# DYNAMIC, DATA-DRIVEN HVAC OPERATIONS FOR MORE EFFICIENT BUILDING OPERATIONS

# IMPLEMENTING SMART HVAC WHERE INDOOR AIR QUALITY DOES NOT DIRECTLY INCREASE PROFITS

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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## Introduction to Indoor Air Quality

Most people spend 90 percent of their time indoors, yet few ever think about how indoor air quality (IAQ) affects their health and productivity (Allen & Macomber 2020a). One should first understand how to measure IAQ in order to understand its varying effects on health and productivity. Three common IAQ measurements are carbon dioxide, volatile organic compounds (VOCs), and fine particulate matter (PM2.5).

The first of these three, carbon dioxide, often builds up from exhalation as indoor spaces approach their capacity. Cars, a compact space, often have carbon dioxide levels that are four to five times higher than what is normally permissible in buildings. This partially explains feelings of drowsiness during long car rides and perhaps justifies rolling down the windows (Allen & Macomber, 2020b). The most widely used standard for indoor carbon dioxide concentrations was set by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) at 1,000 parts per million (ppm), but this standard has since been widely refuted since its implementation in 1989 (Persily 2020). A more reasonable goal for carbon dioxide concentrations in indoor air is about 500 ppm (Allen & Macomber 2020c).

VOCs are compounds that have a high vapor pressure and low water solubility (EPA, 2021a). Indoor air consistently has higher VOC concentrations than outdoor air and can have VOC concentrations that are as much as ten times higher than outdoor air (EPA). Common indoor sources of VOCs include organic chemicals like paints, varnishes, and cleaning products (EPA, 2021b). Their health effects include symptoms that range from eye, nose, and throat irritation to liver and kidney damage (EPA, 2021b). A reasonable goal for VOC concentrations in indoor air is below 500 parts per billion (ppb) (Prill, 2000).

Finally, PM2.5 describes "...tiny particles or droplets in the air that are two and one half microns or less in width," (NY Department of Health, 2018). Sources of PM2.5 include candles, cooking, wildfires, vehicle exhaust, burning fossil fuels, and more (NY Department of Health, 2018). PM2.5 is small enough to travel into the lungs, which is where it does the most damage (NY Department of Health, 2018). It has been linked with a seven percent increase in mortality rates and a four percent increase in hospital admissions for every 10 µg /m3 increase in its concentration (Allen & Macomber 2020d). PM2.5 is also to blame for an estimated five percent of lung cancer deaths globally (Allen & Macomber, 2020e). A reasonable goal for PM2.5 concentrations in indoor air is below 2 µg/m3 (Allen & Macomber, 2020d).

All three of these characteristics are measured by the IAQ sensors placed in the Link Lab in Olsson Hall by Professor Hedarian and his team of undergraduate engineers. The next step is to measure the corresponding occupant counts. From there, an algorithm can be designed for the HVAC control system to optimize indoor air quality (ideally saving energy in doing so). If this system succeeds in Olsson Hall, it may lead to a University-wide transition towards smart HVAC systems. This paper will continue by exploring the technological context around smart HVAC systems. It then moves into investigating the benefits and drawbacks of their implementation, especially in organizations where improved IAQ does not directly increase profits.

## Comparing Current and Smart HVAC Control Systems

UVA facilities currently operate most HVAC systems continuously from 6 a.m. to 7 p.m., regardless of the occupant count within a building. The air quality sensors deployed in Olsson Hall report a noticeable increase in total volatile organic compound (TVOC) and fine particulate matter (PM2.5) outside of these hours (Figure 1). This means anyone in the building outside these hours may be at risk of exposing themselves to higher TVOC and PM2.5 concentrations.

According to the capstone project description by UVA Assistant Professor Arsalan Heydarian, the proposed technological solution is a smart HVAC control system that manages indoor air quality (IAQ) and energy consumption dynamically (Heydarian, 2021). Data streams for occupancy, IAQ, temperature, humidity, and energy consumption can be used to construct statistical models, forecast IAQ, and even predict energy consumption at high resolution (Heydarian, 2021). These analytics will be used to develop optimization algorithms that will be linked to the control systems that drive HVAC operations in the Link Lab at Olsson Hall. Building controls will be optimized to deliver a higher quality, healthier work environment for students, faculty and staff, while reducing demand for energy and associated carbon emissions (Heydarian, 2021). This will be done by providing air "...only when people are there, as opposed to dumping loads of fresh outdoor air into empty conference rooms," (Allen & Macomber 2020f, p. 210). Doing so allows a smart HVAC control system to outperform the current technology in three key ways.

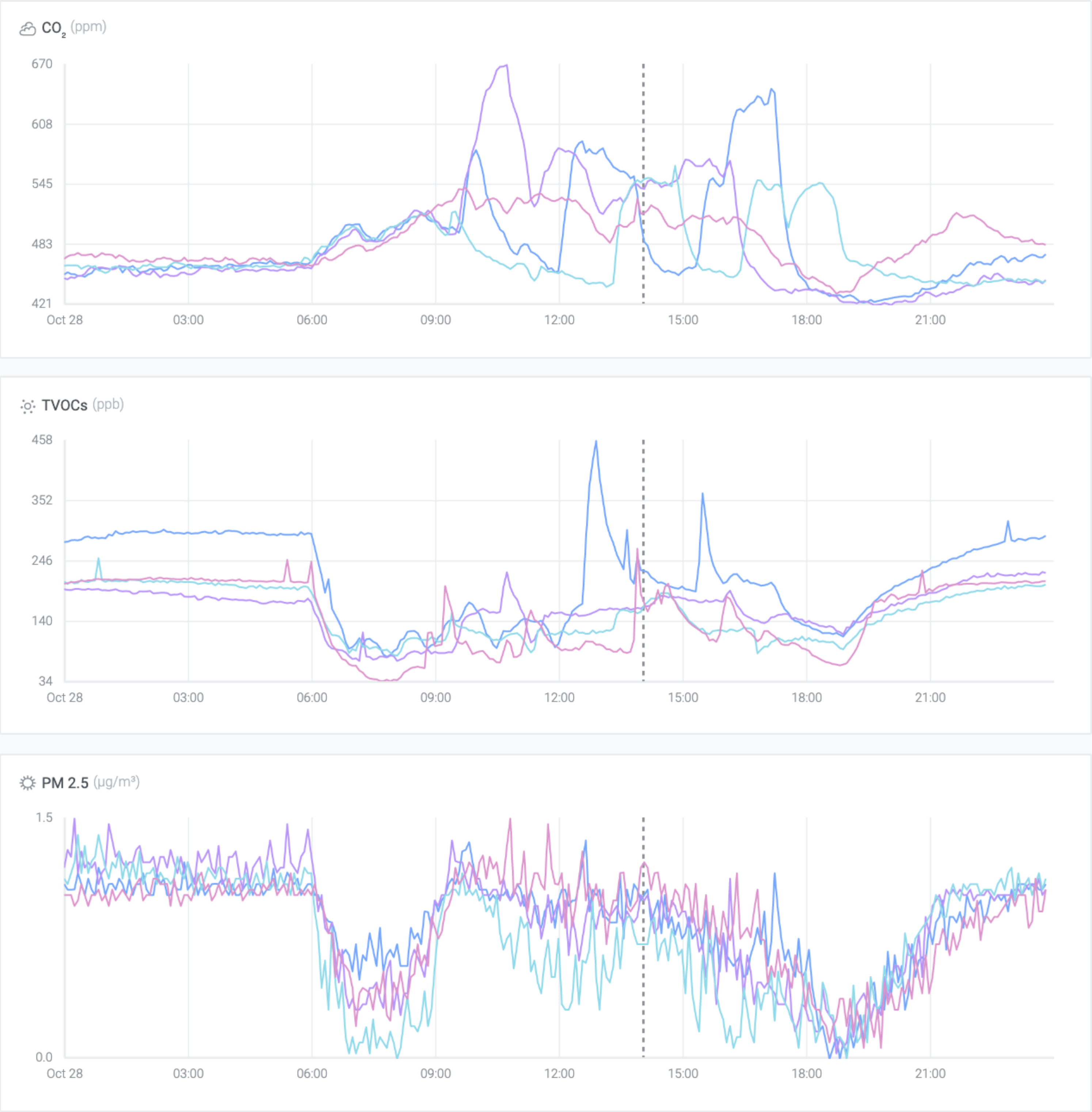

**Figure 1.** Measurements of Carbon Dioxide, TVOC, and PM2.5 for four different rooms in Olsson Hall for October 28, 2021 (Awair, 2021)

First, it enables improved ventilation rates for occupied rooms. A smart HVAC system can deliver higher ventilation rates to “hot spots” within a building. These hot spots can be seen especially in the middle of the day, when carbon dioxide levels peak (Figure 1).

A second way smart HVAC systems outperform the current technology is that it cuts energy consumption and costs for unoccupied rooms. The smart HVAC system can decide to cut ventilation to empty rooms and reactivate air flow in preparation for meetings or in response to newcomers. The trick to such a dynamic HVAC system is accurately understanding how many people are in a room and successfully relaying this data to the HVAC system. One foreseeable system error is underestimating the occupant count of a room and failing to increase its ventilation rates accordingly.

Finally, a third key benefit to using smart HVAC systems is that they account for occupants outside of daytime hours. The current practice is to turn HVAC systems on at 6 a.m. and off at 7 p.m., but this threatens to expose lingering occupants to increased levels of indoor air pollution, students, faculty, and staff. For example, the smart HVAC system has the potential to reduce the evening peaks in TVOC and PM2.5 if it detects a student staying behind to study late into the night (Figure 1).

One reason to care about these measurements is that poor indoor air quality can reduce the performance of office work by 6 to 9 percent (Wyon 2004). For students, this marks nearly an entire letter-grade difference. Further evidence to support this comes from a conducted set of chess matches in which particulate matter (PM2.5) and carbon dioxide (CO2) levels were strategically varied. This study done at MIT by Künn & Pestel found that a 10 µg/m3 increase in the levels of PM2.5 in the room leads to a 2.1 percentage point increase in the probability of making a meaningful error and a 300 ppm increase in CO2 leads to an increase in the probability of making a meaningful error by 1.8 percentage points (Künn & Pestel).

Such figures on productivity can be important for large companies in the decision to switch to higher ventilation rates, but they do not describe all decision-making processes well. The University of Virginia (UVA) and the International Space Station (ISS) are both exceptional in that neither profits directly from its "buildings'" occupants. UVA, for example, does not profit directly from the productivity of its students, staff, and faculty. Likewise, space organizations like the National Aeronautics and Space Administration (NASA) do not profit directly from the productivity of astronauts on board the ISS. As a result, they have fewer monetary incentives to improve indoor air quality. Still, the importance of air quality persists.

## How Occupants Shape Indoor Air Quality

Astronaut Scott Kelly expresses his concerns with high concentrations of carbon dioxide in the International Space Station (ISS) throughout his 2017 memoir, *Endurance: A Year in Space, A Lifetime of Discovery*. In the fifth chapter of his 2017 book, Scott Kelly details an experience tied to indoor air quality aboard the international space station, "The carbon dioxide level is high today, nearly four millimeters of mercury. I can check it on the laptops and see exactly what the concentration of CO2 is in our air, but I don't need to—I can feel it."

In this same chapter of *Endurance*, Kelly notes, "...the Navy has their submarines turn on their air scrubbers when the CO2 concentration rises above two millimeters of mercury, even though the scrubbers are noisy and risk giving away the submarine's location. By comparison, the international agreement on ISS says the CO2 is acceptable up to six millimeters of mercury" (Kelly, 2017).

For reference, a carbon dioxide concentration measurement of two millimeters of mercury is about the same as saying 2,600 ppm. Similarly, a measurement of four millimeters is about 5,300 ppm, and a measurement of six millimeters is about 7,900 ppm -- nearly eight times the maximum expected carbon dioxide concentration for an indoor office space, as set by ASHRAE standards.

To qualify these readings, however, one should note the exceptional environment that both Kelly and the submariners he mentions exist in. In either case, the ISS or submarines, there is no fresh air intake. The ISS exists in the vacuum of outer space, and the submarine exists in the depths of the ocean; neither system continuously pulls air from the Earth's atmosphere. The lower carbon dioxide concentrations of the submarine may perhaps be explained by the fact that submarines may take in fresh air upon surfacing, though a higher quantity of cabin occupants may negate this.

Kelly talks about sharing his experience to a new program manager for the ISS by saying, "...soon after I was back on Earth I helped arrange to bring him on a visit to a Navy submarine under way in the Florida Straits. I thought the submarine environment would be a useful analogy for the space station in a number of ways, and I especially wanted my colleagues to get an up-close look at how the Navy deals with CO2," (Kelly, 2017).

Kelly reports the success of his sharing the experience in the epilogue of his book by writing, "NASA has agreed to manage CO2 at a much lower target level, and better versions of carbon dioxide scrubbers are being developed that will one day replace the Seedra and make life better for future space travelers, and I'm thankful for that," (Kelly, 2017). Kelly's experience supports Pinch & Bijker's Social Construction of Technology (SCOT) framework in showing the influence of astronauts as a social group in shaping technology within a sociotechnical system. Here, the example is found in how Scott Kelly's experience shaped the future of indoor air quality on the ISS after reporting to the new space station manager.

Pinch & Bjiker theorized the SCOT by tracing the history of bicycles through the lens of social influence—i.e. the social constructivist approach. It compares two relationships between technology and society: the Social Construction of Technology (SCOT) and the Empirical Program of Relativism (EPOR). In EPOR, a scientific finding is up to interpretation until scientists, or some community of authority, arrive at a common understanding. Such a finding is only counted as final once society at large agrees with this understanding (Pinch & Bijker, 1984). SCOT, however, presents a different view of the history of a technology -- one that is shaped by social groups rather than by scientific understanding. Here, innovations branch from an existing technology, and the decisions of relevant social groups are what determine the fate of these innovations. For example, the article says the bicycle's air-filled tires caught on largely after racers acknowledged their speed and chose them as the faster bike (Pinch & Bijker, 1984).

Pinch & Bijker propose studying science and technology in an integrated way when approaching the sociology of science and the sociology of technology. Their paper notes that "...the sociology of technology is still underdeveloped," and "...it would be a shame if the advances made in [the sociology of science] could not be used to throw light on the study of technology" (Pinch & Bijker, p. 130).

The social constructivist approach applies well in discussing sociotechnical relationships in the case of Scott Kelly (astronaut) and his experience with high carbon dioxide levels on the International Space Station (ISS). Here, Kelly is the key social group, and his interest in health and productivity drives the technological development of the Seedra on the ISS. It may also carry well into UVA's treatment of indoor air, where students, staff, and faculty have the potential to drive the future of HVAC operations.

## Should UVA Implement a Smart HVAC Control System?

UVA plans to be carbon neutral by the year 2030, but doing so requires a major restructuring of energy usage (Kelly, 2019). On average, more energy is used to enable buildings to transform the outdoor climate into an indoor climate than for any other purpose. About 40% of all energy is used to construct, heat, cool, light, and ventilate buildings (Wyon, 2004). It may be easy to justify maintaining or even cutting ventilation rates, as this would directly cut costs and help UVA work towards its carbon neutrality goal. Reducing ventilation rates, however, would also decrease the air quality of UVA facilities (Persily, 2017).

It may be easier for companies to invest in improved ventilation rates, as it has already been observed that this boosts worker productivity by as much as nine percent (Wyon, 2004). A university like UVA, however, does not profit directly from the profit of its students, and therefore faces a more difficult challenge in justifying increased ventilation rates.

To address these concerns, it may be helpful to look into case studies of universities that have already transitioned towards smart, healthy HVAC systems. The University of British Columbia and University College London are two such universities (University of British Colombia, 2021; Shrubsole, 2016). I intend to break down the steps, if possible, that allowed these universities to transition towards smart, healthy HVAC systems. In doing so, I will especially look to emphasize what justifications these universities found to undertake this transition-- i.e. monetary incentives or otherwise. Perhaps these two universities found other ways to justify their transition to smart, healthy HVAC systems. Either way, their reasoning may prove to be helpful in finding out whether it’s the best solution for UVA.

An effective analysis of whether UVA should switch to smart HVAC control systems may include: (1) long-term costs and savings estimates for smart HVAC control systems, (2) the forecasted health effects of smart HVAC control systems, (3) an improved understanding of varying IAQ in all types of UVA facilities (i.e. dining halls, gyms, dorms, libraries, etc.), and (4) a measurement of health performance indicators (HPIs) for buildings across grounds.

In particular, a more complete understanding of IAQ and occupancy in all of UVA's buildings may lead to the best analysis. This is because each building type has different factors affecting its IAQ and occupancy. Dining halls, for example, may have higher PM2.5 measurements because of the combustion involved in cooking. Dorms, on the other hand, may see a dip in occupancy during the day while students are out attending classes.

The importance of HPIs is similar. Monitoring trends like total employee sick days, health-care utilization, asthma attacks, and influenza cases across space and time should benefit a greater understanding of IAQ and its importance (Allen & Macomber, 2020d). For example, dorms with improved ventilation rates may have fewer students visiting UVA's student health center for respiratory illnesses. Similarly, an academic building with poor ventilation rates may see relatively high counts of sick days or health-care utilization in its employees (such as dining hall staff who are regularly exposed to high PM2.5 concentrations).

Once gathered, these results can be compared with the case studies of the University of British Colombia and University College London. Perhaps the experience and incentives differ for each university. Observing their unique experiences may help determine whether the comparison between universities is fair.

## Conclusion

Just as Kelly describes in his memoir, the air quality of an indoor environment indeed has palpable repercussions. In the case of high carbon dioxide levels, this often means feelings of drowsiness. Such feelings of fatigue and drowsiness may explain or at least correspond with the 6 to 9 percent decrease in productivity observed in Wyon (2004).

These figures, however, are met with opposition -- notably in the justified efforts by institutions like the University of Virginia to reduce energy usage, where cutting costs may mean sacrificing air quality. As a result, Professor Heydarian and his team of undergraduate engineers have devised the goal of implementing an algorithm that will dynamically operate the HVAC control system of UVA facilities, starting with Olsson Hall's Link Lab. The algorithm will do so by reducing ventilation in empty rooms and prioritizing increased ventilation rates in rooms with higher occupant counts. Such occupant counts may likely be determined by measurements such as carbon dioxide and PM2.5 concentrations.

This paper intends to look into the benefits and drawbacks of doing so, especially for organizations like NASA and UVA that do not profit directly from improved air quality. Its results should help inform UVA Facilities Management in the decision of whether to adopt a smart HVAC control system.

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