing building control is designed to meet occupants' thermal comfort while minimizing energy costs. With a new dimension of safety to consider, we need substantially higher airflow rate, which brings in new challenges to thermal comfort conditions and energy efficiency. While our preliminary analysis shows that it is possible to achieve the airflow rate recommended by various guidelines, deeper and more comprehensive analysis is required to examine the impact of such

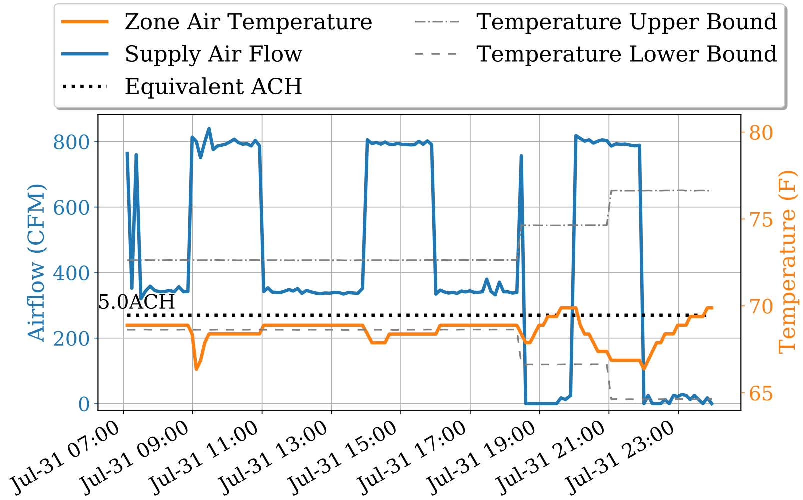


(a) SAT at 60F (default value)

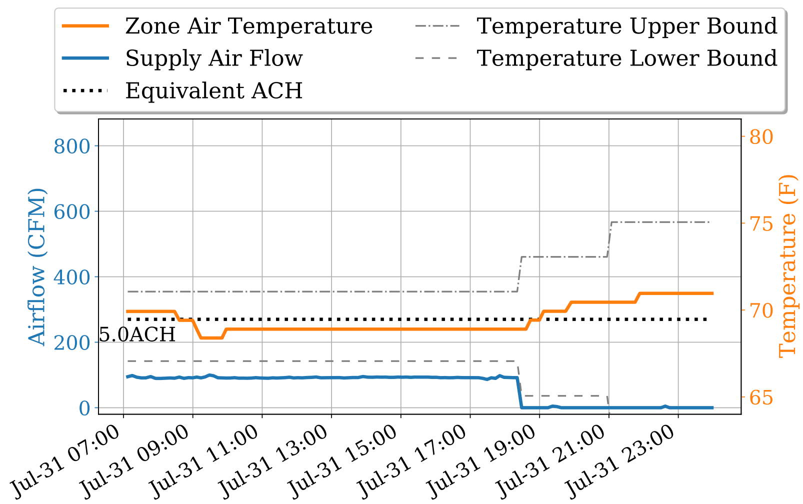


(b) SAT at 65F

Figure 3: A classroom with three high-ACH sessions on two days with different supply air temperature (SAT) used.



(a) Controlled Room



(b) Uncontrolled Room

Figure 4: A controlled zone (conference room) vs an adjacent uncontrolled zone, both without windows.

control on building in face of actual occupants. There are various uncertainties for opening up workplace buildings, and our building systems should be agile to quickly adopt new protocols and applications at scale. A Brick enabled programming platform enables such an adoption.

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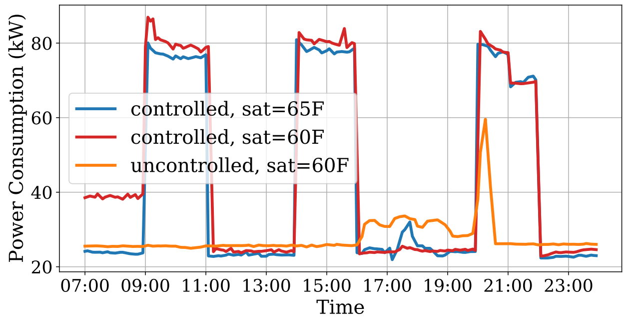

Figure 5: Power consumption of a classroom for experiment on three different days with similar weather.

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