WHY UNIVERSITIES AND INDUSTRY BUILD HEALTHY BUILDINGS

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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 heating, ventilation, and air conditioning (HVAC) control system, which are responsible for circulating the building's air. This algorithm should improve indoor air quality and ideally save energy doing so. If this system succeeds in Olsson Hall, it may lead to a university-wide transition towards smart HVAC systems. This paper continues 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.

The capstone project description by UVA Assistant Professor Arsalan Heydarian describes the proposed technological solution as 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 were used to construct statistical models, forecast IAQ, and even predict energy consumption at high resolution (Heydarian, 2021). These analytics were then used to develop optimization algorithms linked to the control systems that drive HVAC operations in the Link Lab at Olsson Hall. Building controls were 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 was 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 not only by saving energy in empty rooms but also by improving ventilation to occupied rooms.

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 (CO_2) 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 CO_2 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's experience aboard the International Space Station (ISS) supports Pinch & Bijker's Social Construction of Technology (SCOT) framework by showing the influence of astronauts as a social group in shaping technology within a sociotechnical system. Here, Kelly's experience shaped the future of indoor air quality on the ISS. He expresses 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*. For example, 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 in which both Kelly and the submariners exist. Neither the ISS nor submerged submarines take in fresh air. 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).

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.

Research Question and Methods

Why do communities construct buildings that prioritize occupant health, and what different motives do universities and industry have? To answer this question, it may be helpful to look into case studies of universities that have already transitioned towards smart, healthy HVAC systems. Harvard University and Oberlin College are two such pioneering universities. My research focused on the Harvard Smith Campus Center, Klarman Hall at Harvard, and the Adam Joseph Lewis Center for Environmental Studies at Oberlin College.

The rationale of these two universities is compared and contrasted with commercial buildings. Such buildings include: the Bank of America Tower at 1 Bryant Park in New York, the SwissRe building in London ("The Gherkin"), the Bloomberg Headquarters in London, and the Edge building in Amsterdam.

I gathered data by looking into rhetoric on each of the seven buildings mentioned in this section. Such rhetoric came from university websites, architecture firms, and independent journals. I then searched the digital text of rhetoric on each of the seven buildings using Wordcounter.net. This website returned a list of the most frequently mentioned words and a tally of how many times each word was used (e.g. “modern” appears 4 times in a description on the Bank of America Tower). Given this list, I sorted out insignificant words like “the” and “a”. From there, I reproduced these sorted lists in Google Sheets, keeping only the top five most used words. I then read through and identified word themes (e.g. “Sustainable”, “Professional”, “Health”, etc.), assigned each word to a category, and summed up word counts for each category to convey it graphically.

In doing so, I also weighted the word counts so that each building had equal representation in the final results. For example, I collected a total of 26 occurrences of the top five most used words in a description of the Adam Joseph Lewis Center, but I only had 13 occurrences of the top five most used words for the SwissRe Building. To address this, I weighted each article as if there were 20 occurrences of the top five most used words for each. This kept any much shorter or longer articles from throwing off my final results.

Results

Universities may place a higher value on sustainability while commercial buildings value worker health more explicitly (Figure 1). Overall, however, there is no single motivation or rhetoric that dominates building descriptions (Figure 2). University building rhetoric also emphasizes education (Figure 1), which may be seen as analogous to workplace productivity, but all such keywords come from a single article describing Klarman Hall at Harvard. On the other hand, commercial buildings place additional emphasis on architectural and innovative terms

(Figure 1). The following results show differences between university and industry rhetoric in their most discussed themes (i.e. university rhetoric discussed themes of sustainability much more than industry rhetoric). These results suggest university rhetoric focuses more on sustainable and educational themes while industry rhetoric focuses more on architectural, health, and innovative themes.

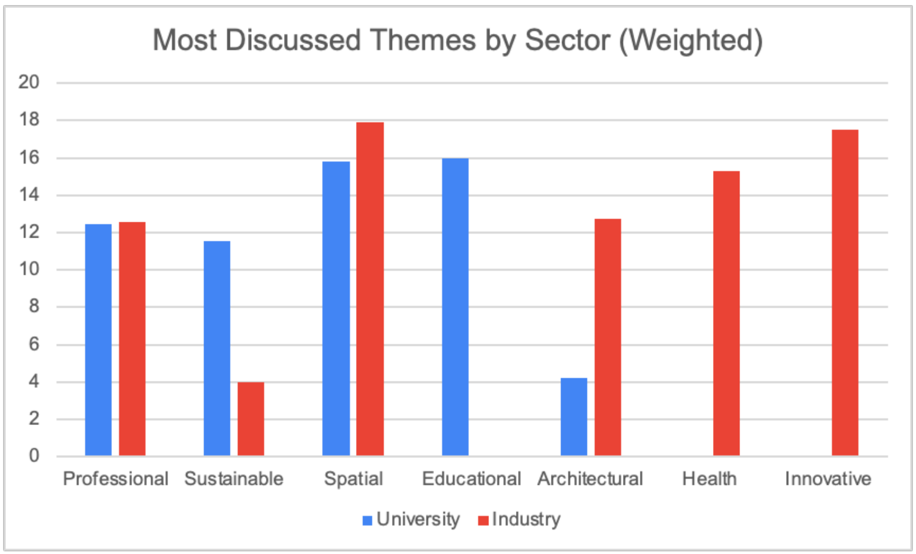

Figure 1. Most Discussed Themes by Sector (Weighted)

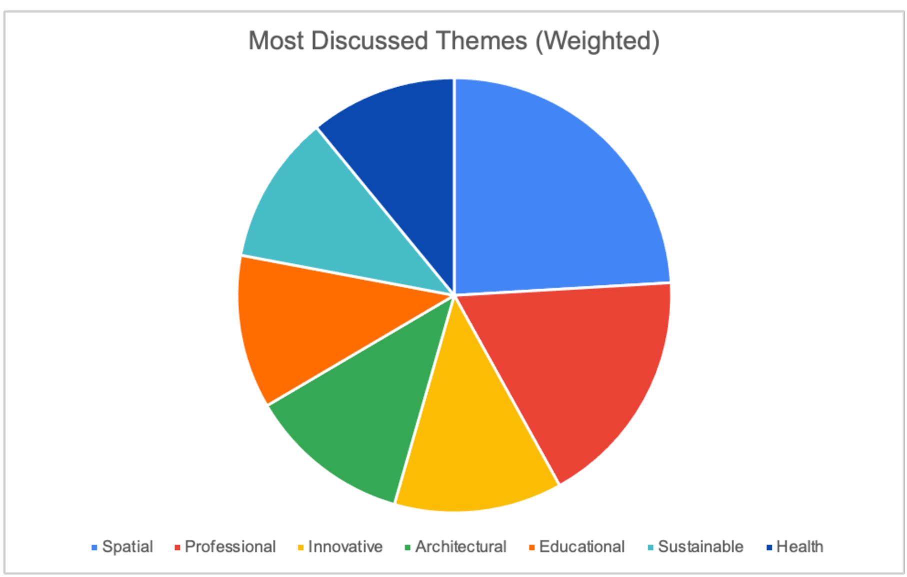

Figure 2. Most Discussed Themes (Weighted)

As mentioned above, rhetoric on university buildings tends to have more keywords related to education and sustainability. Such educational keywords include terms like “learning” and “ideas”, while sustainable keywords include terms like “ecological” and “environment”. For example, the following excerpt comes from a description of Harvard’s Klarman Hall:

“It is my hope that those who come to Klarman Hall will remain open to listening to a productive exchange of ideas, to ***learning*** *from disagreements, and perhaps grow as a result of them. May this space be a place to develop and share* ***ideas*** *which will have a positive impact on the people who come together in this room and on those in the world beyond,” (Kenny, 2018).*

On the other hand, rhetoric on commercial buildings emphasizes architectural and health-related words. One outstanding health-related keyword is “air”, which appears in descriptions of both the SwissRe Building in London and of the Bank of America Tower in New York. The following excerpt comes from a description of the SwissRe building.

“*These spaces are a natural social focus – places for refreshment points and meeting areas – and function as the building*’*s* ‘*lungs*’*, distributing fresh* ***air*** *drawn in through opening panels in the facade. This system reduces the building*’*s reliance on* ***air*** *conditioning and together with other sustainable measures, means that it uses only half the energy consumed by a conventionally air-conditioned office tower,” (Foster + Partners, 2022a).*

Here, “air” is mentioned in the context of (1) personifying the building and (2) emphasizing the innovative energy-saving techniques of this building’s air-handling systems. The description personifies the building by using “lungs” to give the building a natural feeling, and it’s focus on energy-saving innovations makes the building feel both cutting-edge and eco-friendly. The following example from a description of the Bank of America Tower does so as well:

“Drawing on concepts of biophilia – people's innate need for connection to the natural environment – the vision was to create the highest quality modern workplace by emphasizing daylight, fresh ***air****, and an intrinsic relationship to the outdoors,” (Campbell, 2021).*

In this example, just like before, words like “natural” and “fresh” draw the mind towards lively thoughts and away from more stale images of conventional buildings. At the same time, this excerpt follows up with an emphasis on innovation with its mention of the “high quality modern workplace”.

Finally, I should revisit the topic of educational keywords. As mentioned above, educational keywords like “learning” and “ideas” are all from the article describing Klarman Hall at Harvard. It is important to consider that educational and professional categories blur together in a university setting. With this in mind, it may be fair to say that universities indeed value productivity and maximized learning in a healthy building, but the conclusion is still only based on a single building's rhetoric.

Discussion

This study connects to Pinch & Bijker's social construction of technology (SCOT) theory, which discusses how social groups shape technology within a sociotechnical system (Pinch & Bijker, 1984). In the case of rhetoric on healthy buildings, social groups range from architectural firms to university admin– the authors of the various articles and webpages I've pulled from. They are the designers and owners of technological systems that support occupant health within the sociotechnical system of a whole building or complex. I have used the similar case of astronaut Scott Kelly on board the International Space Station as an example of SCOT. In Scott Kelly's case, he is an astronaut shaping indoor air treatment on board the ISS– yet another social group shaping technology within a sociotechnical system. Kelly does so through his complaints of fatigue due to high carbon dioxide concentrations, and also by citing better standards for carbon dioxide on naval submarines. One key difference here is that Kelly is the building's occupant, not its designer or owner.

This brings attention to one shortcoming of my research: I pulled rhetoric from building designers and owners but not from occupants. The results of my research are limited by several other factors as well. One such factor is the limited selection of buildings that prioritize occupant health. A consequence of this limited pool is less confidence in research results. For example, the fact that descriptions of Klarman Hall at Harvard are the only to feature educational keywords makes for weaker conclusions about universities finding value in healthy buildings for improved learning. Similarly, the Adam Joseph Lewis Center at Oberlin is the only university building to include keywords about sustainability.

Another limitation of this research is the limited rhetoric given for each building. The rhetoric on each building is limited to one article in most cases, with the exception of the Adam Joseph Lewis Center at Oberlin, which features descriptions from different parts of the same website. As a result, this data may be coarse, and this prohibits drawing finer, more detailed conclusions. Perhaps such conclusions would be easier to draw if the selected descriptions had higher word counts.

To address these concerns, I would do two things. First, I would look to select more buildings for study. This increased pool of buildings would help diversify and nail down more broad, dominant themes. The second correction I would make is to pull rhetoric from more than just one article on each building. It may also be useful to sift through public comments on each building, as this would diversify the sources of rhetoric to include people outside the professional world. It would also help bring in perspectives from building occupants. Both of these approaches would also provide more words to sift through and thus more data to analyze. At the same time, pulling additional rhetoric may reduce the quality of the data at a certain point (e.g. by using technical specifications).

This research advances my own engineering practice by identifying community values and understanding how such values shape engineered products. In the case of my capstone project, where HVAC systems are the main focus, this research may help articulate values around HVAC renovation. It can do so in two key ways. One way is in studying past example of HVAC renovations, similar to the study done here on previously constructed buildings. Such a study may help understand why communities have renovated in the past. A second key way of articulating values around HVAC renovation would be to survey current members of a community in the midst of a decision. While surveying might not always reveal community values in support of renovation, it nonetheless provides a useful description for decision-making. Both methods of articulating community values can lead a community to better decisions.

Conclusion

Studying the rhetoric of communities that have already built healthy buildings can inform others in making the same decision. Perhaps a closer look at rhetoric reveals otherwise unseen reasons to optimize for occupant health. In the case of UVA, this could mean taking a closer look at why Harvard and Oberlin built healthy buildings. For Oberlin, the Adam Joseph Lewis Center has become a flagship for sustainability and a cornerstone for the university's sustainable future. For Harvard, the Smith Campus Center and Klarman Hall embody efforts to move towards a sustainable future in a way that also benefits learning and productivity.

The future of this research lies in surveying communities that find themselves amidst decisions about whether or not to build healthy buildings. This will help in two ways. First, it articulates constituent values so that community administrators can make decisions that best align with their own community's values. The second and perhaps more important note is that surveys can help understand why communities have not yet chosen to build healthy buildings. Altogether, my research shows that universities comment uniquely on the educational and sustainable aspects of their healthy buildings while commercial rhetoric focuses instead on innovation and occupant health. And though looking to our peers can uncover why others build healthy buildings, it may be just as important to find out what prohibits our own communities from doing so.

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