Title
Integrating Smart Ceiling Fans and Communicating Thermostats to Provide Energy-Efficient Comfort

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Publication Date
2020-04-01

Energy Research and Development Division

FINAL PROJECT REPORT

Integrating Smart Ceiling Fans and Communicating Thermostats to Provide Energy-Efficient Comfort

California Energy Commission

Gavin Newsom, Governor

April 2020 | CEC-EPC-2020-XXX

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ACKNOWLEDGEMENTS

We would like to thank many people whose efforts led to the success of this project:

UC Berkeley: Stefano Schiavon, Sonja Salo, Jovan Pantelic, Fred Bauman, Wenhua Chen, Yingdong He, Maohui Liu, Marta Delgado Lombardo, Carlos Duarte, Tom Parkinson, and Amy Mostacho.

TRC: Mia Nakajima, Abhijeet Pande, Kristen Bellows

Big Ass Fans: Jay Fizer, Christian Taber, Justin Risner, Pete Maley, Michael Smith, Jayme Webb, Michael Harp.

PREFACE

The California Energy Commission's Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The California Energy Commission and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The Energy Commission is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Integrating Smart Ceiling Fans and Communicating Thermostats to Provide Energy-Efficient Comfort is the final report for the Integrating Smart Ceiling Fans and Communicating Thermostats to Provide Energy-Efficient Comfort project (EPC-16-013) conducted by the Center for the Built Environment, a representative of The Regents of the University of California. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

The project goal was to identify and test the integration of smart ceiling fans and communicating thermostats. These highly efficient ceiling fans use as much power as an LED light bulb and have onboard temperature and occupancy sensors for automatic operation based on space conditions. The Center for the Environment (CBE) at UC Berkeley led the research team including TRC, Association for Energy Affordability (AEA), and Big Ass Fans (BAF).

The research team conducted laboratory tests, installed 99 ceiling fans and 12 thermostats in four affordable multifamily housing sites in California's Central Valley, interviewed stakeholders to develop a case study, developed an online design tool and design guide, outlined codes and standards outreach, and published several papers.

The project team raised indoor cooling temperature setpoints and used ceiling fans as the first stage of cooling; this sequencing of ceiling fans and air conditioning reduces energy consumption, especially during peak periods, while providing thermal comfort. The field demonstration resulted in **39% measured compressor energy savings during the April–October cooling season** compared to baseline conditions, normalized for floor area. Weather-normalized energy use varied from a 36% increase to 71% savings, with **median savings of 15%.** This variability reflects the diversity in buildings, mechanical systems, prior operation settings, space types, and occupants' schedules, preferences, and motivations. **All commercial spaces with regular occupancy schedules (and two of the irregularly-occupied commercial spaces and one of the homes) showed energy savings on an absolute basis** before normalizing for warmer intervention temperatures, **and 10 of 13 sites showed energy savings on a weather-normalized basis.** The ceiling fans provided cooling for one site for months during hot weather when the cooling equipment failed. Occupants reported high satisfaction with the ceiling fans and improved thermal comfort. This technology can apply to new and retrofit residential and commercial buildings.

Keywords: *multifamily housing, HVAC, cooling, fans, air movement, thermal comfort, energy efficiency*

Please use the following citation for this report:

Paul Raftery, Dana Miller, Hui Zhang, Therese Peffer, Gail Brager, Lindsay Graham, Elaina Present, Ed Arens, David Douglas-Jaimes, Gwelen Paliaga, Andy Brooks, Sebastian Cohn, Mitch Greene. 2020. *Integrating Smart Ceiling Fans and Communicating Thermostats to Provide Energy-Efficient Comfort.* California Energy Commission. Publication Number: CEC-XXX-201X-XXX.

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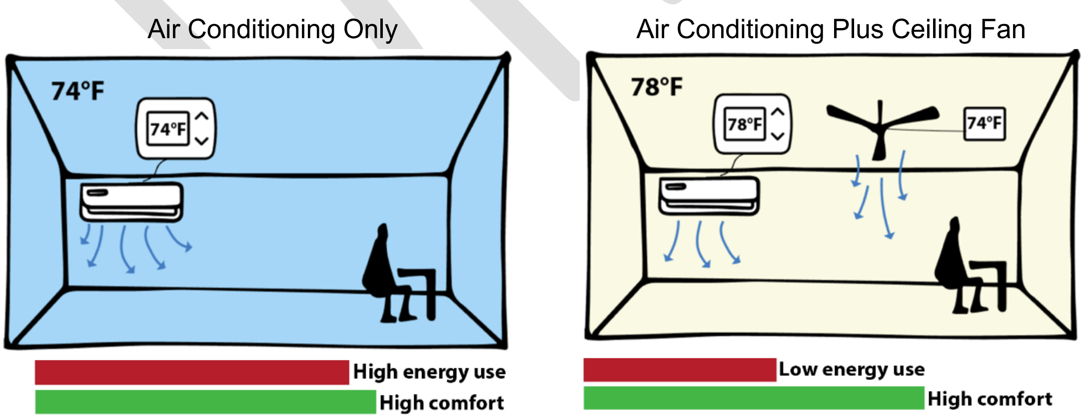
Introduction or Background

The electric peak demand in California is driven by summer-time air conditioning loads in residential and commercial buildings. Air conditioning has become a necessity in many climate zones: extreme heat events kill more Americans every year than any other weather-related disaster (US Department of Homeland Security 2020), and as climate change progresses, heat waves are increasing in intensity and frequency (Center for Climate and Energy Solutions (C2ES) 2017). Low income populations are increasingly more vulnerable as these communities often lie in areas disproportionately warmer than wealthier communities (Anderson and McMinn 2019), their houses tend to be less efficient (Berelson 2014), and they pay more of their income for energy (Alamo, Uhler, and O'Malley 2015).

Air movement, such as provided by ceiling fans, can cool a person while using only a fraction of the energy required by conventional Air Conditioning (AC) systems. Modern efficient ceiling fans with electrically commutated DC motors and improved blade design use only **2–30 watts**—compared to **2,000–3,500 watts** for the typical 1.5–3-ton air conditioning system—and can offset a 4–8 ºF (2.2–4.4 º C) increase in indoor air temperature. Some "smart" ceiling fans have onboard temperature and occupancy sensors for automatic operation based on the conditions in the space. These devices improve the occupant's comfort and perceived air quality while decreasing energy consumption, particularly during peak demand hours. In addition, ceiling fans can provide a potential back-up cooling strategy during power outages, since these low-power devices could feasibly be powered by very small battery or solar photo-voltaic systems. This project studying the use of smart (automated or temperature- and occupancy-based control) ceiling fans in conjunction with thermostats in low-income housing supports three of California's energy efficiency goals: doubling energy efficiency savings by 2030, removing and reducing barriers to energy efficiency in low-income and disadvantaged communities, and reducing greenhouse gas emissions from the building sector.

Figure 1: Using Ceiling Fans to Provide Cooling to Lower Energy Use



Left: Air conditioning provides cooling and comfort—at an energy and carbon cost. Right: Coordinating ceiling fans with air conditioning can provide comparable comfort with less energy.

Credit: Dana Miller, UC Berkeley

Figure 1 shows the basic concept. On the left, traditional air conditioning provides cooling and comfort. On the right, using a ceiling fan to provide a person with the cooling effect of moving air ('wind chill effect') creates comparable comfort at 78 ˚F compared to still air at 74 ˚F. Coordinating and sequencing ceiling fans with air conditioning can provide improved comfort with less energy by initially cooling with air movement (fan starts operating above 74 ˚F) before adding air conditioning at a higher temperature (78 ˚F).

There are several barriers to rapid deployment of ceiling fans to reduce energy consumption or provide emergency cooling. One is the coordination of ceiling fan controls with Heating, Ventilation, and Mechanical System (HVAC) controls such as thermostats in order to adjust air conditioning cooling setpoints when ceiling fans are running. Another is the relatively high cost of automated ceiling fans in the current market, and limited number of models available. Other barriers stem from lack of knowledge of how these technologies benefit people—ceiling fans cool people, not spaces—and a perception that they consume significant amounts of energy, largely driven by familiarity with older, inefficient AC-motor ceiling fans. Other barriers lie in the installation of ceiling fans: designers lack the knowledge of the optimal size, number, spacing, and location of ceiling fans for a given application, particularly for commercial spaces.

These issues cross multiple disciplines (e.g., thermal comfort, architecture, engineering, psychology) and multiple sectors (e.g., manufacturers, housing developers, designers, facilities managers, end users), and as such are not likely to be addressed in the market. Ratepayer support is required for multi-disciplinary research to conduct the field study to demonstrate energy savings of the integrated ceiling fan and thermostat system in retrofit applications and provide a design guide and energy code language to facilitate widespread adoption.

Project Purpose

The goal of the *Integrating Smart Ceiling Fans and Communicating Thermostats to Provide Energy-Efficient Comfort* (EPIC fans) project was to identify and test optimal configurations for the integration of two newly available technologies—smart ceiling fans and communicating thermostats—in order to reduce energy consumption while providing improved comfort. This integrated solution has the potential to automate energy savings in ways customers not only accept, but actually seek, for it provides improved comfort and lower energy costs. The project examined the impact of such technology integrations, and provides guidance to manufacturers, designers and engineers as they implement these new energy-saving technologies. The specific objectives of the study were to: 1) demonstrate the energy saving and improved comfort potential of the integrated system in retrofit applications; 2) identify and address market barriers to wider acceptance and adoption; 3) provide guidance on how to implement this technology into energy efficiency retrofit programs and policies; and 4) develop standard rating methods, a design web tool, a design guide, and energy code language to facilitate widespread adoption.

Residential ratepayers are increasingly looking for ways to reduce energy bills, especially during peak periods. In Pacific Gas & Electric (PG&E) territory in Northern California, beginning in November 2020, residential customers will move to Time Of Use rates where they will experience rates of 32–40 cents[1] per kilowatt-hour (kWh) from 4-9 pm June-September—exactly coinciding with the hottest temperatures of the day (Pacific Gas and Electric (PG&E) 2019). This research provides solutions to lowering energy bills.

The audience of this research are residential or small-commercial ratepayers, designers of commercial and residential buildings, fan and thermostat manufacturers, and policy makers.

Project Approach

The **Center for the Environment (CBE)** at UC Berkeley led the research team including TRC, Association for Energy Affordability (AEA), and Big Ass Fans (BAF) to study the integration of BAF smart Haiku® ceiling fans with SenseME™ control and advanced thermostats through laboratory testing and demonstration pilots at affordable multifamily housing sites. World-renowned building science researchers at CBE have led cutting-edge research leading to standards and codes in thermal comfort for over 30 years; by developing an Industry/University Research Collaboration, CBE provides tools and guidance for building owners and professionals, and supports the development of improved standards to speed the adoption of effective technologies. **TRC** is a national engineering, consulting, and construction management firm that provides integrated services to the energy, environmental, and infrastructure markets. TRC has decades of experience with multifamily retrofit programs. **AEA** is a not-for-profit technical services and training organization at the forefront of increasing energy efficiency in buildings. Over the past 22 years, AEA has carried out a broad range of activities and programs benefitting low-income multi-unit residences including; energy audits, commissioning, technology demonstrations, and energy efficiency training. For over 20 years, **BAF** has been researching, developing, and improving low speed, high volume ceiling fans that exceed Energy Star ratings while achieving low power consumption and low decibel rates.

Figure 2: Field Demonstration Sites

Credit: Therese Peffer, UC Berkeley; David Douglass-Jaimes, TRC

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[1] The Tier 1 rate for most residential homes in PG&E in 2019 was $0.23 per kWh.

The project team conducted six tasks in addition to General Project Tasks: **Task 2 Laboratory Testing** to analyze fan air flows with different furniture and different configurations of ceiling fan parameters (led by CBE), **Task 3 and 4: Multifamily Common Space and Dwelling Unit Field Demonstrations** (led by TRC), which installed 99 ceiling fans and 12 thermostats at four multifamily housing sites in the Central Valley, **Task 5: Technology Readiness** to identify market factors, barriers, and case studies (led by TRC), **Task 6 Evaluation and Project Benefits** (led by CBE), and **Task 7 Knowledge/Technology Transfer Activities** (led by CBE), including development of a Design web tool, Design Guide, and codes and standards outreach. CBE also participated on significant components of the demonstrations, particularly with occupant surveys, comfort, indoor environmental quality, and Measurement & Verification. AEA installed all necessary equipment and provided support on-site for Tasks 3 and 4, which included sites in three cities in California's Central Valley: Stockton, Newman, and Madera (Figure 2).

The main technical and nontechnical barriers were found in the field study portion of the project. The smart ceiling fan and smart thermostat did not directly integrate as expected; ideally, the ceiling fan would communicate directly to the thermostat to adjust the air conditioning setpoint and/or prompt the occupant to increase the thermostat setpoint to save energy. The project team switched to a different smart thermostat manufacturer in order to obtain better access to the data; the team worked closely with BAF to change the firmware on the ceiling fan controller and user interface in order to achieve project objectives. The end users would sometimes change the target temperature or setpoints on the thermostats, perhaps to more familiar settings, but those that reduced energy savings. The project team produced educational material to inform occupants and engaged the facilities managers on appropriate setpoints. Some users inadvertently changed the operation of the HVAC blower fan, which wasted energy and highlighted thermostat usability concerns. In addition, many end users in the project spoke Spanish as their native language, but Spanish languages resources for the installed hardware were limited or not available from manufacturers. While occupants generally found the ceiling fan remote control intuitive, many found the newly installed thermostats more challenging. The team worked to produce appropriate bilingual educational material to inform occupants about thermostat settings and appropriate blower fan operation.

Project Results

The research team successfully conducted laboratory and field tests, interviewed stakeholders to develop a case study, developed an online design tool and guide, and outlined codes and standards outreach, meeting the goals and objectives of the project.

Field studies

The results at individual demonstration locations varied considerably. Overall, the field demonstration resulted in **39% measured compressor energy savings during the April–October cooling season compared to baseline conditions**, across all sites and normalized for floor area served. Ceiling fans used an average of just 8.0 Watts when operating. Total ceiling fan energy consumption during the April–October cooling season was **less than 3%** of compressor energy use, normalized for floor area. When additionally normalized for weather due to warmer outdoor conditions (1.7 ˚F (0.95 ˚C)) during the intervention compared to the baseline period, **energy use per zone varied from an increase of 36% to savings of 71%** across all 13 compressors across four sites. The median per-compressor weather-normalized savings was 15%. This variability reflects the diversity in buildings, mechanical systems, prior operation settings, and space types, as well as occupants' schedules and preferences. All commercial spaces with regular occupancy schedules (as well as two irregularly-occupied commercial spaces, and one home) had measured energy savings on an absolute basis (even before normalizing for warmer temperatures after the fans were installed), and 10 of 13 sites showed energy savings on a weather-normalized basis. The three sites that did not experience weather-normalized energy savings were an infrequently occupied commercial space (with irregular air conditioning use) and two residential units where residents opted to maintain lower air conditioning cooling setpoints (typically below 75 ˚F). Energy savings also frequently coincided with peak electricity demand periods, which has additional emissions and grid benefits.

The size and energy consumption of a compressor correlates with floor area; the floor area served by each individual compressor varied more than six-fold. The research team normalized reported energy savings by floor area to avoid sites with larger floor area unduly weighting the percentage savings estimate. Zones in commercial buildings were also classified as either 'regularly occupied' or 'irregularly occupied' to reflect that zones with infrequent occupancy had less savings potential compared to zones with lengthy frequent cooling demand. These zones also had irregular usage patterns that likely contributed to variability in savings, particularly as the research team does not know if total occupied hours increased (or decreased) substantially between the baseline and intervention periods.

The low-energy ceiling fans provided an additional resilience benefit when air conditioning at one site unexpectedly failed for several months during hot weather. The ceiling fans improved comfort while the site continued to operate, and the project team helped the facilities manager identify the problem and solution. While not the focus of this study, the ability of efficient ceiling fans to provide cooling for an order of magnitude less power than traditional air conditioners suggests they could additionally provide supplemental cooling during equipment failure, or feasibly powered by battery or solar-powered sources during power outages.

Per the occupant interviews and surveys, *all* occupants reported high satisfaction with the ceiling fans. The presence of the fans increased the range of thermal comfort and acceptability across participants; the fans' presence in the space also had a positive impact on air movement acceptability. All participants felt the fans provided adequate cooling, and improved indoor environmental quality; occupants were pleased with its ability to cool the space quickly and effectively. Even in sites where the measured energy data does not show savings, the occupants still used and interacted with the fans regularly and reported being satisfied with the fans. As noted above, these smart, or automated, ceiling fans have temperature and occupancy sensors which allow them to operate automatically based on the conditions in the space. This automated speed feature was widely accepted and liked by the occupants. One office worker reported, "[The ceiling fans have helped me] by not having to worry about being too hot or too cold in the office. Because when you're too hot or too warm it's hard to concentrate. By having the fan, it helps me stay focused because I don't have to worry about the temperature."

The project team has outlined several lessons learned, especially regarding behavior change. In some sites the occupants were not responsible for paying energy costs, which likely impacted air conditioning setpoints and thus energy savings, though the occupants still reported improved comfort. While there is no evidence supporting this perception, some believed that moving air drafts were not healthy, especially for a newborn infant; this impacted the use of ceiling fans compared to air conditioning. The research team communicated with occupants, actively encouraging desired thermostat setpoint and fan use behaviors several times over the 15-month period after the fans had been installed, and in some instances, assisted in changing the setpoints to energy-saving setpoints with occupant approval (particularly for those occupants who experienced difficulty with the new thermostat). Future work should explore feedback and incentives to encourage optimal behavior change. Development of custom fan firmware was required to fully implement the automated fan operation as the research team envisioned—namely, to 'learn' new setpoints for the fans based on user interaction. Although the results of the field demonstrations show substantial percentage energy savings, there is need for further development to achieve widespread adoption. The technologies could be simplified, and usability could be improved, especially for the thermostat. Many occupants felt the Ecobee thermostats had a steep learning curve and were challenging to use at first. The lack of multiple language support in the thermostats was an issue for many of the occupants, particularly in the residences. At least one occupant inadvertently scheduled the blower fan on continuously, which substantially increased the overall energy consumption. Additionally, the networked fans and thermostat reportedly caused WiFi interference for a few residents, potentially due to router congestion.

Case Studies

The research team at CBE conducted 13 interviews with architects, engineers, and facilities managers from California and around the country to create a case study of commercial spaces with existing ceiling fans. The researchers also took in-situ airspeed measurements at five of the projects to provide insight into real-world conditions in commercial buildings with ceiling fans. The ceiling fans' operation resulted in generally relatively low airspeeds, often under 0.2 m/s. The researchers also found just 25% of the 20 projects discussed by interviewees had any type of automation in the ceiling fan controls. Occupants often choose to have the ceiling fans on even when the resulting airspeeds were too slow to create an appreciable cooling effect. One building used upward air flow to provide more even distribution of air flow throughout the space. Ceiling fans provided benefits not only for comfort conditioning and energy use reduction, but also provided individual control with more spatial resolution than a thermostat controlling a whole zone, non-thermal benefits such as improved air quality, or an aesthetic choice to eliminate visible ductwork.

Laboratory studies

The laboratory studies performed during this project yielded new insights such as developing a new method for designers to estimate the airspeeds achieved under a given set of fan and room conditions, airflows around furniture due to ceiling fans, and the design of distribution ductwork in co-ordination with ceiling fans. These findings, and guidance on best practices, have been incorporated into the reports, as well as an online design tool and design guide made publicly available as part of this project. The aim of these resources is to make it easier for designers to incorporate air movement into their designs.

Technology/Knowledge Transfer/Market Adoption (Advancing the Research to Market)

The project team shared results of the project through multiple channels. Outreach include six papers published (and more in process) and 18 presentations at various venues (CBE Industry Advisory Board meetings, ACEEE Summer Study, ASHRAE, LBNL) to practitioners/ developers, manufacturers, policy makers, and potential end users. Through students hired, future thought leaders were trained. The project developed the online Design Tool, cbe.berkeley.edu/fan-tool, and the Ceiling Fan Design Guide, https://cbe.berkeley.edu/wp-content/uploads/2020/04/CBE-Ceiling-Fan-Design-Guide-V0.pdf. These can be used by designers, architects, and engineers to provide ceiling fan recommendations for optimal overall airflow.

Ceiling fans are already relatively common in residential applications, with the U.S. Energy Information Administration estimating roughly 80% of single-family homes and over 40% of multifamily units have at least one ceiling fan.[2] However, the majority of these are likely older, far less efficient models, and very few have onboard sensors and controls for automation. As an established market for ceiling fans, the residential sector is an ideal near-term market for integrating the benefits of smart ceiling fans and communicating thermostats. These combined technologies are also applicable across nearly all nonresidential building types, though those market sectors are likely to take longer to develop due to barriers in the design and construction industries such as a lack of reliable data on ceiling fan performance and limited information to communicate the benefits of ceiling fans. However, large-diameter ceiling fans are increasing in popularity in industrial and warehouse applications, both as a supplement and as an alternative to mechanical cooling. Similarly, the continued development of resources and information on the thermal comfort and energy saving benefits of ceiling fans can lead to longer-term growth in the full range nonresidential building types, including but not limited to offices, schools, hospitality, and other commercial applications.

Though the widespread presence of ceiling fans in residential applications implies a nearly saturated market, a single ceiling fan is insufficient to provide consistent thermal comfort conditions through a home. Multiple ceiling fans, thoughtfully placed throughout a home, can provide thermal comfort and energy savings. On the nonresidential side, with the exception of relatively specialized applications such as warehouse and industrial, ceiling fan market penetration is nearly nonexistent, presenting a significant opportunity for as yet unrealized energy savings.

To date there have been limited resources to reliably communicate the performance of different ceiling fan models, the expected outcomes of a ceiling fan design, or the benefits of ceiling fans to building owners or clients. The output of this research have made significant progress in

[2] https://www.eia.gov/todayinenergy/detail.php?id=31312

bridging these barriers. Additionally, the team conducted codes and standards outreach activities including:

- Development of a new ASHRAE Standard, ASHRAE 216 – Methods of Test for Determining Application Data of Overhead Circulator Fans
- Proposed Addendum C to ASHRAE Standard 55 defining Thermal Environmental Control Classification Levels for certain compliance options
- A description of barriers and opportunities for ceiling fans in the California Building Energy Efficiency Standards
- A discussion of building code considerations, including fire code requirements, and opportunities for additional clarification of the code requirements related to ceiling fans

The development of these new industry standards, including ASHRAE Standard 55 Addendum C and ASHRAE Standard 216, provide metrics and performance data to reliably integrate alternative thermal comfort strategies, such as ceiling fans and increased thermostat setpoints, as alternative compliance strategies in building energy standards.

Benefits to California

"Smart" (automated or temperature- and occupancy-based control) ceiling fans in conjunction with communicating thermostats can provide greater energy security and reliability in the form of energy and cost savings, peak energy reduction, emission reductions, and a source of cooling (especially as a back-up) to IOU electricity ratepayers. Energy savings stem from allowing an increase to the space cooling temperature setpoint and by turning off the fans when no occupancy is detected. Though ceiling fans are often considered a purely residential appliance, and are often categorized as a lighting product (including in the Energy Star program), ceiling fans can provide thermal comfort benefits in nearly any nonresidential application as well.

The project team estimated statewide energy, cost, and CO_2 emission reductions assuming a combined cooling energy savings of 30% from both the ceiling fans and thermostats, and a target installation in sites that have high cooling loads. The team estimates that a 15% market penetration of California buildings over the next 15 years will yield an annual reduction of 736 GWh, $125M, and 537M pounds of CO_2 emissions. This estimate includes multifamily (24 GWh, $4M and 18M pounds), single family (228 GWh, $39M, 166M pounds), and schools, offices, and retail spaces (484 GWh, $82M, 353M pounds). While this demonstration focuses on the multifamily sector, the technology is a scalable energy retrofit solution for a broad range of commercial and residential buildings throughout California. For commercial sites that are frequently occupied with high cooling energy potential, the technology can represent a cost-effective retrofit (less than 7-year payback) even at current market pricing and current utility rates. Targeting buildings and spaces with these characteristics will maximize energy savings potential. In other sites, including the residences, the cost of the equipment and installation currently exceeds the annual utility bill cooling energy costs, and will not prove to be a cost-effective solution considering energy savings alone. This study developed and documented best practices, leading to increased market penetration that will reduce the cost of adoption, cost of operation, and will increase payback. This will enable building owners to invest in the technology at lower risk. Additionally, installation costs will likely be substantially lower for new construction than for retrofit applications.

CHAPTER 1: Introduction

Background

The key impact of this research project is to demonstrate cooling through sequenced ceiling fans and air conditioning in low-income multifamily housing that reduces energy consumption and improves comfort, and to provide improved guidance on incorporating controllable air movement into the built environment.

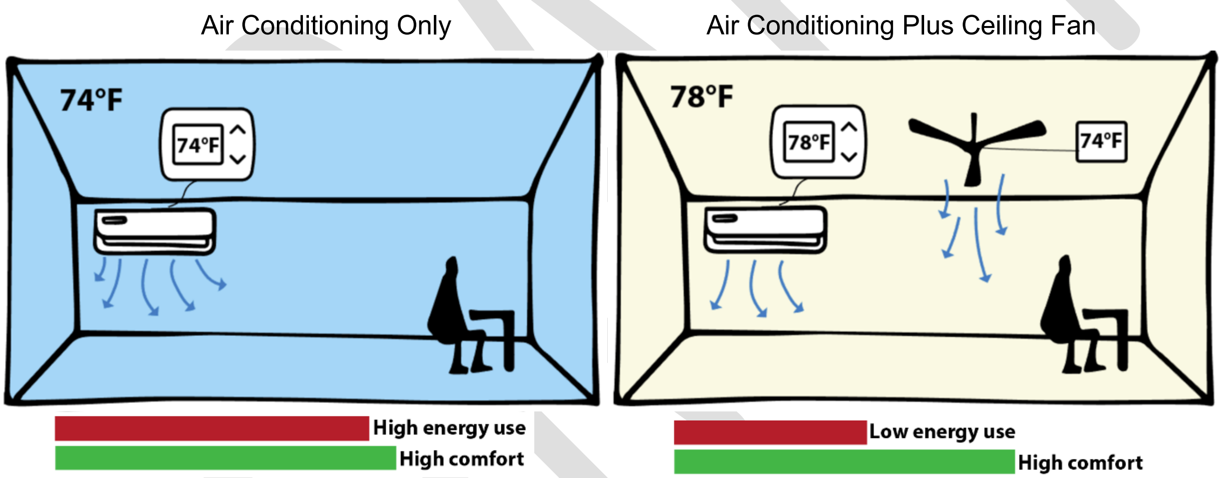
The electric peak demand in California is driven by summer-time air conditioning loads in residential and commercial buildings. Air conditioning has become a necessity: extreme heat events kill more Americans every year than any other weather-related disaster (US Department of Homeland Security 2020), and as climate change progresses, heat waves are increasing in intensity and frequency (Center for Climate and Energy Solutions (C2ES) 2017). Cooling workplaces and homes through air conditioning has saved lives during heat waves and provided thermal comfort that leads to improved satisfaction and productivity, especially in the last few decades—but at a tremendous cost. The US uses more electricity for cooling than the country of Africa uses for everything (Cox 2012). More and more residences in the US have air conditioning: in 2015, 87% of American residences had air conditioning (U.S. Energy Information Administration (EIA) 2015). This ever-increasing energy use contributes to greenhouse gases[3] and ozone depletion. In addition, prevalent air conditioning use leads to physiological "addiction" that causes people to become less tolerant of temperature excursions outside a narrow temperature range. In California, residential air conditioning exacerbates the already high cost of living, which contributes to California's high poverty rate—the highest in the US. Low-income households in California spend 67 percent of their income on housing, about 11 percent more than low–income households in the rest of the US (Alamo, Uhler, and O'Malley 2015). Compared to average households, low-income households are less likely to have compact fluorescent bulbs and low-flow showerheads, but 25% more likely to have energy-intensive space heaters and 50% more likely to rely on window air conditioning units (Berelson 2014). Furthermore, the cost for power from California's privately-owned utilities ranges from 18 cents to 23 cents per kilowatt hour, compared with 13 cents as the national average (U.S. Energy Information Administration (EIA) 2019). In Pacific Gas & Electric (PG&E) territory in Northern California, beginning in 2020, the residential customers will move to Time-Of-Use rates where they will experience rates of 32-40 cents per kilowatt-hour (kWh) from 4-9 pm June-September—exactly coinciding with the hottest temperatures of the day (Pacific Gas and Electric (PG&E) 2019).

[3] Project Drawdown's number one (e.g., most effective) solution for reducing greenhouse gas emissions is the management and destruction of refrigerants (found in air conditioners and refrigerators) already in circulation (Project Drawdown 2019).

Air movement, such as provided by ceiling fans, can cool a person, but uses only a tiny fraction of the energy required by HVAC systems. Modern efficient ceiling fans with electrically commutated DC motors and improved blade design use only 2–30 watts (compared to 2,000–3,500 watts for the typical 1.5–3 ton air conditioning system). By producing 1.5 to 2 miles per hour (mph) (0.7–0.9 meters per second) air movement near building's occupants, these fans can offset a 4–8 ºF (2.2–4.4 ºC) increase in indoor air temperature. Some of these modern, highly efficient ceiling fans also have onboard temperature and occupancy sensors that allow them to operate automatically based on the conditions in the space, improving usability and occupant satisfaction. These devices improve the occupant's comfort and perceived air quality while decreasing energy consumption overall, but especially during California's peak electricity demand periods. In addition, ceiling fans can provide a potential back-up cooling strategy during power outages, since these low-power devices can be powered by battery.

Allowing higher indoor temperatures reduces a building's total HVAC energy by an average of approximately 5% per ºF, and even greater in climate zones where natural ventilation or evaporative cooling systems are used instead of compressor-based cooling, or where there are a large number of airside economizer hours (such as California).

Figure 3: Using Ceiling Fans to Provide Cooling to Lower Energy Use



Left: Air conditioning provides cooling and comfort—at an energy and carbon cost. Right: Coordinating and sequencing ceiling fans with air conditioning can provide comparable comfort with less energy by initially cooling with air movement (fan starts operating above 74°F) before adding air conditioning at a higher temperature (78 °F). The immediate cooling effect of moving air ('wind chill effect') creates comparable comfort with gentle air movement at 78 °F or still air at 74 °F.

Credit: Dana Miller, UC Berkeley

Project Goals and Objectives

The research team led by the Center for the Built Environment (CBE), at the University of California, Berkeley, along with TRC, Association for Energy Affordability (AEA) and Big Ass Fans, proposed an applied research and development project that targets an energy retrofit for multifamily buildings, including both dwelling units and common spaces. World renowned Building Science researchers at **CBE** have led cutting-edge research leading to standards and codes in thermal comfort for over 30 years; by developing an Industry/University Research

Collaboration, CBE provides tools and guidance for building owners and professionals, and supports the development of improved standards to speed the adoption of effective technologies. **TRC** is a national engineering, consulting, and construction management firm that provides integrated services to the energy, environmental, and infrastructure markets. TRC has decades of experience with multifamily retrofit programs. **AEA** is a not-for-profit technical services and training organization at the forefront of increasing energy efficiency in buildings. Over the past 22 years, AEA has carried out a broad range of activities and programs benefitting low-income multi-unit residences including; energy audits, commissioning, technology demonstrations, and energy efficiency training. For over 20 years, **BAF** has been researching, developing, and improving low speed, high volume ceiling fans that exceed Energy Star ratings while achieving low power consumption and low decibel rates.

The goal of the project was to identify optimal configurations for the integration of two technologies: smart ceiling fans and communicating thermostats. This integrated solution has the potential to automate energy savings in ways customers not only accept, but actually seek, for it provides improved comfort and lower energy costs. The project examined the impact of such technology integrations, and provides guidance to manufacturers, designers and engineers as they implement these new energy-saving technologies.

This project conducts primary research to yield understanding and insight regarding the energy use patterns and customer acceptance of an integrated installation of smart ceiling fans and smart thermostats in both dwelling units and common areas of multifamily buildings. The objective of this project is to 1) demonstrate energy savings and improved comfort of an integrated smart ceiling fan and smart thermostat system in retrofit applications, 2) identify and address market barriers to wider acceptance and adoption, 3) provide guidance on how to implement this technology into energy efficiency retrofit programs and policies, and 4) develop standard rating methods, a design guide, and energy code language to facilitate more widespread implementation.

To achieve these goals, the interdisciplinary team from industry and academia team studied the integration of smart Haiku® ceiling fans from Big Ass Fans with SenseME™ control and the Ecobee smart thermostat through **laboratory testing** and **demonstration pilots** at affordable multifamily housing sites. The project team also conducted a series of interviews with designers and engineers to develop a **case study**, developed a **Design Guide and online Design Tool**, and have explored relevant **energy codes and standards**.

An interdisciplinary team from industry and academia installed 99 smart ceiling fans and 12 smart thermostats in four multifamily sites in California's Central Valley. The research team installed monitoring equipment in the sites (Summer 2017), installed the fans and thermostats (Summer 2018), conducted several laboratory tests to discovers the impact of various parameters (e.g., multiple fans, ceiling height, fan diameter), surveyed the office workers and residents who occupy the common rooms and a small number of dwelling units, and monitored the effects of raised indoor temperature and use of ceiling fans to reduce energy consumption while maintaining comfort through to the end of October 2019.

CHAPTER 2: Project Approach

This project consisted of four technical tasks: laboratory testing, multifamily common area site demonstrations, multifamily dwelling unit site demonstrations, and technology readiness, described in a case study here and further in Chapter 4.

Lab Studies

Lab Study 1: Scale Configuration Optimization

Lab Study #1 described laboratory testing at CBE and BAF to determine the velocity and temperature profiles of various fan configurations, which aid in evaluating thermal comfort. The objective of the first CBE lab study was to experimentally measure and compare air speed profiles with obstacles placed in different locations in the airflow path of a ceiling fan. Specifically, researchers placed a table and partition in different locations within a test chamber and evaluate the resulting variations in the air speed profile. This study was performed at UC Berkeley in CBE's climate-controlled environment chamber[4] with one ceiling fan and a single table and partition. The objective of the BAF lab study was to conduct pilot measurements in BAF lab with one and two fans to explore the changes of air speed field in the occupied zone as a function of fan blade to floor height and interaction of flows generated by two ceiling mounted fans as a function of the fan speed. This study took place at BAF facilities in Kentucky with multiple ceiling fans in different configurations (e.g., spacing, height).

Lab Study 2: Multi-fan and ASHRAE 216 Design Tool

The Lab Study #2 examined the airflows due to multiple fan parameters, and helped develop the Design Tool and guidance for sizing and spacing fans. The goal of the Design Tool is to specify and locate a fan or fans to achieve a desirable air distribution within a space. This work is based on laboratory testing of variation in ceiling-fan-driven air movements in terms of room size, fan mounting height, and other influencing factors. The research team measured air speeds in rooms due to ceiling fans in 78 full-scale laboratory tests using different fan models and manufacturers. The factors were the room size, fan diameter, type, speed, up/down direction, blade height, and mount distance (i.e. blade to ceiling height). This study took place at BAF facilities in Kentucky.

Lab Study 3: Comfort Performance

The Lab Study #3 reviewed ceiling fans and other Personal Comfort Systems and thermal comfort. This includes describing the *Corrective Power Index* for quantifying the effect of Personal Comfort Systems such as ceiling fans in providing comfort and reducing energy. The

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[4] http://www.cbe.berkeley.edu/aboutus/facilities.htm

CP index can be used to evaluate both the equivalent change in ambient temperatures caused by fans as well as the changes in subjective responses, such as thermal sensations and comfort.

Field Studies

The goals of the field studies were to 1) assess installation and operation of ceiling fans plus thermostats in common rooms and dwelling units in multifamily sites, 2) assess operation and power consumption of air conditioning plus fans over two cooling periods compared to just air conditioning, 3) assess general impressions of users (office, common room occupant, and residential occupants), and 4) assess indoor air quality and thermal comfort during interventions of raised temperature setpoints. The original schedule was to run the field study through summer 2018, but delays in obtaining the sites and installing monitoring equipment pushed the study period through 2019. The overall schedule of the field demonstrations was as follows:

- July 2017: Installation of monitoring equipment
- July 2017 – June/July 2018: Pre-installation monitoring period
- June/July 2018: Installation of ceiling fans and thermostats
- June/July 2018 – October 2019: Post-installation monitoring period
- December 2019: Removal of monitoring equipment

Site Recruitment

Site recruitment consisted of first establishing a set of criteria for participating sites, such as:

- Must have electrical service provided by an investor-owned utility (SCE, PG&E, or SDG&E)
- Sites must be in an area with a CalEnviroScreen score of at least 75%[5]
- No additional planned retrofits or renovations between now and December 2018
- Existing air conditioning, controlled by thermostats.

The criteria for shared common spaces in the demonstration study included: multiple types/sizes of spaces (offices, dining rooms, lobbies), greater than 1000 sq. ft., regularly used spaces, and with lighting systems that can accommodate fans. Criteria for individual residential dwelling unit spaces in the demonstration study included: ability to accommodate living room, bedroom, dining room ceiling fans, currently occupied, and with lighting systems that can accommodate fans. TRC and AEA solicited sites through owners of the several affordable housing sites and existing contacts from utility incentive programs managed by TRC or AEA.

Site Description

Following the evaluation of the original committed sites, and recruitment of additional sites, the research team proceeded with four sites for participation as demonstration sites:

- Franco Center, Stockton, CA (climate zone 12)

[5] A map showing CalEnviroScreen scores for the entire state is available http://oehha.maps.arcgis.com/apps/Viewer/index.html?appid=112d915348834263ab8ecd5c6da67f68.

- Rolling Hills, Newman, CA (climate zone 12)
- Parksdale Village (two separate sites), Madera, CA (climate zone 13)

All buildings lie in PG&E territory. Figure 4 shows the locations of each site.

Figure 4: Field Demonstration Sites

The project sites included four common rooms in three towns in California's warm Central Valley, and six individual dwelling units at one site.

Credit: Therese Peffer, UC Berkeley; David Douglass-Jaimes, TRC

The **Franco Center Apartments** serve senior citizens, and is owned and operated by WNC & Associates. One on-site manager and one janitorial staff live on the property full time. Franco Center staff manage and occupy the main office, located on the first floor.

Study locations include the community rooms, offices, and kitchen prep area located on the first floor of the building, a total floor area of 6,070 square feet (sq. ft.). Offices are used during standard business hours (9:00am–5:00pm Monday-Friday), while the community areas are lightly used during the day, with heavier periods of use at mealtimes and during events.

The building was constructed in 1967 and renovated in 2007, and is built of solid concrete masonry with no additional insulation (that was verifiable). The first-floor retail, office, and common areas are served by six rooftop-located VRF compressors that provide conditioned refrigerant to eight 3-phase fan coil units (FCUs).

Rolling Hills is owned and operated by Self Help Enterprises. One on-site manager and one janitorial staff lives on the property full time. Rolling Hills staff manage and occupy the main office, located in the community center. The site consists of the community center/office and thirteen tenant buildings containing a total of 52 units. The central community building is approximately 2,750 sq. ft. Residents of Rolling Hills are a mix of couples and families.

The focus of the study is the central community building, that includes an open community space, a kitchen, a computer room, and an office. The office is used during standard business hours (9:00am–5:00pm Monday-Friday), while the community area and kitchen are very lightly used during the day.

The buildings were constructed in 2004, and are built of stucco over wood framing. The community building is serviced by two outdoor condensing units for air conditioning and two furnaces installed in the attic for heating. Both the condensing units and furnaces are connected to air handlers located in the attic. The first air conditioning unit and furnace service the office and computer room, while the second service the community room and kitchen. Air conditioners provide 30–60 MBtu/hr (2.5–5 ton) of cooling, while the furnaces supply up to 88 MBtu/hr. Each of the two zones has a separate programmable thermostat.

The **Parksdale Village** properties are owned and operated by Self Help Enterprises. One on-site manager and one janitorial staff live on each property full time. Parksdale Village staff manage and occupy the main office of each property, which is located in the community center of each property.

Parksdale Village consists of two neighboring identical developments (Parksdale 1 and Parksdale 2) of townhome residential units and central common buildings. Parksdale 2 was the location for all six residential unit demonstrations. Each is a complex consisting of the community center/office and twelve tenant buildings containing a total of 48 units (four units each, arranged side by side). Each unit has two, three, or four bedrooms, is one to two stories tall, and is accessible from the ground floor. The central community building is approximately 3,190 sq. ft. Residents of Parksdale Village are a mix of couples and families.

Study locations are the two central community buildings and six units of Parksdale Village #2. The community buildings include an open community space, a kitchen, a computer room, and two offices. The main office of each building is used during standard business hours (9:00am-5:00pm Monday-Friday), while the second office is rarely used. The community area and kitchen are very lightly used during the day, and the computer room is frequently used.

Residential units either have all spaces on the first floor, or the kitchen, living room, laundry room, and bathroom on the first floor, with the bedrooms and a bathroom on the second floor.

The buildings were constructed in 2009, and are built of stucco over wood framing.

The community building is serviced by two outdoor condensing units for air conditioning and two furnaces installed in the closet outside the building for heating. Both the condensing units and furnaces are connected to air handlers attached to the furnaces. The first air conditioning unit and furnace service the offices and computer room, while the second service the community room and kitchen. Air conditioners provide 42-60 MBtu/hr (3.5–5 ton) of cooling each, while the furnaces supply up to 80 MBtu/hr. Each of the two zones has a separate programmable thermostat.

Dwelling units each have an outdoor compressor for air conditioning and a furnace located in a closet in the rear of the unit. Air conditioners provide 18–24 MBtu/hr (1.5–2 ton) of cooling per hour, while furnaces provide 48 MBtu/hr of heating.

Figure 5: Field Demonstration Space Types

The four sites included different space types: community rooms, computer rooms, offices, and dwelling units.

Credit: AEA and UC Berkeley

Monitoring Installation

The research team installed monitoring equipment at each site to monitor energy use and indoor environmental quality (IEQ) conditions for all common area spaces and each residential unit included in the study. Pre-installation monitoring included approximately one year of data collection before the fans and smart thermostats were installed; the data included:

- Air-conditioning energy use:
    - **Power** metering at each air conditioning compressor serving common areas or residential units included in the demonstration study.
    - **Amperage metering** at each of HVAC system fans (e.g. a fan coil unit)
    - Collected data was transmitted to the research team in real-time via Wi-Fi.
- IEQ measurements:
    - **Temperature, relative humidity and light levels** were collected in all common areas and in each residential unit included in the demonstration study using Hamilton sensors.[6]
    - Collected data was available to the team in real-time, at 20-second intervals.
- Ceiling fan measurements and settings:

[6] www.HamiltonIOT.com

    - **Temperature, cooling setpoint, occupancy, and other fan settings and measurements** were collected in all ceiling fans.
    - Collected data was available to the team in real-time, at 5-minute intervals.
- Thermostat settings:
    - The research team observed and recorded **thermostat settings** in common spaces and residential units in the demonstration study during visits to the site whenever possible. This included asking residential unit occupants about their thermostat use. The team collected data from the installed thermostats collected data at 5-minute intervals in real time.
- Monitored data communication:
    - The research team installed cellular data Wi-Fi hotspots to provide live communication of energy monitoring and IEQ measurement data.

AEA and BAF performed the installation of monitoring equipment at all four sites over the course of two weeks in July 2017. Installations typically took between one to two days per site.

Details of the field study are in Appendix D.

Figure 6: Parksdale 2 Typical Dwelling Unit Monitoring Equipment Installation

Credit: AEA

Demonstration Preparation

Equipment Preparation

In testing the ceiling fan and thermostat in the test chamber at CBE, the researchers discovered several challenges. The Haiku Home smartphone app for the ceiling fan allows for integration with smart thermostats from Nest and Ecobee. The team chose to use Ecobee thermostats for the demonstration sites due to the ability to download thermostat data for the entire field study period directly through the Ecobee API. The Haiku product was designed primarily for use with a single fan in a room in a residence with one individual using the smartphone app to control the fan. However, the goal of the study was to test applications of the Haiku technology in combination with smart thermostats in multi-room, multi-user, and nonresidential applications. The Haiku product functionality and user interface were not optimized for these types of applications. This initial testing at CBE resulted in two primary concerns about the technology functionality at the demonstration sites:

- The Haiku product's automatic "smarter cooling" functionality did not operate in the transition phase (or "deadband") between heating and cooling modes on the thermostat, posing problems when heating and cooling occur in the same day (e.g., heating mode during cool early morning hours and cooling mode during daytime hours). The fan's smarter cooling mode, which automatically increases air movement in a space to match a user's comfort setting, would not be activated until the thermostat switched to cooling mode. This may create a comfort gap if thermostats are set to higher temperatures with the expectation that the fan will provide additional cooling before the AC is triggered.
- The current fan and smartphone interface allow access to fans from any device on the same Wi-Fi network; and smartphone control is only possible when connected to the same network as the fan. This poses challenges for user permissions in common areas, or in shared spaces like offices.

The research team worked with BAF to develop a custom version of the fan firmware to better coincide with the demonstration research goals. These changes included improvements to the control protocols and smartphone app (Haiku Home) control interface for the Haiku fan.

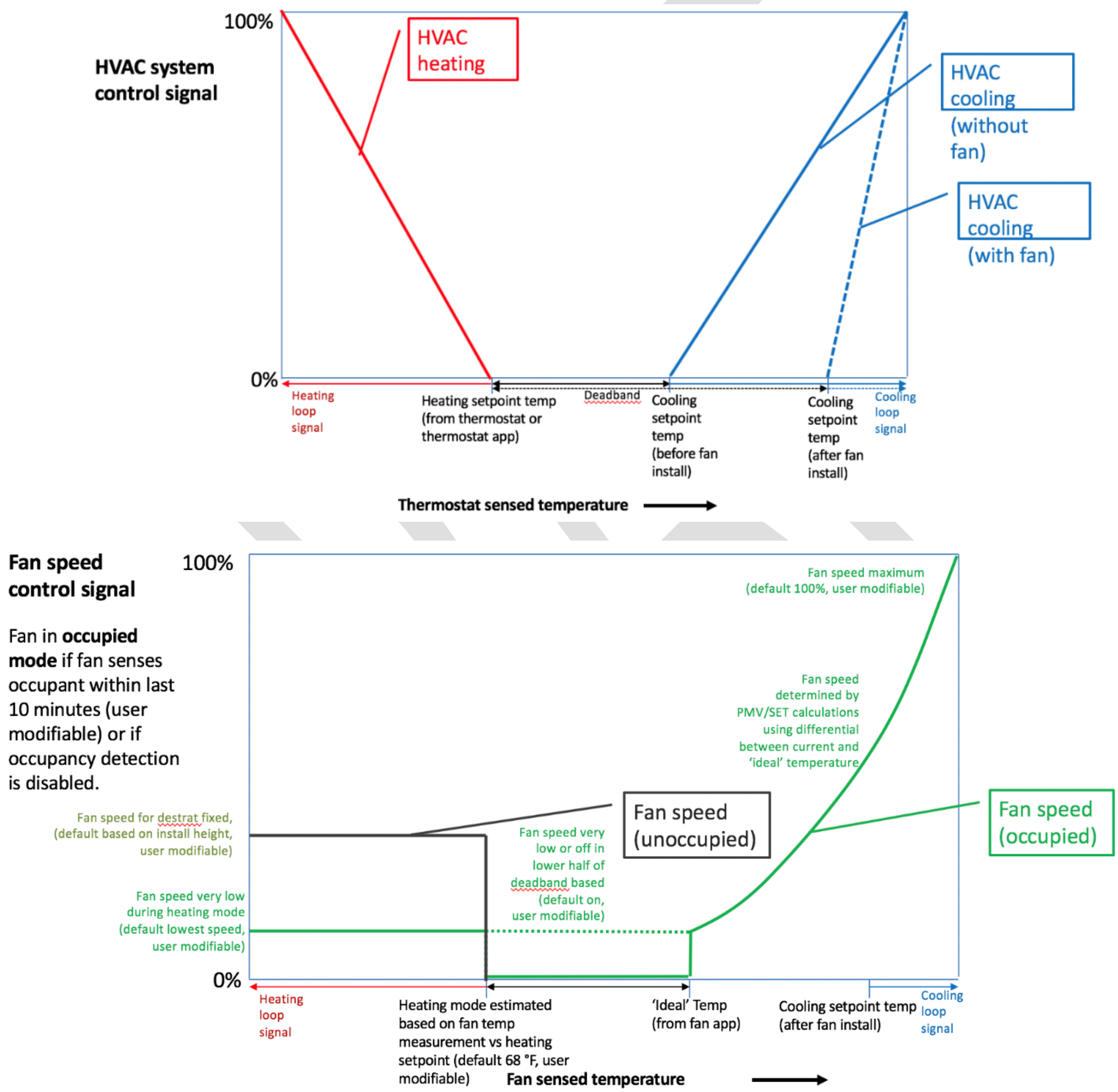
Following the initial testing, CBE and TRC developed the following priorities for updates to the Haiku Home interface:

- Address the switchover between "smarter cooling" and "smarter heating" modes so that ceiling fans will continue to operate to provide comfort cooling as needed in the thermostat "deadband" between heating and cooling modes, allowing for higher cooling setpoints. This could potentially be resolved by separating the operation and control of "smarter cooling" and "smarter heating" modes from the thermostat settings.
- Limit user access to fans in common areas or other shared spaces. Because anyone with the Haiku Home app connected to the same Wi-Fi network as the fans could potentially control the fans in that space, it may be necessary to establish user profiles that could limit controls in public spaces to a facility manager, or limit access to a specific user's space in settings like an office suite with a single shared Wi-Fi network.
- Allow for multiple fans in different rooms to be connected to a single thermostat, especially in instances such as separate rooms within a single dwelling unit. This could also potentially be resolved by separating the function of the "smarter cooling" and "smarter heating" modes from the thermostat settings, as described above.
- Provide easier access to Ecobee thermostat control within the Haiku Home app, potentially including proactive suggestions to adjust thermostat setpoints to increase energy savings, and with more clear communication about what effect the control options and setpoints will have.

- Implementing learning functionality – where the fan cooling setpoint gradually changes based on user interactions with the fan.
- Improve the user interface for setting the smart cooling "ideal temperature," clarify how the setting works, and how the "learning" functions.

CBE and TRC collaborated directly with BAF to develop solutions for these strategies to provide a fully functioning product for installation in the demonstration sites.

Figure 7: Control Sketch for Air Conditioning and Fan Operation



Top: When staged with ceiling fan operation to increase the setpoint, air conditioners can use less energy from less overall runtime. Bottom: Fan operation is based on both temperature and occupancy. A ceiling fan will run if a space is occupied and above a setpoint temperature; fan speed gradually increases at higher air temperatures up to a defined limit.

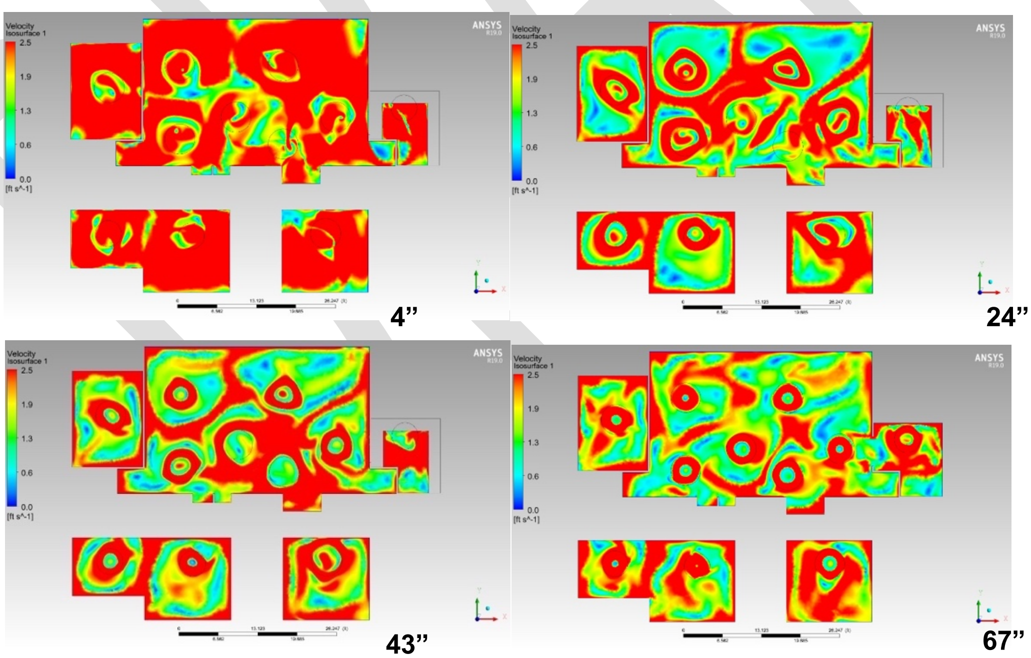
Credit: CBE

Additionally, the project team incorporated learning functionality that modifies the fan's 'Ideal' temperature based on user feedback. Simply put, if a user increases the fan speed when the fan is operating automatically, the Ideal temperature setpoint decreases slightly, so that in future the fan will operate at higher speed at this temperature. The same applies in reverse if a user decreases the fan speed. In this manner, the fan's automated speed features will gradually adjust to a user's preferences without any explicit interaction with the fan *settings* themselves – it happens in the background, whenever a user changes the fan speed.

Site Preparation

Since the goal of the site demonstrations was to test the potential to use ceiling fans to maintain comfort at increased thermostat setpoints, the determination of the fan layout was critical to the overall success of the project. To that end, BAF provided computational fluid dynamic (CFD) simulation to test and develop proposed fan layouts for each site. The research team developed an overall goal of achieving an average of up to 150 feet per minute (fpm), or 2.5 feet per second (fps), of air flow in each demonstration space. This velocity was determined based on previous studies that found that speeds above 150 fpm start to move papers on desks. Thus, this was considered the upper limit air velocity to maximize cooling effectiveness without becoming disruptive. (This air flow target assumes the highest fan speed setting, so occupants could always use the fans at lower speeds to achieve lower air velocities.) Using this target, BAF ran CFD simulations that measured air flow at four different levels to determine the effectiveness of various fan layouts. The four heights were 4", 24", 43" and 67" above the floor. Figure 8, below, shows an example of the CFD analysis results for an initial fan layout plan at the Rolling Hills community building.

Figure 8: Example Rolling Hills CFD Analysis



CFD analysis visualizations showing air speeds at vertical heights of 4", 24", 43", and 67" above the floor.

Credit: BAF

Based on the results of the CFD analysis, and the existing conditions (light fixtures, fire sprinklers, etc.) at each site, BAF proposed initial layouts for all of the spaces at all four sites.

Prior to finalizing the designs for each of the sites, CBE, TRC, and AEA conducted site visits at each of the demonstration sites with the BAF installation team to become familiar with the spaces in the study, and to confirm the final layouts and details for the fan installations.

Fan and Thermostat Installation

Based on the CFD analysis and site visits described above, the research team arrived at the final fan layout designs. In addition to the fan installations, the full installation scope included installing and configuring thermostats (at Rolling Hills and Parksdale sites), and lighting reconfigurations in areas where the fans and the existing lighting would be in conflict.

Network and Connection Issues

After the physical installation of the fans the research team ran into multiple challenges with getting the fans and thermostats connected to internet networks, and connecting fans to the BAF Haiku app. The initial intent was to connect all of the new devices to whatever local network occupants used at the site, but this posed several challenges. At some sites the research team was not able to access the same network that on-site staff use due to privacy concerns with tenant records. In addition, the ceiling fans are required to be connected to a password-protected network to function properly, which also limited connection options at the Franco Center site where the public wireless network does not require a password for access.

Separately, the installation team ran into challenges connecting the fans to the Haiku app at several sites, requiring multiple return visits from AEA, and coordination with BAF to resolve the connection problems. These two connection issues were largely resolved in community spaces with the addition of separate wireless routers and using separate network connections to get all the fans up and running. However, post-installation, some of the occupants of the demonstration residential units experienced problems connecting their personal devices to their existing wireless networks, which were shared with the new fans and thermostats. Residential units at the Parksdale 2 site each use an internet modem/router that is provided by the property for internet access. The project team found that these systems allow a maximum of 15 individual IPs to be registered at any given time. Since each fan and thermostat counted as a separate IP these, in addition to existing smartphones, computers, TVs, and other internet-connected devices frequently exceeded the maximum number of IP addresses. To remedy this AEA installed separate mobile internet hot spots at each unit that were dedicated for the fans, removing them from the residents' networks.

Supplemental Desk Fans and Lighting

In order to ensure personal comfort, and to supplement the ceiling fans in areas where air circulation may be less optimal, the research team decided to provide the option of small desk fans for all office occupants at each site, as well as for each computer lab station at each site, though relatively few occupants availed themselves of these devices.

In addition, the light kit for the ceiling fan at the Franco site was found to not sufficiently meet the lighting needs in the small office and computer lab spaces. To address this issue, the research team provided supplemental desk lighting for each computer station in the computer lab, and a desk light and floor light for the small office to supplement light from the ceiling fan.

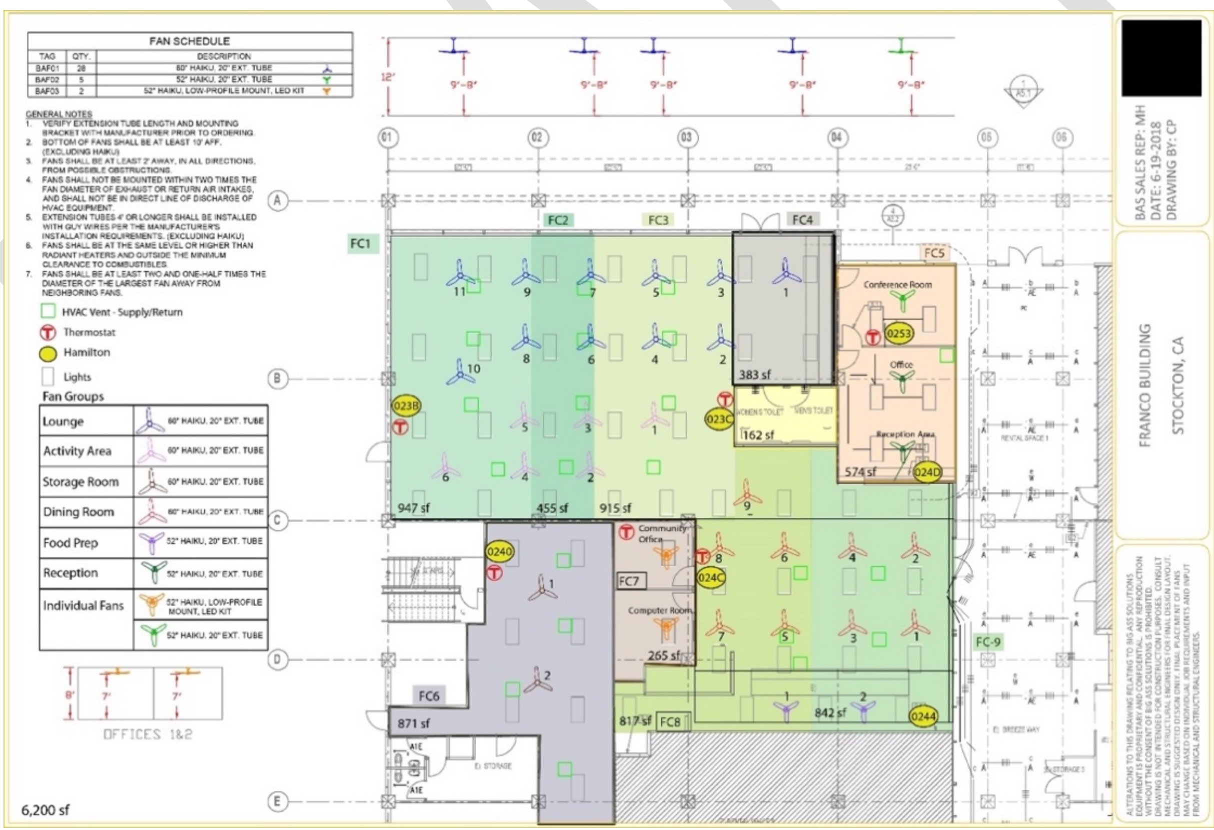
Final Installation Conditions

In total, 99 ceiling fans and 12 thermostats were installed across the four demonstration sites in June-July 2018, as follows:

- Franco Center: 35 ceiling fans, six existing thermostats (VRF system)
- Rolling Hills Community Building: 13 ceiling fans and 2 thermostats
- Parksdale 1 Community Building: 7 ceiling fans and 2 thermostats
- Parksdale 2 Community Building: 8 ceiling fans and 2 thermostats
- Parksdale 2 Three 2-Bedroom Units: 5 ceiling fans each (15 total), 3 thermostats
- Parksdale 2 Three 3-Bedroom Units: 7 ceiling fans each (21 total), 3 thermostats

The details of all the installations may be found in Appendix D, Final Field Report. Figures 9 and 10 show an example of the final installation layouts for the ceiling fans, thermostats, and other equipment in a common room and dwelling unit.

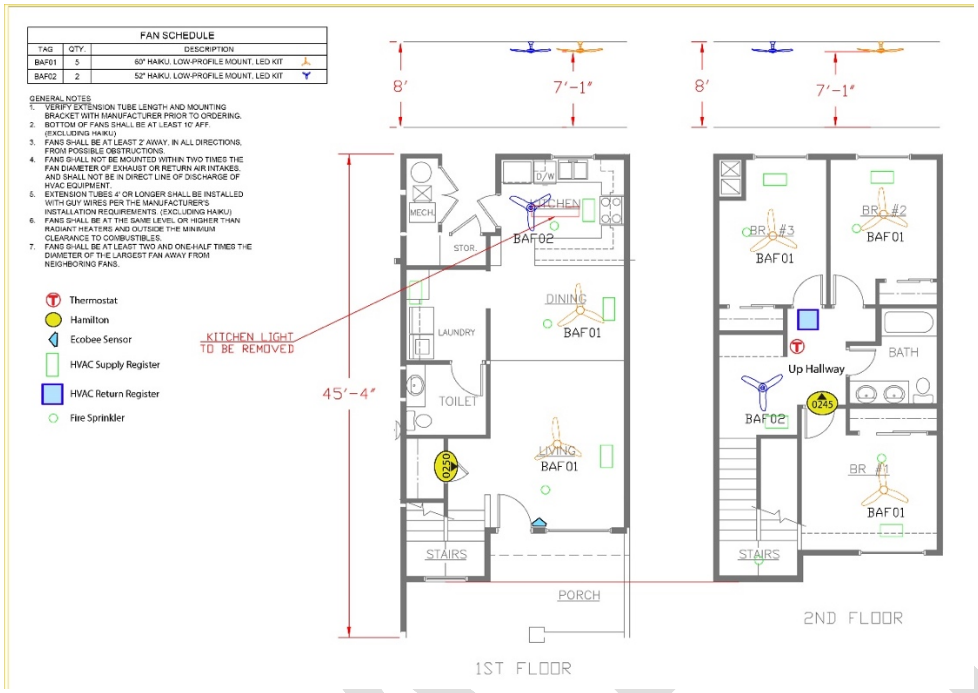
Figure 9: Franco Center Installation Layout



Layout of Franco Center demonstration site showing ceiling fan and thermostat locations, HVAC control zones, Hamilton temperature and humidity sensors, and lighting and HVAC vents.

Credit: Mia Nakajima, TRC

Figure 10: Parksdale 2 Typical 3-Bedroom Unit Installation Layout



Layout of Parksdale 2 Typical 3-Bedroom Unit demonstration site (1286 sq. ft.) showing ceiling fan and thermostat locations, HVAC control zones, Hamilton temperature and humidity sensors, and lighting and HVAC vents.

Credit: Mia Nakajima, TRC

Figure 11: Photo of Franco Center Community Room with Ceiling Fans Installed

Credit: Paul Raftery, CBE, UC Berkeley

Site Interventions

During the first cooling season after the baseline period, June-September 2018, the project team monitored occupant interaction with the fans and thermostats and conducted two "Right Now" surveys at the Franco common room, before and after the ceiling fans were installed.

Before the second cooling season began (late April 2019), AEA adjusted setpoints and schedules. With worker/resident approval, thermostat and fan setpoints and scheduling were adjusted to be consistent across sites, at levels that were designed to be comfortable with moderate ceiling fan usage. Fans were set to an "ideal" temperature of 74° F (temperature above which the fans turn on), except in bedrooms where the ideal temperature was raised to 78° F to avoid overcooling residents while sleeping. Temperature setpoints for thermostats were:

- 80° F during the day while occupants were present ("Home" setting on Ecobee thermostats)
- 78° F during the night in residences ("Sleep" setting on Ecobee thermostats)
- 86° F while occupants were not present ("Away" setting on Ecobee thermostats)

When the setpoints were adjusted, AEA and CBE conducted an education campaign to ensure that all residents and workers were comfortable using the fans and thermostats as needed. Education had been carried out at the initial installation, but follow-up surveys indicated that there was still some confusion on proper use of the equipment. In particular, use of scheduling on the thermostats, temporary versus permanent temperature setpoints, and using fans prior to reducing thermostat setpoints for cooling needed to be emphasized. Education was carried out verbally in person, using an English-to-Spanish translator when needed, and with flyers that were left with each user.

Surveys

To capture occupant perceptions, the research team collected data with two primary methods: interviews and surveys. Interviews were conducted at two time points with both residential and office worker occupants. Surveys were distributed during Summer and early Fall 2018 with office workers and at community events, and at a final community event in Summer 2019.

All participants were given two surveys: the "Personal Characteristics Survey" and the "Right Now Survey". The Personal Characteristics Survey asked occupants for their basic demographics and their general perceptions of energy use. The survey asked occupants about their age, gender, use of heating and cooling devices, whether they get hot or cold easily, and typical energy-saving behavior. The Right Now survey was a brief 10-item survey aimed at understanding occupants' perceptions of the space they were in at that given moment the survey was deployed. This survey asked questions around thermal comfort, perceptions of air movement, and perceptions of air quality in situ. Further, it asked what articles of clothing occupants were wearing that day.

Participants included the office workers for the common rooms at two sites and the residential occupants at one site, both of whom took part in both surveys and interviews, and common room occupants at one site (Franco) during events, who participated in surveys only.

Technology Readiness

Case Study Method

The project developed a Case Study. The purpose of the Case Study of Ceiling Fan Automation is to evaluate the current landscape of technologies similar to the ceiling fan and thermostat demonstration, evaluate the current installations of these technologies and the market opportunities and barriers to the technologies. The Case Study of Ceiling Fan Automation:

- Includes interviews with owners and designers to determine design features, control approach and owners' perceptions of technology
- Includes spot measurements using CBE Building Performance Toolkit to determine typical air speeds with automated control settings
- Describes challenges and successes of planning and executing retrofits
- Discusses lessons learned.

Technology Readiness Report

The project developed a Technology Readiness Report, which provides:

- Identification of current product availability and estimate market size.
- Estimated current market penetration.
- Evaluation of market barriers to adoption.
- Likely market penetration with and without intervention through building codes.

CHAPTER 3: Project Results

Lab Studies

This section describes the results from the three laboratory studies.

Lab 1 Results

The research team conducted tests in the CBE chamber at UC Berkeley and at the BAS test facility in Kentucky. See Appendix A for more details.

The CBE chamber tests looked at six different configurations of furniture (rectangular table and partition) on air velocity contours. With the table, the air flow spreads further.

The tests in the BAS facility observed the effect of ceiling height on air speed and the effect of air speed from two fans compared to one fan. For the single fan test, the highest speeds are directly below the fan and then at low height; the lowest speeds are fairly uniform outside the fan diameter. At 7 ft and 10 ft heights, the flow is undisturbed 0.9 m from the fan center (point 4). For the 15 ft height case, the velocity increases, suggesting that flow had spread laterally. For the two-fan test, the presence of the additional operating fan has a significant impact on the flow field. Two fans at similar speeds create an upward flow from collision of two floor bounded flows and has an inherent oscillatory nature, However, one can manipulate the speeds of both fans to intentionally adjust the location of this higher air speed region.

Lab 2 Results

The research team measured air speeds in rooms due to ceiling fans in 78 full-scale laboratory tests. The factors were the room size, fan diameter, type, speed, up/down direction, blade height, and mount distance (i.e. blade to ceiling height). See Appendix B for more details.

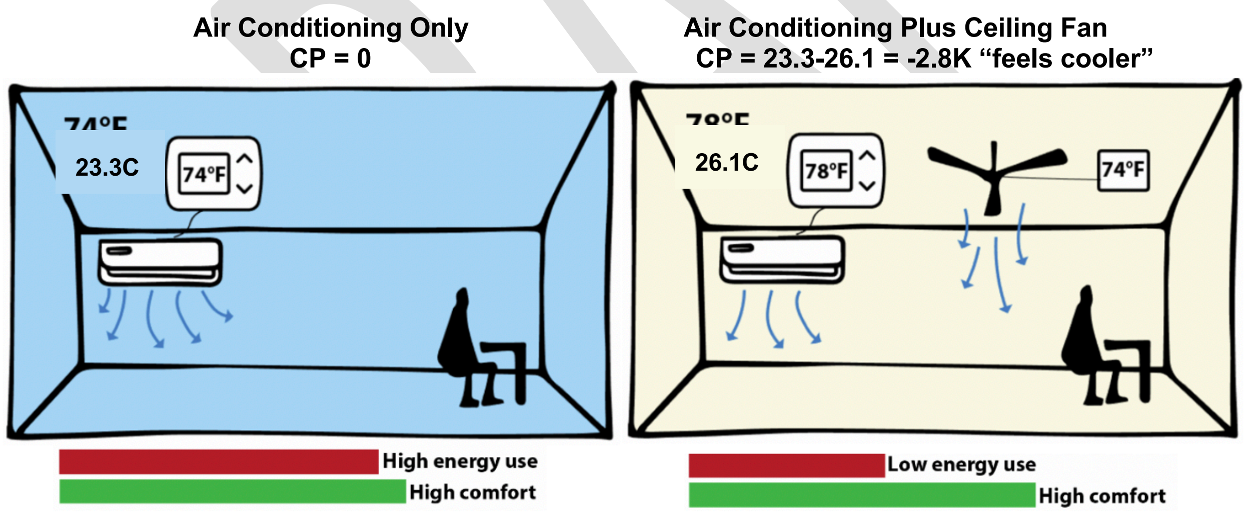
The team demonstrated the influence of these factors, showing that the most significant are *speed, diameter and direction*. With other factors fixed, the area-weighted average room air speed increases *proportionally* with fan air speed and diameter. *Fans blowing upwards yields lower but far-more-uniform air speeds than fans blowing downwards.* Additionally, fans blowing upwards will use more power to achieve the same area weighted average air speed as downwards. For the same diameter and rated airflow, fan type has little effect on the air speed distribution in the region outside the fan blades. The team developed dimensionless models and demonstrate that they are appropriate for comparisons over a wide range of fan and room characteristics. Dimensionless linear models predict the lowest, area-weighted average, and highest air speeds in a room with a median (and 90th percentile) absolute error of 0.03 (0.08), 0.05 (0.13), and 0.12 (0.26) m/s respectively over all 56 downwards tests representing typical applications. These models allow the team to answer the question 'What air speed distribution can I expect for a given fan and room?'

In addition to the lab studies and case study measurements, the project team conducted a field validation of the upward-blowing ceiling fans, which can be found in Appendix F.

Lab 3 Results

The research team proposed a **Corrective Power (CP)** index to quantify the extent to which a fan can "correct" a warm ambient temperature toward neutral (Zhang, Arens, and Zhai 2015). See Appendix C for more details. The project reviewed over 40 studies with Personal Comfort Systems (PCS), including ceiling fans, whose published human subject and manikin studies allow their cooling and heating effects to be represented as corrective power (CP) value. CP is defined as the difference between two ambient temperatures at which the same thermal sensation is achieved—one with no PCS (the reference condition), and one with a PCS in use. CP is expressed in degrees in Kelvin (K), the standard way of expressing temperature differences on the Centigrade scale. If subjects voted a neutral thermal sensation at a particular combination of warm air temperature and air movement (see Figure 12 on right), and also voted neutral sensation with a lower air temperature in still air (Figure 12, left), then the temperature difference is the CP, which will have a negative value. Cooling CP ranges from -1 to -6K, and heating CP from 2K to 10K. As an offset to normal ambient room temperature, the CP allows building engineers and operators to modify temperature setpoints and control sequences when PCS is included in their designs.

Figure 12: The Corrective Power of Ceiling Fan Cooling



Left: Air conditioning provides cooling. Right: As a Personal Comfort System, ceiling fans can provide the same thermal sensation as the temperature provided by air conditioning, allowing a 26.1 C room to feel 2.8 degrees Kelvin cooler, thus showing a negative CP.

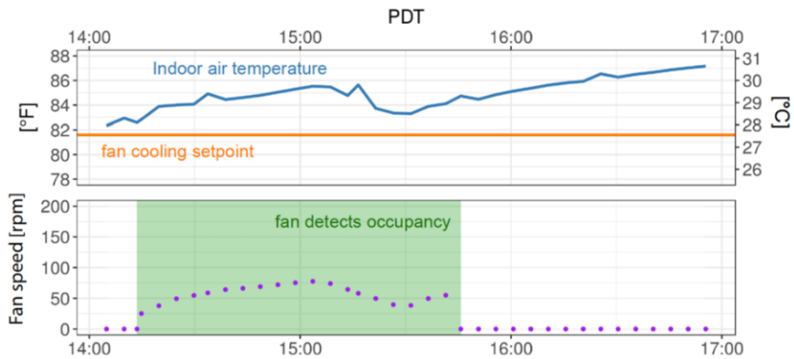
Credit: Dana Miller, Therese Peffer, UC Berkeley

Field Studies Results

Automated Ceiling Fan Operation

Coordinating and sequencing ceiling fans and air conditioning can be achieved with multiple operation strategies and commercially-available products. The strategy demonstrated in this field study used highly efficient ceiling fans with onboard temperature and occupancy sensors. These fans were configured to operate automatically, so that when occupancy was detected they would automatically start moving air above a configurable setpoint temperature, and gradually increase speed as ambient air temperatures increased. Importantly, occupants could always manually adjust and override fan operation by using the provided remote controls for each fan. Figure 13 below shows an example of ceiling fan turning on when occupancy was detected and modulating speed based on the indoor air temperature.

Figure 13: Automated Ceiling Fan Operation Based on Temperature and Occupancy



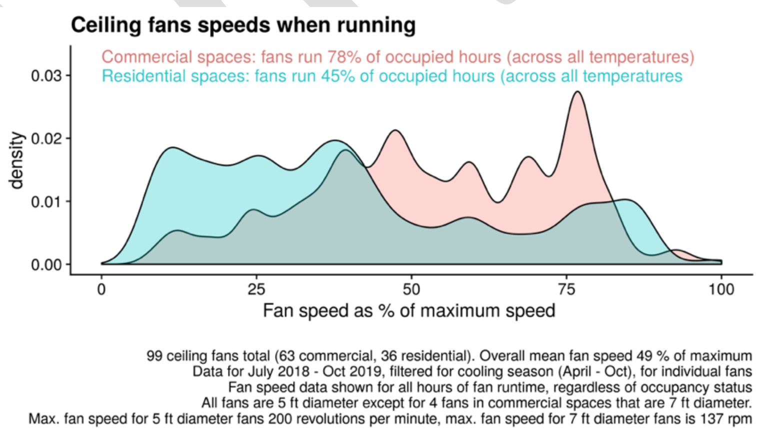
Top: Indoor air temperature and fan operation setpoint. Bottom: Ceiling fan speed adjusting based on occupancy and temperature.

Credit: Dana Miller, UC Berkeley

Ceiling Fan Power Consumption and Runtime Analysis

Figures 14 and 15 below summarize how all 99 ceiling fans operated over the field study during the April to October cooling period. Overall, the ceiling fans were frequently used at all sites, typically operated at low speeds, as shown in Figure 14, and used very little power, as shown in Figure 15. The low power consumption of these efficient ceiling fans during operation (mean power consumption when operating was 8 W) is comparable to that of an LED lightbulb.

Figure 14: Ceiling Fan Speeds During Operation

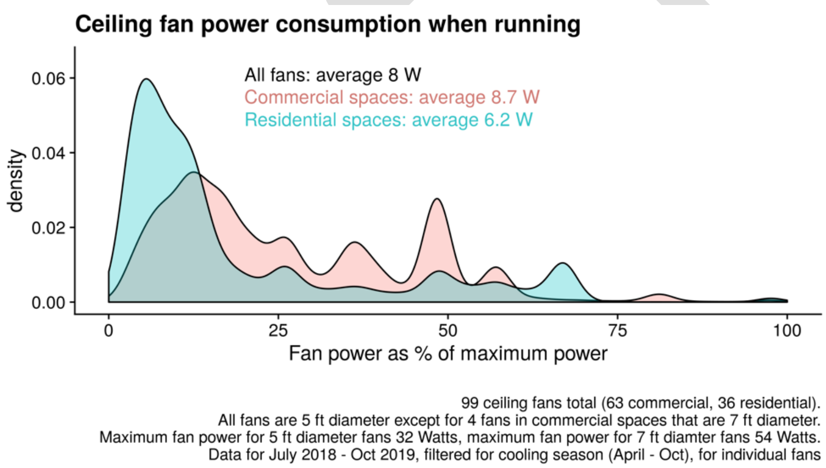


Ceiling fan speed during operation, as a percentage of maximum speed. For the majority of runtime in both residential and commercial buildings, fans run at 75% or less of the maximum speed.

Credit: Dana Miller

Across all hours during the April to October cooling season and all temperatures, the ceiling fans usually operated below 75% of the maximum speed, and in residences usually operated at below 50% of maximum speed, as shown in Figure 14. In commercial spaces across all temperatures, the fans operated the majority of occupied hours (78%), ranging from a minimum of 29% to a maximum of 96% of occupied hours for fans in different locations. Variation in runtimes comes from variation in indoor temperatures (occupants are less likely to desire air movement at cooler temperatures) and variation in occupant preferences (preferring fans to run more or less). In residential spaces across all temperatures, the fans operated about half (45%) of occupied hours, ranging from a minimum of 2% to a maximum of 83% of occupied hours for fans in different locations, with similar variation due to indoor air temperatures, occupancy frequency, and occupant preferences.

Figure 15: Ceiling Fan Power During Operation



Ceiling fan power during operation, as a percentage of maximum speed. Since power consumption scales with the cube of fan speed, the mean fan speed of 49% equates to a mean fan power consumption of 24% of maximum fan power.

Credit: Dana Miller

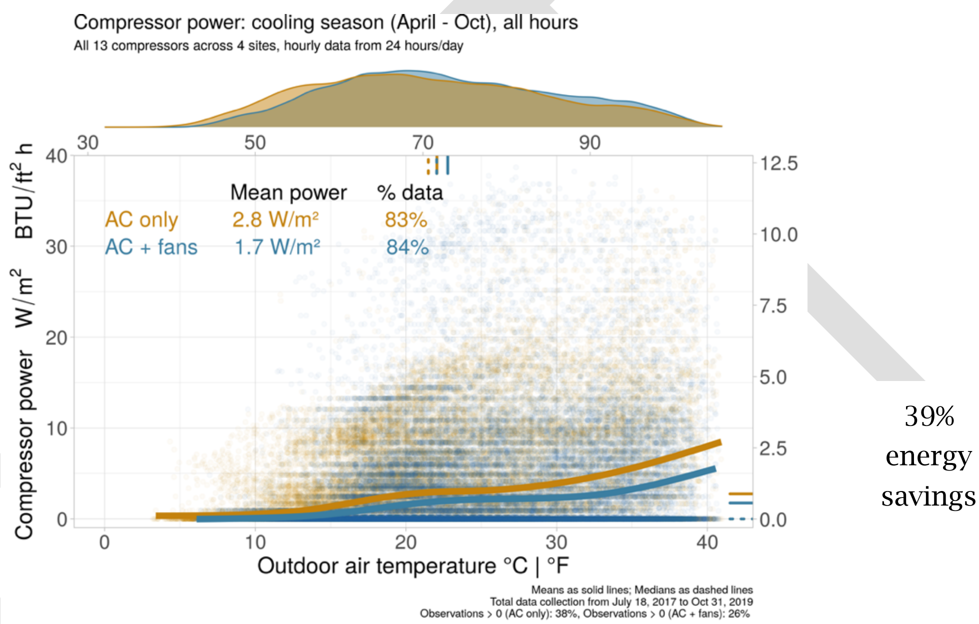
Energy Analysis

The research team collected air conditioner compressor and system fan energy consumption at each site from July 18, 2017 to October 31, 2019. The team also acquired measured weather data for the same period from the NOAA weather station nearest each installation site. Data acquisition difficulties resulted in numerous periods of missing data for some of the sites, and in one residential unit, the team was unable to measure compressor energy consumption.

Overall, the intervention of adjusting air conditioning setpoints to cool first with ceiling fans and then with both ceiling fans and air conditioning, and educating occupants about potential energy and comfort benefits yielded substantial compressor energy savings. **Overall, the field demonstration resulted in 39% measured compressor energy savings during the April–October cooling season compared to baseline conditions, across all sites and normalized for floor area served.** Over all months of the year, mean measured compressor power per floor area during the intervention period was 30% lower than the baseline period. The floor area served by each individual compressor varied more than six-fold, and the size and energy consumption of a compressor correlates with floor area. Thus, the research team normalized reported energy savings by floor area to avoid sites with larger floor area unduly weighting the percentage savings estimate in one direction or the other. Without normalizing by floor area, the total project percentage savings during the cooling season was 48%, as the larger floor area sites had substantially higher percentage savings than the smaller floor area sites.

Figure 16 below shows the hourly average compressor power use across all sites, normalized by floor area served, compared to outdoor drybulb air temperature.

Figure 16: Hourly Mean Air Conditioning Compressor Power



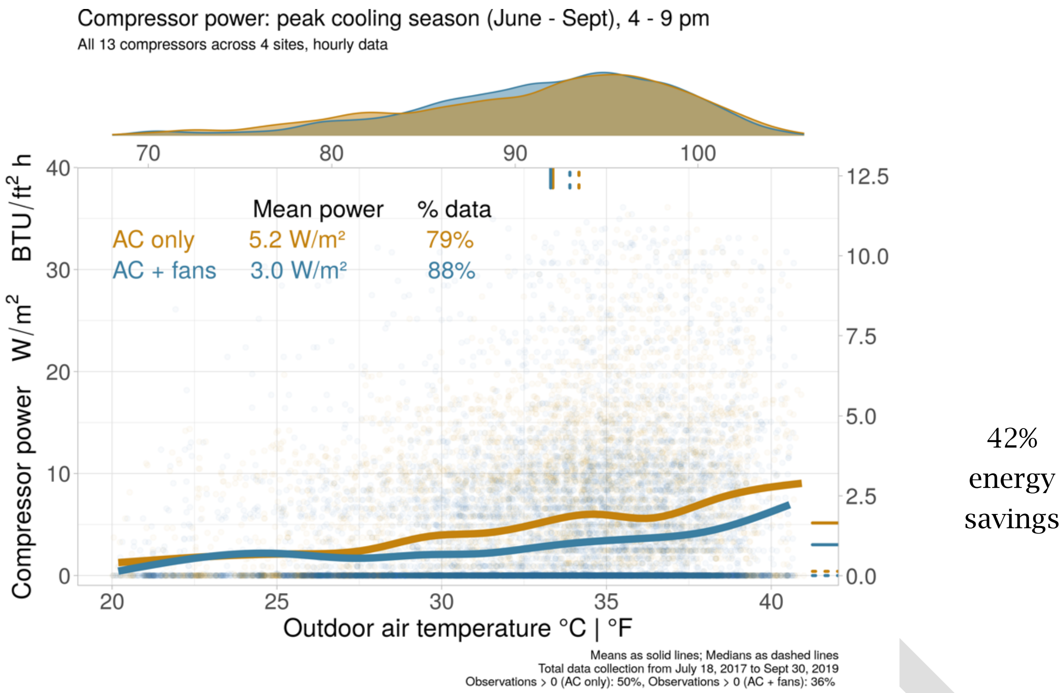
Hourly average compressor power use during baseline and intervention periods across all field study sites, normalized per floor area served, with respect to outside drybulb temperature for all 13 compressors measured in the project. Overall compressor energy savings shown is 39%.

Credit: Dana Miller, UC Berkeley

Average hourly outdoor air temperatures across all sites were warmer during the intervention period than the baseline period by (1.7 ˚F (0.95 ˚C)), as the density curves at the top of Figure 16 show. The research team normalized energy savings values using both breakpoint regression and random forest models (shown in Figure 21 below). The team fit individual models for each compressor during the baseline period, then used them to predict power consumption during the intervention period. The team reported normalized energy savings as the difference between the predicted and observed intervention period power consumption. The team reported overall weather normalized savings as the mean of savings estimated for each compressor from each model.

Figure 17 below shows air conditioning compressor energy consumption during hours with peak residential and commercial Time-Of-Use charges (4 – 9pm) in PG&E territory during the warmest months of June – September. Energy savings during this period averaged 42%, normalized by floor area.

Figure 17: Hourly Mean Air Conditioning Compressor Power During Peak Cooling Hours



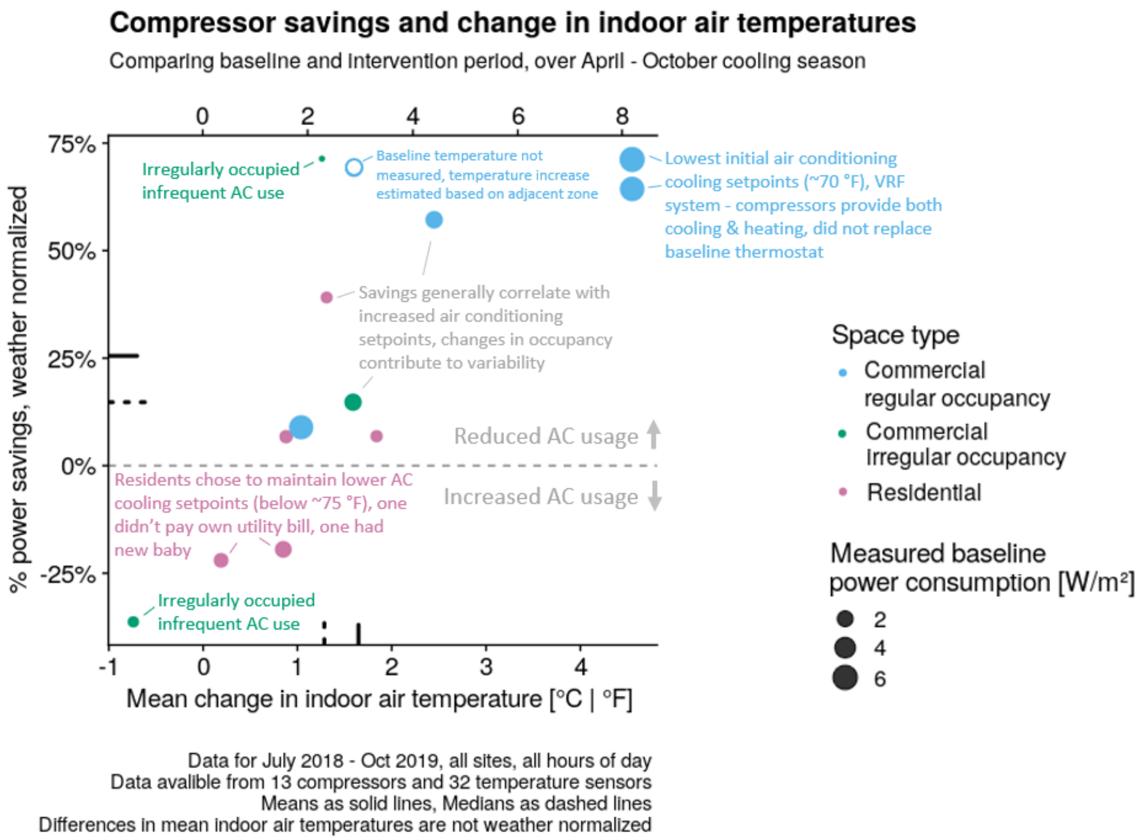
Hourly average compressor power use during peak time-of-use rate period during baseline and intervention periods across all field study sites, normalized per floor area served, with respect to outside drybulb temperature for all 13 compressors measured in the project. Overall energy savings shown is 42%. Note x axis differs from above plot.

Credit: Dana Miller, UC Berkeley

Zones in commercial buildings were also classified as either 'regularly occupied' or 'irregularly occupied'; zones with infrequent occupancy had less savings potential compared to zones with lengthy and frequent cooling demand. These spaces also had irregular usage patterns that likely contributed to variability in savings between baseline and intervention periods.

When additionally normalized for weather due to warmer outdoor conditions during the intervention compared to the baseline period, energy use per zone varied from an increase of 36% to savings of 71% across all 13 compressors across four sites, with **median per-compressor weather-normalized savings of 15%.** This variability reflects the diversity in buildings, mechanical systems, prior operation settings, and space types, as well as occupants' schedules and preferences. **All commercial spaces with regular occupancy schedules (as well as two irregularly-occupied commercial spaces, and one home) had measured energy savings on an absolute basis before normalizing for warmer intervention temperatures, and 10 of 13 sites showed energy savings on a weather-normalized basis.** Zones where indoor air temperatures did not increase (occupants did not raise air conditioning setpoints) did not realize energy savings. The zones with the largest increase in air conditioning temperature setpoints and largest increase in indoor air temperatures realized the largest energy savings. Three sites did not realize energy savings on a weather-normalized basis. Two of these sites were residences that opted not to increase air conditioner setpoint temperatures after initially trying setpoint temperatures of 78 F (setpoints were typically below 75 ˚F), and one was an infrequently-occupied commercial space where the air conditioning was not operated regularly.

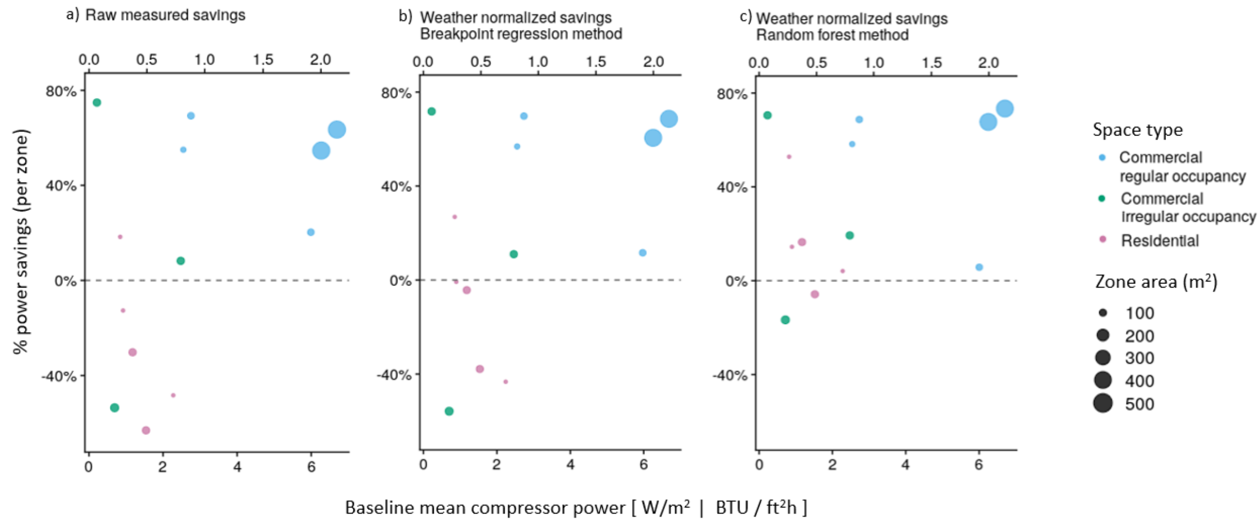
Figure 18: Weather-Normalized Power Savings Versus Increase in Indoor Temperature



Comparison of weather-normalized compressor energy savings against the mean hourly increase in indoor temperatures in each HVAC zone after ceiling fans began to operate and occupants were encouraged to increase air conditioner setpoints. Larger energy savings are correlated with larger increases in indoor air temperatures. Median savings per compressor, normalized for weather and floor area, are 15%, and ranged from an increase of 36% (in an infrequently used space), to savings of 71% (in a large zone with low initial setpoints). Credit: CBE

Figure 18 compares the compressor power savings, normalized by weather, versus increased indoor temperature compared to the baseline period. Larger increases in indoor air temperature, driven by increased thermostat setpoints, correlate with greater savings. Sequencing ceiling fans and air conditioning can only save energy if air conditioning is adjusted to run less often and less intensely by raising air conditioning cooling setpoints, so zones where occupants did not raise setpoints did not realize energy savings.

Figure 19: Observed and Weather-Normalized Power Savings Per Compressor, by Space Type



Comparison of a) measured raw energy savings per compressor, by space type, b) Weather normalized savings using breakpoint regression, c) Weather normalized savings using random forest modelling. Savings exclude the period at Site 1 when the mechanical system failed. Weather-normalized values throughout this report are based on the mean value of both weather-normalization methods.

Credit: Dana Miller, UC Berkeley

Table 1 below summarizes the energy and cost savings across all sites for 13 compressors, separated by building type and occupancy. The table includes measured energy savings for the whole year, for the cooling season, and for the peak period in the cooling season as defined by PG&E Time-Of-Use (TOU) rate (4-9pm, June-September). The table also includes weather-normalized energy savings and the change in mean hourly indoor air temperature between the baseline period and the intervention period after ceiling fans were installed and occupants were encouraged to increase air conditioning setpoints. The site with the largest floor area, a regular occupancy schedule, and the largest increase in indoor air temperatures (Compressors C1 and C2) saw the greatest cost savings—an estimated $6,300 for a single cooling season. The residential sites showed less energy savings in general, and less cost savings with a simplified fixed tariff of $0.1945 per kWh. The three residential sites that did achieve energy savings all have greater savings during the peak period compared to all hours. The project team estimates that the new PG&E residential TOU-B and TOU-C rates of $0.32–$0.40 per kWh during the peak period will improve these savings numbers. Note also that all of the residences are well insulated, relatively new construction (2009), relatively small (900–1,300 sq. ft.), and share adjacent walls with other units. All of these substantially decrease cooling energy consumption compared to a more typical California home. Sequencing ceiling fans and thermostats for cooling in older, leakier and larger homes with would see greater savings. Lastly, the table illustrates that this technology should first target buildings/zones with high cooling energy consumption in order to maximize savings and cost-effectiveness. The research team did not attempt to do so in this study, as the sites were already constrained at proposal stage, and the team chose the actual buildings without access to occupancy or energy consumption data.

Table 1: Summary of Measured and Weather-Normalized Energy Savings and Estimated Cost Savings for All Zones

Measured compressor energy use and weather-normalized energy savings per zone											
Zone	area [m^2]	Measured compressor power Cooling season (April - Oct)		Measured compressor energy savings			Weather-normalized energy savings	Mean zone temperature Cooling season (April - Oct)			Weather-normalized cost savings @ $0.2/kWh
		Baseline [W/m^2]	Intervention [W/m^2]	Whole year	Cooling season (April-Oct)	Peak cooling (June-Sept)	Cooling season (April-Oct)	Baseline [°C]	Intervention [°C]	Δ T [°C]	Cooling season (April - Oct)
Commercial - regular occupancy											
C1	564	6.8	2.4	57%	65%	72%	71%	20.5	25.7	5.2	$3,400
C2	564	6.4	2.8	48%	56%	66%	64%	20.5	25.7	5.2	$2,900
C4	91	2.5	1.1	43%	55%	62%	57%	26.0	28.9	2.9	$140
C5	107	2.7	0.8	61%	69%	74%	69%	NA	NA	NA	$200
C7	107	5.9	4.7	7%	21%	15%	9%	24.9	25.2	0.3	$58
Commercial - irregular occupancy											
C3	136	0.7	1.1	−95%	−54%	−39%	−36%	27.1	27.0	−0.1	−$35
C6	122	2.4	2.2	−5%	8%	2%	15%	25.4	26.9	1.4	$51
C8	122	0.2	0.1	68%	73%	64%	71%	25.0	24.9	−0.1	$18
Residential											
R1	83	0.9	1.0	−37%	−11%	9%	7%	25.4	26.6	1.1	$8
R2	83	2.2	3.4	−176%	−51%	−5%	−19%	25.2	25.5	0.4	−$35
R4	83	0.8	0.7	−10%	19%	55%	39%	26.6	27.1	0.5	$41
R5	119	1.2	1.5	−78%	−31%	20%	7%	25.9	26.4	0.5	$17
R6	119	1.5	2.5	−219%	−65%	−4%	−22%	24.6	23.9	−0.7	−$50

Measured compressor power consumption and measured energy savings values are based on measured values normalized by floor area, and have not been weather-normalized.
Weather-normalized cost-savings estimates are based on weather-normalized power consumption estimates (not shown).
Electricity costs are based on average of Energy Information Administration August 2019 California statewide residential and commercial rates, at $0.1945 / kWh.
New residential TOU-B and TOU-C Time-of-Use rates in PG&E territory starting January 1 2020 are summer (June - Sept) peak $0.32 - 0.40/kWh and summer off-peak $0.25-0.29/kWh.
Data not successfully collected for zone R3 compressor power due to hardware issue. Data for C5 baseline period indoor temperature not available.

Credit: Dana Miller, UC Berkeley

The examples below highlight some of the findings at specific sites and zones.

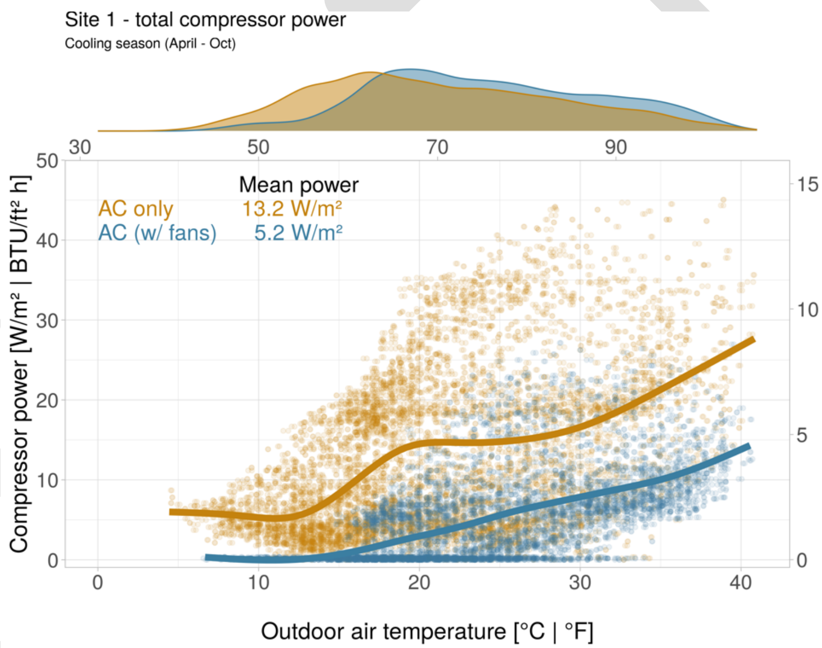
Examples of successful energy savings sequencing ceiling fans and air conditioning for cooling:

1 - Commercial site with largest sustained cooling setpoint change and energy savings

This site had a regular occupancy schedule, relatively low and stable air conditioning cooling setpoints, and substantial cooling energy consumption during the baseline period. It is the largest site in this study (6070 sq. ft.), and has a high thermal mass building of concrete construction that is conditioned using a Variable Refrigerant Flow (VRF) heat recovery system that provides both heating and cooling to the space. Additionally, the existing programmable thermostats were not replaced at this site as interoperability with thermostats other than those provided by the VRF manufacturer was not supported. Thus, this is the only site in which the team can assess the effect of installing the ceiling fans without the confounding effect of replacing the thermostat.

As shown in Figure 20 below, the absolute measured savings at this particular site were substantial (61% reduction in compressor power), even prior to normalizing for warmer weather during in the intervention period. This particular site also encountered an extended HVAC failure during the study period due to a failure of the condensate pump system. During this period, the ceiling fans continued to operate, and the research team collected surveys and data. **Despite indoor temperatures reaching temperatures higher than design recommendations, the majority of the occupants were still comfortable, demonstrating that the ceiling fans can provide a measure of resilience during mechanical system failures.** Note that savings estimates due to the automated ceiling fans are comparable using data from either before or after the HVAC equipment was repaired, so the HVAC failure was *not* a driver of the large energy savings.

Figure 20: Compressor Power at Commercial Site with the Largest Energy Savings



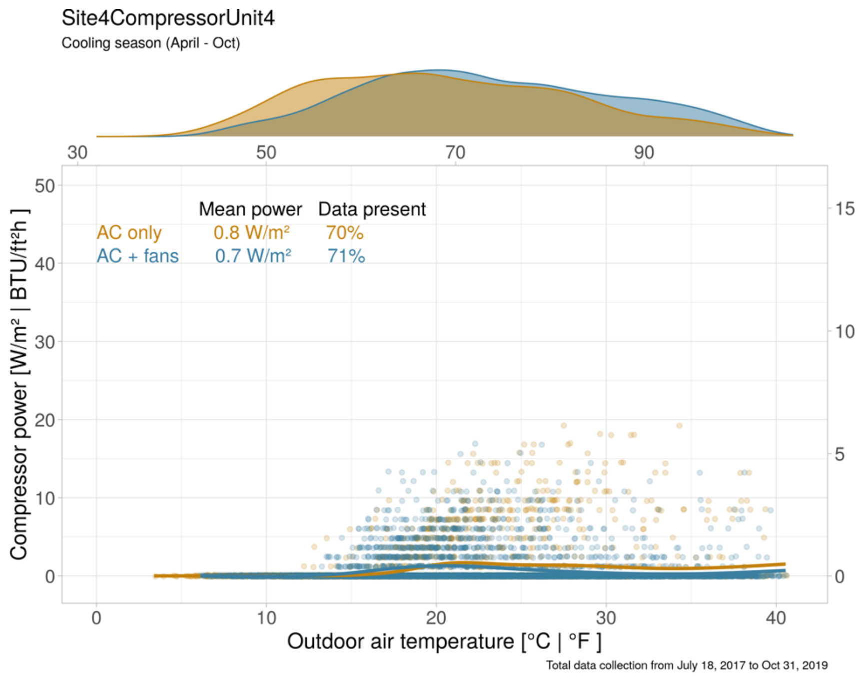
Compressor power use, normalized per floor area served, with respect to outside drybulb temperature for the large zone at Site 1 with both offices and a community room. Raising cooling setpoint temperatures (from ~72 °F up to 78 °F) resulted in much lower air conditioning energy use, in addition to less hours of runtime.

Credit: Dana Miller, UC Berkeley

2 - Residential unit with energy savings

Figure 21 below summarizes energy use in one of the one-story multifamily residential units. When the new programmable occupancy-sensing thermostat was installed as part of the retrofit, the occupants were encouraged (and agreed to) set their cooling setpoint to 78 ˚F. While the air conditioning compressor ran for a comparable fraction of hours during the baseline and intervention periods (14 % and 16%), the average cooling energy use during the intervention period was lower than the baseline period, despite the substantially warmer temperatures (as can be seen in the distribution plot above the upper x axis). While the occupants' schedule did not permit an interview for more detailed feedback, ceiling fan data showed that the fans operated frequently throughout summer 2019. Thermostat data showed the thermostat was frequently off during summer 2019, and that occupants adjusted the air conditioning cooling setpoints to 80 and 86 ˚F. This likely reflects occupants not needing to run the air conditioning as often due to the cooling effect of air movement provided by the ceiling fans.

Figure 21: Compressor Power at Residential Site with Energy Savings



Compressor power use, normalized per floor area served, with respect to outside drybulb temperature for one multifamily residential unit. Despite higher temperatures during the intervention period, energy use was comparable or lower.

Credit: Dana Miller, UC Berkeley

Examples of limitation of this retrofit approach

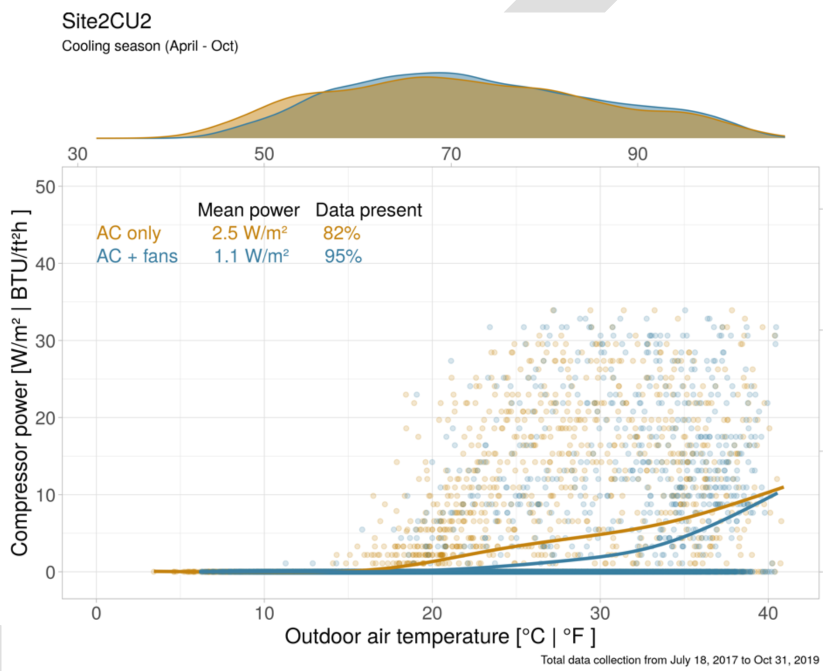
3 - Commercial site with infrequent occupancy

Figure 22 below summarizes energy use in the one-story community room at Site 2. While the average energy for air conditioning decreased in the intervention period after the fans and occupancy-sensing programmable thermostats were installed, the space is very infrequently occupied and mechanical cooling was not operated on a regular schedule. This is because unlike the adjoining offices, the community room is primarily used for evening or weekend events booked by residents. The air conditioner compressors used less energy after the fans were installed (an average of 56% less compressor power), with positive feedback from the site manager. However, since the compressors operate for fewer hours than a more frequently occupied space, the total energy savings are less than could have been realized if the demand for cooling was more frequent.

Reduced potential for energy savings due to infrequent space usage was also an issue in the community room at site 3, where despite measuring small energy savings in the intervention period, the compressor only ran for about 2% of total hours in both the baseline and intervention periods.

This highlights an important consideration for future retrofits: **the potential savings from sequencing air movement and air conditioning is greatest at sites that have more frequent and/or more intense air conditioning use.** Note that in this project, the sites were selected prior to having any insight into level of air conditioning use.

Figure 22: Compressor Power at Commercial Site with Infrequent Occupancy



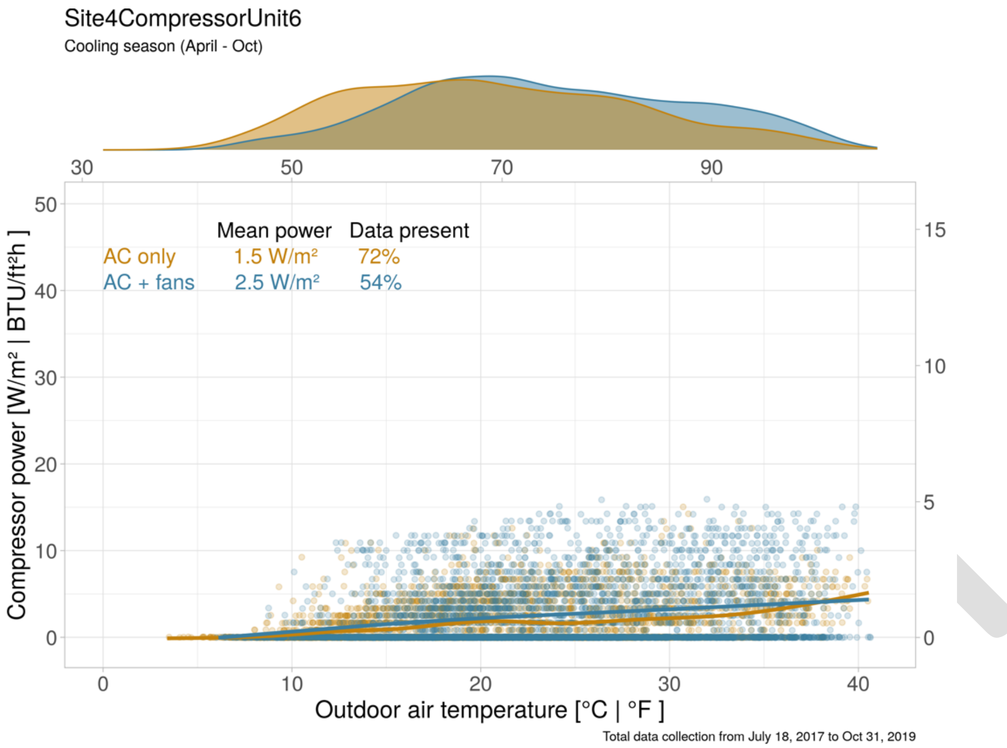
Compressor power use, normalized per floor area served, with respect to outside drybulb temperature for a less-frequently used community room. Across comparable temperatures, the site used less air conditioning energy during the intervention period, but greater savings could have been realized if the space had required more frequent cooling.

Credit: Dana Miller, UC Berkeley

4 - Residential unit that did not adopt increased air conditioner cooling setpoints

Figure 23 below summarizes energy use in one of the two-story multifamily residential units. When the programmable occupancy-sensing thermostat was installed as part of the retrofit, the occupants were encouraged to set their cooling setpoint to 78 ˚F, but afterwards typically selected lower air conditioning cooling setpoints of ~ 71 ˚F. The air conditioning compressor ran for a comparable fraction of hours during the baseline and intervention periods (40 % and 44%), however the intervention period was warmer, with about twice as many 95 ˚F degree hours than the intervention period. Without normalizing for the warmer weather, the observed compressor cooling energy use increased by 66%. In interviews, one occupant expressed that the fans improved their comfort in the space, particularly in one of the upstairs rooms, and was excited to have the fans installed and would recommend the fans. Ceiling fan data also showed that one of the bedroom fans operated regularly during the summer. At the same time, occupants reported that the cooling setpoint reflected their comfort preference, and that one adult occupant was home most of the day. Despite not saving energy, likely due to the lower cooling setpoints, the occupants reported a comfort benefit.

Figure 23: Compressor Power at Residential Site with Low Cooling Setpoints



Compressor power use, normalized per floor area served, with respect to outside drybulb temperature for one multifamily residential unit that did not realize energy savings. The occupants preferred to maintain relatively low thermostat cooling setpoints (~71 °F) after fan installation.

Credit: Dana Miller, UC Berkeley

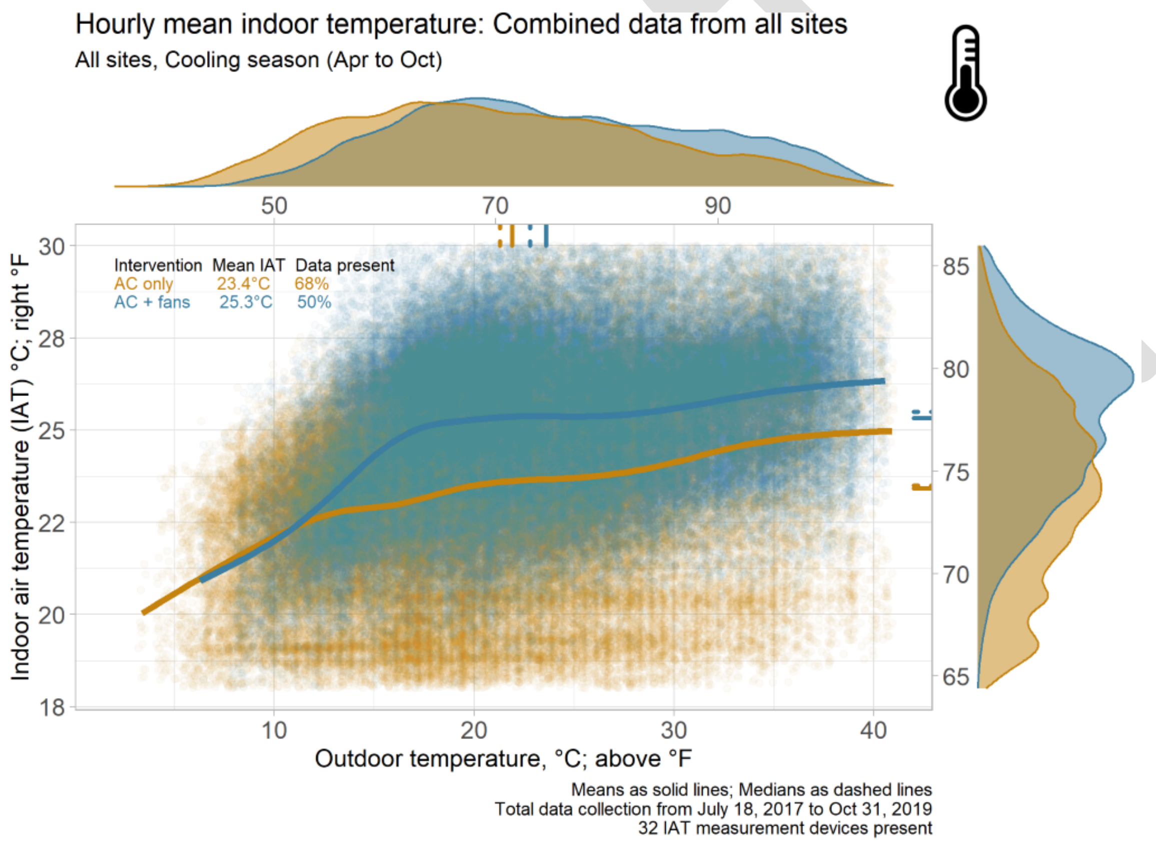
Indoor Environmental Quality Analysis

Indoor temperature sensors were installed at each site in summer 2017, one year prior to the retrofit installation of the ceiling fans and new thermostats. Multiple temperature sensors were installed at some sites to capture potential variation across larger spaces (such as a large zone or a two-story residential unit). Due to data transmission issues, some sensors had periods of missing data. In the plots below, temperatures for each HVAC zone are based on the mean hourly temperature from all temperature sensors in each zone.

After the new ceiling fans and thermostats were installed, occupants at each site were encouraged to increase their air conditioning cooling setpoints to account for the cooling effect of the fans through verbal explanations and printed educational materials. In commercial spaces, depending on the previous cooling setpoint, the cooling setpoints for the new thermostats were either directly increased to 78 ˚F at install, or gradually raised over a period of several weeks in cooperation with the site. Occupants were free to adjust the thermostat at all times, and were provided with information on how to do so. In residential units, the default cooling setpoints were increased to 78 ˚F during installation. Residents were similarly free to adjust the thermostat and were provided with instructions on how to do so. Based on thermostat usage data, occupants in both commercial and residential spaces adjusted their thermostats, with changes ranging from permanently changing the schedule or default setpoints to temporary overrides.

Consistent with the reductions in air conditioning compressor use and the observed increases in thermostat setpoints, mean measured indoor air temperatures (Figure 24) were higher in the intervention period than the baseline period across a similar range of outdoor temperatures. The mean hourly indoor air temperature across all sites increased approximately 2 °C (3.4 °F).

Figure 24: Mean Hourly Indoor Air Temperatures Across All Sites



Mean hourly Indoor air temperature compared to outside drybulb temperature across all 32 temperature sensors across all hours (including unoccupied hours) and all zones across all field study sites.

Credit: Sonja Salo, UC Berkeley

The subsequent Figures (25–28) show the indoor air temperatures for the same four sites compressor usage was shown for in the section above (Figures 20–23).

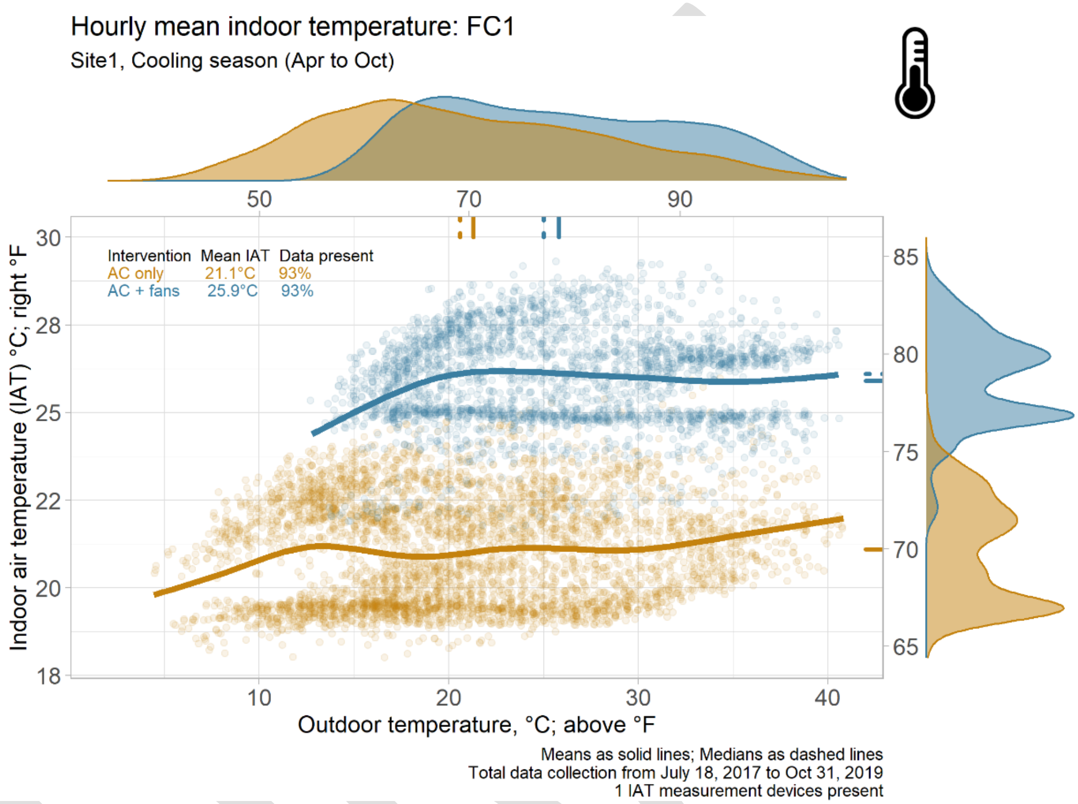
Examples of successful energy savings:

1 - Commercial site with largest sustained cooling setpoint change and energy savings

As shown in the previous section, this particular site had substantial savings, an overall 61% reduction in compressor power use.

Figure 25 below demonstrates that the mean indoor temperatures also substantially increased, by approximately 4.5 ˚C (9 ˚F). This is partly attributable to the relatively low cooling setpoint (70–72 ˚F) the site had been operating at prior to the intervention. The facilities manager, office staff and occupants had positive feedback about the fans, and point-in-time occupant surveys showed a similar thermal comfort between baseline and intervention periods.

Figure 25: Indoor Air Temperature at Commercial Site with the Largest Energy Savings



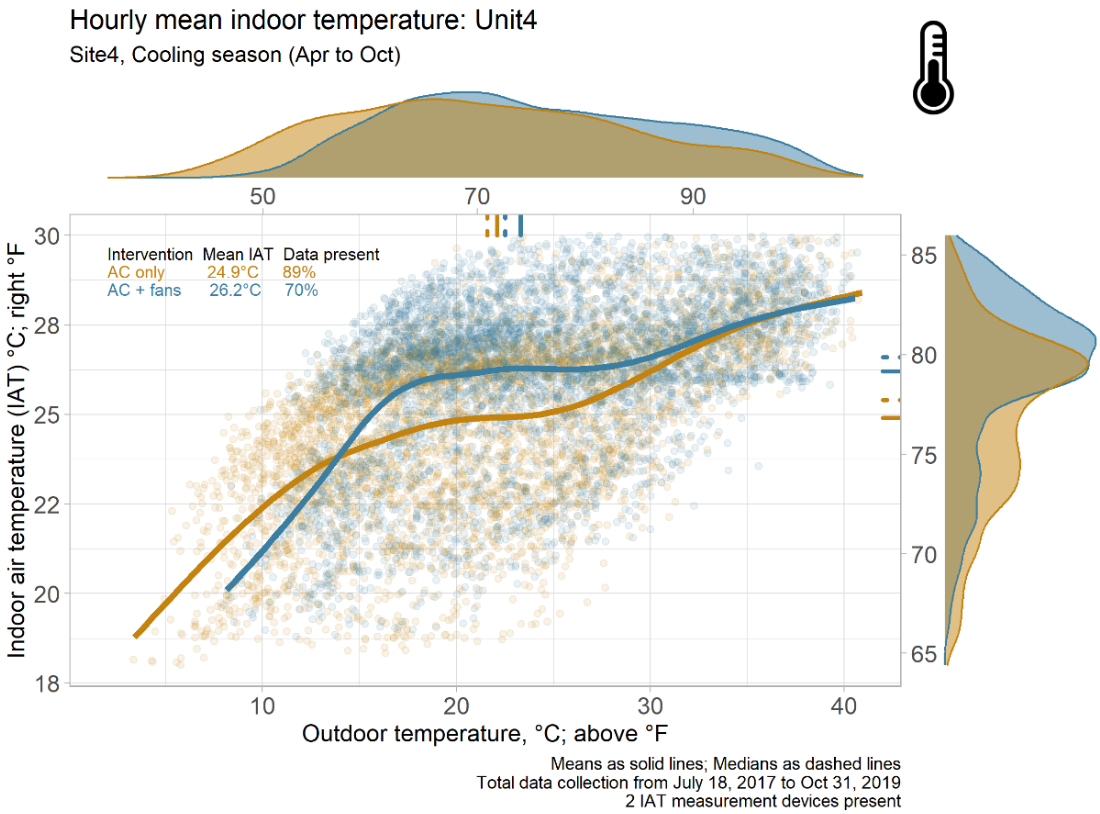
Indoor air temperature compared to outside drybulb temperature for a large zone at Site 1 that increased cooling setpoints from 72 F to 78 F, resulting in higher indoor air temperatures, while maintaining occupant comfort.

Credit: Sonja Salo, UC Berkeley

2 - Residential unit with energy savings

Figure 26 below summarizes indoor air temperatures in one of the one-story residential units at Site 4 that used less energy during the intervention period, despite higher outdoor temperatures. Mean and median indoor air temperatures are about 1 ˚C (~ 2 ˚F) higher in the intervention period after fan installation, and are noticeably higher between outdoor air temperatures of approximately 15 and 30 ˚C (60 – 86 ˚F). The data shown is for all hours, which may include periods when residents were not at home for extended periods of time.

Figure 26: Indoor Air Temperature at Residential Site with Energy Savings



Indoor air temperature compared to outside drybulb temperature for a one-story multifamily residential unit that realized energy savings despite warmer temperatures during the intervention period. Mean and median indoor air temperatures are about 1 °C (~ 2 °F) higher in the intervention period after fan install.

Credit: Sonja Salo, UC Berkeley

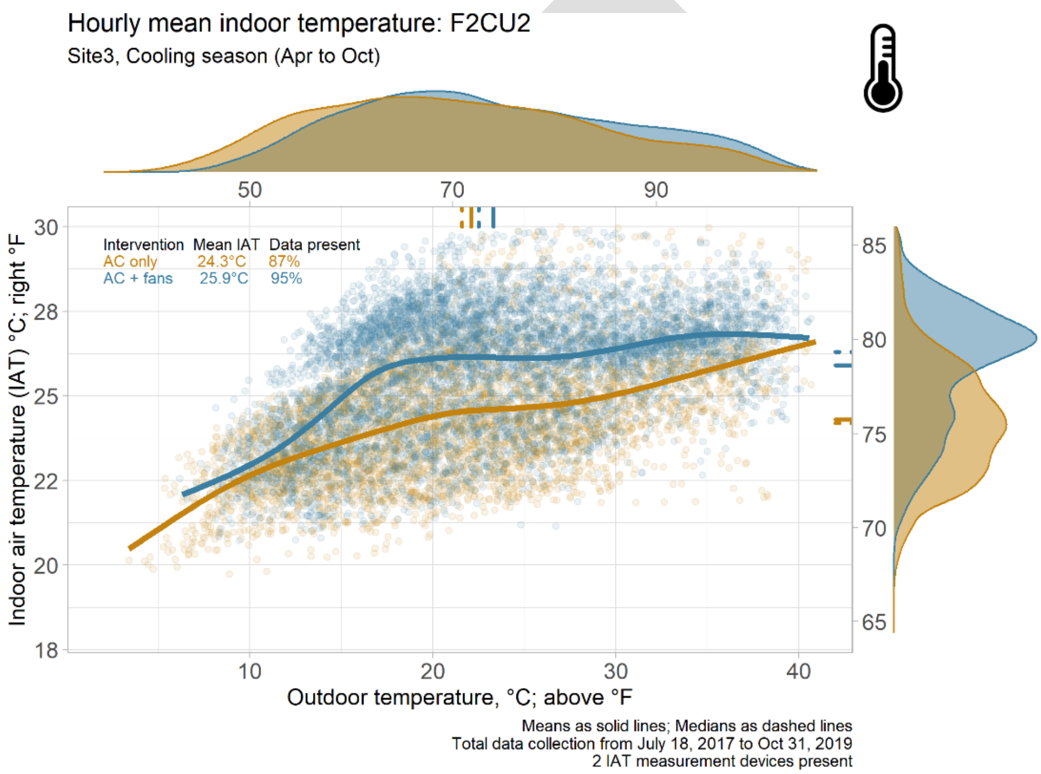
Examples of limitation of this retrofit approach

3 - Commercial site with infrequent occupancy

As discussed above, this space is infrequently occupied and thus the HVAC system operates infrequently and the total cooling energy savings are relatively low. Despite this,

Figure 27 below shows the combined intervention of the new occupancy-sensing thermostat and ceiling fans appears to have led to higher indoor temperatures in the intervention period (consistent with the reduction in air conditioning use). This is likely due to the new thermostat schedule, setpoints, and occupancy sensing, including an unoccupied cooling setback setpoint of 82 ˚F.

Figure 27: Indoor Temperature Compared to Outside Temperature for Less-Frequently Used Community Room



Indoor air temperature compared to outside drybulb temperature for a less-frequently used community room. Across comparable temperatures, the site with higher indoor temperatures during the intervention period used less air conditioning energy during the intervention period, but greater savings could have been realized if the space had required more frequent cooling.

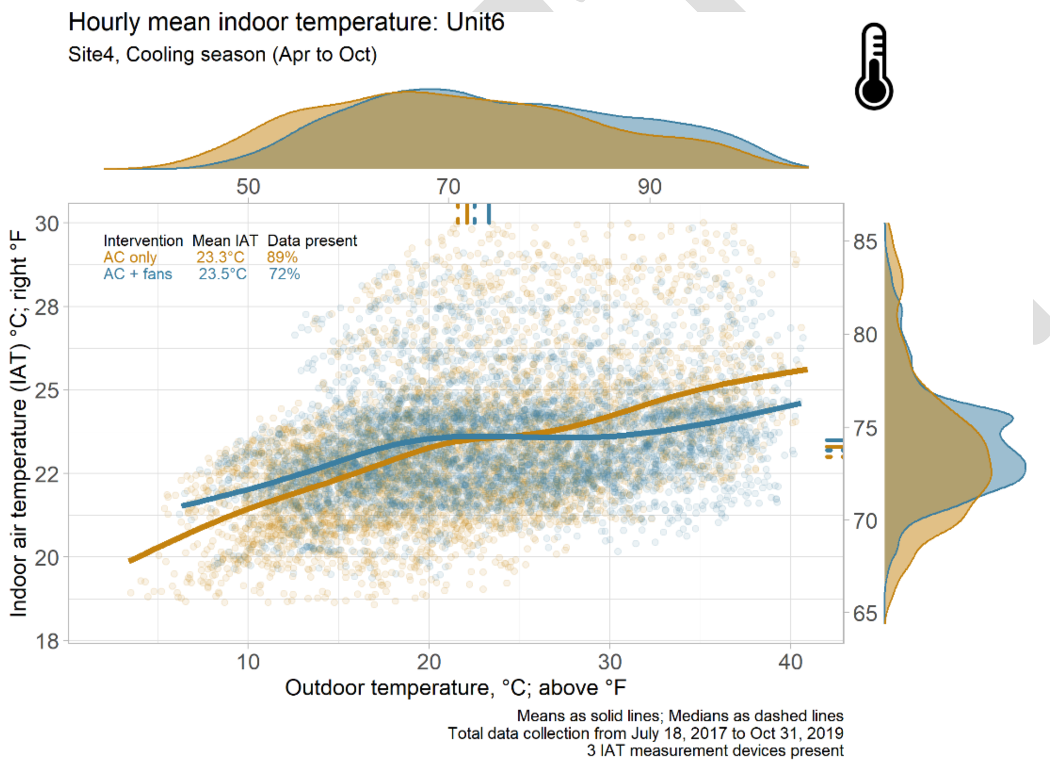
Credit: Sonja Salo, UC Berkeley

4 - Residential unit that did not adopt increased air conditioner cooling setpoints

Occupants in this residential unit preferred not to increase the air conditioning cooling setpoints after fan installation. Unsurprisingly, mean hourly indoor air temperatures were comparable in both the baseline and intervention periods as shown in Figure 28. The occupants received written and verbal information about how increasing cooling setpoints could contribute to energy savings with comparable comfort, but preferred their existing setpoints.

This highlights the conditional potential for energy savings using air movement: while ceiling fans staged with air conditioning can save substantial amounts of cooling energy, this intervention is only effective if the cooling effect from fans enables occupants to raise cooling setpoint temperatures. Personal needs and preferences, including differences in indoor activities, clothing levels, and health status, all contribute to cooling temperature preferences.

Figure 28: Indoor Air Temperatures at Residential Site with Low Cooling Setpoints



Indoor air temperature compared to outside drybulb temperature for a residential unit that maintained comparably low air conditioner cooling setpoints after the intervention, and therefore did not realize energy savings prior to weather normalization.

Credit: Sonja Salo, UC Berkeley

Survey Results

Office Workers

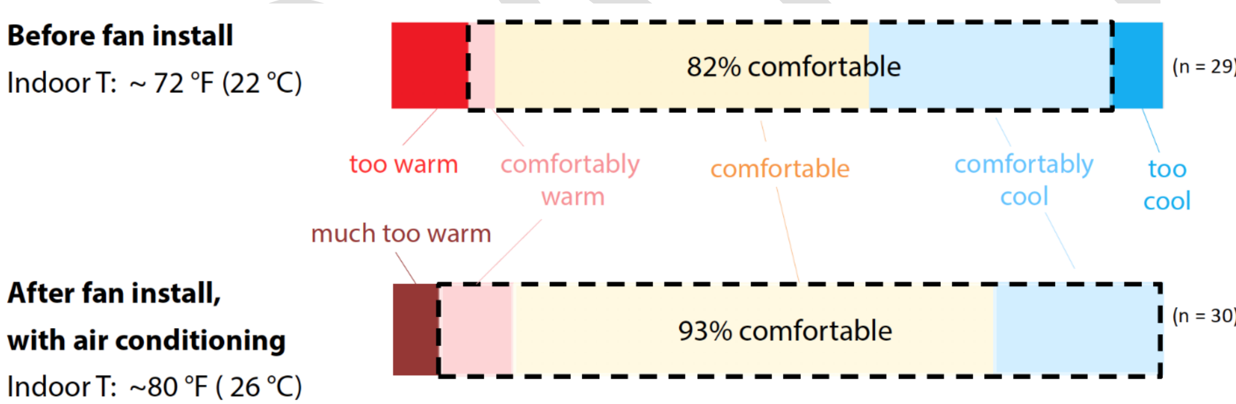
Because recruitment was a challenge to get office workers to complete surveys, little data is available and thus the generalizability of this particular data source is limited. The findings from the "Right Now" survey suggests that there are likely individual differences across participants that account for shifts in preferences in thermal sensation, air movement acceptability, and thermal acceptability. These differences are possibly physiological, psychological, and situationally dependent. There is less variation visible in air quality acceptability, however, there are still likely individual differences in this perception, most likely due to situational circumstances of the space.

Common Room Users

The research team analyzed residential perceptions of the common room spaces at the Franco site at three time points: before installation of the fans, after fan installation when the air conditioning was not functioning at the end of summer 2018, and with functional AC in mid-summer 2019.

Overall, very little change was detected within the survey data from time point to time point. This lack of change in perspective is impressive given the average temperature had shifted across each time point. While surveying at pre-install, the average indoor temperature was 72 ˚F (22 ˚C). During the second survey, (when the mechanical system failure occurred and only the fans were operating), the mean indoor temperature was warmer, 80 ˚F (27 ˚C). Finally, at the third survey point, both fans and the air conditioning were operating as planned, and the average indoor temperature was 80 ˚F (26.5 ˚C). These results overall suggest that **the presence of the fans increased the range of thermal comfort and acceptability across participants**.

Figure 29: Comfort Votes and Indoor Air Temperatures



The upper bar shows the votes of occupants before the fan install—note the number of 'too cool' votes. The bottom graph shows votes after ceiling fans were operating together with air conditioning (at a higher air conditioner cooling setpoint).

Credit: Dana Miller, UC Berkeley

The surveys indicate an increase in air movement acceptance after the installation of the fans. These results highlight that in addition to increasing one's range of thermal comfort, **the fans' presence in the space also seems to have a positive impact on air movement acceptability.** Other possible influencers over any variance across time points could include individual differences of the participants (e.g., age, personality, background) and/or of the circumstances occurring within the physical environment at the time of the data collection. Results also reveal that perhaps future work should explore other questions (like those found in the interview methods) that could help detect more of the nuanced variation across participant perceptions.

Interviews

The purpose of the interviews was to better understand occupants' experiences and perceptions across a number of factors related to the equipment: perceptions and attitudes of the occupants, ease of use, impacts on indoor environmental quality (caused by the equipment), perceived impact on energy costs, and perceived value. Also, at the end of the second interview occupants were asked if they had any feedback on how the research team could have improved the study, and answered any questions they had as the study concluded.

Both occupant types were asked questions about their experiences in using both the fans and thermostat equipment. Overall, occupants felt the equipment was easy to use though they did remark that they felt the Ecobee thermostats have a steep learning curve. However, each of those respondents explained they eventually felt comfortable with the Ecobee once they understood how to best engage with it. No challenges were expressed in ease of use of the fans.

Manual Versus Automatic Control

By the end of the study, all participants reported using the fan remote on a regular basis and felt satisfied with that tool. None of the occupants reported use of the mobile app, and many described that they did not see the purpose behind the application. Initially one resident was using the browser login for the thermostat, but had stopped by the end of the study.

When the team inquired about occupants' preferences for the fans to be functioning automatically or manually before the fan installation, participants were split in which setting they would prefer. After fan installation, **all office workers reported preferring the automatic setting and most (80%) of residential occupants preferred manual usage of the fans.** Desire for manual control seemed to stem from occupants' desire for more control. Many of the residents described that the fans in some cases cooled too much or that they did not always enjoy the air movement. In the exit interviews, office workers also expressed a desire for more control, but several voiced that they actually liked the fact that the fans did the work for them. One office worker said, "They've helped (me) by not having to worry about being too hot or too cold in the office. Because when you're too hot or too warm it's hard to concentrate. By having the fan, it helps me stay focused because I don't have to worry about the temperature."

Difference in preference for manual versus automatic control across these two participant types unveils a couple of possibilities. It seems there is intrinsic motivation across most if not all people to have some sense of control over their environment; however, perhaps there are individual differences across people in one's level of need for control. Second, these results also suggest the activity within the environment may have an effect over the level of need for control. Office spaces, unlike homes, tend to support a specific set of tasks (focus, productivity), whereas homes support a multitude of tasks (working, relaxing, childcare, socialization). Perhaps in spaces where activities vary more broadly, more occupant control (or the perception of control) is more important.

Indoor Environmental Quality

The team also asked participants about how the fans impacted their perception of indoor environmental quality (IEQ). Overall, perceptions were quite positive from both occupant groups as they related to IEQ. **All participants felt the fans provided adequate cooling, and**

importantly, none could recall an instance in which the fans did not provide effective cooling in their space. One resident reported the use of an additional portable fan during cooling season, but he explained this was used only in the bathroom (i.e., a space that did not have access to the ceiling fans). Additionally, most (100% of residents, 75% of office workers, one simply did not respond to this question) reported that the fans improved their overall air quality at the first interview, and 100% of all participants reported this at the second. Further, though two residential occupants reported random hot and cold spots throughout the space at the first interview, by the second, all occupants believe the fans eliminated this issue and that the air was evenly mixed. Finally, all residents reported that they felt the fans improved their overall IEQ at both interviews, and 50% and 100% (at the first and second respectively) of all office workers reported that the **fans improved their IEQ**. (Two office workers did not comment on this at the first interview).

The researchers also asked occupants whether or not the fans influenced the functionality of other aspects of IEQ specifically: Wi-Fi effectiveness, lighting, noise levels, ceiling clearance, and the safety of occupants. At the first interview, two residential occupants reported having had **issues with Wi-Fi interference** due to the fans. The research team worked with those occupants to alleviate this situation and the problem was remedied. One issue that was also voiced, but not specifically asked by the team, related to occupants' television sets.

Design Perceptions

Fans: Overall, both user groups expressed a lot of enjoyment with the fan equipment. They were all incredibly **pleased with its ability to cool the space quickly and effectively**. Most users also enjoyed the design of the fans and the ability to adjust the equipment easily and with the remote. Some occupants were troubled by the light on the fans. They believed they were too dim, and then they were also confused by the blue sensor light. All occupants seemed satisfied with the air circulation that the fans provided, though many (especially residents) felt the fans speeds were too high at times.

Both groups felt both satisfied and dissatisfied with the automation of the fans. One interpretation of this may be that they are simply craving more perceived control. The fan automation seemed to be appreciated at times, but frustrating at others. Frustration seemed most palpable in the resident user group compared to office workers who seemed more accepting and appreciative of the automatic nature of the equipment. This difference could be due to the different needs or expectations one has in a workspace compared to a home.

Thermostats: Consistently, across user types, each reported that they felt the thermostat equipment was **challenging to use at first**. However, it should be noted that by the second interview, all reported that they felt they had mastered the equipment. This finding suggests that over time the thermostats become understandable, but that there is likely a steep learning curve for users at installation.

Residents reported satisfaction with the lower energy costs from the installation of the fans and the thermostats. Both groups also expressed happiness from reduced use of the AC as much as they had prior to having the fans installed. Many users, especially residents also reported appreciation for the look and feel of the thermostat interface.

Suggested Design Improvements

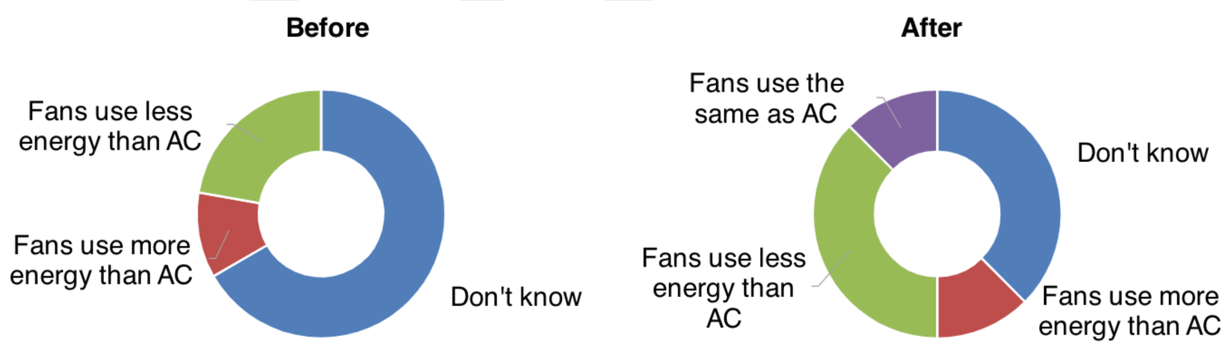
Overall, most occupants (regardless of type) did not have any suggestions for design improvements. One resident explained that perhaps having a slower start speed for the fans would be useful. Many occupants explained they felt the phone app was not useful and that they would never use it. And in general, most occupants reported they would keep the design of both the fans and the thermostat equipment exactly as is.

Though occupants did not provide much direct feedback when they were asked explicitly about design improvements, reviewing their likes and dislikes of both types of equipment is useful. For instance, in the case of the thermostats it seems as though **some effort should be put forth in either a) user education at time of installation, or b) in making the system more intuitive to use.** Some users also mentioned that they would have preferred the thermostat interface to be **available in Spanish** (only English and French were available on the Ecobee). Over time, occupants seemed to learn how to use the thermostat, but almost unanimously mentioned that they were initially a challenge to understand. As for the fans, one issue that came up a couple of times across occupant groups was the light. Occupants seemed to **want more control over the light** in both their ability to adjust it and its level of brightness. Also, both occupant groups mentioned the fan speed was problematic at some times and expressing interest in having the ability to have an even lower speed option than what currently exists.

Overall Value and Perceptions of Energy Use

During each interview the team asked participants their perception regarding whether fans use more or less energy than air conditioning systems. Results revealed that overall most occupants from both groups were unsure. One resident and one office worker believed they used less energy, and one office worker believed they used more. The data from the second interview is likely less reliable due to the fact the team asked occupants to recall across a year and a half time frame after numerous points of education they received from the study intervention.

Figure 30: Occupants' Perceptions of Fan Energy



Before fans were installed, more occupants didn't know the relative energy use of fans compared to air conditioning.

Credit: Sonja Salo, UC Berkeley

Finally, occupants were also asked whether or not they would recommend the fans to family and friends. At both time points, all occupants (except one employee who did not respond to this at the first interview) reported that they would recommend. At the end of the exit interview most of the office workers expressed that they wished they had the fans in their own homes.

Close Out & Handover Challenges

The research team worked with manufacturer (BAF) to specify, implement, and iteratively improve three successive versions of a new ceiling fan control algorithm based on temperature, occupancy, and user interaction, and install it on 99 fans. As intended, occupant interaction did cause fan setpoints to gradually adjust over time. All occupants surveyed preferred the temperature-based fan operation with the firmware developed for this study (always with the option of manual override) to reverting to a commercially available version that did not support temperature-based control.

Since all the equipment used in this study was chosen for its network integration and smart functionality, both fans and thermostats require being connected to a network to provide all features. Removing equipment from the networks reduced the features available to the users unless they reconnected to their own networks, which isn't guaranteed. Additionally, network control and usage by the users was limited during the study so that the research team could control, update, and monitor equipment as needed. Thus residents and workers had limited knowledge before the close out of how to set up and use these additional features. While training and handouts were made available, most of the users were not interested.

Field Study Lessons Learned

Some space types, such as bedrooms, require special consideration for controls. For example, occupants sleeping under blankets may have a lower metabolic rate and accordingly desire a higher fan setpoint, and may not be detected by motion or infrared-based occupancy sensors. In addition, blinking LEDs to indicate fan speed are disruptive at night.

The end users in this study did not use the mobile phone apps or websites; furthermore, the learning curve for the thermostat was particularly steep. Both devices would benefit by further usability efforts. Most users did not change settings, which indicates the default setting should be a) more robust, and preferably learned from user behavior and b) should revert to a sensible default value after a reasonable amount of time (e.g., a few weeks) to prevent people accidentally locking themselves into poor performance that they are not aware of (or don't have the time or don't understand enough to figure out how to change).

Few of the interior spaces operated above 80°F for substantial periods of time, even with air movement. This contradicts lab study findings that suggest much higher temperatures are feasible and comfortable in the presence of air movement.

Ongoing Maintenance and Demonstration Site Challenges

Post-install visits were frequently required for a variety of concerns and data monitoring issues. All data was uploaded remotely to be visible either in real time or through daily downloads.

This allowed the research team to see immediately when there was a problem, but made it difficult at times to diagnose whether a lack of data was due to equipment or the network it was connected to.

For convenience and price, Wi-Fi hotspots used were consumer models with minimal range, requiring a range extending device to be used with each one. For the residential units this equipment, in addition to the data monitoring equipment, was installed in the water heater closets outside the units. During high summer temperatures these closets would become hot enough to cause the range extenders to shut down, so that any equipment connected to them could not transmit data. While the range extenders did restart as the temperature cooled, the research team found that the equipment transmitting HVAC energy use would not reconnect and had to be restarted. This problem was solved by replacing all range extenders submitted to high temperatures with outdoor models built to withstand extreme temperatures.

Wi-Fi hotspots in exterior locations did not shut down in high temperatures, however the regular temperature swings are thought to cause extreme battery expansion in many units, which required battery replacement and sometimes caused loss of power and charging ability.

Ceiling fans were only able to be controlled and adjusted via smartphone connected to the same local area network as the fan, and so required frequent visits. In order to retrieve fan data from the BAF servers properly, all fans needed to be registered under known users, and running firmware tailored to this project. This required visits to register the fans and update firmware. Fans in residential kitchens were found to have an incorrect logic board that did not allow them to be updated to the correct firmware version, and were replaced by BAF installers December 3rd - 4th 2018. Additionally, two of the installed fans developed problems with the motor, and needed to be replaced by BAF.

Many of the times when equipment lost connection with the network, or the network itself went down, the solution was to restart the item in question, which was only possible manually. To try and avoid this problem AEA installed “smart plugs” where possible, which could be controlled remotely and would automatically turn equipment off and on at least once per week.

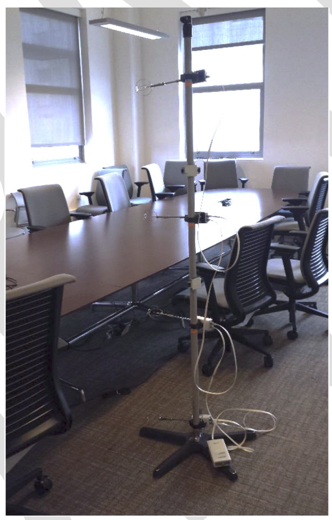
One location that Hamilton sensors were installed was at HVAC supply vents, in order to determine whether compressors were in heating or cooling mode, as thermostat data was not available at this site. However, the project team found that being in the changing temperature air streams caused condensation to form on the devices, which was sufficient in some cases to short out the device. To eliminate this problem two methods were used: installing Hamiltons in plastic bags with a desiccant included, and installing separate temperature sensors wired directly into the Hobo U-30 data loggers.

Technology Readiness

Case Study Results

Ceiling fans are infrequently included in commercial spaces even though they have the potential to bring benefits including increased occupant comfort and decreased energy use either through raised setpoints in cooling or destratification[7] in heating. This case study provides practical insights into the case of ceiling fans in commercial spaces. The research team at CBE conducted 13 interviews with architects, engineers, and facilities managers from California and around the country to compile common motivations and applications, control strategies, barriers to market adoption, best practices, and airspeeds. These professionals provided lessons learned from 20 operational projects that include ceiling fans serving a wide set of functions in commercial spaces. Understanding the challenges they faced and the lessons they learned from these projects can facilitate prioritization of research and communication efforts. The researchers also took in-situ airspeed measurements at five of the projects to provide insight into real-world conditions in commercial buildings with ceiling fans. For these, the ceiling fans' operation results in generally relatively low airspeeds, often under 0.2 m/s. The researchers also found just 25% of the 20 projects discussed by interviewees had any type of automation in the ceiling fan controls. This study serves as a resource for designers and for the wider industry, to frame a path forward for the inclusion of ceiling fans in commercial buildings. The full report may be found in Appendix E and (Present et al. 2019).

Figure 31: Measurements in Existing Buildings with Ceiling Fans



A tree of air flow sensors replaces a chair at a conference room.

Credit: Elaina Present, UC Berkeley

Although interviewees revealed many challenges and barriers during the design process, their feedback about the fans is generally positive once installed. Occupants often choose to have the ceiling fans on even when the resulting airspeeds are too slow to create an appreciable cooling effect. This aligns with findings from the interviews, that ceiling fans provide benefits not only for comfort conditioning and energy use reduction, but also provide individual control, non-

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[7] Destratification refers to dispelling the natural thermal stratification of air where in heating environments, the hot air rises to the ceiling. Destratification would mix the room's air so make better use of the hot air.

thermal benefits (such as perceived and measurable air quality), or an aesthetic choice not only in their own right, but sometimes as a way to eliminate visible ductwork.

Furthermore, though the encountered-on-site fan settings and resulting airspeeds were low, it is important to note that these zones were already operating within ASHRAE 55 comfort conditions in the absence of air movement. Higher airspeeds would have overcooled the occupants unless one also increased the zone temperature. This indicates a potential opportunity to reduce HVAC energy consumption by increasing zone cooling setpoints and running ceiling fans faster to provide the first stage of comfort cooling.

Among the projects studied, there were few applications of automatic control, and interviewees did not offer a consensus about whether manual or automated control was preferable, seeing pros and cons of each. A viable option is that of occupancy- and temperature-responsive automated controls that can be configured and temporarily overridden by occupants— similar to current best practice in the lighting industry.

As with many strategies that aim to improve building performance, best practices start with an integrated design process where different stakeholders communicate early in the process and coordinate decision making. This would facilitate overcoming many of the identified barriers to implementing ceiling fans, such as perceived concerns about noise, maintenance, or papers blowing; ability to clearly explain the benefits of fans to building owners or other design team members; cost tradeoffs; and lack of design guidelines. It's also important that the process does not end with design but is maintained through occupant education so that users fully understand the range of performance characteristics of ceiling fans (i.e., cooling vs. destratification), so the benefits are fully realized.

This study found substantial uncertainty around designing with ceiling fans despite the significant potential benefits. **Lack of design guidance and measured performance is a significant barrier to downsizing HVAC equipment based on ceiling fan inclusion.** Designers would benefit from outside support, such as from industry, government, or academia. The most significant support would be in the form of design guidance, backed by laboratory testing, CFD, and field studies, for commercial spaces with ceiling fans. This would make designers less reliant exclusively on manufacturers' guidance, and improve communication regarding the abilities and design goals of ceiling fans, and make the designers more confident that their designs would perform as intended. Another need is an expansion of the set of available standardized product test specifications, which would allow designers to more directly compare ceiling fan products. This will require industry effort; ASHRAE has completed Standard 216, Methods of Test for Determining Application Data of Overhead Circulator Fans, which will meet most of this need. **Industry could also better support ceiling fan products that can easily communicate with building automation systems or, ideally, that are BACNET-capable. In general, a more standardized design process would reduce several of the barriers to implementation.**

CHAPTER 4: Technology/Knowledge Transfer Activities

This chapter documents technology, knowledge or other market transfer activities to the public from this project; the Online Design Tool, the Design Guide, Codes and Standards Support, and other outreach. The project team shared results of the project through multiple channels. Outreach include six papers published to date (and several more in process) and 18 presentations at various venues to practitioners/developers, manufacturers, policy makers, and potential end users. Through students hired, future thought leaders were trained. The project has also developed the online Design Tool, found at cbe.berkeley.edu/fan-tool and the Design Guide, found at https://cbe.berkeley.edu/wp-content/uploads/2020/04/CBE-Ceiling-Fan-Design-Guide-V0.pdf. The tool and design guide can be used by designers, architects, and engineers to provide ceiling fan spacing and other recommendations for optimal overall airflow across a space. The team also conducted codes and standards outreach.

Outreach

Papers Published

Chen, Wenhua, Hui Zhang, Ed Arens, Maohui Luo, Zi Wang, Ling Jin, Junjie Liu, Fred Bauman, Paul Raftery. 2020. Ceiling-fan-integrated air conditioning: Airflow and temperature characteristics of a sidewall-supply jet interacting with a ceiling fan. Build Environ. 2020 Mar 15;171:106660. https://escholarship.org/uc/item/8cj7n6ps

Gao, Y, Hui Zhang, Ed Arens, Elaina Present, B. Ning, Y. Zhai, Jovan Pantelic, Maohui Luo, Paul Raftery, S. Liu. 2017. Ceiling fan air speeds around desks and office partitions. Build Environ. 2017;124. https://escholarship.org/uc/item/3pq2j9mh

He, Yingdong, Wenhua Chen, Zhe Wang, and Hui Zhang. 2019. “Review of Fan-Use Rates in Field Studies and Their Effects on Thermal Comfort, Energy Conservation, and Human Productivity.” Energy and Buildings. Elsevier Ltd https://escholarship.org/uc/item/7hx9338z

Present, Elaina, Paul Raftery, Gail Brager, Lindsay T. Graham. 2018. Ceiling fans in commercial buildings: In situ airspeeds & practitioner experience. Building and Environment. 147 (2019) pp. 241-257. https://escholarship.org/uc/item/84h3z7nx)

Raftery, Paul, Jay Fizer, Wenhua Chen, Yingdong He, Hui Zhang, Edward Arens, Stefano Schiavon, and Gwelen Paliaga. 2019. “Ceiling Fans: Predicting Indoor Air Speeds Based on Full Scale Laboratory Measurements.” Building and Environment 155 (May). Elsevier Ltd: 210–23. doi:10.1016/j.buildenv.2019.03.040. https://escholarship.org/uc/item/4p479663

Parkinson, Tom, Paul Raftery, Elaina Present. 2020. "Spatial Uniformity of Thermal Comfort from Ceiling Fans Blowing Upwards." ASHRAE Transactions, Orlando Conference 2020 https://escholarship.org/uc/item/5fs9q6fq

Open-Source Software Released

Design tool: cbe.berkeley.edu/fan-tool.

Students Hired

Elaina Present, Dana Miller, Marta Delgado Lombardo, Mia Nakajima

This project was the subject of two masters' theses, for Dana Miller and Elaina Present.

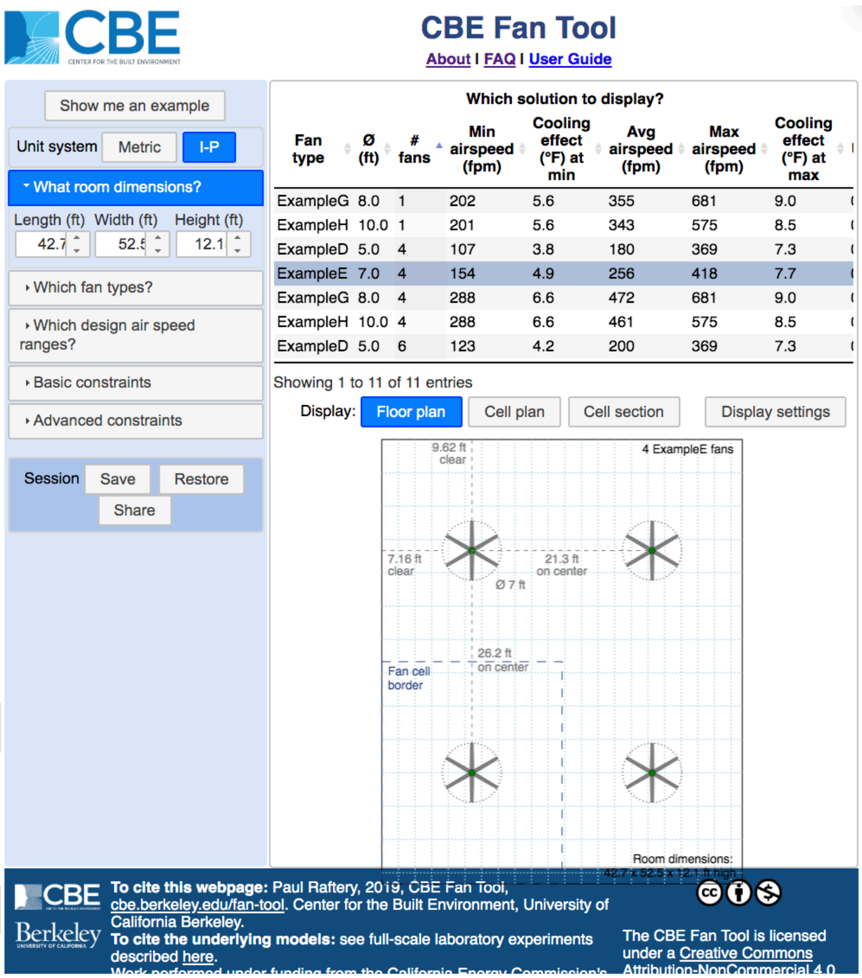
Presentations

- **CBE Industry Advisory Board Meetings** from April 2017, October 2017, April 2018, October 2018, April 2019, October 2019
- **ACEEE Summer Study for Energy Efficiency in Buildings 2018**: Elaina Present, won a Linda Latham Scholarship and presented a poster: *Ceiling Fans in Commercial Buildings: Identifying Common Obstacles and Sharing Lessons Learned from Experience*
- **CEC EPIC Symposium, February 2019**, Paul Raftery gave a presentation entitled "Energy Efficient Comfort Cooling" on this project.
- **Lawrence Berkeley National Lab Rosenfeld Symposium on Grid Interactive and Energy Efficient Buildings, April 2019,** Dana Miller was selected from a student competition to give a presentation and present a poster on this project entitled "Air movement for energy efficient cooling: Perspectives from a field study coordinating ceiling fans and air conditioning"
- **2019 ASHRAE Summer Conference Seminar,** "Seminar 43: Advances in Ceiling Fans for Comfort Cooling", June 25, 2019. Research Team Members were the chair of the seminar (Gwelen Paliaga) and two of the presenters (Hui Zhang and Paul Raftery).
    - What Air Speeds Can I Expect for a Given Fan and Room? Predicting Indoor Air Speeds Based on Full Scale Laboratory Measurements, Paul Raftery
    - The Importance of Air Movement for Comfort When Occupants' Activity Levels Change, Hui Zhang
- **Cool Buildings Workshop, Lawrence Berkeley National Lab, July 2019,** Dana Miller gave a presentation entitled "Move air, then cool it –Integrating air movement for energy efficient comfort" on this project
- **Science of Drawdown Conference, October 2019,** Penn State University, Dana Miller presented a lightning talk and poster that included this project, entitled "Move air, then cool it: low-carbon comfort with air movement"
- **2020 ASHRAE Winter Conference**, Orlando: six presentations on fan-related topics
    - **Indoor Environmental Quality with an Emphasis on Thermal Comfort**
        - Spatially Uniform Comfort from Ceiling Fans Blowing in the Upwards Direction (OR-20-C011) Thomas C. Parkinson, Paul Raftery, and Elaina Present
    - **Best Practices for Ceiling Fan Comfort Cooling.** Research Team Members were the chair of the seminar (Gwelen Paliaga) and presenters (Paul Raftery, Dana Miller, Sonja Salo, Christian Taber).
        - Publicly Available Ceiling Fan Design Guide and Tool. Paul Raftery.
        - Staging Ceiling Fans and Air Conditioning for Energy Savings and Comfort. Dana Miller.
        - Human Interactions with Ceiling Fans and Smart Thermostats: Learnings from Case Studies in Office Buildings. Sonja Salo.
        - Selecting Ceiling Fans Based on ASHRAE Standard 216 Performance Metrics. Christian Taber, Member, Big Ass Fans.
        - Application and Design Consideration for Ceiling Fan and HVAC Integration Stet Sanborn, AIA, Smith Group, San Francisco, CA (CBE alumni)

Online Design Tool

The online CBE Fan design Tool allows designers to quickly select and lay out ceiling fans in a given room to meet their airspeed requirements and other constraints. The Fan Tool may be found at [cbe.berkeley.edu/fan-tool.](https://cbe.berkeley.edu/fan-tool) See also Appendix H.

Figure 32: Screenshot of Online CBE Fan Design Tool



The Fan Design Tool is an online tool (https://cbe.berkeley.edu/fan-tool) that can help designers figure out how many fans they need to provide cooling in space.

Credit: Paul Raftery, UC Berkeley

The tool loads with a blank set of inputs for describing: the room dimensions (e.g., ceiling height), the candidate fan types being considered by the designer, airspeed related constraints (e.g., the range of desired minimum airspeeds in the room), basic constraints (e.g., limit the range of acceptable blade heights), and advanced settings (e.g,. the acceptable minimum mount distance). Using the 'Add' button, users can add specific fan types that they are considering, and then select the newly added candidate(s) for consideration.

The 'Which solution to display?' table (top right) then shows the set of solutions that are considered viable given the selected inputs (e.g., size of room, selected candidate fan(s)) and constraints (e.g., range of acceptable minimum air speeds). A viable solution is defined as one in which the ceiling fan meets safety requirements, conforms with recommended guidance, and provides results that are within the constraints defined by the user.

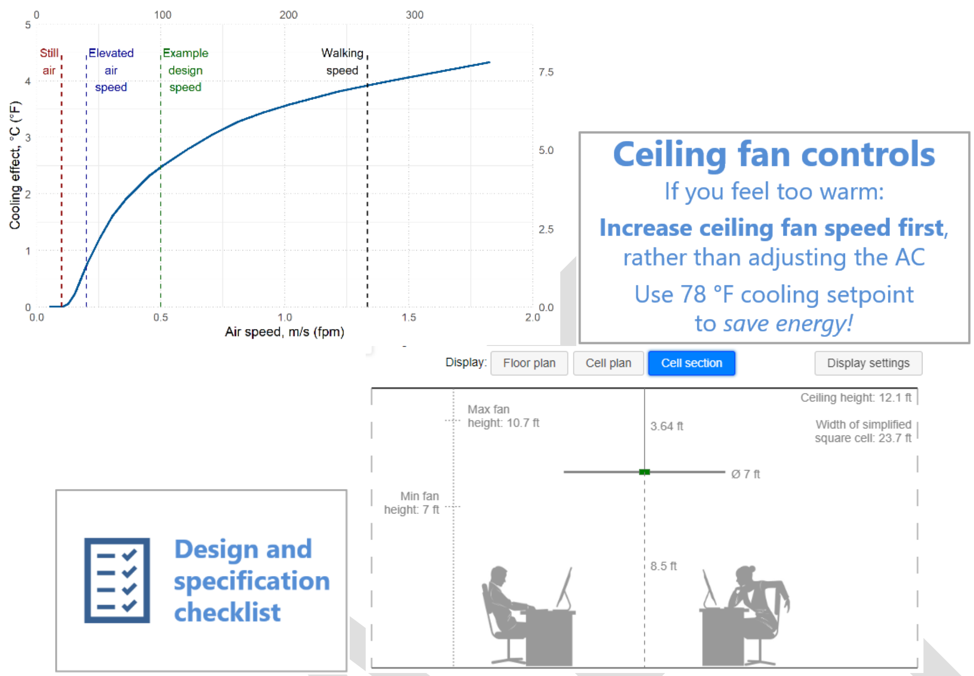
The tool's intent is to provide a relatively even coverage of air speeds across an entire room. With a single fan, the best way to achieve that is to place the fan at the center of the space. With multiple fans, the best way to achieve that is to locate adjacent fans at equal center-to-center spacing, with half that spacing between the fan center and any wall that is immediately adjacent to a fan. Thus, these are the solutions that the tool identifies. However, ceiling fans can be installed anywhere that meets manufacturer, safety and code related requirements for that fan and application; fans certainly do not need to be centered in a room, or to be laid out in a perfectly uniform grid. Ceiling fans can be located so as to better co-ordinate with aesthetic, lighting and/or structural requirements, or located to best reach the intended target: people (e.g., above seated areas). However, due to the limitations of the measurement dataset on which the models underlying this tool were built, the further the actual fan layout differs from that identified by the tool, the less accurate the airspeed estimates will be.

Design Guide

As part of this research project, the research team developed the CBE Ceiling Fan Design Guide, available at https://cbe.berkeley.edu/wp-content/uploads/2020/04/CBE-Ceiling-Fan-Design-Guide-V0.pdf. The guide enables architects, designers, and engineers to maximize the benefits of integrating ceiling fans into building systems. It introduces the advantages of using ceiling fans and how ceiling fans work, and provides guidance and resources for designing spaces with ceiling fans, and for specifying ceiling fan products. Content and information in the design guide includes the following:

- **Ceiling fans and thermal comfort** – details and resources to understand human thermoregulation and thermal comfort, and information on how ceiling fans can improve thermal comfort
- **About ceiling fans** – details on various ceiling fan types and how ceiling fans work
- **Fan selection, sizing, and layout** – guidance on how to evaluate different ceiling fan performance metrics, and recommendations on how to determine fan sizing, layout, and location within a space
- **Controls** – considerations and recommendations on how to implement ceiling fan controls, including guidance on user interface, automation, integration with other building systems, and airflow direction
- **Applications** – recommendations for design and performance criteria, controls, and other considerations for various application types
- **Design, specification, and installation checklist** – an additional reference to guide designers and specifiers through the process of designing, specifying, and installing ceiling fans on a building project
- **Additional resources** – details on other factors and considerations for designing with ceiling fans, including occupant interface and education, codes and standards, costs, modeling and simulation, project case studies, and further references and research

Figure 33: Highlights of the CBE Ceiling Fan Design Guide



Highlights of the design guide include thermal comfort benefits of ceiling fans, guidance for control and user interface strategies, a ceiling fan design and specification checklist, and an introduction to the CBE Ceiling Fan Design Tool

Source: CBE Ceiling Fan Design Guide

Codes and Standards Support

The research team has been supporting and researching a variety of issues related to building codes and standards. Appendix G summarizes those activities and findings.

Codes and Standards support activities include:

- Development of a new ASHRAE Standard 216 – Methods of Test for Determining Application Data of Overhead Circulator Fans
- Proposed Addendum C to ASHRAE Standard 55 defining Thermal Environmental Control Classification Levels for certain compliance options
- A description of barriers and opportunities for ceiling fans in the California Building Energy Efficiency Standards
- A discussion of building code considerations for ceiling fans, including a description of fire code requirements, and opportunities for additional clarification of the code requirements related to ceiling fans

Technology Readiness Report

The technology readiness report discusses both ceiling fans in general, and automated or “smart” ceiling fans more specifically, and can be found in Appendix I.

CHAPTER 5: Conclusions/Recommendations

The research team conducted laboratory tests, conducted field tests with 99 ceiling fans and 12 thermostats in four affordable multifamily housing sites in California's Central Valley, interviewed stakeholders to develop a case study, developed an online design tool and design guide, outlined codes and standards outreach, and published several papers.

The project demonstrated networked thermostats working in conjunction with highly efficient ceiling fans with onboard temperature and occupancy sensors for automatic operation in order to reduce energy consumption. The project team raised indoor temperature cooling setpoints and used ceiling fans as the first stage of cooling; this sequencing of ceiling fans and air conditioning can reduce energy consumption, especially during peak periods, while providing thermal comfort. The mean hourly indoor air temperature across all sites increased approximately 2 ˚C (3.4 ˚F). Overall, the field demonstration resulted in **39% measured compressor energy savings during the April–October cooling season** compared to baseline conditions, normalized for floor area. Energy savings during peak electrical demand periods, (4–9pm June–September), was 42%, suggesting that sequenced ceiling fans can provide a feasible demand response strategy.

Weather-normalized energy use varied from a 36% increase to 71% savings across all 13 compressors, with median savings of 15%. This variability reflects the diversity in buildings, mechanical systems, prior operation settings, space types, and occupants' schedules, preferences, and motivations. **All commercial spaces with regular occupancy schedules (and two of the irregularly-occupied commercial spaces and one of the homes) showed energy savings on an absolute basis** before normalizing for warmer intervention temperatures, **and 10 of 13 sites showed energy savings on a weather-normalized basis.** Of the three sites that did not realize energy savings on a weather-normalized basis, two of these sites were residences that opted not to increase air conditioner setpoint temperatures, and one was an infrequently-occupied commercial space where the baseline energy consumption was relatively low and air conditioning was not operated regularly.

Overall, the ceiling fans were frequently used at all sites, typically operated at low speeds, and used very little power. The mean power consumption of a ceiling fan when operating was 8 W; this is comparable to that of an LED lightbulb.

The ceiling fans provided cooling for one site for several months during hot weather when the HVAC equipment failed. The project team worked to help the facilities manager identify the problem and solution; the ceiling fans provided the only source of cooling for this period. Despite indoor temperatures reaching temperatures higher than design recommendations, the majority of the occupants were still comfortable, demonstrating that the ceiling fans can provide a measure of resilience during mechanical system failures.

Per the occupant interviews and surveys, all occupants reported high satisfaction with the ceiling fans. The presence of the fans increased the range of thermal comfort and acceptability across participants; the fans' presence in the space also seem to have a positive impact on air movement acceptability. All participants felt the fans provided adequate cooling, and improved indoor environmental quality; occupants were pleased with its ability to cool the space quickly and effectively. Even in sites where the measured energy data do not show savings, the occupants still used and interacted with the fans regularly. One office worker reported, "The ceiling fans have helped [me] by not having to worry about being too hot or too cold in the office. Because when you're too hot or too warm it's hard to concentrate. By having the fan. it helps me stay focused because I don't have to worry about the temperature."

The project team has outlined several lessons learned, especially regarding behavior change. In some sites the occupants were not responsible for paying energy costs, which impacted air conditioning setpoints and thus energy savings, though they reported improved comfort. Some believed that moving air drafts were not healthy, especially for a newborn child; this impacted the use of ceiling fans compared to air conditioning. One occupant inadvertently scheduled the blower fan on continuously, which increased the overall energy consumption. The occupants felt the Ecobee thermostats had a steep learning curve and were challenging to use at first. The lack of multiple language support in the thermostats was an issue for many of the occupants, particularly in the residences. The research team had extensive interaction with occupants, producing educational material to inform occupants about appropriate setpoints and blower fan operation, actively encouraged desired thermostat setpoint and fan use behaviors, and in some instances, changed the setpoints to energy-saving setpoints. Future work should explore feedback and incentives to encourage optimal behavior change.

The smart ceiling fan and smart thermostat did not directly integrate as expected; development of custom fan firmware was required to fully implement the automated fan operation as the research team envisioned.

The project demonstrated that the potential savings from sequencing air movement and air conditioning is greatest at sites that have more frequent and/or more intense air conditioning use. Although the measured results of the field demonstrations show substantial energy savings, there is a need for further development to achieve widespread adoption. The technologies could be further simplified, and usability could be further improved; some effort should be put forth in user education at time of installation, and/or in making the system more intuitive to use. The networked fans caused WiFi interference for a few residents.

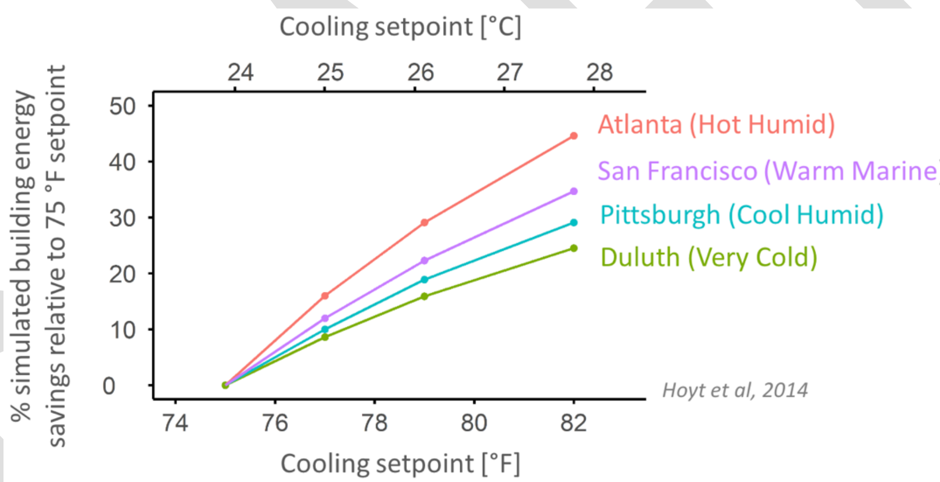
The laboratory studies performed during this project yielded new insights, such as developing a new method for designers to estimate the airspeeds achieved under a given set of fan and room conditions, airflows around furniture due to ceiling fans, and the design of distribution ductwork in coordination with ceiling fans. The online Design Tool, may be found at cbe.berkeley.edu/fan-tool and the Design Guide found at https://cbe.berkeley.edu/wp-content/uploads/2020/04/CBE-Ceiling-Fan-Design-Guide-V0.pdf. These can be used by designers, architects, and engineers to incorporate ceiling fans into design by providing ceiling fan spacing and other recommendations for optimal overall airflow across a space.

CHAPTER 6: Benefits to Ratepayers

This project studying the use of ceiling fans in conjunction with thermostats in low-income housing to reduce electricity consumption supports three of California's energy efficiency goals: doubling energy efficiency savings by 2030, removing and reducing barriers to energy efficiency in low-income and disadvantaged communities, and reducing greenhouse gas emissions from the building sector.

Regarding energy savings, simulations have shown that raising the cooling setpoint for air conditioning can save up to 35% in mild climates such as in San Francisco (Figure 32). Integrating ceiling fans with temperature setpoints enables this savings while providing comfort.

Figure 34: Simulated Building Energy Savings Relative to Cooling Setpoint



Savings in the mild San Francisco area ranges from 10–35% depending on the temperature setpoint; ceiling fans can maintain comfort while raising setpoints.

Credit: Dana Miller, Tyler Hoyt, UC Berkeley

Energy Savings: This project found an average of 39% compressor energy savings across sites in the hot Central Valley climate due to the use of raised HVAC temperatures and using ceiling fans to provide cooling.

Grid reliability: Energy used by the air conditioning compressors was reduced 42% during peak electricity demand periods, thus there are additional emissions and grid benefits other than the energy savings generated.

Safety: Ceiling fans can provide an additional low-power source of cooling, especially as a back-up in case of HVAC failure (which occurred in this project) or using a very small battery system to operate in case of power outage.

“Smart” (automated or temperature-based sequenced) ceiling fans in conjunction with communicating thermostats can provide greater energy security and reliability in the form of energy and cost savings, peak energy reduction, emission reductions, and a source of cooling (especially as a back-up) to IOU electricity ratepayers. Energy savings stem from allowing an increase to the space cooling setpoint and by turning off the fans when no occupancy is detected. Though ceiling fans are often considered a purely residential appliance, and are often categorized as a lighting product (including in the Energy Star program), ceiling fans can provide thermal comfort benefit in nearly any nonresidential application as well.

The project team estimated statewide energy, cost, and CO_2 emission reductions assuming a combined cooling energy savings of 30% from both the ceiling fans and thermostats, and a target installation in sites that have high cooling loads. The team estimates that a 15% market penetration of California buildings over the next 15 years will yield an annual reduction of 736 GWh, $125M, and 537M pounds of CO_2 emissions. This estimate includes multifamily (24 GWh, $4M and 18M pounds), single family (228 GWh, $39M, 166M pounds), and schools, offices, and retail spaces (484 GWh, $82M, 353M pounds). While this demonstration focuses on the multifamily sector, the technology is a scalable energy retrofit solution for a broad range of commercial and residential buildings throughout California. For commercial sites that are frequently occupied with high cooling related energy consumption, the technology can represent a cost-effective retrofit (less than 7-year payback) even at current market pricing and current utility rates. Targeting buildings and spaces with these characteristics will maximize energy savings potential. In other sites, including the residences, the cost of the equipment and installation currently exceeds the annual utility bill cooling energy costs, and will not prove to be a cost-effective solution considering energy savings alone. This study developed and documented best practices, leading to increased market penetration that will reduce the cost of adoption, cost of operation, and will increase payback. This will enable building owners to invest in the technology at lower risk. Additionally, installation costs will likely be substantially lower for new construction than for retrofit applications.

GLOSSARY

Term	Definition
Alliesthesia	The sensation of pleasant relief from a non-neutral (too-cold or too-hot) sensation to neutral
CP (Corrective Power)	Corrective Power is the quantification of the thermal comfort effect provided by Personal Comfort Systems
EPIC (Electric Program Investment Charge)	The Electric Program Investment Charge, created by the California Public Utilities Commission in December 2011, supports investments in clean energy technologies that benefit electricity ratepayers of Pacific Gas and Electric Company, Southern California Edison Company, and San Diego Gas & Electric Company.
HVAC	Heating Ventilation and Air-Conditioning system
IEQ	Indoor Environmental Quality
manikin	A full-size human-looking full body sensor used in thermal comfort testing.
Personal Comfort System	A device that provides heating or cooling to an individual independent of the central Heating and Cooling system
smart grid	Smart grid is the thoughtful integration of intelligent technologies and innovative services that produce a more efficient, sustainable, economic, and secure electrical supply for California communities.
Thermal comfort	Thermal comfort is defined as the condition of the mind that expresses satisfaction with the indoor environmental temperature.

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APPENDIX A:
Lab Report #1: Scale Configuration Optimization

EXECUTIVE SUMMARY

The EPIC fans project consists of four technical tasks: laboratory testing, multifamily common area site demonstrations, multifamily dwelling unit site demonstrations, and technology readiness. This lab report is the first of three, and discusses measurements in laboratory conditions that correspond to the expected conditions at the field sites.

The purpose of this report is to validate the work needed to develop an application method for fans, determine the optimum cost effective fan layout, and discuss the results of the scale configuration optimization laboratory test (configuration guidelines that scale from a single fan to multiple fans in the field). This lab report covers research conducted in the CBE chamber as well as in the BAS testing facilities in Kentucky. For the UC Berkeley tests, the first step was to identify the most appropriate thermostat(s) to use, then set up a single fan in the CBE chamber that integrates with the BAS Haiku fan (e.g., install thermostat and fan, check communication/data/function), evaluate the integration of thermostat with the fan, and conduct several tests to determine efficacy of air movement with the fan(s). For the BAS tests, the research team developed a testing plan and conducted a test of multiple fans at the BAS testing facility (e.g., test in three dimensions the optimal spacing of the fans). Thus the team developed and tested a full scale version of the proposed solution in a test facility that will be used as a mock up prototypical demonstration space with multiple fans.

The researchers evaluated both the Ecobee3 and the Nest thermostats and found either to be acceptable; these thermostats were then integrated with the BAS Haiku fan in the CBE chamber. The mobile phone app presents some communication, usability, and functionality challenges; the research team is communicating with BAS to achieve a workable solution.

The CBE chamber tests looked at six different configurations of furniture (rectangular table and partition) on air velocity contours. With the table, the air flow spreads further.

The tests in the BAS facility observed the effect of ceiling height on air speed and the effect of air speed from two fans compared to one fan. For the single fan test, the highest speeds are directly below the fan and then at low height; the lowest speeds are fairly uniform outside the fan diameter. At 7 ft and 10 ft heights, the flow is undisturbed 0.9 m from the fan center (point 4). For the 15 ft height case, the velocity increases, suggesting that flow had spread laterally. For the two fan test, the presence of the additional operating fan has a significant impact on the flow field. Two fans at similar speeds create an upward flow from collision of two floor bounded flows and has an inherent oscillatory nature, However, one can manipulate the speeds of both fans to intentionally adjust the location of this higher air speed region.

CHAPTER 1: Introduction

Background

Air movement can be used to extend the thermal comfort range in the built environment, as per ASHRAE 55 (ASHRAE, 2015; Arens et al, 2009). In buildings with mechanical cooling systems, increased air movement allows the mechanical cooling systems to operate fewer hours over the course of the year, resulting in energy savings (Fountain et al, 1993, Schiavon and Melikov, 2008). In buildings without mechanical cooling systems, providing air movement (e.g., through fans) increased the number of comfortable hours. In addition, Zhang et al. (2007) showed that many building occupants are dissatisfied with the amount of air movement in modern buildings.

The amount of cooling effect produced by air movement depends upon the speed of the air at the surface of the occupants' skin (Hoyt et al, 2015). Thus in order to use air movement effectively throughout a space, designers must have knowledge of the expected air speeds from the use of air movement devices such as ceiling fans.

Research shows that ceiling fans provide comfort at 5-8˚F higher temperatures than the conventional range during the cooling season. The use of ceiling fans thus represents potential savings in reducing air conditioning (AC) use, since fans (that can consume less than 10 watts) consume two orders of magnitude less energy than conventional AC (that consume thousands of watts). Achieving this energy savings requires the integration of ceiling fans with AC-control, such as thermostats. However, currently there are no design guidelines for developers, architects, and engineers; these guidelines could include the optimal placement in a room, best distance from the ceiling, appropriate width of a fan, or optimal spacing of fans, and guidance on how best to coordinate the fan(s) with the HVAC system to maximize comfort with energy savings. Laboratory research is needed to determine the expected "cool" zone given various configurations before the field testing can begin. Ultimately, the testing can ascertain the best way for low-cost smart ceiling fans integrated with smart thermostats to save energy while still providing comfort for disadvantaged households for whom energy costs constitute a large part of income.

Over the past decade, researchers from CBE and former CBE graduate Gwelen Paliaga have led the effort to understand the importance of increased air movement on thermal comfort, especially studying the effects of ceiling fans. Figure 3 below show some of the major milestones of this team: in 2006 Taylor Engineering designed an installation of ceiling fans using best guesses, in 2008-2009 the team helped develop a standard for moving air in comfort, in 2012 saw a full scale test and Building Management System integration with ceiling fans, and between 2014-2016 the team produced several developments: this CEC EPIC project, the development of an ASHRAE proposed standard (SPC 216P[8]) and Department of Energy rulemaking 81 FR 48620[9] on the testing of ceiling fans, and a recent study and white paper by the General Services Administration's Green Proving Ground on smart ceiling fans.[10]

Figure 35: Progress in developing guidelines for ceiling fans with respect to thermal comfort and energy savings (Source: Gwelen Paliaga).

Previous research has been conducted both experimentally and computationally to develop the air speed profiles that result from the use of a ceiling fan (Rohles et al, 1983). Jain et al. (2004) developed air speed profiles, qualitative descriptions, and visualizations for a ceiling fan operating in a closed room. Bassiouny and Korah (2011) developed an analytical and computational model to predict the airflow in an empty room from a ceiling fan operating at different speeds. Sonne and Parker (1998) experimentally measured air speed profiles in a closed room for four commercially available ceiling fan types. All of these studies examined the flow from a single ceiling fan operating in an empty room.

In the field, the rooms in which ceiling fans operate contain obstacles such as furniture and occupants. These obstacles have the potential to significantly affect the air speed profiles produced by the ceiling fans and therefore the thermal comfort occupants experience at

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[8] https://www.ashrae.org/standards-research--technology/standards--guidelines/titles-purposes-and-scopes#spc216p

[9] https://www.regulations.gov/document?D=EERE-2013-BT-TP-0050-0020
[10] https://www.gsa.gov/portal/content/149810

various locations in the room. Several studies have considered the effect of obstacles on air speed profiles from ceiling fans. Ho et al. (2009) conducted numerical CFD simulations to evaluate the 2D and 3D airflow and heat transfer profiles in a room. The room contained an air conditioner, a ceiling fan, and a person standing under the ceiling fan. However, the experimental variable was the speed of the fan and not the location of the person. Scheatzle et al. (1989), as part of determining where to place subjects for their thermal comfort experiment, took air speed profile measurements in a room with desks. However, these measurements are not quantitatively reported in their paper. While these studies did measure or model air speed profiles in rooms with obstacles, we did not locate any studies evaluating the effect the location of the obstacles has on the air speed profiles in the room.

The EPIC fans project consists of four technical tasks: laboratory testing, multifamily common area site demonstrations, multifamily dwelling unit site demonstrations, and technology readiness (Figure 2). This lab report is the first of three, and discusses measurements in laboratory conditions that correspond to the expected conditions at the field sites.

Laboratory testing will help determine the velocity and temperature profiles of various fan configurations, which will aid in evaluating thermal comfort. The objective of the CBE lab study is to experimentally measure and compare air speed profiles with obstacles placed in different locations in the airflow path of a ceiling fan. Specifically, researchers place a table and partition in different locations within a test chamber and evaluate the resulting variations in the air speed profile. This study will be performed at UC Berkeley in CBE's climate controlled environment chamber[11] with one ceiling fan and a single table and partition. The objective of the BAS lab study is conduct pilot measurements in BAS lab with one and two fans to explore the changes of air speed field in the occupied zone as a function of fan blade to floor height and interaction of flows generated by two ceiling mounted fans as a function of the fan speed. This study will take place at BAS facilities in Kentucky with multiple ceiling fans in different configurations (spacing, height).

[11] http://www.cbe.berkeley.edu/aboutus/facilities.htm

CHAPTER 2:
Thermostat-fan integration

One goal of the CBE chamber laboratory testing is to connect a smart thermostat with the Haiku fan and test the communication and controls of the thermostat-fan integration.

BAS is a partner in the project, donating many of their Haiku fans with the SenseMe technology for the CBE chamber testing and field demonstrations. Since the EPIC grant proposal was written, BAS has announced a partnership and compatibility with the Ecobee3 smart thermostat in addition to that previously established with the Nest thermostat. The research team decided to evaluate both thermostats with respect to functionality required of the project including usability.

Thermostat Evaluation

Similarly priced at $250, the Ecobee3 and Nest (3rd generation) both have the ability to use occupancy sensing to augment the programmed schedules. Nest uses motion-based occupancy sensors (near-field and far-field passive infrared sensors built into the single thermostat unit) and can learn occupancy patterns over time. Nest has an Eco function (formerly known as Auto-Away) that widens the heating and cooling temperature range (settable EcoTemperatures[12]) when it senses no one at home, either through the onboard sensors or smart phone proximity. Ecobee has motion sensing onboard the main unit but also can communicate via WiFi with multiple satellite sensors spread throughout a home, prioritizing different sensors at different times (Sensor Participation) or when motion detected (FollowMe function). Ecobee3 has a Smart Home/Away function that trims the heating/cooling 1-4 ˚F when the sensors do not detect activity (after two hours).

[12] Eco Temperatures can also be used to save energy when someone is home.

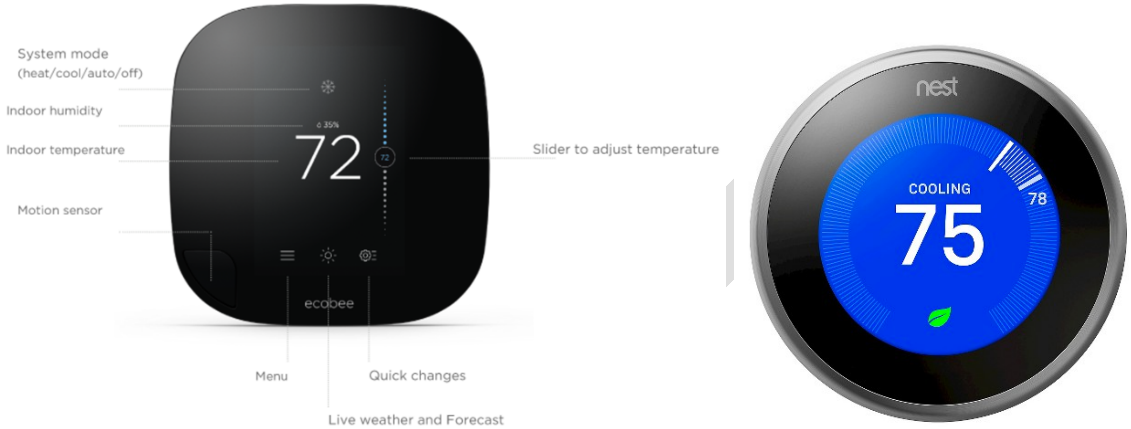


Figure 36: Ecobee 3 thermostat and Nest (3rd generation) thermostat.

Both thermostats have adaptive recovery to learn the home's thermal dynamics and HVAC equipment. Nest uses a thermal model[13] to calculate the amount of time until the target temperature is reached, and requires no input from the user to save energy. Ecobee3 has DataRhythm technology that uses weather, schedule and the house's equipment/thermodynamics to turn on the equipment (it is not clear if Ecobee3 learns using occupant interaction with the thermostat as Nest does).

There are reports of Ecobee3 being simpler and more intuitive to program and, when used with multiple sensors, more accurate in sensing occupancy. Ecobee3 also has more detailed energy use reporting. However, Nest has been around longer, has a sleeker aesthetic appeal and can react with more nuance over time to changes in occupancy that are not reflected in its programmed schedule. The research team considers both to be solid options for this study, but ultimately converged on the Nest.

Connection with Haiku fan

The BAS Haiku fan is a low power three-blade (or air foil) ceiling fan with SenseMe technology. This embedded and networked device has motion sensing (for automatic control when people enter or leave the space), Whoosh mode (varies fan speed to emulate natural breezes), Sleep mode (adjust fan speed during sleeping hours), Smarter cooling (saves energy by adjusting the thermostat a few degrees higher during warm weather), Schedule, and Smarter heating (gently pushing down the hot air at the ceiling or destratifying the air). Haiku has a mobile phone application to enable remote control and house the smart functionality.

The research team installed the Haiku fan, thermostat, and a WiFi wireless access point in the CBE chamber. Similar to other devices the fan creates its own Ad Hoc network by broadcasting its own WiFi Hotspot signal for purposes of setting the connection. One should be able to "see"

[13] https://nest.com/downloads/press/documents/thermal-model-hvac-white-paper.pdf

the fan's network, and then connect one's computer or mobile device to the fan; the thermostat (Nest) connects in a similar fashion to the same network. However, using an Android smart phone, the initial fan setup failed without an error message. The research team went through the fan setup process to connect to the WiFi. The Android mobile app reported a successful connection, but then did not show the fan in the app. The iPhone app, the user was able to connect with the network that the fan was connected to, and successfully show the fan; however, the instructions described how to set up the fan the first time, not to a fan already connected to a network.

The SenseMe phone app works for multiple fans, distinguishing them by a unique name (e.g., Living room fan); the remote control controls whichever fan it is pointed toward or is closest to. The Haiku wall control turns off the power for the fan, but with a $150 upgrade, one can add a controller that allows wall control as well as remote and app control.

Multiple fans may be grouped to allow a share the same control; it is unclear whether this grouping affects the thermostat zone.

In evaluating the smart phone app, the researchers discovered several other issues with the Android app:

- The app signs one out periodically.
- Sometimes the app does not show fans on the network
- Significant lag times occur in several cases, such as updating current status of fan (fan state and speed, ideal temperature, etc.) and functionality with Smart Thermostat

With respect to communicating with the thermostat, the fan does not see or recognize the thermostat's temperature setpoints. In addition, if the thermostat's last active state was heating mode, then the fan will only switch into 'Smarter cooling' mode once the thermostat switches into cooling mode. This prevents the research team from using the fan to provide comfort at higher cooling setpoints, as the fan will not activate until that higher setpoint has been reached.

Overall, it is unclear what the priorities are for the various smart features. For example, if one sets both Motion and Smart Cooling on, does Motion take precedence over Smart Cooling? What about if you set a schedule—does this take priority over Motion? The phone app asks one to select an Ideal Temperature, but it is unclear how this affects the controls of the fan and AC. There is not a secure authorization/authentication process to grant permission for who can control the fans or to lock out certain features for some users.

For multiple users in multifamily common areas, a potential problem is that each user's smart phone would have to download the app and connect to the same WiFi network as the fan in order to communicate with and control it. One solution is to have someone set up the fan and thermostat with a smart phone, then have remote controls cabled to the walls or other permanent surfaces.

The research team has many more questions and will continue to investigate the applications on both Android and iPhone platforms, in conjunction with the Nest thermostat. The team has spoken to BAS about issues with the app, and BAS is interested in fixing the issues and working to develop a more usable solution.

CHAPTER 3: Testing in the CBE chamber

This chapter describes the testing and results in the controlled environment chamber in Wurster Hall at UC Berkeley. The objective of the testing is to understand how different configurations of furniture affect velocity contours (measured in vertical and horizontal planes). For more details, please see Gao et al, 2017 at https://escholarship.org/uc/item/3pq2j9mh.

Test facilities

A test room (LxWxH, 5.5x5.5x2.5 m (18x18x8 ft)) was set up to represent a realistic office environment and a standard space for measuring airflow from ceiling fans. This room is the climatic controlled chamber at CBE at UC Berkeley. A BAS Haiku ceiling fan was installed in the ceiling of the chamber for testing.

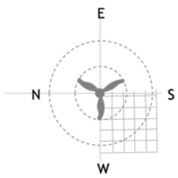
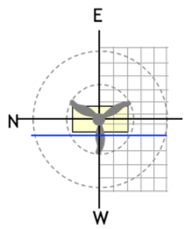
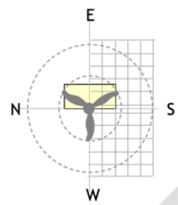
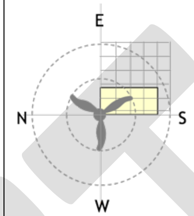
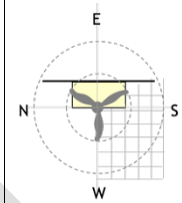
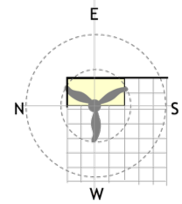
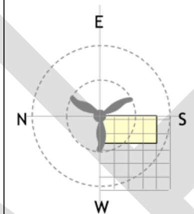
Five velocity sensors are installed in a measurement “tree”, a structure hosting the five sensors (Figure 5). The sensors are located at 0.1, 0.6, 0.75, 1.1, and 1.7m. The 0.75m represents table height, and the remaining four heights are defined by ASHRAE Standard 55 on thermal comfort as standard heights to measure temperature and air speed for seated and standing people.

Figure 37: The ceiling fan in the chamber, and the velocity sensors

Test configurations

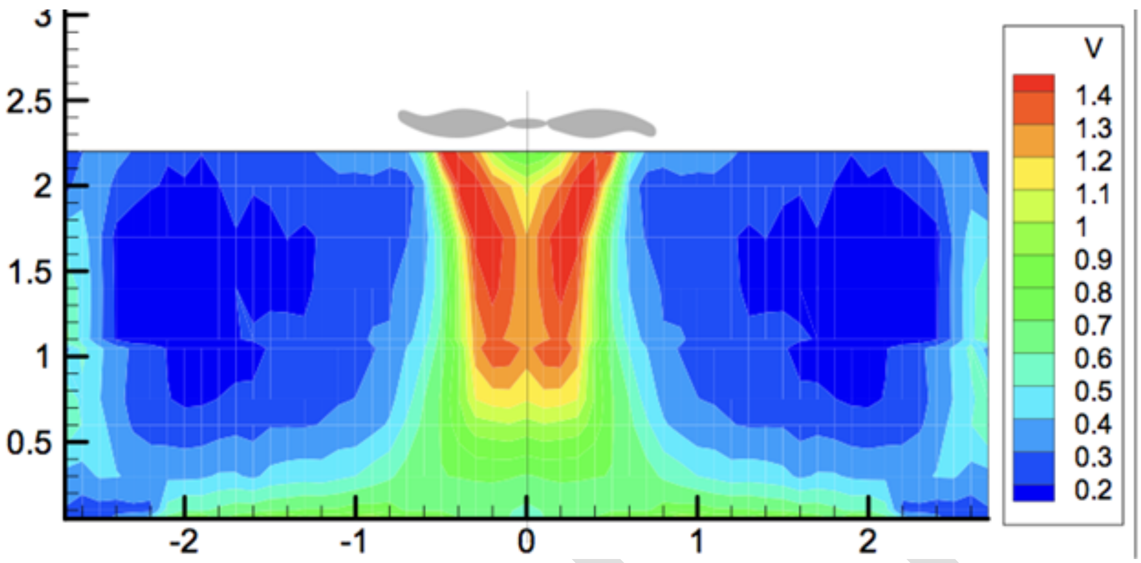
The tests were conducted under six configurations (six cases, reflected ceiling plans shown in Table 1). In all cases the fan direction is clockwise as seen in the plan. Case 1 is the configuration without furniture. Case 2 – 4 represent configurations for various table and ceiling fan locations; the table is represented by the small rectangle (yellow). Case 2 represents a condition when the table is directly underneath the ceiling fan: the center of the table is directly below the center of the fan. Case 3 is when the edge of the table is directly below the center of the fan. Case 4 is when the corner of the table is directly below the center of the fan. During the tests, the researchers found that there is a swirling air flow pattern along the fan rotating direction at the horizontal plane. Since the swirling air flow might have a different impact when the air hits the longer or shorter dimension of the table, the researchers tested two configurations: when the air hits the shorter dimension of the table (top figure for Case 4) and when the air hits the longer side of the table (bottom figure for Case 4). Case 5 and case 6 are two configurations with partitions (as represented by the black lines), one with a linear partition (Case 5), and one with a L-shape partition (Case 6). The orientation for the chamber is also shown (N means north, S - south, E - east and W – west). The dashed grids in the table represent the measurement points.

Table 2: Reflected ceiling plans showing the six experimental configuration cases for the chamber.

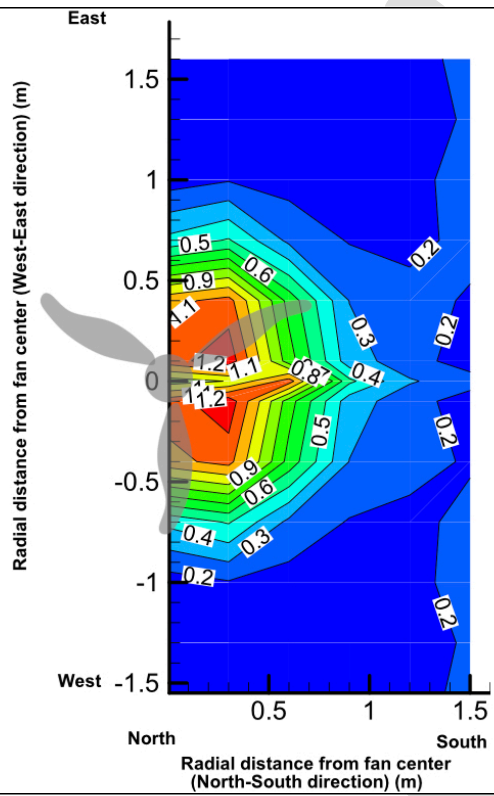
Case 1: No furniture	Case 2: Table under fan	Case3: Table besides fan	Case 4: Table at corner	Case 5: Table with linear partition	Case6: Table with L shape partition
					
					

Preliminary results

Figures 6 – 8 below show how the table and partition interact with the air flow from the ceiling fan. The figures are represented as vertical sections through the velocity contours at the fan center, and the horizontal direction at the table height, 0.75m.



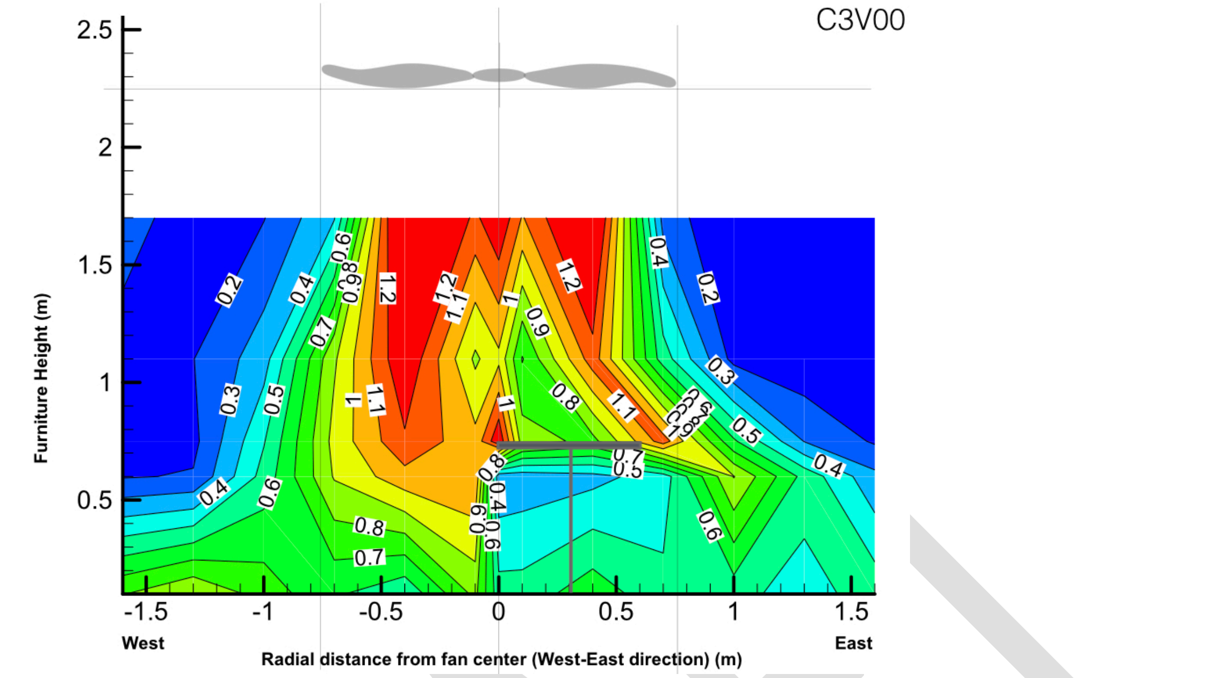
a. Vertical section showing velocity contours at the fan center (X, Y, distance, m)



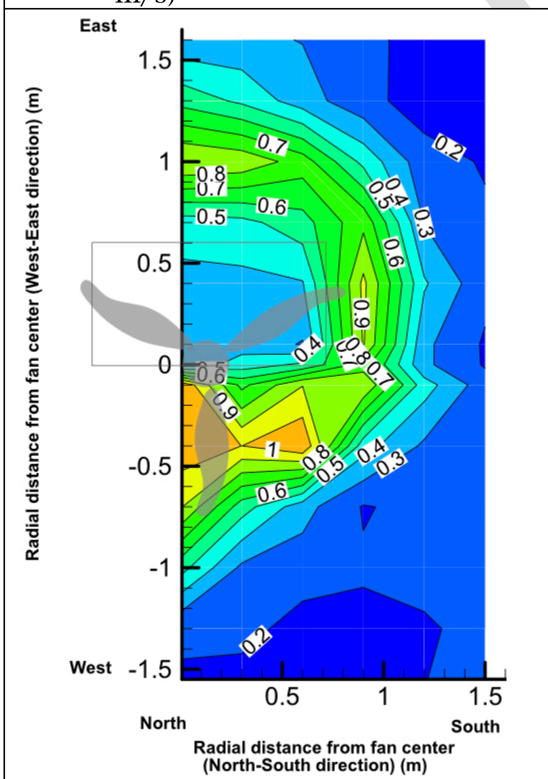
b. Horizontal contours at 0.75m height (values in the chart: velocity, m/s)

Figure 38: Velocity profile contours for Case 1 – without furniture

Without furniture, the air profile from the ceiling fan does not spread much (Figure 6). Whenever the air flow hits a table, the table would push the air flow spread along the table (Figure 7).



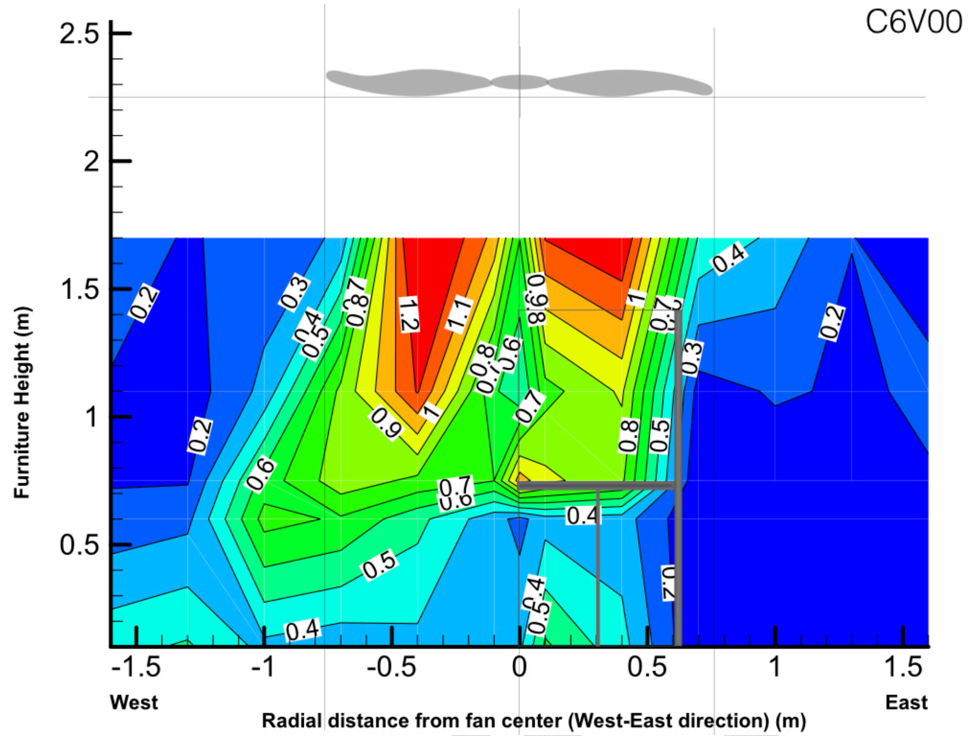
a. Vertical section of velocity contours at the fan center (values in the chart: velocity, m/s)



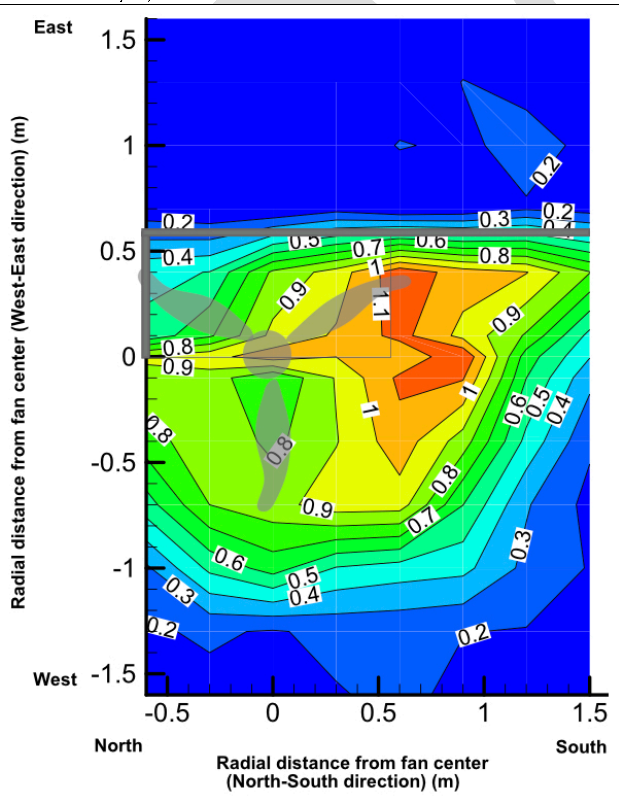
b. Horizontal contours at 0.75m height (values in the chart: velocity, m/s)

Figure 39: Velocity profile contours for Case 3 – table at the east side

Partitions push the air out further into the workstation further (Figure 7).



a. Vertical section of velocity contours at the fan center (values in the chart: velocity, m/s)



b. Horizontal contours at 0.75m height (values in the chart: velocity, m/s)

Figure 40: Velocity profile contour for Case 6 – table + L-shape partition

Thus furniture such as a table or partitions affects the velocity contours of the fan. The table acts to disperse and throw the air more widely than the condition without the table. The partition tends to block or contain air movement.

CHAPTER 4:
Test Method: BAS facility

In March 2017, the researchers performed a two week test at the BAS facilities in Kentucky. BAS's test facility in Lexington, Kentucky is a 200 foot by 200 foot by 60 foot open test space that is dividable into 100 foot by 100 foot quadrants. Each quadrant has moveable walls and ceiling for full-scale room mockups. Instrumentation includes a suite of high quality sensors for measuring airflow, temperature and energy use.

Testing plan

CBE and BAS researchers conducted the experiments from March 28th until March 31st, each conducted with the 52" Haiku fan.

The objective of the visit to the BAS laboratory was to:

- Conduct pilot measurements in BAS lab with one and two fans and get familiar with the measurement process in their facility.
- Find out possible limitations of the lab size.
- Determine how long each measurement should take, and how long it takes to vary experimental setup parameters such as room size, fan height, and number of fans..
- Determine the realistic number of experiments that researchers can plan to conduct in the BAS facility given the co-funding commitment from the BAS
- Mock up a laboratory configuration that is of similar dimensions to a field study site to ensure that there is a reasonable air speed distribution in the space, particularly for the multiple fan cases.

The objective of the experiments was to investigate:

- Methodologies that can be applied in the BAS facilities that reveal various aspects of the flow field (e.g., speed measurement with omnidirectional probes, airflow pattern smoke visualization).
- Changes of air speed field in the occupied zone as a function of fan blade to floor height (Figure 9)
- Interaction of flows generated by two ceiling mounted fans as a function of the fan speed (Figure 10)

Experimental Design

Each experiment used the 52 inch BAS Haiku ceiling fan.

The measurements conducted in the CBE environmental chamber were for a fixed floor-to-fan-blade height (approximately 7 feet). The results show that with no furniture or impingement, the flow field does not affect the region outside the cylindrical volume below the fan blades. Thus, the researchers designed the first set of experiments at the BAS facility to evaluate the impact of the fan height (floor to fan blade) on the velocity field generated in the room. The researchers mounted the fan in the center of the 20 ft x 20 ft square chamber. The chamber has an electronically moveable roof that increased the height from 7 ft to 10 ft and to 15 ft. The main objective was to determine lateral spread of the flow field generated by the fan at three different heights. Designers and installers often mount a fan at heights above 7 ft in practice, and fan height might have important impact on the amount of space that has significantly altered air speed due to the presence of the fan.

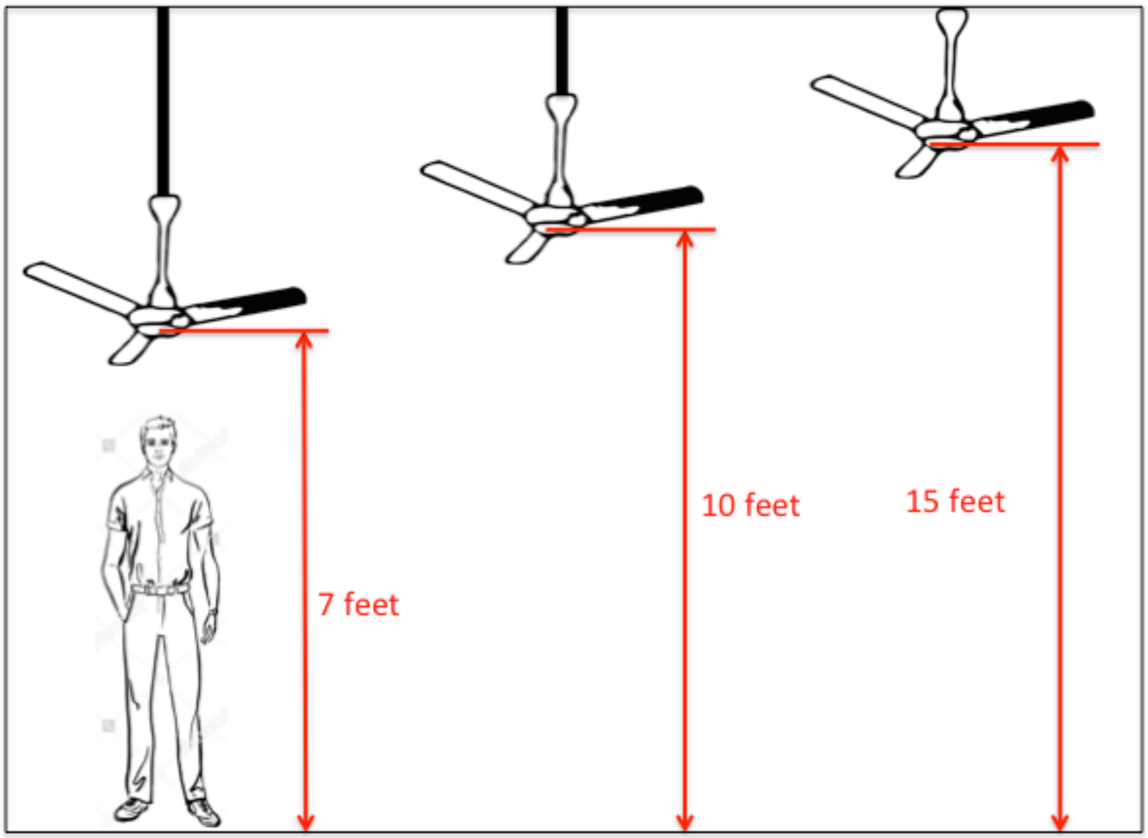


Figure 41: The floor to fan blade height variation.

Multiple fans within a space are also a common occurrence in practice. Very little is known about this flow interaction, and protocols for flow field evaluations are not available. The researchers explored how the airflow field changes when two fans are used instead of one. Researchers designed experiments to characterize the region of interaction between two flow fields with floor impingement. This flow interaction also depends on the fan speed. The researchers expect that this interaction will generate upward flow, and would like to visualize that flow and measure its magnitude. The upward flow velocity magnitude might have an effect on comfort, hence it is important to properly quantify this.

Since the 20 ft x 20 ft square chamber floor area was the available size, the researchers fixed the distance between the fans to 10 ft between the fan centers. The researchers positioned both fans along the centerline of the chamber, 5 ft from the fan center from the closest wall (Figure 10).

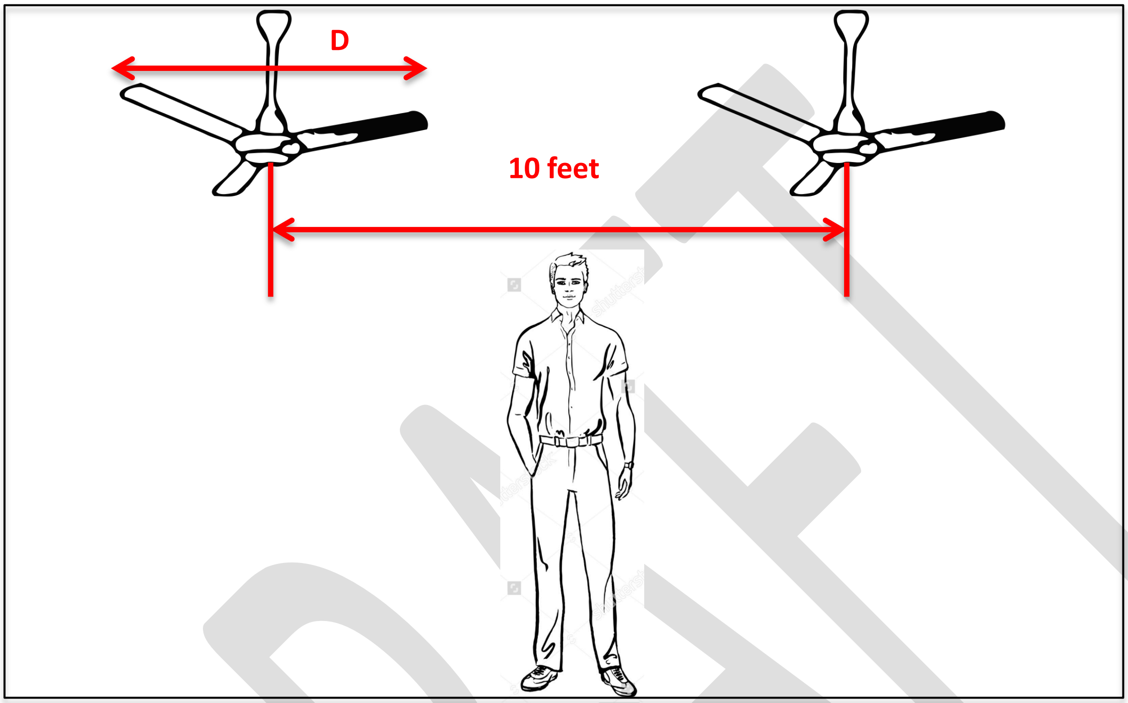


Figure 42: Interaction of two ceiling fans.

Measurement equipment and method

The researchers measured air speed using omnidirectional probes in a 30 cm x 30 cm grid (Figure 11 and Figure 12). The measurement grid consisted of 36 points distributed in a square. A vertical measurement tree was used for each of the points. The researchers mounted the omnidirectional probes at 0.1 m, 0.3 m, 0.45 m, 0.6 m, 0.75 m, 1.1 m and 1.7 m from the floor. .

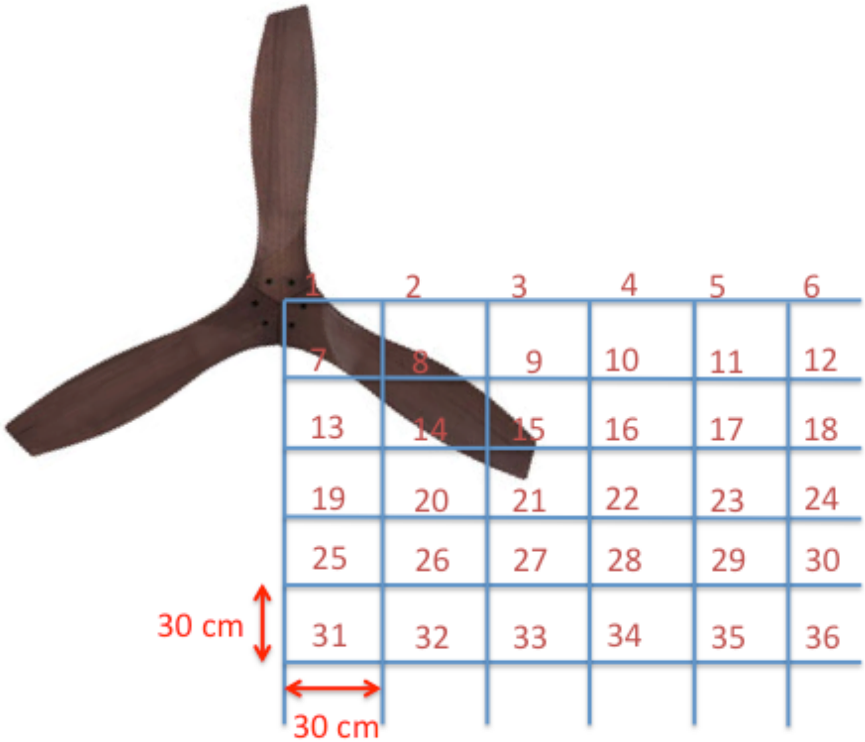


Figure 43: Measurement grid for a single fan case

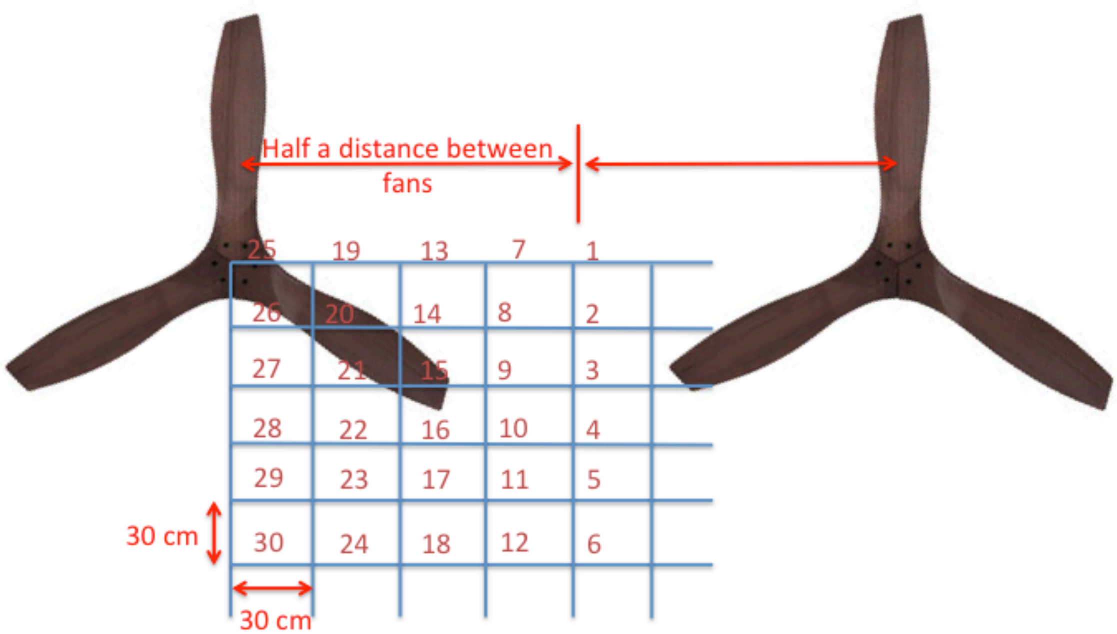


Figure 44: Measurement grid for a two fans case

Single fan assessment

- Fan heights of 7 ft, 10 ft and 15 ft
- Measurement grid depicted in Figure 11 with measurement trees
- Operated the fans at speed setting 4 (of 6).

Two fan assessment

- Two fans were 10 ft apart at 7 ft height in the 20 ft x 20 ft room
- Measurement grid depicted in Figure 12 with measurement trees
- Operated the fans at speed 2 and speed 4.

Results

Single fan assessment

For the single fan assessment, the following graph shows the impact of the fan blade height. Figure 13 shows the distribution of speeds measured at three places in the horizontal and vertical dimensions: directly below a fan (point 1 in the measurement grid), 0.9 m from the fan center just outside the blade diameter (point 4) and slightly outside the blade diameter, 1.2 m from the fan center (point 5) for 7 ft, 10 ft and 15 ft mounting heights. The highest speeds (far right of graph) are directly below the fan and then at low height; the lowest speeds are fairly uniform outside the fan diameter.

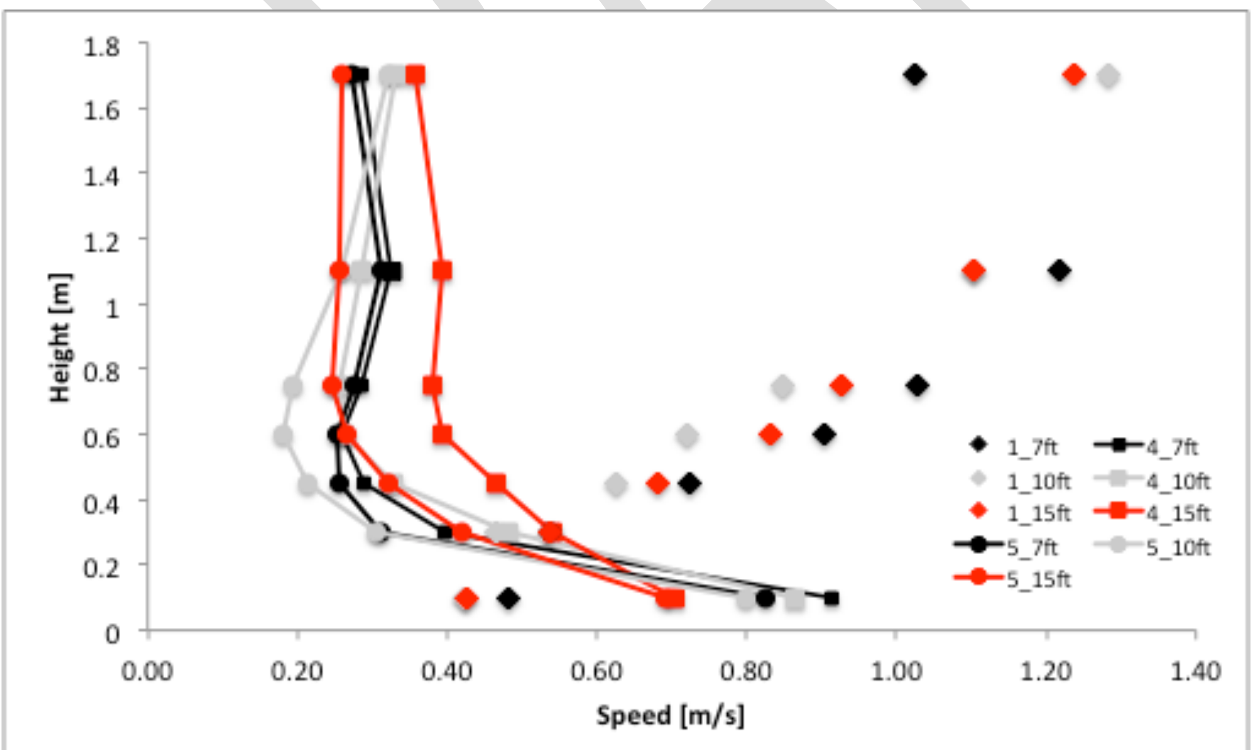


Figure 45: Distribution of speeds measured for a single fan.

In the BAS lab, the researchers measured at heights of 7 feet, 10 feet and 15 feet. The results show that acceleration of the flow beyond the blade diameter was minimal. The results presented in Figure 13 show that for all three heights examined in this study,the floor boundary layer flow field is undisturbed by the fan at a distance of 1.2 m from the center of the fan (point 5). At 7 ft and 10 ft heights, the flow is undisturbed 0.9 m from the fan center (point 4). For the 15 ft height case, the velocity increases, suggesting that flow had spread laterally. This is aligned with the jet flow theory (Rajaratnam, 1976) that states that the developed flow region will be reached at the distance of 5.2 orifice diameter from the orifice.

The researchers also observed that with the increase of the fan blade height, the thickness of the boundary layer on the floor increased. For the 7 ft and 10 ft height case, the air speed at 0.1m from the floor is 0.86 m/s and 0.91 m/s respectively. For the 7 ft and 10 ft height cases, this air speed reduces to 0.41 m/s and 0.48 m/s respectively at a height of 0.3 m from the floor. These results suggest that floor boundary layer thickness was between 0.1 m and 0.3 m. For the 15 ft height case, researchers measured air speeds of 0.48 m/s, 0.54 m/s and 0.69 m/s at 0.45 m, 0.3 and 0.1 m from the floor respectively, suggesting much thicker boundary of up to 0.45 m, with lower air speeds than the cases in which the fan was mounted closer to the floor

Close to the floor the researchers were not able to determine the direction of the flow using omnidirectional probes. This is a major shortcoming in describing the flow field, but not for the velocity magnitude. The flow field description requires hot wire anemometers to determine velocity direction at 0.1 m, 0.3 m and 0.45 m from the floor.

Two fan assessment

For the assessment of two-fans in the space, researchers detected changes in the flow field due to the flow interaction. In Figure 14 below, the 1_2-fan represent air speed in point 1 (1.2 m from the fan center, in Figure 12) when two fans were running. The 1_1-fan represents air speed in point 1 in Figure 12 when one fan was on while the second one was off. Point 25 is below the working fan and location of the point 6 is in Figure 12 (furthest diagonal away from fan center).

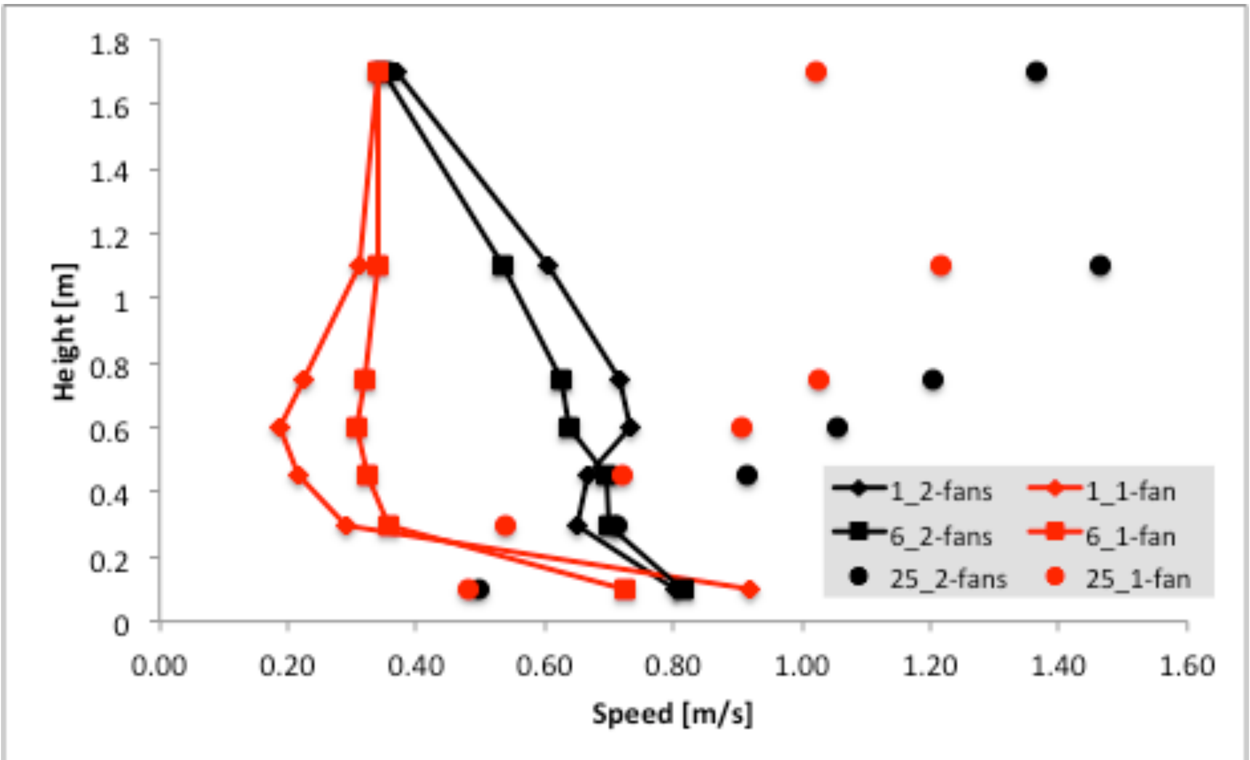


Figure 46: Comparison of the velocity fields for the two fan configuration when one fan and both fans were active.

In the 20 ft x 20 ft room, the maximum fan separation distance was 10 feet. Interaction created by the presence of the airflow fields was substantial. In between the two fans, as observed in point 1 and point 6 (Figure 14), upward flow was generated at heights between 0.3 m to 1.1 m, at half of the distance between fans. Measured speeds in the region between fans were 0.55 m/s to 0.75 m/s. At the same locations when only one fan was running air speeds were 0.19 m/s to 0.35 m/s. This suggests that air speeds were doubled in the region in between two fans. Air speed at 1.7 m was not strongly affected by the presence of additional fan (Figure 15).

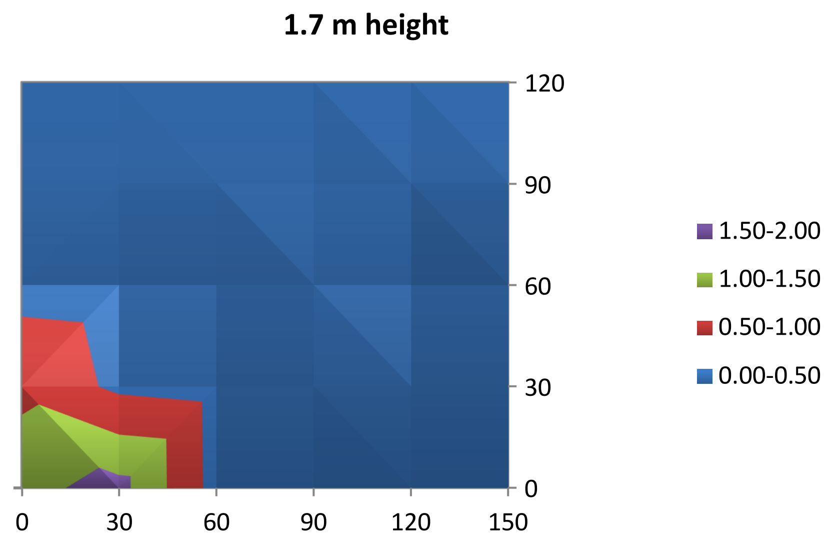
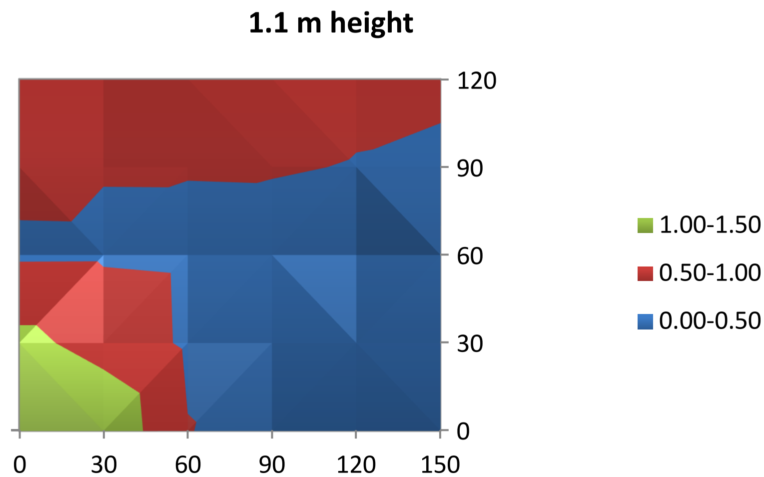


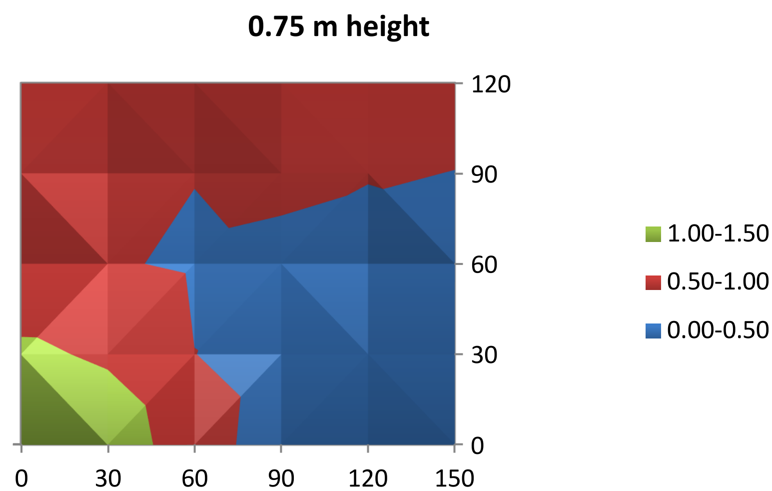
Figure 47: Air speed contour in plan view at 1.7 m height for two fans. Coordinate (0, 0) is the middle point of the fan and corresponds to the point 25 in the Figure 12. 150 refers to the 150 mm in the x direction and 120 refers to the 120 mm in the y direction.

Figures 16a-c show that upward flow was generated in the area with a half thickness of approximately 0.3 m, from 120 to 90 mm region with speeds between 0.5 m/s and 1 m/s. This upward flow originates from collision of two floor bounded flows and has an inherent oscillatory nature, hence half thickness of 0.3 m or full thickness of 0.6 m should be considered only as a time averaged value. The oscillatory nature can be observed when comparing Figure 16a and Figure 16b. The region with the air speed range of 0.5 m/s to 1 m/s can reach thickness up to 0.6 m closer to the fan center.

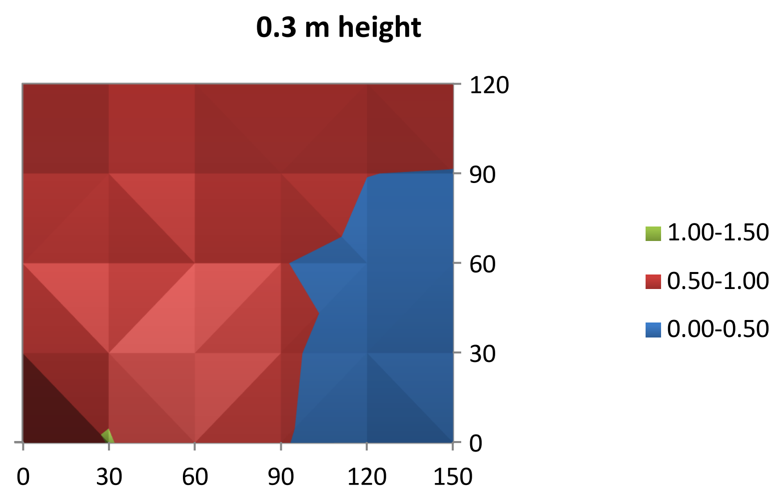
a)



b)



c)



Figures 48a, 16b, 16c: Air speed contours in plan view. Coordinate (0, 0) is the middle point of the fan and corresponds to the point 25 in Figure 12. 150 refer to the 150 mm in the x direction and 120 refer to the 120 mm in the y direction. Figure 16a represents 1.1 m, Figure 16b represents 0.75 m, and Figure 16c represents 0.3 m.

When the researchers compared air speeds below a fan for the two-fan and one-fan cases, they observed that the presence of the additional operating fan has a significant impact on the flow field. This can be attributed to the increase of the overall air momentum in the space and much stronger 'pushing' effect due to collision of floor boundary layer flow and 'pull' effect due to the suction side of the ceiling fan.

Collision of the two floor boundary layers created by each fan generated upward flow in between two fans. Fans were operated with identical speeds and the flow was symmetrical. Manipulation of the fan speed of one of the fans could modify the position and intensity of the upward flow. When one fan operates at a lower speed, it will have a weaker boundary layer, hence the upward flow will be closer to the weaker flow and will have lower intensity. This fan speed manipulation can potentially be used as a mechanism to intentionally adjust the location of this higher air speed region.

Measurement of the air speed conducted in the CBE chamber showed that three minute measurement with 0.5 Hz frequency will be sufficient. Each measurement at BAS took three minutes and three minutes was necessary between the measurements to change the measurement location and reestablish steady state after disturbing the experimental chamber conditions. Thus, overall it took 6 minutes to measure each point. Thus, it will require 216 minutes to measure a 36-point grid. During the experiment we used two sets of probes, hence measurement was taken with one and then the second set. This doubled the time necessary to complete experiments. In order to double measurement efficiency we should have one set of six probes (or however many points we wish to measure vertically) that can do simultaneous measurements. CBE currently has a set of four omnidirectional probes, and so would require two additional omnidirectional probes if the number of vertical measurement points does not increase. Changing between various setups (e.g., increasing the roof height, adding second fan) typically requires about two hours.

CHAPTER 5: Conclusion and Next Steps

The goals of the laboratory testing are to finalize the configuration, controls and measurement protocols of the Fan-thermostat System in order to inform the installation at the demonstration sites. This first lab report endeavored to validate work needed to develop an application method for fans, determine the optimum cost-effective fan layout, and discuss the results of the scale configuration optimization laboratory test. The research team conducted tests in the CBE chamber at UC Berkeley and at the BAS test facility in Kentucky.

The researchers evaluated both the Ecobee3 and the Nest thermostats and found either to be acceptable; these thermostats were then integrated with the BAS Haiku fan in the CBE chamber. The mobile phone app presents some communication, usability, and functionality challenges; the research team is communicating with BAS to achieve a workable solution.

The CBE chamber tests looked at six different configurations of furniture (rectangular table and partition) on air velocity contours. With the table, the air flow spreads further.

The tests in the BAS facility observed the effect of ceiling height on air speed and the effect of air speed from two fans compared to one fan. For the single fan test, the highest speeds are directly below the fan and then at low height; the lowest speeds are fairly uniform outside the fan diameter. At 7 ft and 10 ft heights, the flow is undisturbed 0.9 m from the fan center (point 4). For the 15 ft height case, the velocity increases, suggesting that flow had spread laterally. For the two fan test, the presence of the additional operating fan has a significant impact on the flow field. Two fans at similar speeds create an upward flow from collision of two floor bounded flows and has an inherent oscillatory nature, However, one can manipulate the speeds of both fans to intentionally adjust the location of this higher air speed region.

In general the next steps are to conduct more lab testing to develop a dimensionless approach for estimating airspeed spatially within a room with a single fan. The next lab tests at BAS will incorporate furniture.

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APPENDIX B:
Lab Report #2 and
ASHRAE 216 Design Tool Report

EXECUTIVE SUMMARY

The purpose of this report is to examine the interactions of airflows due to multiple fan applications, help develop the Design Tool and guidance for sizing and spacing fans, and predict the air speeds in typical furnished spaces. The goal of the Design Tool is to specify and locate a fan or fans to achieve a desirable air distribution within a space. This work is based on laboratory testing of variation in ceiling-fan-driven air movements in terms of room size, fan mounting height, furniture, partitions and other influencing factors; part of this work was described in Lab Report #1 and part described in this report.

The research team measured air speeds in rooms due to ceiling fans in 78 full-scale laboratory tests. The factors were the room size, fan diameter, type, speed, up/down direction, blade height, and mount distance (i.e. blade to ceiling height). The team demonstrated the influence of these factors, showing that the most significant are speed, diameter and direction. With other factors fixed, the area-weighted average room air speed increases proportionally with fan air speed and diameter. Blowing fans upwards yields lower but far more uniform air speeds than downwards. For the same diameter and rated airflow, fan type has little effect on the air speed distribution in the region outside the fan blades. The team developed several new dimensionless representations and demonstrate that they are appropriate for comparisons over a wide range of fan and room characteristics.

Dimensionless linear models predict the lowest, area-weighted average, and highest air speeds in a room with a median (and 90th percentile) absolute error of 0.03 (0.08), 0.05 (0.13), and 0.12 (0.26) m/s respectively over all 56 downwards tests representing typical applications. These models allow the team to answer the question 'What air speed distribution can I expect for a given fan and room?'.

CHAPTER 1: Introduction

The EPIC fans project consists of four technical tasks: laboratory testing, multifamily common area site demonstrations, multifamily dwelling unit site demonstrations, and technology readiness (Figure 2). This lab report is the second of three, and discusses measurements in laboratory conditions that correspond to the expected conditions at the field sites.

The purpose of this report is to examine the interactions of airflows due to multiple fan applications, help develop the Design Tool and guidance for sizing and spacing fans, and predict the air speeds in typical furnished spaces. The goal of the Design Tool is to specify and locate a fan or fans to achieve a desirable air distribution within a space. This work is based on laboratory testing of variation in ceiling-fan-driven air movements in terms of room size, fan mounting height, furniture, partitions and other influencing factors; part of this work was described in Lab Report #1 and part described in this report.

Lab Report #1 described laboratory testing to determine the velocity and temperature profiles of various fan configurations, which will aid in evaluating thermal comfort. The objective of the first lab study was to experimentally measure and compare air speed profiles with obstacles placed in different locations in the airflow path of a ceiling fan. Specifically, researchers place a table and partition in different locations within a test chamber and evaluate the resulting variations in the air speed profile. This study was performed at UC Berkeley in CBE's climate controlled environment chamber[14] with one ceiling fan and a single table and partition. The objective of the BAF lab study was to conduct pilot measurements in BAF lab with one and two fans to explore the changes of air speed field in the occupied zone as a function of fan blade to floor height and interaction of flows generated by two ceiling mounted fans as a function of the fan speed. This study took place at BAF facilities in Kentucky with multiple ceiling fans in different configurations (spacing, height).

[14] http://www.cbe.berkeley.edu/aboutus/facilities.htm

CHAPTER 2: Lab testing

Background on need for testing

Having the ability to increase the air speed in a room in a controlled manner provides many advantages. It increases the heat transfer from occupants to the environment by convection and evaporation, allowing them to remain comfortable in warmer conditions (Tanabi et al, 1993, Tanabi and Kimura, 1994, Arens et al., 2009). Many laboratory studies show that air movement provides comfort in warmer conditions (Rohles, Konz, and Jones, 1982; Huang et al., 2013, Zhang, Arens, and Zhai, 2015), even up to 30 ℃ and 80% RH (Zhai et al., 2015), and this is accepted in existing thermal comfort standards (ASHRAE 2017). A field study intervention adding ceiling fans to an air-conditioned office found that increasing temperature from 23 to 26˚ C (approximately 2 ˚ C above neutral comfort conditions without air movement) was the condition preferred by occupants (Lipczynska, Schiavon, and Graham, 2018). Giving occupants control over increased air movement provides an instantaneous way to respond to changing thermal comfort needs, responding faster than is possible with Heating Ventilation and Air Conditioning (HVAC) equipment designed to condition the whole room.

Providing comfort in warmer conditions can produce significant energy savings. Estimates range from 5-10% per degree Celsius increase in room air temperature (Zhang, Arens, and Zhai, 2015; Sekhar, 1995; Schiavon and Melikov, 2008; Hoyt, Arens, and Zhang, 2015). Other benefits to increased air movement include improved productivity (Zhang et al., 2017), perceived air quality (15-17), and destratification (mixing air so that hot air does not remain at the top layer or strata at the ceiling). Finally, thousands of occupant satisfaction surveys with coincident measurements of indoor conditions show that occupants prefer more air movement than they are currently experiencing in buildings (Arens et al., 2009). Thus, the ability to increase air movement in a room in a controlled way is desirable from many perspectives.

Possibly the largest technical barrier to the use of increases air movement is the lack of a simple method to determine what the air speed will be in the room for a given design. Much of this is due to a clear lack of measured data on air movement from ceiling fans in spaces.

The US Code of Federal Regulations (Office of Federal Register, 2017) determines airflow for ceiling fans sold in the USA using standard test-methods. For fans 7 ft (2.13 m) diameter and under, the test-method measures an air speed traverse below the fan [18]. For larger fans, the test-method (AMCA [19]) measures thrust. (Air Movement and Control Association (2015)).

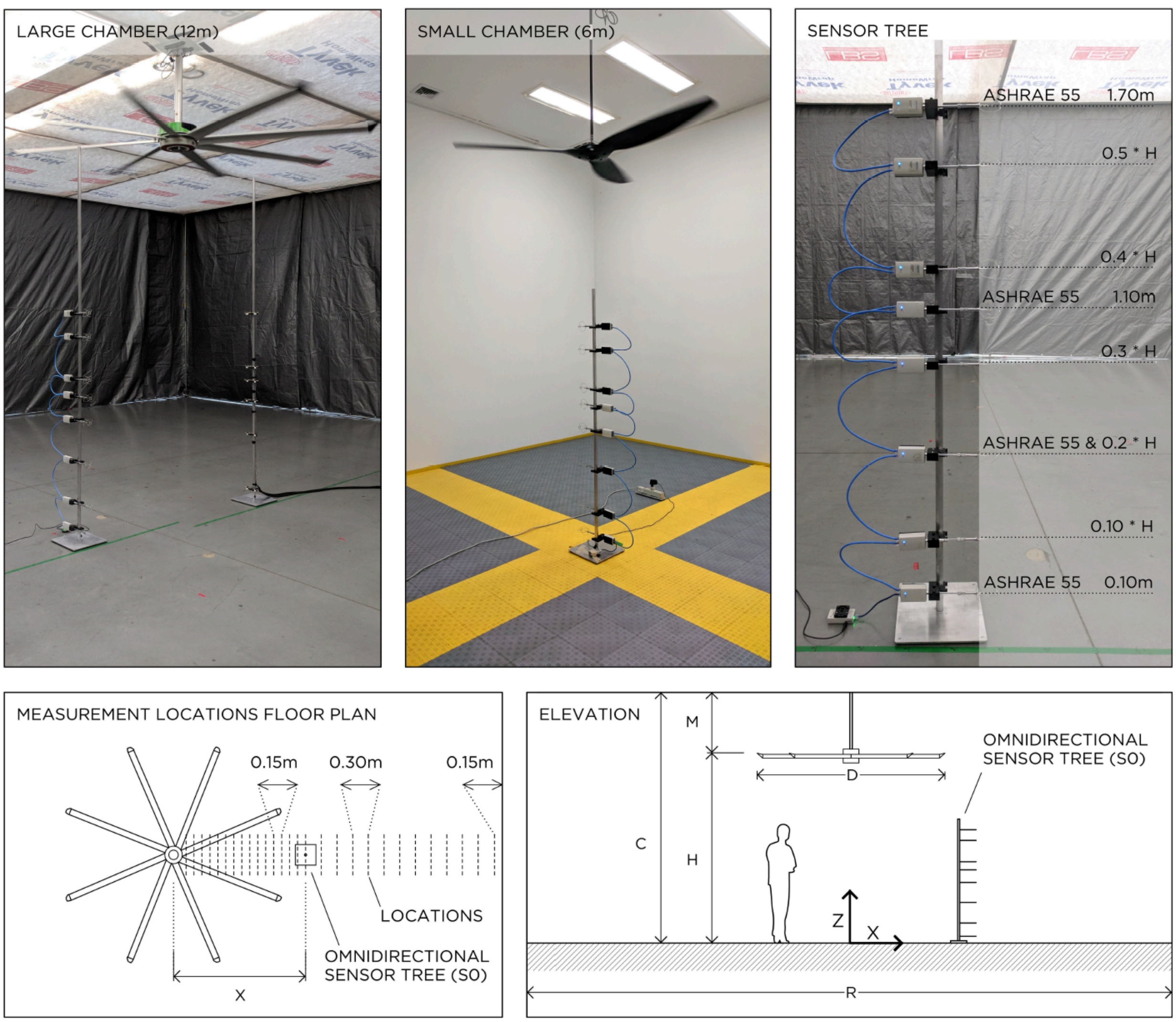
To date, there is no clear, generalized model of the effects that many characteristics—fan diameter, blade height, ceiling height, room size, direction, and even fan speed, etc.—have on air speed distribution in the room. In addition to this lack of a model, there is the issue of variability in air speed within a room caused by air movement devices: the room air speed distribution. Ceiling fans cause high air speeds in the area directly under the fan blades, but this decreases rapidly outside the fan blades. This creates an environment in which the thermal comfort condition varies depending on an occupant's position in the room. In addition to the horizontal variability for air speed within the room, there is also variation in the vertical distribution. Typically, air speeds are higher at head height than at foot height while directly under the fan, but this relationship reverses when outside the fan.

This paper's primary goals are: (1) measure how different room- and fan-related factors (room size, fan diameter, type, rotational speed, direction, blade height & mount distance) affect the air speed distribution; and (2) develop simple-to-use dimensionless models requiring only inputs that are readily available (rated airflow and aforementioned factors).

CHAPTER 3:
Lab methods

The research team conducted tests in the Big Ass Fans facility in Kentucky, shown in Figure 6 below. For each test, the researchers took measurements at fixed locations along an axial line out from the fan center perpendicular to the wall of the chamber. These measurements were in 15 cm increments from the center out to 2.44 m, increasing to 30 cm increments from there out to the wall of the test chamber. This yields a higher density of measurements in the region directly underneath the fan where air speed changes more quickly with distance from the fan center.

Figure 49: Laboratory setup for testing ceiling fans.



Air flow sensor layout for laboratory testing at the Big Ass Fans testing facility in Kentucky.

Credit: Paul Raftery

Additionally, the team included an additional measurement location 0.15 cm from the wall to capture the airspeed close to this boundary. The team took measurements at 8 heights at each location, 4 of which we kept fixed at 0.1, 0.6, 1.1, and 1.7 m to correspond with existing thermal comfort literature and standards such as ASHRAE 55. The team took the other 4 height measurements at fixed fractions of the fan blade height in increments of 0.1.

CHAPTER 4:
Results

The results and analysis may be found in the paper in the Appendix.

CHAPTER 5: Conclusion and Next Steps

The research team defined the concept of fan air speed as the rated airflow of the fan divided by the area swept by the blades. The results show that normalizing the air speed at any point in the room against the fan air speed provides comparable profiles across a wide range of fan and room sizes. For a fixed set of fan and room characteristics, the measured air speed at any location is linearly proportional to the fan air speed, rotational speed, and airflow. This applies for fans blowing both upwards and downwards, regardless of fan type, though the relationship is less accurate at very low fan air speeds (< 1 m/s). The results also show that the maximum air speed at any individual measurement point (a specific height and distance from the fan) in the occupied zone was typically 1.2 to 1.6 times the fan air speed for all 56 downward direction tests.

The results demonstrated that in the region outside of the fan blades, the seated and standing average air speeds increase proportionally with the ratio of fan diameter to room width. The team quantified the spatial uniformity of the air speed distribution and showed that larger diameter fans (or larger diameter to room ratios) provide a more uniform environment. The team also showed that mount distance does not have a significant effect until it approaches approximately 0.2 times the fan diameter. The results showed that for the otherwise similar conditions (i.e. same diameter, estimated fan airflow, blade height, etc.) but different fan types, the air speed distribution is very similar in the region outside the fan blades. Air speeds differ under the blades, however, the effect on the air speed distribution is minor overall. Furthermore, there is circumstantial evidence that the rated airflow depends on the test-method used. It seems beneficial for all fans to be rated using the same test, or to quantify the difference between test-methods for an identical fan to provide further validation.

The researchers also reversed the fan direction, blowing upwards towards the ceiling. This yielded a much more uniform air speed distribution than blowing downwards and has applications where having a homogenous air speed may be desirable (e.g. when occupants cannot choose their location in the room). The air speeds are lower than for a comparable downward test, however, they are still high enough for an appreciable cooling effect.

The upper quartile and maximum of the area weighted average air speeds for seated occupants for the upwards tests were 0.5 and 1.17 m/s respectively, indicating that it is feasible to select fans that will provide equivalent comfort conditions at substantially higher temperatures while blowing upwards and providing a more uniform air speed distribution. Upwards tests with larger fan to room size ratios, higher fan rotational speeds, or inverted blades (so that the geometry is symmetrical with the downwards case), provided higher air speeds.

The researchers developed dimensionless models that apply to the majority of practical ranges of fan and room sizes. The inputs are: fan diameter, blade height, ceiling height, room size, and fan air speed. The fan air speed is calculated using the fan diameter, rotational speed (as a percentage of maximum), and a linear regression to the rated fan airflow at different fan rotational speeds. The models predict the lowest, area-weighted average, and highest air speeds for a seated or standing occupant in the room, with a median absolute error of 0.03, 0.05 and 0.12 m/s respectively. Further work could focus on extending the model to address current limitations, such as developing modifiers for non-square rooms, multiple fans, and furniture.

The hope is that this paper will allow designers to better understand air distribution in rooms due to ceiling fans, and more easily select an appropriate fan for their application.

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Appendix

Ceiling fans - Predicting room air speed distribution based on full scale laboratory measurements.

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Abstract

We measured air speeds in rooms due to ceiling fans in 78 full-scale laboratory tests. The factors were the room size, fan diameter, type, speed, up/down direction, blade height, and mount distance (i.e. blade to ceiling height). We demonstrated the influence of these factors, showing that the most significant are speed, diameter and direction. With other factors fixed, the area-weighted average room air speed increases proportionally with fan air speed and diameter. Blowing fans upwards yields lower but far more uniform air speeds than downwards. We show that for the same diameter and rated airflow, fan type has little effect on the air speed distribution in the region outside the fan blades. We developed several new dimensionless representations and demonstrate that they are appropriate for comparisons over a wide range of fan and room characteristics. Dimensionless linear models predict the lowest, area-weighted average, and highest air speeds in a room with a median (and 90th percentile) absolute error of 0.03 (0.08), 0.05 (0.13), and 0.12 (0.26) m/s respectively over all 56 downwards tests representing typical applications. These models allow us to answer the question - 'What air speed distribution can I expect for a given fan and room?'. We include all measured data and analysis code in this paper.

Keywords:
Ceiling fan; Air speed distribution; Full-scale laboratory testing; Rotational speed; Fan diameter; Fan direction

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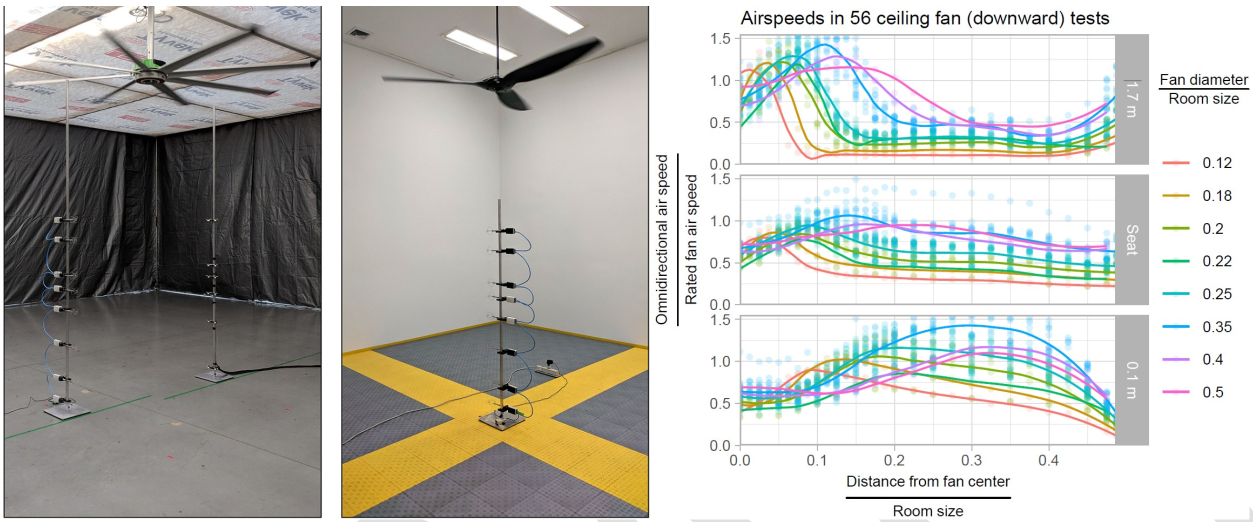
Preprint submitted to Building and Environment *December 4, 2018*

Highlights:

- Measured air speed distribution in 78 full-scale laboratory tests
- Average air speeds increase proportionally with fan air speed and diameter
- Blowing fans upwards yields lower but more uniform air speeds than downwards
- Fan type does not significantly affect air speed distribution outside fan blades
- Developed dimensionless linear models to predict air speed distribution in a room



Graphical Abstract

1. Introduction

1.1. Benefits of air movement in buildings

Having the ability to increase the air speed in a room in a controlled manner provides many advantages. It increases the heat transfer from occupants to the environment by convection and evaporation, allowing them to remain comfortable in warmer conditions [1–3]. Many laboratory studies show that air movement provides comfort in warmer conditions [4–6] even at 30°C and 80% RH [7] and this is accepted in existing thermal comfort standards (e.g. [8]). A field study intervention adding ceiling fans to an air-conditioned office found that increasing temperature from 23 to 26°C (approximately 2 °C above neutral comfort conditions without air movement) was the condition preferred by occupants [9]. Giving occupants control over increased air movement provides an instantaneous way to respond to changing thermal comfort needs, responding faster than possible with Heating Ventilation and Air Conditioning (HVAC) equipment designed to condition the whole room [10].

There are significant energy savings from being able to provide comfort in warmer conditions. Estimates range from 5-10%/°C temperature increase [6,11–13]. There are other benefits to increased air movement: improved productivity [14], perceived air quality [15–17], and destratification (where this is problematic). Finally, thousands of occupant satisfaction surveys with coincident measurements of indoor conditions show that occupants prefer more air movement than they are currently experiencing in buildings [3]. Thus, it is clear that the ability to increase air movement in a room in a controlled way is desirable from many perspectives.

1.2. Terminology

We commonly see different terms used to describe similar, but not identical concepts, which differ between papers and sometimes even within the same paper. We describe each term here and use it throughout.

- Fan rotational speed (N): Physical fan rotational (rpm).
- Fan airflow (Q): Volumetric airflow rate through the fan blades (m3/s).
- Fan air speed (SF): Average air speed through the area swept by the fan blades (m/s).
- Air speed (SO): Air speed (m/s) at a point in the room, or a summary statistic of air speed distribution.
- Occupied zone: Volume of the room at or below 1.7 m height.
- Air speed distribution: The full set of measured air speed data in the occupied zone.
- Blade height (H): Distance from floor to blade, measured at hub (m).
- Mount distance (M): Distance from blade to ceiling (m).
- Ceiling height (C): Distance from floor to ceiling (m).

1.3. Technical barriers to use of increased air movement

Possibly the largest technical barrier to designing for increased air movement is the absence of a simple method for determining the air speed distribution a fan (or fans) will produce in a room. The absence isn't surprising, since the fan design problem is potentially complex and there is an absence of measured air speed data in realistic conditions that might otherwise provide design insight. Literature to date is sparse and in aggregate explores a very small range of parameters that designers need to evaluate. For example, all published experiments to date used fan diameters from 1.1 - 1.5 m, though they are available in diameters from 0.6 - 7.3 m, and measured one-size fan in a one-size room, though the fan-to-room size ratio affects the air speed distribution.

The US Code of Federal Regulations [18] determines airflow for ceiling fans sold in the USA using standard test-methods. For fans 7 ft (2.13 m) diameter and under, the test-method measures an air speed traverse below the fan [18]. For larger fans, the test-method (AMCA [19]) measures thrust. There are databases containing performance data for thousands of ceiling fans [20,21]. Additionally, there is a proposed standard for measuring the air speed distribution in a specified room size [22,23]. However, these resources fall short of meeting designers' needs. There is no clear, generalized model of the effects that many characteristics - room size, fan blade height, furniture, etc. - have on air speed distribution. Even basic questions that many designers have, such as 'What size fan do I need to achieve this air speed in this room?', are as yet, unanswered even by approximation.

In addition to this, while ceiling fans have an overall cooling effect in the room, they also create a non-uniform thermal comfort environment. Air speeds are higher under the fan than elsewhere in the room, so thermal comfort varies depending on an occupant's location [24]. Gao et. al. [25] showed that when the fan jet impinges directly on furniture, it widens the higher air speed region beyond the fan diameter, however, the majority of the room still has lower air speeds. This difference between high air speeds in one location than in others may be problematic where there are multiple occupants who cannot freely or easily move about the room, with some too cool and some too warm depending on where they happen to be located. For example, a shared office where one desk is directly under the fan and others are far from the fan. In cases where occupants can move about freely and easily, such as a lobby or cafeteria, this may be beneficial in addressing the natural variability among people - those who desire more cooling can position themselves closer to the fan. Note that this variability affects both steady state (e.g. people who typically prefer cooler temperatures, or are more heavily clothed than others) and transient scenarios (e.g., one's changing comfort needs directly after commuting to work on a summer day or coming up stairs [10]), and that a non-uniform thermal environment may be beneficial in both, as long as it is trivial for occupants to relocate. Investigating these scenarios thoroughly - though valuable to designers - is outside this paper's scope.

Last, in addition to the horizontal variability of air speed within the room, there is also vertical variability. Air speeds increase with height while directly under the fan, but this relationship reverses outside the fan jet where they are higher at the foot than the head. Occupants who feel warm tend to prefer cooler heads [26] and people have more surface area in the upper body than the lower body. Thus this vertical variability may exacerbate the horizontal variability mentioned above. However, current thermal comfort standards ignore this effect, representative air speed using an unweighted average of the measurements at three heights.

Thus, it is clear that information about the air speed distribution in a given scenario is valuable to a designer. Experimental and numerical studies can provide this, but both are too resource-intensive to use at design stage - this requires simplified models.

1.4. Review of prior studies investigating ceiling-fan driven air speed distribution in a room

We reviewed previous investigations on air speed distribution induced by a ceiling fan, focusing on the factors which affect that distribution. These factors include fan rotational speed [7,27–29], blade shape and number [28–31], airflow direction (upward or downward) [32–34], mount distance [29,32], ceiling height [29], and furniture [25].

Many prior studies focus on the airflow through a ceiling fan and show that blade geometry and number of blades affect airflow and efficiency [28,31,35–40]. However, these generally don't focus on the air speed distribution within the room.

Mount distance has received some attention. An empirical study [32] showed that mount distance affected airflow only when the distance between the ceiling and fan (diameter: 1.4 m) was 0.4 m or less. A CFD study [29] found that when the mount distance was > 0.3 m (diameter: 1.5 m), it does not affect air speeds in the room. Chen et al. [29] examined increasing ceiling height and found that with a fixed mount distance, airflow was similar but the air speed decreased in the occupied zone directly below the fan. They also normalized air speeds using the peak air speed at the corresponding height and achieved similar dimensionless profiles at high fan rotational speeds, but not at low speeds.

Several CFD studies [27,33,34] focused on improving disinfection efficacy using fans. Though not the primary focus, they visualize the room air speed distribution, and in the later two studies, also simulated fans blowing upwards and downwards. Similarly, regarding fan direction, one other study evaluated the effect of fan direction [32]. Although they measured air speed near the fan operating in both directions, the study focused on providing a benchmark for CFD, and made no comparison between the two.

Last, studies have examined other factors that are commonplace in buildings: multiple fans and furniture. Liu et al. [41] measured the effect of single and multiple fans running at different speeds on air speed distribution (fixed fan and room size). Gao et. al. ([25]) measured air speed distribution with different types of furniture directly underneath the fan blades, showing that the furniture deflected higher air speed towards the edge of the table, notably increased seated average air speeds compared to cases without. Both studies provided extensive data sets and proposed conceptual models of air circulation for the evaluated cases. Mihara et al. [24] used a thermal manikin to measure local cooling effects in a room with furniture and two fans (fixed size and location, running at three different speeds) and visualized air speed distribution.

1.5. Objective

This paper's primary goals are: (1) measure how different room- and fan-related factors (room size, fan diameter, type, rotational speed, direction, blade height & mount distance) affect the air speed distribution;

and (2) develop simple-to-use dimensionless models requiring only inputs that are readily available (rated airflow and aforementioned factors).

2. Method

2.1. *Factors and factor levels*

Based on prior research and engineering experience, we included factors that we thought most likely to affect air speed distribution, with levels covering typical applications:

- Room size (2 levels: 6.1 & 12.2 m)
- Fan diameter (7 levels: 1.22, 1.32, 1.52, 2.13, 2.44, 3.05 & 4.27 m)
- Fan type (9 anonymously reported fan types from 5 different manufacturers, ranging from 3-8 blades/airfoils)
- Fan air speed (from 0.63 to 2.76 m/s, as described later)
- Fan direction (Down or Up)
- Blade height (4 levels: 2.13, 3.05, 3.66 & 4.27 m)
- Mount distance (3 target levels: 0.6, 1.2 & 1.8 m. We report the actual mount distance, which differed slightly from these due to each fan type's mounting constraints.)

2.2. *Test description*

Figure 1 shows the layout of the experiment and the nomenclature used throughout this paper. For each test, we installed the fan in the center of a square test chamber (6.1 m or 12.2 m wide) at the desired mount distance, then raised the ceiling to achieve the desired blade height. We measured air speed (*SO*) at fixed locations along one radial line from the center perpendicular to the wall in 15 cm increments, increasing to 30 cm increments at 2.44 m from center (just outside the blades of the largest fan). This yields a higher measurement density near the fan where air speed changes more quickly. We included an additional measurement 0.15 cm from the wall to measure air speed close to this boundary. Using this approach, we assume a symmetrical air speed distribution orthogonally around the fan axis. Preliminary testing showed symmetry along 4 orthogonal traverses, and the close fit between replications in the experimental dataset also demonstrates symmetry.

We took measurements at 8 heights at each location, 4 of which we fixed at 0.1, 0.6, 1.1, and 1.7 m to meet the requirements of existing thermal comfort standards. We report the seated and standing averages as "Seat" (average of 0.1, 0.6 & 1.1 m) and "Stand" (average of 0.1, 1.1, & 1.7 m). We took 4 other height measurements at fixed fractions of the blade height in increments of 0.1 so that we can compare measurements at the exact same dimensionless fraction of the fan height in different scale tests[1].

We measured air speed using omnidirectional probes designed for low-speed measurements (AirDistSys5000, Sensor Electronics, Poland), accurate to ±0.02 m/s or 1% of reading from 0.05 to 5 m/s. We reported each measurement as the average of 90 samples at 2 second intervals over 3 minutes.

2.3. *Characterizing how fast a fan moves*

Ceiling fans sold in the USA are required to have a rated maximum airflow [18]. The rated airflow may be available at other speeds, though the fan affinity laws easily can approximate this - the airflow is linearly proportional to the fan rotational speed[2]. Figure 2 illustrates this by showing rated airflows for each of the 9 fan types in this experiment at different rotational speeds. Following another fan affinity law, with all other design parameters identical, airflow is proportional to the diameter cubed. Separately from the affinity law relationships, in practice the maximum airflow for a given diameter varies based on the fan type due to the

[1] Where the fixed fraction measurements and the fixed height measurement were within 5 cm of each other, we measured exactly at the fixed height value and added an additional fixed fraction measurement. For example, with a 3m blade height, the fixed fraction measurement heights were 0.3, 0.9, 1.2 and 1.5 m, corresponding to fixed height fractions of 0.1, 0.3, 0.4 and 0.5 respectively. The 0.2 fixed fraction measurement equals the fixed height measurement of 0.6 m.

[2] The linear fit intercept is below 0 in all cases. When only a single airflow datapoint is available (typically at the maximum fan rotational speed), a linear fit must assume the intercept is zero. This overestimates the airflow at fan rotational speeds other than the maximum. This does not affect the results in this paper as we tested fans for which we have only one rated airflow (Types A-C) at the maximum rotational speed.

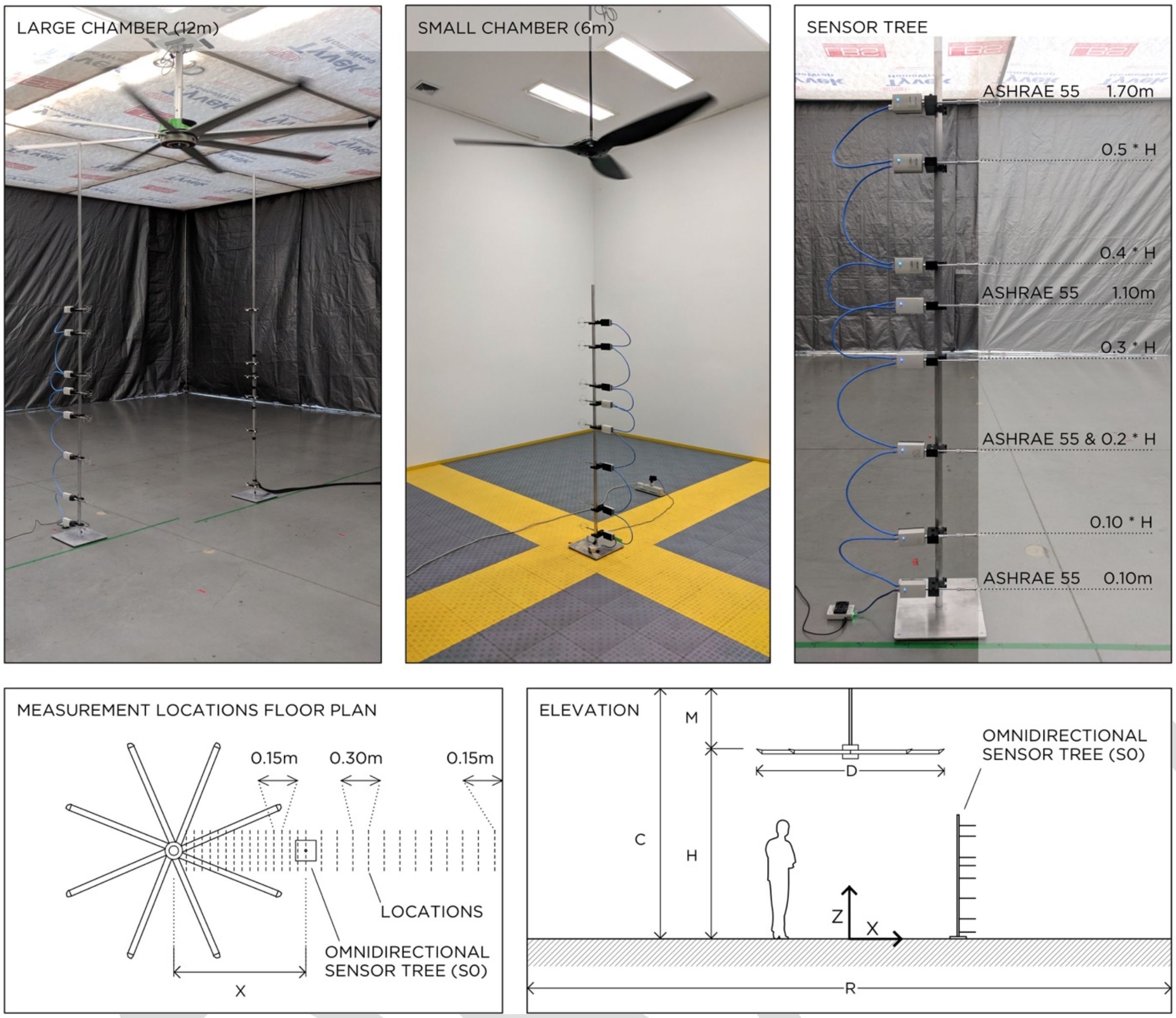


Figure 1: Overview of experimental setup

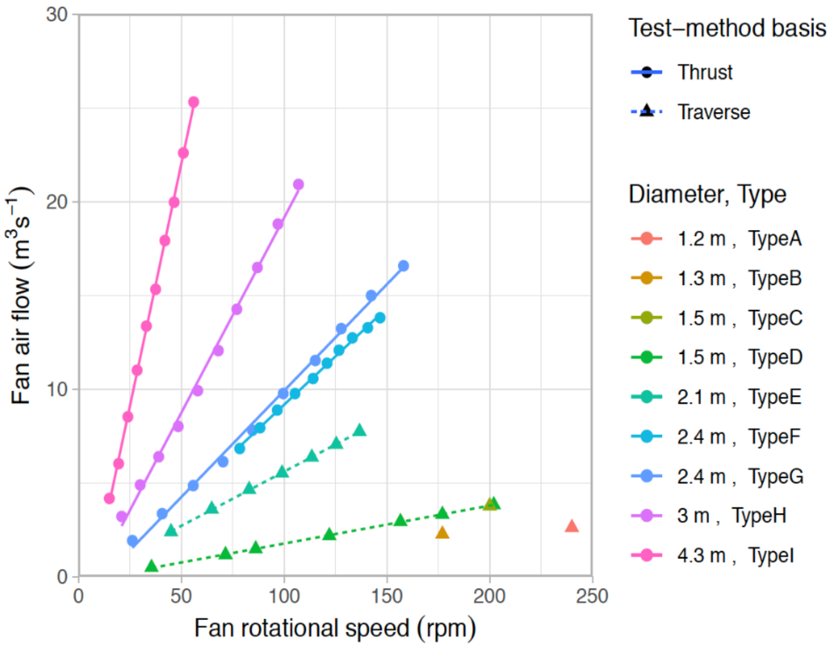


Figure 2: Airflows for each fan in the experiment.

maximum fan rotational speed, blade geometry and number of blades. Additionally, in practice the maximum fan rotational speed decreases as fan diameter increases due to UL 507 blade tip speed constraints for a given blade thickness. This safety constraint applies to any fan that can be mounted under 10 ft (3.05 m) blade height.

Given these four different relationships, when comparing different fans it is not possible to characterize how fast a fan moves using the fan rotational speed or airflow in a way that is generally applicable across a range of fan types, rotational speeds, and diameters. However, that is what we (and designers) require. We compared several potential approaches based on the rated airflow divided by different powers of the diameter or the rotational speed. Divided by the diameter squared shows the smallest relative difference between the minimum fan speeds and maximum fan speeds across all fan diameters and types, taking into account the combined effects of the affinity laws and fan type-dependent differences. Thus, we characterize the concept of how fast the fan moves using the 'fan air speed', defined as the airflow divided by the area swept by the blades. This is an easily understandable concept - a combination of physical measurements representing the average air speed through fan blades.

In the experiment we controlled this factor by setting the fan rotational speed to achieve a target fan air speed (in increments of 0.5 m/s). For fans with discrete speed settings, we chose the setting to minimize the difference between fan air speeds across all of the fan types. For variable speed fans we matched the fan air speed to the average of the discrete speed fans. For example, for a fan air speed level from 1 to 1.5 m/s, two fans with discrete speed settings had fan air speeds of 1.19 and 1.3 m/s respectively, within that range. For variable speed fans we determined the fan rotational speed to yield the average of these (1.25 m/s).

2.4. *Design of experiment*

There were a large number of factors (7) in this experiment, many with several levels, and certain combinations are not feasible.[3] Thus, a full or fractional factorial design of experiments is not feasible. We used the following approach to determine which factor combinations to test, given a total lab time constraint.

- Local sensitivity tests: For each factor we determined a region that is relatively typical in practice, and in which test multiple levels was feasible. We tested each of those levels with all other factors held at identical values (or as similar as possible given practical constraints).
- Scale tests: We applied a scalar to each of the dimensional factors to evaluate similarity in the air speed measurements in both cases. For example, repeating a test with double the fan diameter, blade height, mount distance, and room size.
- Similar dimensionless values: We developed some preliminary dimensionless ratios: the ratio of blade height to diameter and the ratio of fan diameter to room size. We performed several tests in which we held those ratios constant with the ratios in other tests, but at a larger scale, while keeping other factor levels constant. For example, we matched the 4.3 m diameter fan at 4.3 m blade height with a 2.1 m diameter, 2.1 m blade height test, but other parameters, such as room size, remained the same.
- We performed 12 replications.
- We performed one still air test in each chamber.

We used R's "AlgDesign" package to optimize the tests ([42]) for the remaining time available accounting for the tests described above. This maximized the value of the remaining tests in creating a mixed effects model. We chose an I- instead of D-optimal design instead as those perform better in prediction applications when the model is not known in advance ([43]). We randomized the test order where feasible[4] and performed a total of 78 tests. The Appendix contains a table describing the factors and summary statistics of the results for each test.

2.5. *Reproducible research*

We wrote this paper using R Markdown. All the text, references, bibliography, data analysis and visualization occurs in one file (.Rmd), which automatically builds the document that we submitted to the journal editor. The Appendix contains the entire measurement dataset and .Rmd file.

3. Results

We analyze the results starting with the still air and replication tests and then show local sensitivity tests for a particular factor. Due to space constraints we display only some of the tests to illustrate a particular concept and we display only the lowest and highest measurement heights in the occupied zone (0.1 m and 1.7 m), and the seated average. The Appendix contains figures showing every measurement for each test. We named the figures using a shorthand notation and use similar notation in this paper where appropriate. For example: "R12 D2.4 H3 M0.69 TypeF Down N108 SF2.1 RepA.pdf" corresponds to a test in a 12 m room using a 2.4 m diameter, 3 m blade height, 0.69 m mount distance, TypeF fan blowing downwards at 108 rpm. The fan air speed is 2.1 m/s and this is replication A. The Appendix figures include measurement uncertainty error bars and overlay the standard error for the smoothing line fits, whereas we omitted these in the paper for visual clarity.

Lastly, we often report summary statistics using either the lowest, the highest, or the area-weighted average air speed that a seated or standing occupant would experience in the room. We calculate the last by weighting each seated or standing average measurement by the fraction of floor area which it best represents (see analysis code for detail).

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[3] Due to safety, physics, or fan type constraints. For example, large diameter fans cannot be used with blade heights lower than 3.1 m for safety reasons as they typically do not meet UL 507 requirements on blade velocity and thickness. However, smaller diameter fans are commonly used at lower blade heights.

[4] Changing most factors (e.g. changing a 4.3 m diameter fan, or moving the ceiling) takes longer than the time to perform a single test and thus, full randomization is infeasible as it would vastly reduce the total number of tests. We grouped tests by these difficult factors and then randomly selected the sequence of the remaining factors.

3.1. Still air

The median, lower and upper quartiles of the still air test measurements are 0.04, 0.03, and 0.05 m/s respectively. This corresponds with measurements in 5 case study buildings [44], which showed similarly low air speeds in the absence of fans, and Rohles' paper [4]. These still air measurements are well below the 0.2 m/s threshold that defines "elevated air movement" for thermal comfort in ASHRAE 55 [8]. The median measurements differ by just 0.0011 m/s between two still air tests performed in random order months apart, indicating that there's little sensor drift or issues with changing conditions.

3.2. Replications

We performed 11 replicated tests in randomly selected order covering a wide range of factors, and they show very close agreement. The median difference between air speeds measured at the same point in replicated tests is effectively zero (0.0061 m/s). The median absolute difference - which represents the typical air speed difference at any given location, ignoring whether one is higher or lower than the other - is 0.03 m/s; the upper quartile is 0.06 m/s across all replications. These differences are close to instrument accuracy (±0.02 - ±0.03 m/s over the dataset's range) indicating that the tests are highly replicable. The median absolute difference between replicated tests was slightly higher (by 0.02 m/s) in the larger test room (see Appendix figure). Also, we note that the small fraction of the dataset (1.7%) where the absolute difference between tests exceeds 0.2 m/s all occur in the region under the fan blades, and predominantly occur for tests at higher fan air speeds (>2 m/s). This may indicate that air speeds in this region - relatively close to the stagnation point - are less stable than in others.

3.3. Fan air speed

Varying fan air speed with other factors fixed has a directly proportional effect on air speed measured at any location. This applies across the range of diameters we tested where speed was the only modified factor. The proportional relationship becomes less accurate at low fan air speeds (<1.0 m/s), which is likely due to inaccuracies in measuring airflow (and thus the fan air speed) in the test-methods and momentum effects. Figure 3 shows how changing fan air speed affects the air speed distribution with all other factors fixed, and visualizes the directly proportional relationship to fan air speed.

In Figure 3, the mean standard deviation at each measurement height and location, expressed as a percentage of the average measurement, decreases from 37% (left column) to 7.7% due to normalizing the data against fan air speed (right column). For context, the same metric for all replicated tests is 3.4%, indicating that much of the remaining variation is measurement uncertainty.

3.4. Fan diameter

Figure 4 shows that increasing the fan diameter with other factors constant, or approximately constant (i.e. estimated fan air speed, mount distance), has the following effects: 1) increases the width of the high air speed region below the fan in proportion to the diameter without noticeably changing the maximum air speed at head height within that region. 2) increases the air speed in the region outside the blades proportionally to the diameter. The right column shows that SO/D has a similar profile for each test in this region. It is interesting to note the difference between the two smaller and two larger fans, potentially due to the airflow test-method changing between these tests. 3) decreases the range between minimum and maximum seated average air speeds in the room. i.e., it increases the uniformity of the air speed distribution.

3.5. Blade height, ceiling height and mount distance

We used fixed mount distances (regardless of fan diameter) in three target levels (0.6, 1.2 & 1.8 m) and fixed blade heights, which means that ceiling height (the sum of blade height and mount distance) varies between tests. Thus, we can't independently assess these factors' effects.

Below a certain mount distance, the proximity of the ceiling to the blades reduces the fan airflow and causes the width of the fan jet to narrow. This relationship accelerates at extremes - often termed the 'starvation' region - causing the airflow to decrease quickly with mount distance. A simple rule is that starvation occurs when the mount distance is significantly less than 0.25 times the diameter - this equates the surface area of the cylinder swept between blade tip and ceiling to the circular area swept by the blades. Most fan manufacturers have a fan-specific minimum mount distance, often short enough to cause some airflow reduction, but without

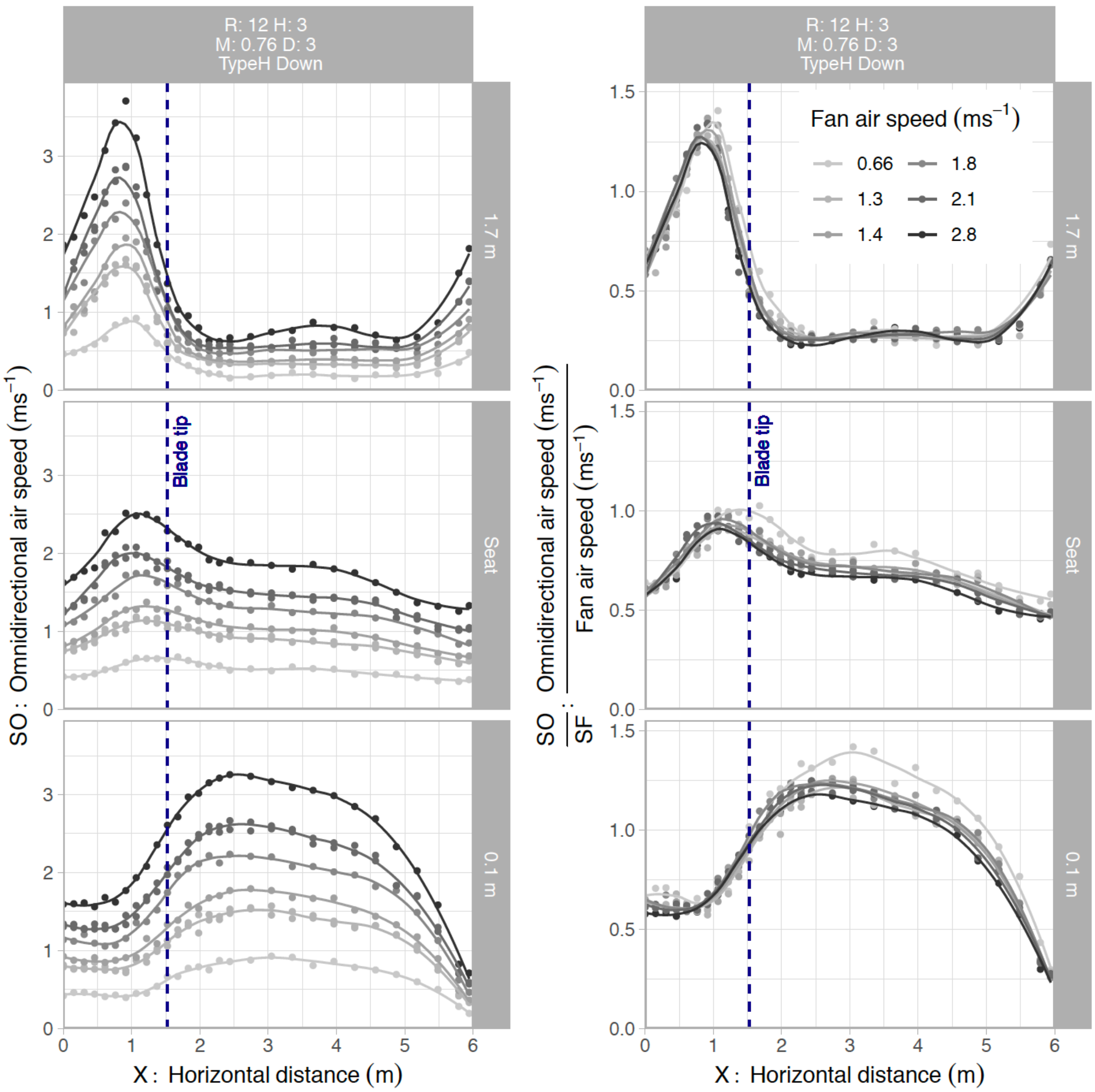

Figure 3: Tests in which the fan air speed (and rotational speed) change but all other factors are identical. Left column: measured air speeds; Right column: normalizes these against fan air speed.

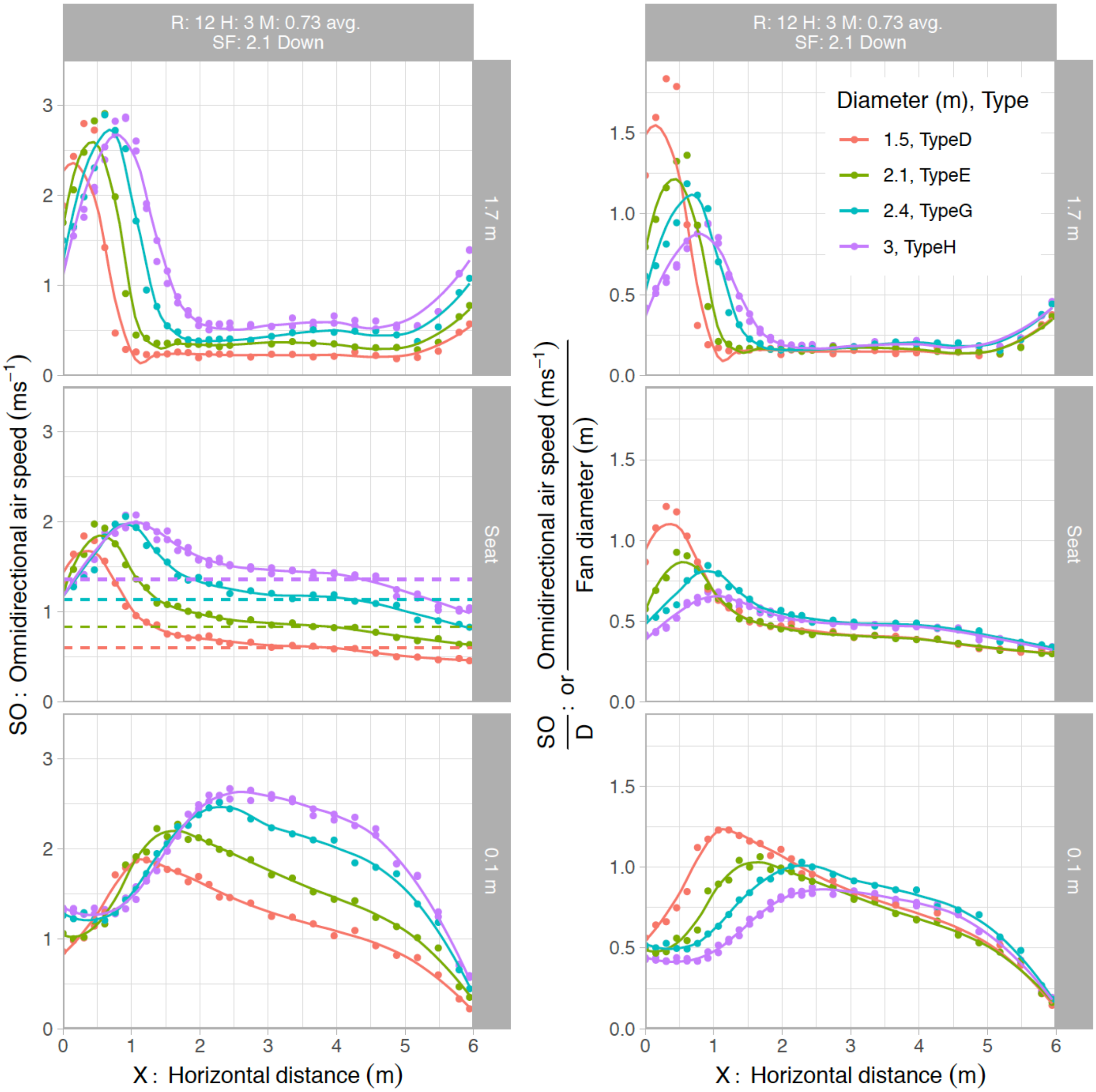

Figure 4: Four different tests of varying diameter with otherwise similar conditions. Dashed lines indicate the area-weighted average of the seated data.

causing starvation. Studies [29,32] investigated this and found values over 0.28 and 0.2 times the diameter, respectively, didn't affect airflow. Fan rotational speed also has an effect, with slower speeds allowing smaller mount distances before reducing airflow. Further research would be beneficial to develop a model of airflow, rotational speed, and mount distance that is generalizable across fan types and diameters. In the experiment, we expect the shortest mount distance (0.76 m) to have some effect for the largest two diameter fans (3 m and 4.3 m) as it is 0.25 and 0.18 times the fan diameter respectively. For these tests (visualized in the Appendix), decreasing the mount distance with other factors fixed significantly reduced the maximum air speed observed at any of the seated or standing average heights, moved the maximum air speed measurement closer to the center of the fan, and reduced the median measured air speed. For small diameter fans, the shortest mount distances that we tested don't affect the room air speed distribution as noticeably. The difference between tests with different mount distances, but otherwise comparable, is only slightly more than a typical replication test. This difference may be due to confounding effect of changing ceiling height, instead of an issue related specifically to the mount distance.

The blade height and ceiling height effects are particularly difficult to decouple from one another given our dataset, however, both have smaller effect on the air speed distribution than either fan air speed and diameter. Blade height mainly affects air speeds directly under the fan blades, and less so in the region outside. In tests where we only increased blade height with other factors constant, the maximum air speed directly under the fan decreased and that maximum point's location moved radially outwards from the center. It is likely that for very small fans, very large heights, and or very low fan air speeds, blade height will have a larger effect, but these are not recommended applications.

3.6. *Fan type*

We compared different fan types to each other under conditions as similar as possible. As discussed in the Methods section, we matched the fan air speeds between types based on linear regression to the rated airflow data as closely as possible given the available speed settings. However, even if the estimated air speed was identical, the measurement error in the airflow test-method and in the regression incurs a difference between the two fans.

Figure 5 (upper row) compares the 2.4 m Type G (8 blades with winglets, M: 0.76 m, SF: 2.12 m/s) and Type F (6 airfoils without winglets, M: 0.69 m, SF: 2.14 m/s) to each other under similar conditions. The median, lower and upper quartiles of the difference in air speeds are 0.05, -0.01, 0.13 m/s. Although larger than the replication test difference, considering that not all factors are exactly equal (mount distance, ceiling height, fan air speed), fan type has a minimal effect in this comparison, particularly outside the blades.

Figure 5 (lower row) compares the 1.5 m Type D (3 airfoils, cross-section varying from hub to tip, M: 0.7 m , SF: 2.11 m/s) and Type C (5 blades, uniform cross-section, M: 0.76 m , SF: 2.05 m/s). The median, lower and upper quartiles of the difference in air speeds are 0, -0.05, 0.19 m/s. There is a notable difference in the region directly under the fan blades, likely due to the differing cross-section from hub to tip. Type D has higher air speeds close to the center and Type C has higher air speeds close to the blade tips. Outside the fan diameter, the seated average data is very similar.

These comparisons show that air speeds differ directly under the fan - more so when the blade cross-section varies from hub to tip for one type but not the other - however, there is little difference outside the blades. Overall, the seated average data is similar for a given fan diameter, regardless of type, assuming each type is capable of operating at that airflow. This allows for simplified comparison of fan types to each other, though types still compete on other factors such as maximum and minimum airflow capabilities, energy efficiency, control and sensing options, reliability, maintenance, noise, cost and aesthetics.

3.7. *Dimensionless representation*

We create several dimensionless variables for the analysis:

- xd: horizontal distance from fan center to measurement location (X) divided by fan diameter (D)
- xr : X divided by room size (R)
- zh, vertical distance from floor to measurement location (Z), divided by blade height (H)
- dr : D divided by R
- do: D divided by the occupied zone height (1.7 m)
- hd: H divided by D
- md: mount distance (M), divided by D

- cd: ceiling height (C), divided by D
- so: omnidirectional air speed (SO), divided by estimated fan air speed (SF)

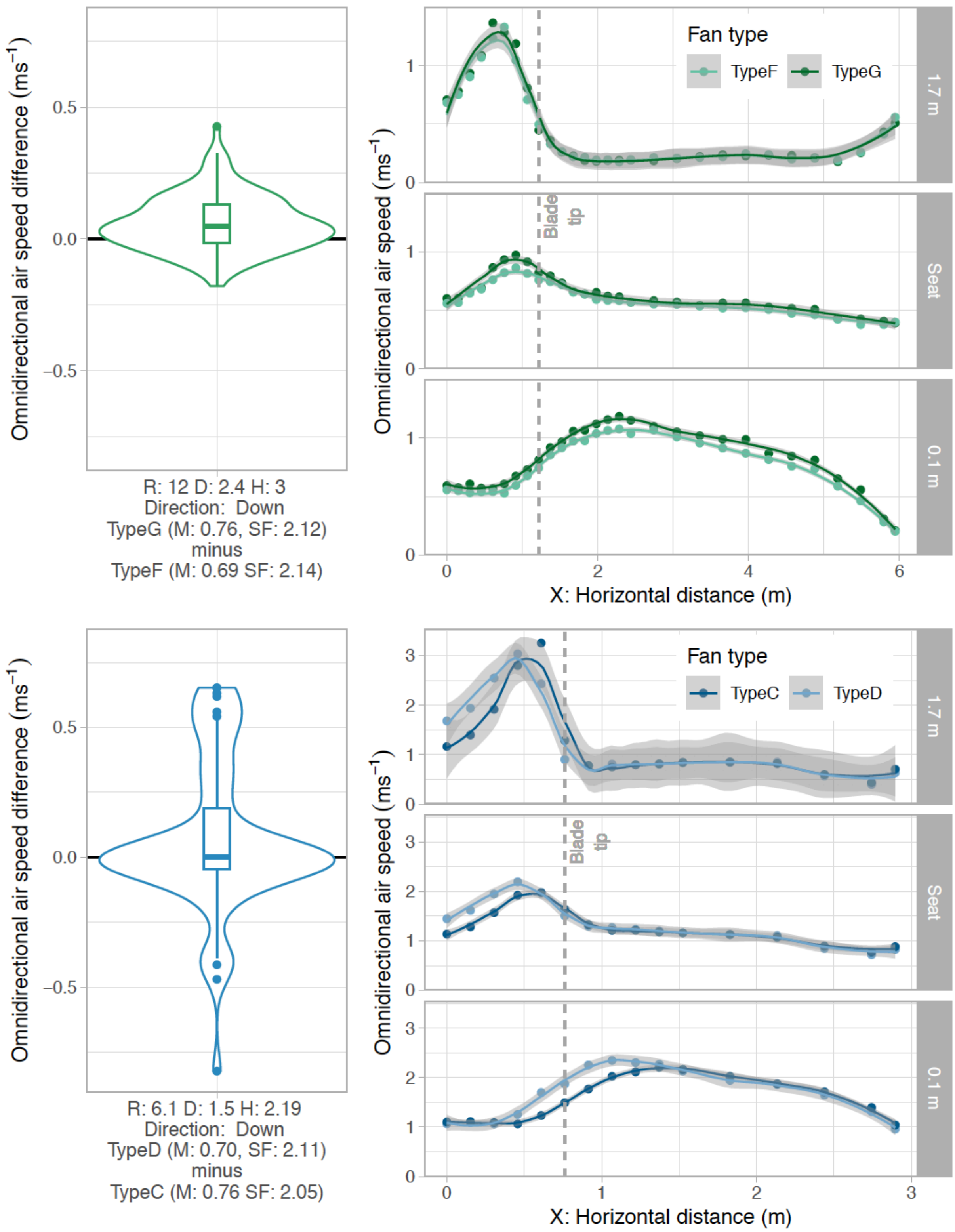

Figure 5: Two fan-to-fan comparisons where the fan type changes, but both operate under very similar conditions.

As the fan air speed proportionally increases the air speed measured at any point in the whole room, normalizing by fan air speed (i.e. *so*) allows comparison of all 56 downward tests in Figure 6. The Appendix contains a similar plot with *xd* as the x-axis. As discussed in the literature review, [29] noted a similar linear effect with fan rotational speed, noting that the relationship breaks down at very low rotational speeds. They normalized against the maximum air speed measured in the room at each particular height, for one fan. However, this information is not known without performing an experiment, whereas the fan air speed is apriori obtained from publicly available information. Additionally, normalizing by fan air speed (instead of either rotational speed or airflow) has the major advantage that it allows comparison across a broad range of fan types and diameters. This makes a strong case that the concept of 'fan speed' should be presented using fan air speed, particularly so when discussing more than one fan type.

Using *so* also allows us to easily extract information about that is generalizable about fans and may be relevant to a designer. For example, the maximum air speed at any measured point (i.e. at any height or location) in the occupied zone is a median, lower and upper quartile of 1.39, 1.33 & 1.49 times the fan air speed. This applies for all downward direction tests, regardless of fan type or diameter.

Figure 7 uses all dimensionless variables to present a total of 14 double scale tests at different fan air speeds and replicated different numbers of times. Here, every geometry factor is scaled by two, or as close to two as possible due to mount constraints. This includes the measurement height, which we express as a ratio of the blade height. Overall, the profiles are remarkably similar to each other. Note that because of the diameters involved at the two scales, the airflow test-method (and thus the fan air speed, and the dimensionless value, *so*) changes. These figures suggest that the traverse test-method may report slightly lower airflows than the traverse.

3.8. Dimensionless model

We created models to aid in ceiling fan selection, allowing designers to rapidly estimate the air speeds that an occupant would experience in a room for a given set of fan and room characteristics[5]. The models predict the lowest, area-weighted average, and highest seated and standing air speeds in the room.

We chose to use multiple linear regression so that the resulting model can be explained in text, and the calculation can be performed quickly and easily. Such simply defined models - even if less accurate than other approaches[6] - are valuable to the designer as there is typically limited time available to dedicate to more detailed analyses.[7] The following table describes models for predicting the lowest, area-weighted average, and highest values of *so*, and the associated fit to the results. We include all downwards cases except those in which the mount distance strongly affects the airflow estimate - where $md < 0.20$. We identified these models by searching through all candidate 3-term linear models without interactions (including an intercept and boolean for seated or standing) and selecting the best fitting model using 3-fold cross-validation, repeated 20 times. The linear models for the lowest and area-weighted average data show a slightly better fit using ceiling height instead of blade height. However, when predicting the highest air speed in the room, the opposite was true. The models are notably less accurate in predicting the highest air speed in the room; unsurprising as this occurs in the region directly under the fan blades, the same region in which we showed that fan type has an effect. The ratio of the diameter to the height of the occupied zone accounts for the effect of a fixed height occupied zone in the dimensionless model.

Figure 8 shows a close model fit, with typical absolute error for *so* within 0.03 for the area-weighted or lowest air speed models, and within 0.05 for the highest air speed. The 90th percentile and maximum absolute errors for all three models are 0.1 and 0.21 respectively. The largest errors typically occur for test cases that

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[5] Blowing downwards only. Though there are 20 upwards tests, we do not have the data needed to develop a generalizable model for the upwards direction as airflow testing isn't required for fans blowing upwards.

[6] The tests cover a wide range that includes most recommended fan applications. More accurate predictions are possible by performing a regression on a subset of tests that most closely match the desired case.

[7] Even if more time was available, there are other aspects of design that could potentially be more impactful to focus on. Furthermore, other factors (such as furniture, typically unkown at design stage and changeable within the building's life) will likely have a larger effect on the air speed distribution than the error incurred by these models.

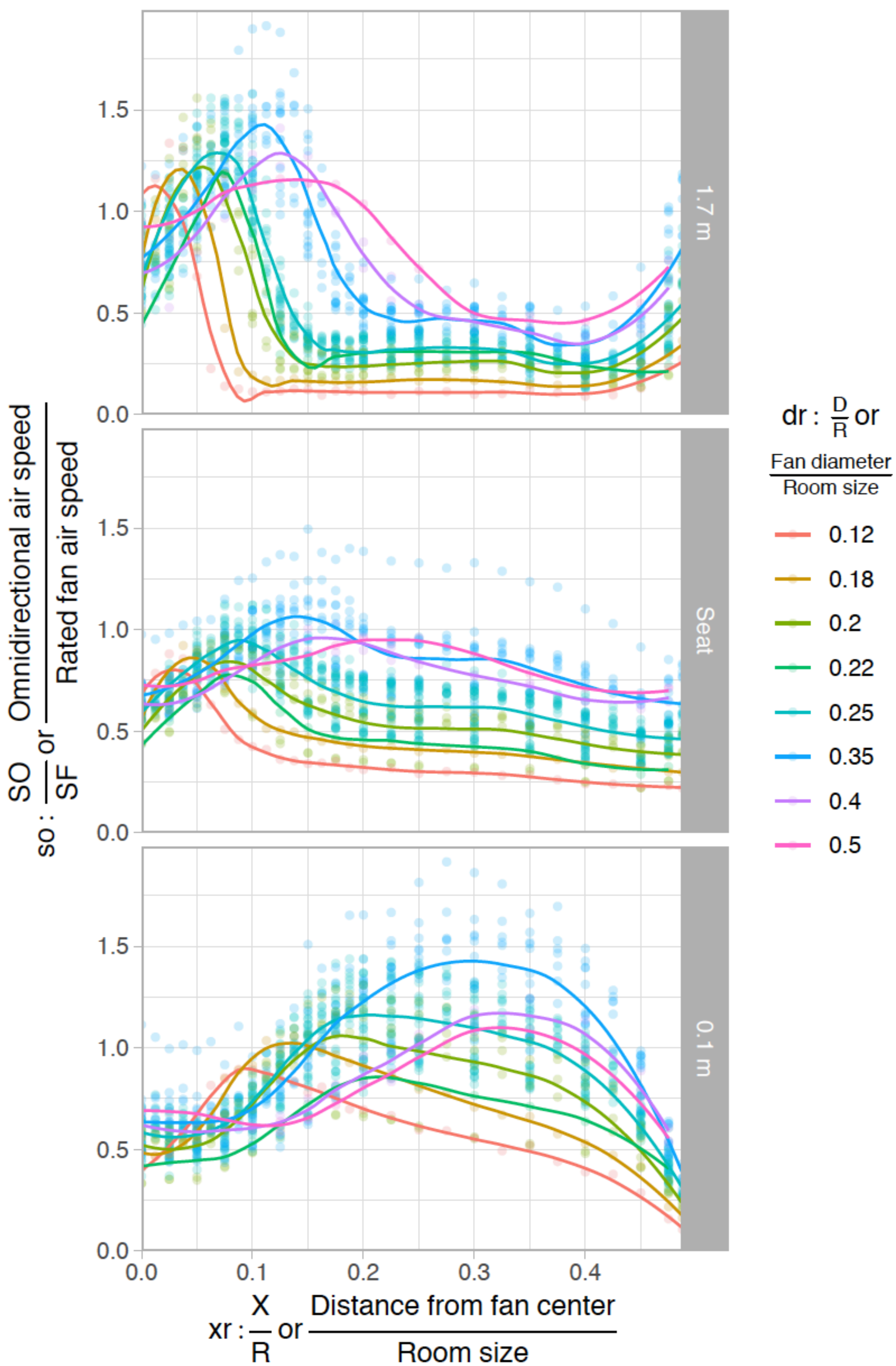

Figure 6: Dimensionless representation of all 56 downward tests at three measurement heights.

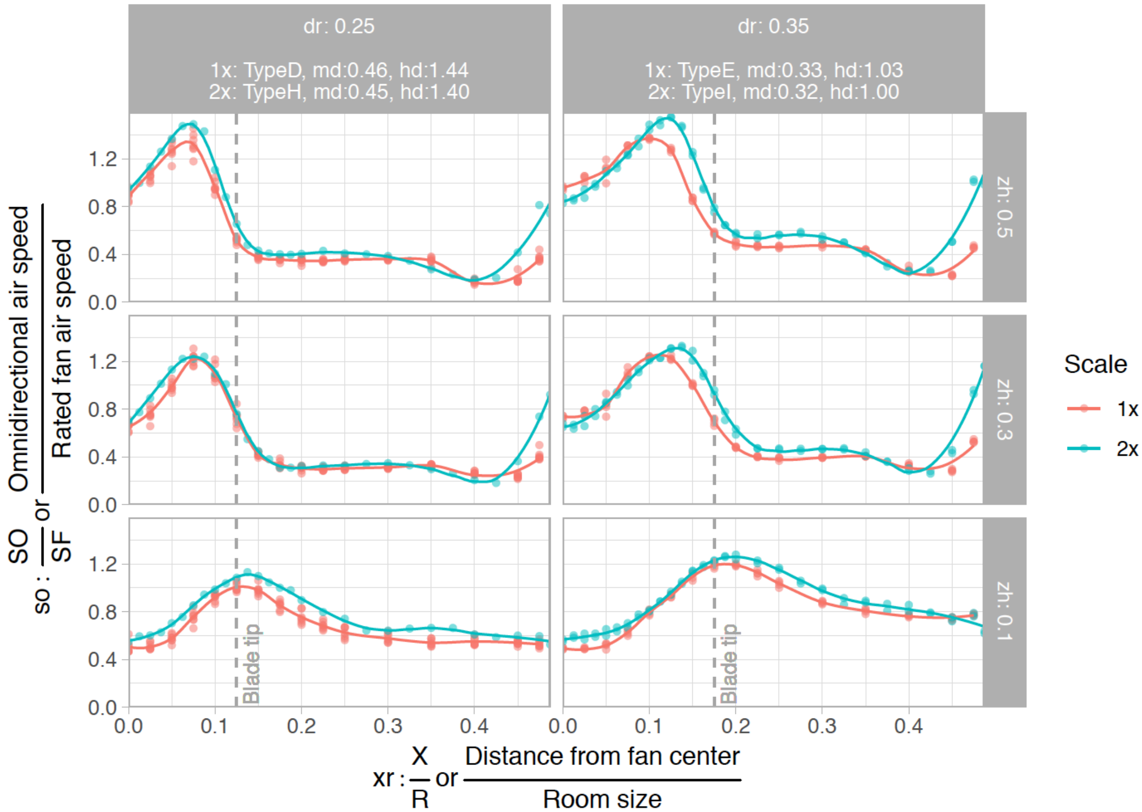

Figure 7: Dimensionless comparison of double scale tests. Results for three dimensionless heights (0.1, 0.3, & 0.5 times the blade height) shown for a total of 14 tests, including multiple different speeds and replications.

Table 1: Dimensionless models for predicting lowest, area-weighted average, and highest air speed in a room, normalized by fan air speed

	Dependent variable:		
	Lowest	Area-weighted average	Highest
	(1)	(2)	(3)
dr: Diameter ÷ room size	0.900***	0.990***	
	(0.045)	(0.071)	
cd: Ceiling height ÷ diameter	−0.017**	−0.060***	
	(0.008)	(0.013)	
do: Diameter ÷ occupied zone height	0.110***	0.110***	
	(0.009)	(0.014)	
hd: Blade height ÷ diameter			−0.180***
			(0.022)
Add for seat vs. stand	0.024***	0.024***	−0.100***
	(0.006)	(0.009)	(0.018)
Constant	0.047*	0.250***	1.300***
	(0.028)	(0.044)	(0.033)
Observations	104	104	104
R^2	0.920	0.880	0.490
Adjusted R^2	0.920	0.880	0.470
Residual Std. Error	0.029 (df = 99)	0.045 (df = 99)	0.092 (df = 101)
F Statistic	304.000*** (df = 4; 99)	188.000*** (df = 4; 99)	48.000*** (df = 2; 101)
Note:			*p<0.1; **p<0.05; ***p<0.01

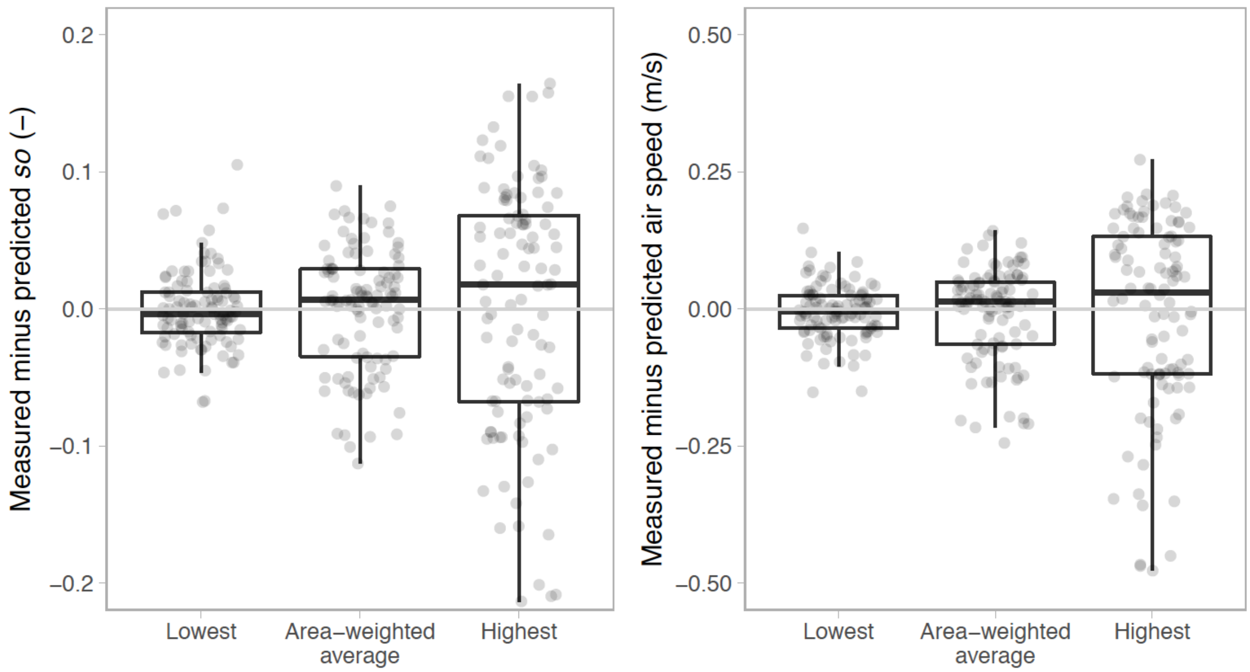

Figure 8: Linear model residuals for predicting three air speed summary statstics in the room.

are outside the range of expected applications (e.g. a very small diameter fan for the room size, or a very high ceiling height) or in a region where non-linear effects become apparent (e.g. the relationship between fan air speed and measured air speed becomes less accurate below the "Very Low" speed level). The absolute air speed errors scale with the measured air speed and thus are larger with higher air speeds. For context, the median (and 90th percentile) absolute error for the lowest, area-weighted average, and highest air speeds (*SO*) in the room are 0.03 (0.08), 0.05 (0.13) and 0.12 (0.26) m/s respectively. These errors seem sufficiently accurate for most applications, particularly when considering the instrument error (0.02 to 0.03 m/s) and that the median replication error between tests was 0.03 m/s).

3.8.1. Worked example

Clear examples are often useful and thus we provide one here along with a spreadsheet tool (see Appendix). What is the area-weighted average air speed for seated occupants in this scenario? A 5 m square room and 3.5 m ceiling (R= 5 m, C = 3.5 m), with a 2 m diameter ceiling fan at a blade height of 3 m from the floor (D = 2 m, H = 3 m). The fan has a rated airflow of 6 m//s (Q = 6 m//s) at 120 rpm, and is currently operating at 70 rpm.

The linear model predicts the area-weighted average *so*:

$$so_{avg} = 0.99 * \frac{D}{R} - 0.06 * \frac{H}{D} + 0.11 * \frac{D}{1.7} + 0.024 + 0.250 = 0.68$$

To convert that to an actual air speed, we first calculate the fan air speed (*SF*) at the rated airflow.

$$SF_{rated} = \frac{4 * Q}{\pi * D^2} = 1.91\ m/s$$

We then calculate the fan air speed at the operating rotational speed, assuming that rotational speed and airflow are linear through zero[8]:

[8] If rated airflow is available at other rotational speeds, then a better linear fit can be developed and used.

$$SF_{@70rpm} = SF_{rated} * \frac{70}{120} = 1.11\ m/s$$

The estimated area-weighted average air speed for a seated occupant is:

$$SF_{@70rpm} * so_{avg} = 0.76\ m/s$$

3.9. Fan direction

All fans sold in the US must be capable of reversing direction, such that they blow upwards towards the ceiling. Of all the tested factors, this had the most effect. Figure 9 shows four examples in which fan direction changes but other factors are constant. In contrast to blowing downwards, blowing upwards creates a highly uniform seated air speed distribution regardless of location in the room. Air speed also tends to increase with measurement height - higher at the head than the feet - at most locations. However, the air speeds are lower for the upwards direction. When a blade geometry is optimized to perform well in a given rotational direction, it tends to have an asymmetrical blade geometry (due to blade curvature), and will be less effective at moving air when rotating in the reverse direction (i.e. blowing upwards). Figure 9 is ordered approximately from least symetrical (left) to fully symmetrical (right), and demonstrates this concept by the decreasing effect that reversing the fan direction has on average air speed. One can maintain full symmetry in both directions by inverting the physical fan blades (where feasible) as well as reversing the rotational direction. We performed one test where we did this (Figure 9, right-most column). With this configuration, the fan airflow should approximately equal the rated airflow for the downwards direction.

We performed fewer upwards tests (20) than downwards (56), and thus have less data to draw conclusions from. However, in upwards tests where only one other factor changes, we observed the same relationships identified for downwards tests: air speeds increase linearly with fan rotational speed; and increase linearly with the ratio of fan diameter to room size. Blade height, ceiling height and mount distance have less impact (see appendix for visualizations).

In the fully symmetrical (i.e. inverted blade) comparison, we measured an area-weighted seated average of 1.17 m/s, or 0.55 times the rated fan air speed. That is -34% lower than the identical downwards test (average: 1.17 m/s)[9]. Thus, for the same design area-weighted average air speed in this scenario, a fan blowing downwards could be approximately -34% smaller - or run at -34% slower speed - than a fan blowing upwards with inverted blades.

The upper quartile area-weighted seated average for all of the upwards tests were 0.5 m/s, which is high enough to provide significant cooling.[10] The maximum area-weighted seated average was 1.17 m/s, indicating that despite the lower air speeds achieved by blowing upwards, it's feasible to select fans to achieve a given design air speed. There are limitations to blowing upwards (e.g. the space must be bounded by a ceiling and walls or interaction with the flow field caused by another fan; and the fan must either be larger, or run faster to achieve the same area-weighted average air speed as downwards), and there is a lot of scope for further research (e.g. how satisfied occupants are with the resulting flow field, how furniture and ceiling obstructions affect air speed distribution in practice, etc.), however, it creates a more uniform air speed distribution which may have many applications[11].

3.10. Uniformity

We quantify the uniformity (U) of the air speed distribution using the following equation for both seated and standing:

[9] For context, we also compare the inverted blade upwards test (area-weighted seated average: 1.17 m/s, M: 1.22 m) to the closest matching upwards test without inverted blades (average: 0.77 m/s, M: 0.76 m). These are otherwise identical except for mount distance (and ceiling height). The area-weighted average air speeds differ by 52%.

[10] 0.5 m/s is sufficient to maintain comfort while increasing temperature by approximately 2.5 °C above the upper comfort threshold for still air according to ASHRAE 55. Also, note here that we didn't attempt to maximize the achieved air speeds in the set of upwards tests and thus higher speeds were achieveable in many cases - e.g. fans didn't run at maximum speed.

[11] Note that thermal stratification was not a part of the study, thus we cannot evaluate how direction affects de-stratification.

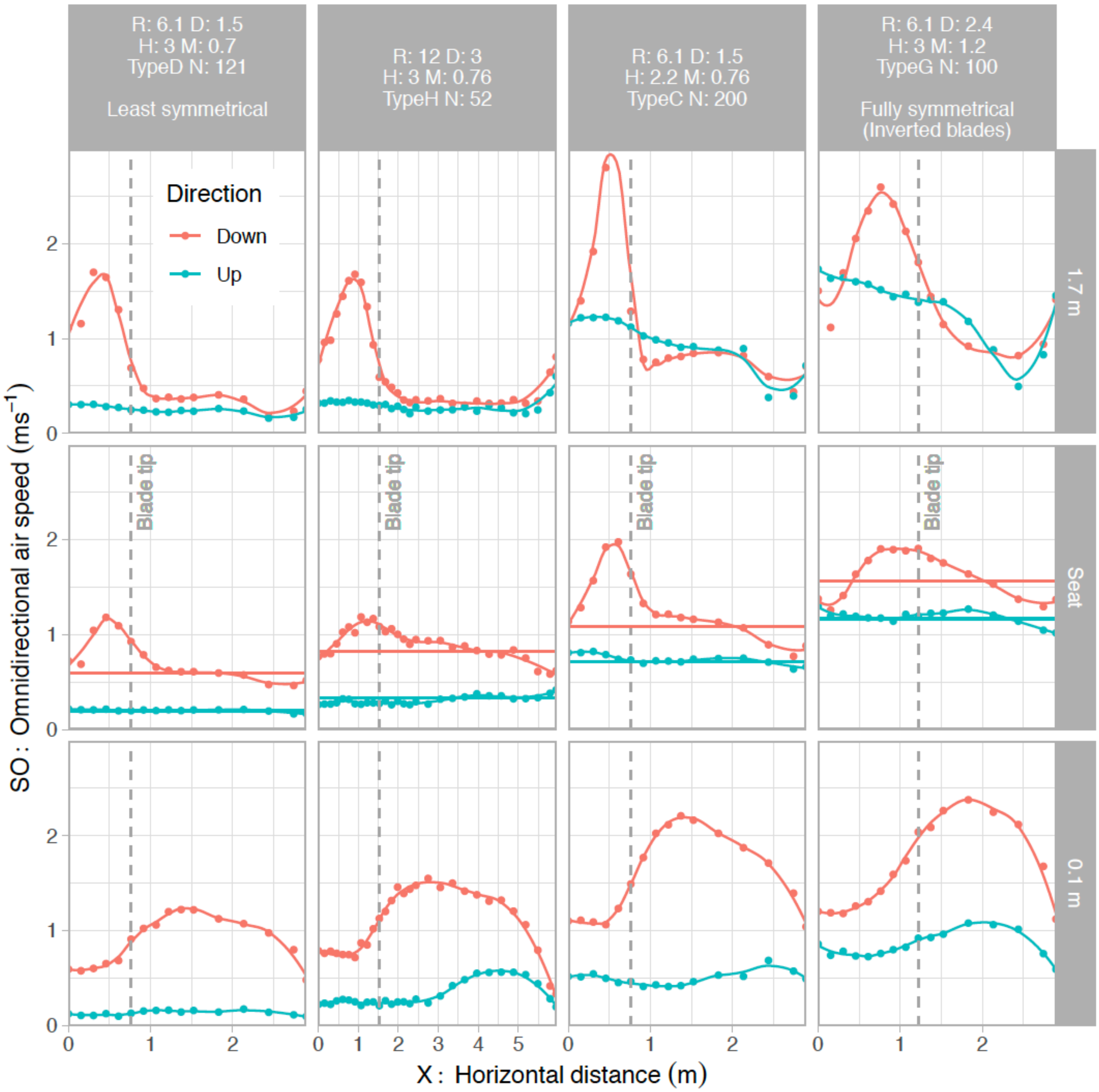

Figure 9: Comparison between four scenarios in which the fan direction changes and other factors remain fixed. Horizontal lines indicate the area-weighted seated average.

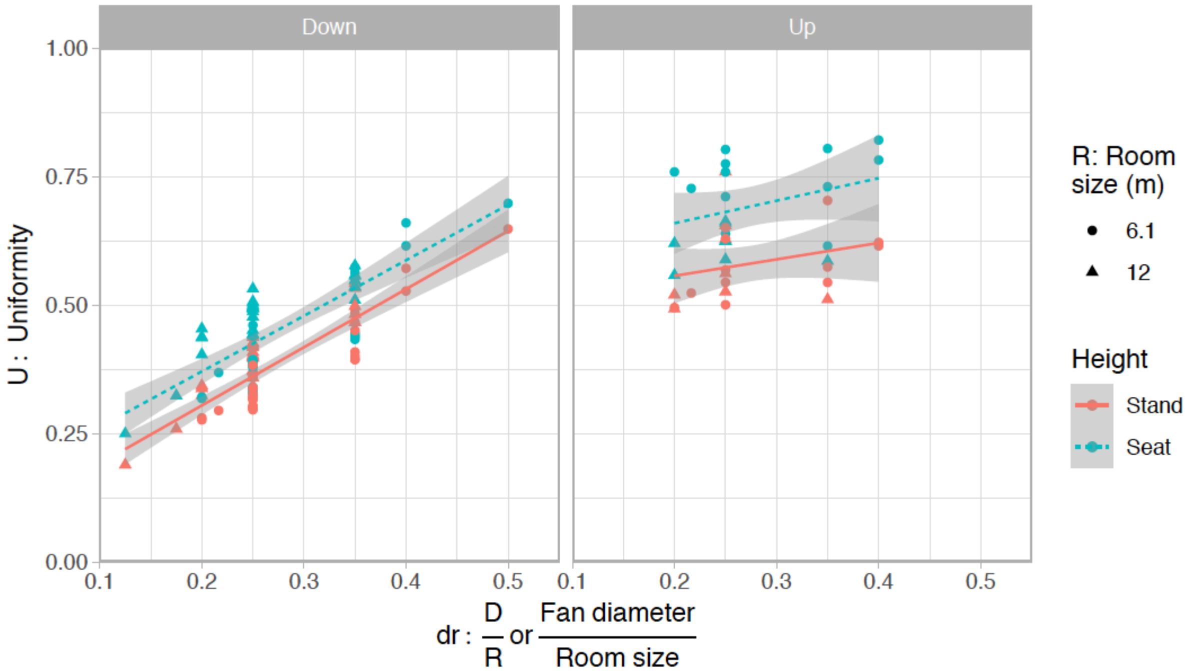

Figure 10: Uniformity air speed distribution for all tests (except still air conditions)

$$U = 1 - \frac{SO_{max} - SO_{min}}{SO_{max}}$$

Thus, a value of 1 means a completely uniform air speed distribution and a value of 0 means completely non-uniform. Figure 10 visualizes the uniformity achieved for all tests (except still air), demonstrating that: uniformity is higher for the upwards direction than downwards; uniformity increases with increasing fan diameter with respect to room size, particularly for the downwards cases; and these relationships are similar for both the seated and standing average data, with seated slightly more uniform than standing.

3.11. Limitations of this study and practical guidance

These experiments detail the air speed distribution along a radial line from fan center perpendicular to one wall in a square room with a centered fan. The air speed distribution will differ along the diagonals from fan center to room corner. Similarly, it will differ when the fan is off center in the room and the room is not square (demonstrated in [41]). Additionally, many applications of ceiling fans use multiple fans in the same space. Thus, the simple models presented in this paper are at best a broad approximation. Though designers will often encounter scenarios that do not match the underlying simplifications, the models still provide useful information, particularly considering the absence of other guidance.

Until more information becomes available, for non-square cells/rooms (e.g. approximately rectangular), we suggest using the square root of the floor area to determine a representative value for the room size (R). It seems that further research could test fans located off-center or in rooms of different aspect ratios, and that we could use that information to extend the models in this paper. For cases with multiple fans, in a prior exploratory experiment with multiple fans where all fans operated at the same speed, each identical 'cell' created by an individual fan had a similar (slightly higher) air speed distribution than a comparable single fan case with the same set of dimensionless ratios. Further experiments could validate this and develop regressions to adjust the models accordingly. Finally, it is important to note that [25] shows that furniture strongly affects the air speed distribution. Furniture layout isn't typically known at design stage and in any case changes often within the building lifetime. Given such a scenario, an appropriate approach may be to measure the aggregate effect that different types of furniture and layout have, and to use that data as a modifier to the models presented in this paper.

4. Conclusions

We defined the concept of fan air speed as the rated airflow of the fan divided by the area swept by the blades. We show that normalizing the air speed at any point in the room against the fan air speed provides comparable profiles across a wide range of fan and room sizes. For a fixed set of fan and room characteristics, the measured air speed at any location is linearly proportional to the fan air speed, rotational speed, and airflow. This applies for fans blowing both upwards and downwards, regardless of fan type, though the relationship is less accurate at very low fan air speeds (< 1 m/s). We also show that the maximum air speed at any individual measurement point (a specific height and distance from the fan) in the occupied zone was typically 1.2 to 1.6 times the fan air speed for all 56 downward direction tests.

We demonstrated that in the region outside of the fan blades, the seated and standing average air speeds increase proportionally with the ratio of fan diameter to room width. We quantified the spatial uniformity of the air speed distribution and showed that larger diameter fans (or larger diameter to room ratios) provide a more uniform environment. We also showed that mount distance does not have a significant effect until it approaches approximately 0.2 times the fan diameter. We showed that for the otherwise similar conditions (i.e. same diameter, estimated fan airflow, blade height, etc.) but different fan types, the air speed distribution is very similar in the region outside the fan blades. Air speeds differ under the blades, however, the effect on the air speed distribution is minor overall. Furthermore, there is circumstantial evidence that the rated airflow depends on the test-method used. It seems beneficial for all fans to be rated using the same test, or to quantify the difference between test-methods for an identical fan to provide further validation.

We also reversed the fan direction, blowing upwards towards the ceiling. This yielded a much more uniform air speed distribution than blowing downwards and has applications where having a homogenous air speed may be desirable (e.g. when occupants cannot choose their location in the room). The air speeds are lower than for a comparable downward test, however, they are still high enough for an appreciable cooling effect. The upper quartile and maximum of the area weighted average air speeds for seated occupants for the upwards tests were 0.5 and 1.17 m/s respectively, indicating that it is feasible to select fans that will provide equivalent comfort conditions at substantially higher temperatures while blowing upwards and providing a more uniform air speed distribution. Upwards tests with larger fan to room size ratios, higher fan rotational speeds, or inverted blades (so that the geometry is symmetrical with the downwards case), provided higher air speeds. We developed dimensionless models that apply to the majority of practical ranges of fan and room sizes.

The inputs are: fan diameter, blade height, ceiling height, room size, and fan air speed. The fan air speed is calculated using the fan diameter, rotational speed (as a percentage of maximum), and a linear regression to the rated fan airflow at different fan rotational speeds. The models predict the lowest, area-weighted average, and highest air speeds for a seated or standing occupant in the room, with a median absolute error of 0.03, 0.05 and 0.12 m/s respectively. Further work could focus on extending the model to address current limitations, such as developing modifiers for non-square rooms, multiple fans, and furniture.

Our hope is that this paper will allow designers to better understand air distribution in rooms due to ceiling fans, and more easily select an appropriate fan for their application.

5. Acknowledgements

The California Energy Commission Grant:EPC-16-013, supported this work, with cost share provided by the Center for the Built Environment and Big Ass Fans. We thank Jayme Webb, Michael Harp & Michael Smith for setting up and acquiring data for this experiment, and Marta Delgado for preparing the first figure.

6. Declaration of interest

We performed these experiments in a fan manufacturer's test facility and one of the authors is an employee of that organization. We anonymously report the fan types and all other authors declare no interest.

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APPENDIX C:
Lab #3 Report and Corrective Power Index

EXECUTIVE SUMMARY

Project Results

The purpose of this Lab 3 Report is to review ceiling fans and other Personal Comfort Systems and thermal comfort. This is combined with describing the *Corrective Power Index* for quantifying the effect of Personal Comfort Systems such as ceiling fans in providing comfort and reducing energy. The CP index can be used to evaluate both the equivalent change in ambient temperatures caused by fans as well as the changes in subjective responses, such as thermal sensations and comfort. As an offset to normal ambient room temperature, the CP allows building engineers and operators to modify temperature setpoints and control sequences when PCS is included in their designs.

CHAPTER 1: Introduction

The EPIC fans project consists of four technical tasks: laboratory testing, multifamily common area site demonstrations, multifamily dwelling unit site demonstrations, and technology readiness (Figure 2). This lab report is the third of three, and discusses the rating system and comfort performance index.

Lab Report #1 described laboratory testing to determine the velocity and temperature profiles of various fan configurations, which will aid in evaluating thermal comfort. The objective of the first lab study was to experimentally measure and compare air speed profiles with obstacles placed in different locations in the airflow path of a ceiling fan. Specifically, researchers place a table and partition in different locations within a test chamber and evaluate the resulting variations in the air speed profile. This study was performed at UC Berkeley in CBE's climate-controlled environment chamber[15] with one ceiling fan and a single table and partition. The objective of the BAF lab study was to conduct pilot measurements in BAF lab with one and two fans to explore the changes of air speed field in the occupied zone as a function of fan blade to floor height and interaction of flows generated by two ceiling mounted fans as a function of the fan speed. This study took place at BAF facilities in Kentucky with multiple ceiling fans in different configurations (spacing, height). The Lab Report #2 examined the interactions of airflows due to multiple-fan applications, helped develop the Design tool and guidance for sizing and spacing fans and predicting the air speeds in typical furnished spaces.

Lab #2 Report examined the interactions of airflows due to multiple fan applications, helped develop the Design Tool and guidance for sizing and spacing fans, and predicted the air speeds in typical furnished spaces (. The goal of the Design Tool is to specify and locate a fan or fans to achieve a desirable air distribution within a space. This work is based on laboratory testing of variation in ceiling-fan-driven air movements in terms of room size, fan mounting height, furniture, partitions and other influencing factors. The research team measured air speeds in rooms due to ceiling fans in 78 full-scale laboratory tests. The factors were the room size, fan diameter, type, speed, up/down direction, blade height, and mount distance (i.e. blade to ceiling height). The team demonstrated the influence of these factors, showing that the most significant are speed, diameter and direction. With other factors fixed, the area-weighted average room air speed increases proportionally with fan air speed and diameter. Blowing fans upwards yields lower but far more uniform air speeds than downwards. For the same diameter and rated airflow, fan type has little effect on the air speed distribution in the region outside the fan blades. The team developed several new dimensionless representations and demonstrate that they are appropriate for comparisons over a wide range of fan and room characteristics. Dimensionless linear models predict the lowest, area-weighted average, and highest air speeds in a room with a median (and 90th

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[15] http://www.cbe.berkeley.edu/aboutus/facilities.htm

percentile) absolute error of 0.03 (0.08), 0.05 (0.13), and 0.12 (0.26) m/s respectively over all 56 downwards tests representing typical applications. These models allow the team to answer the question ‘What air speed distribution can I expect for a given fan and room?’.

The purpose of this Lab 3 Report is to review ceiling fans and other Personal Comfort Systems and thermal comfort. This is combined with describing the *Corrective Power Index* for quantifying the effect of Personal Comfort Systems such as ceiling fans in providing comfort and reducing energy. The CP index can be used to evaluate both the equivalent change in ambient temperatures caused by fans as well as the changes in subjective responses, such as thermal sensations and comfort. As an offset to normal ambient room temperature, the CP allows building engineers and operators to modify temperature setpoints and control sequences when PCS is included in their designs.

CHAPTER 2:
Comfort Performance

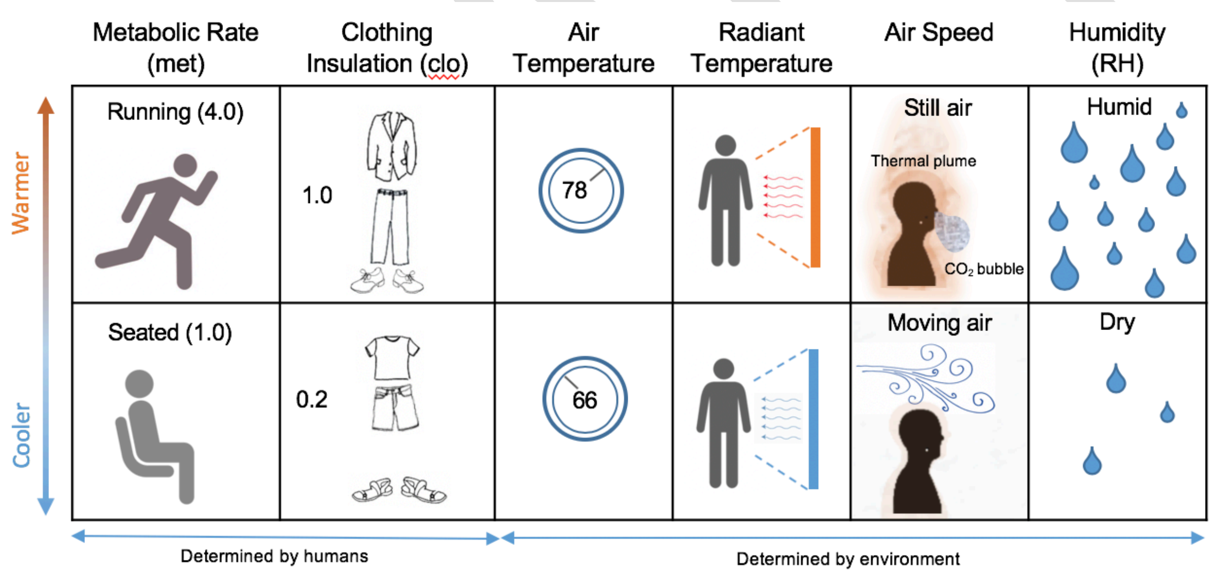
This chapter describes the background of ceiling fan cooling indoors, describes the use of personal comfort systems to provide comfort and save energy, defines the Corrective Power Index, and outlines fan use for comfort across the globe.

Background

Proximity to People

Fundamentally, ceiling fans cool *people* and not spaces. Thermal comfort is influenced by personal factors (clothing and activity level) as well as environmental factors (air temperature, radiant temperature, relative humidity, and *air speed* (Figure 5)). Moving air disrupts and disperses the thermal plume created by warm bodies and engenders a cooling effect, especially if skin is exposed. Since ceiling fans do not cool spaces, occupancy sensors can be used to turn off fans when no one is present.

Figure 50: Factors in Thermal Comfort.



Air Speed is just one factor in thermal comfort

Credit: Therese Peffer

Spatial Placement

Many factors affect the placement of ceiling fans, including physical building layout (walls), architectural detail (placement of light fixtures, structural ceiling elements (dropped ceiling joists), HVAC supply vents and return grilles, other ceiling affixed items (such as fire/smoke alarms, sprinkler systems, occupancy sensors, security cameras), and thermal comfort.

Since ceiling fans cool people, one design criterion is to locate ceiling fans where people can most directly feel the air movement: above seating areas. Sometimes this location is in conflict with aesthetics, such as architectural patterns of symmetry and balance in ceilings, typically with lighting or structural elements. In rooms such as living rooms, the fans would ideally be located above the seated area (e.g., chairs or couches). In large rooms such as common rooms of multifamily housing, the fans should be spaced evenly to produce an even flow of moving air.

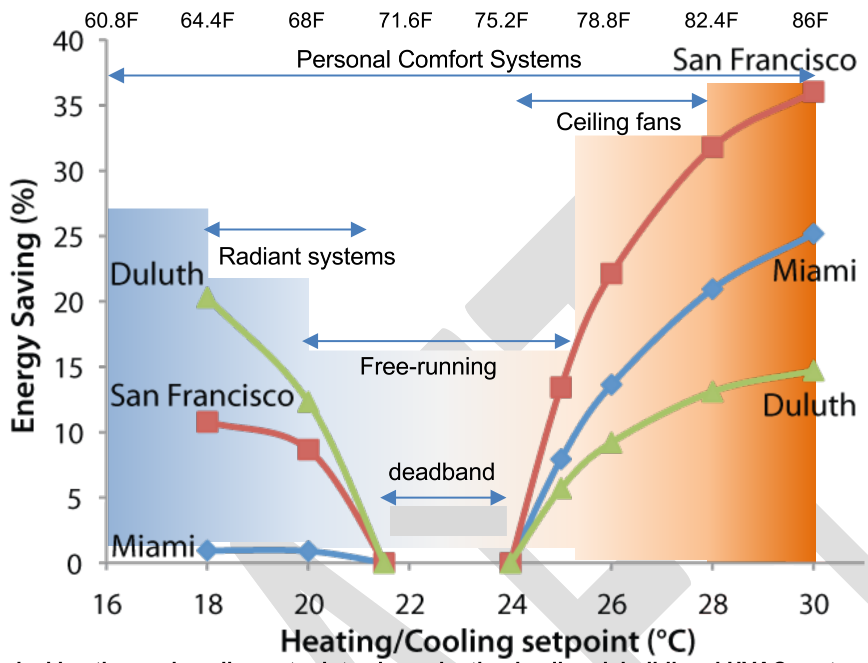
Control, Comfort and Energy Savings

Many buildings provide indoor thermal environments with a narrow range of temperature and humidity that is constant over time, uniform throughout space, and targeting the occupants' perceptual thermal "neutrality." This has two undesirable consequences: first, achieving narrowness, constancy, and uniformity of thermal conditions in a space requires far more energy than looser forms of control (Hoyt, Arens, and Zhang 2015; Ghahramani et al. 2016). Second, because groups of occupants contain individuals with widely varying thermal neutralities and comfort requirements, even the most optimized group neutrality will leave a substantial proportion of the group (~20%) either too warm or too cold (E. A. Arens et al. 2010). Therefore, the best performance for this type of control is quite limited (Zhang, Arens, and Pasut 2011).

In contrast to this are two general approaches: 1) personal control over the ambient space temperature, as provided by thermostats in private offices, and 2) localized thermal conditioning of occupants' bodies, as achieved by **Personal Comfort Systems (PCS).** Personal Comfort Systems are devices that provide cooling or heating effects to an individual person independent of a central Heating Ventilation and Air Conditioning (HVAC) system. PCS devices include chairs with heating and cooling elements, desk or ceiling fans, and other devices that provide heating or cooling to the hands, wrists, neck, face, legs or feet. PCSs have been found capable of providing 100% occupant thermal comfort in spaces where substantial numbers of people occupy each temperature control zone (Bauman et al. 1998). Local thermal conditioning also promises to lower the energy consumed by central HVAC (unlike the private office approach) because it is inherently more efficient to heat and cool the individual occupants directly than to condition the entire ambient space (Zhang et al. 2015).

Energy savings from using ceiling fans stems from raising temperature setpoints so that air conditioning systems cycle less frequently. Figure 6 below shows energy savings from simulations conducted in different climates to evaluate potential savings in commercial buildings due to wider temperature setpoints while utilizing Personal Comfort Systems, such as fans for warmer weather. Ceiling fans can provide the effect of cooling for hot-humid to mid climates. A wider deadband (the interval between cooling and heating setpoints) reduces HVAC energy 7-15% per degree ˚C.

Figure 51: Savings in Energy due to Widening Setpoints Allowed by Personal Comfort Systems

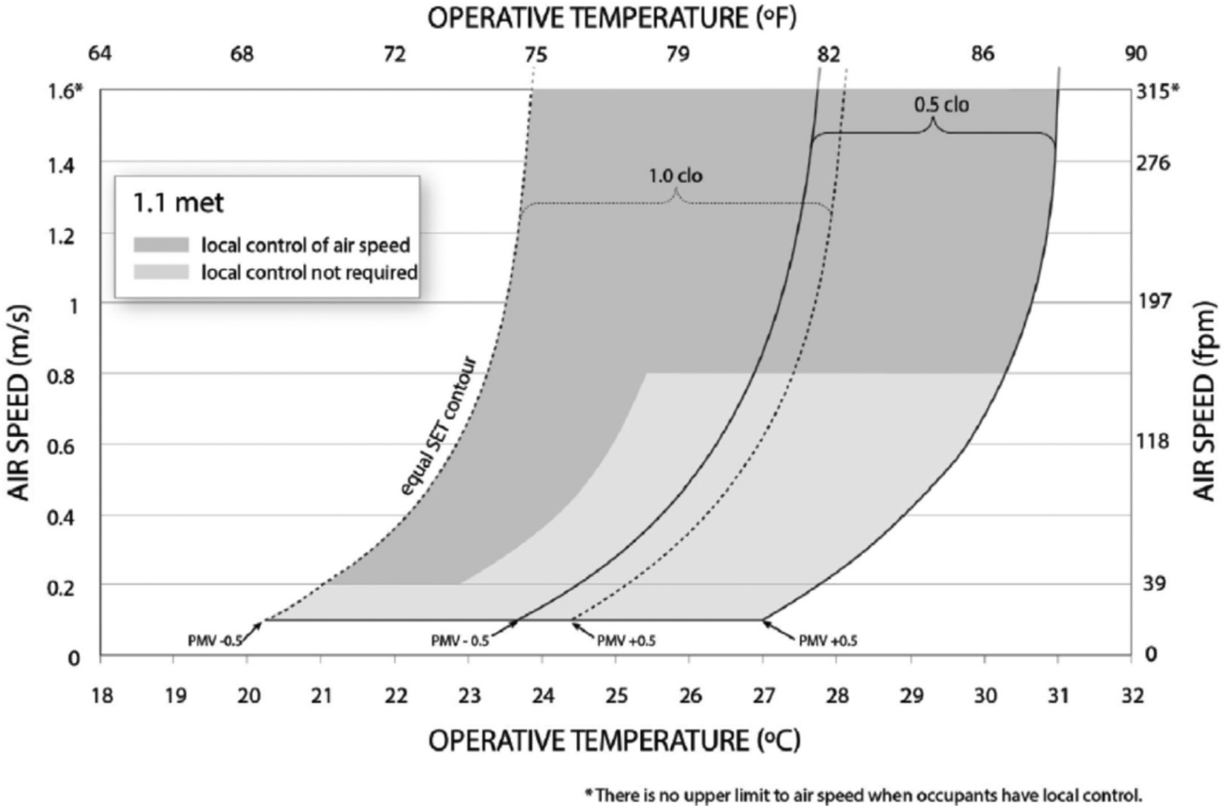


Compared to typical heating and cooling setpoints shown by the deadband, buildings' HVAC systems using a wider temperature range made comfortable by Personal Comfort Systems save energy. A free-running building has no mechanical heating and cooling system.

Credit: Hui Zhang, UC Berkeley

The American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) provides guidance on thermal comfort in buildings, including using air movement. Figure 7 below shows acceptable ranges of Operative Temperature (essentially the average of air temperature and radiant temperature (temperatures that radiate from surfaces)) for different clothing levels and a constant metabolic rate with local or personal control of air speed. Air movement in general expands the comfort zone in providing acceptable conditions with increased indoor temperature.

Figure 52: Acceptable Ranges of Operative Temperature with Air Movement



Providing personal control of air speed extend the upper temperature range of the comfort zone.

Credit: ASHRAE (ANSI/ASHRAE 2017)

Local thermal conditioning devices can take advantage of the sensation of pleasantness or *alliesthesia* they induce in people that occurs with the relief of physiological thermal stressors (Cabanac, Massonnet, and Belaiche 1972). Many people can relate to the sensation of coming into a warm house on a cold day, or entering a cool space on a very hot day: a sense of relief and pleasure washes over oneself, resulting in feeling "very" comfortable. Alliesthesia may be categorized in time and in space. Temporal alliesthesia occurs during transitions in the body's thermal state from too warm or too cool toward just-right; a person is more sensitive to changes in temperature than in static states (Cabanac, Massonnet, and Belaiche 1972; Hensel 1982; Ring and de Dear 1991). Local conditioning devices typically have rapid response times, making them capable of activating this form of alliesthesia in occupants whose thermal conditions or activity levels vary during the course of the day. Spatial alliesthesia refers to effects of too warm or cool thermal conditions occurring on various body parts at the same time (Zhang, Arens, and Zhai 2015; Parkinson 2015; Parkinson, De Dear, and Candido 2016).

It is possible to target a small amount of energy on the most sensitive body part(s) to achieve a strong whole-body comfort effect. Spatially non-uniform thermal comfort was first documented in Zhang (Zhang 2003), in which individual portions of the body were isolated and heated/cooled while the surrounding environment was kept independently warm, cool or neutral. The extremities (hands, feet, face, neck) temperatures were observed to be very important to the perception of whole-body thermal comfort. Discomfort from a cold foot/hand for example would dictate whole-body discomfort, so by concentrating warming on the foot and hand, whole-body comfort can be efficiently maintained in cool environments. Similarly, cooling the head and back/seat are critical for comfort in warm environments (E. Arens, Zhang, and Huizenga 2006; Zhang et al. 2010). These psychophysiological principles will underlie the most effective and efficient Personal Comfort System (PCS) designs.

Systems and devices that heat or cool individual occupants (or small groups of occupants) have existed for many years. Various forms of desk, wall, and ceiling fans, radiant or convective heaters, and temperature-controlled surfaces on chairs, desks, and floors, are available in the marketplace. They are mostly used as correctives by individuals whose thermal requirements are warmer or cooler than that of the average population. Their use has rarely been thought of as integral to the building's conditioning system. An example of this are room fans; although their cooling efficiency per occupant is higher than that of HVAC cooling, they have rarely been interfaced with the HVAC thermostatic control. Since fans cool occupants individually or in small groups, with spatial coverage that is inherently nonuniform, the engineer's design concern about how to assure that there is full coverage (or availability) to occupants is a legitimate one that has not yet been seriously addressed.

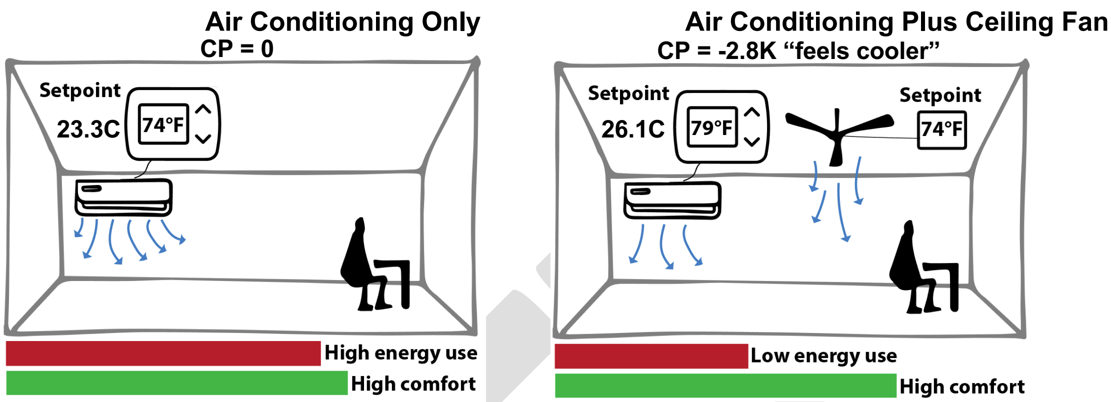
Corrective Power Index

A range of commercial and prototype PCS devices have been investigated in laboratory and field studies. A literature review by Vesely and Zeiler (Veselý and Zeiler 2014) found that personalized heating/cooling devices maintaining thermal comfort at ambient temperatures 4–5 Kelvin (K) higher or lower than those recommended in current standards.

Several studies have found that fans in particular relieve occupants' discomfort in warm environments, and make it possible to elevate setpoint temperatures of air conditioning systems, and thus reduce the energy consumption of buildings (He et al. 2019; Hoyt, Arens, and Zhang 2015). Some researchers have proposed ways to evaluate the effects of fans on thermal comfort and energy saving. Yang et al. (Yang et al. 2015) used the cooling fan efficiency (CFE) index to evaluate the ratio between the fan-generated whole-body cooling effect (as measured with a thermal manikin) and fan power consumption.

The research team proposed a **Corrective Power (CP)** index to quantify the extent to which a fan can "correct" a warm ambient temperature toward neutral (Zhang, Arens, and Zhai 2015). The project reviewed over 40 studies with PCS systems whose published human subject and manikin studies allow their cooling and heating effects to be represented as corrective power (CP) value. CP is defined as the difference between two ambient temperatures at which the same thermal sensation is achieved—one with no PCS (the reference condition), and one with a PCS in use. CP is expressed in degrees in Kelvin (K), the standard way of expressing temperature differences on the Centigrade scale. If subjects voted a neutral thermal sensation at a particular combination of warm air temperature and air movement (see Figure 8 on right), and also voted neutral sensation with a lower air temperature in still air (Figure 8, left), then the temperature difference is the CP, which will have a negative value. Published studies of PCS were reviewed to extract their CP values. Cooling CP ranges from -1 to -6K, and heating CP from 2K to 10K.

Figure 53: Using Ceiling Fans to Provide Cooling to Lower Energy Use

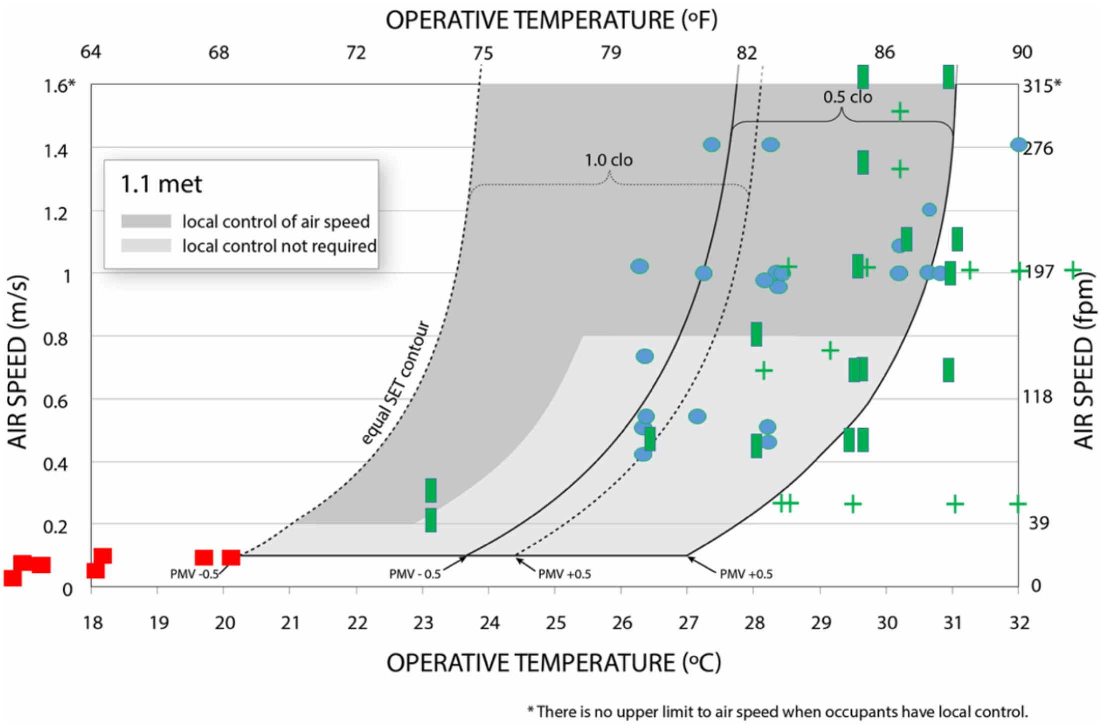


Left: Air conditioning provides cooling. Right: Ceiling fans provide the "first stage" of cooling, thus showing a negative CP.

Credit: Dana Miller, UC Berkeley

The project reviewed four studies of vertical air flow on occupants through ceiling fans to determine CP (Figure 9). Cooling by ceiling fans and large-area box fans covering all directions provide similar effects. These devices' CP is stronger than for frontal air jets. At lower ambient temperature (26ºC, 27ºC) and a low air speed of 0.25 – 0.6 m/s, CP was -3K. At 28ºC ambient temperature, CP can be as great as -4K. Generally, CP is about -1K – 2K stronger than the frontal air jet within this temperature and air speed range. At the higher speed of 1 m/s, the CP can be -4K to -7K. One study showed a ceiling fan can provide comfort up to 33ºC ambient temperature.

Figure 54: Review of Studies on Acceptable Ranges of Operative Temperature with Air Movement



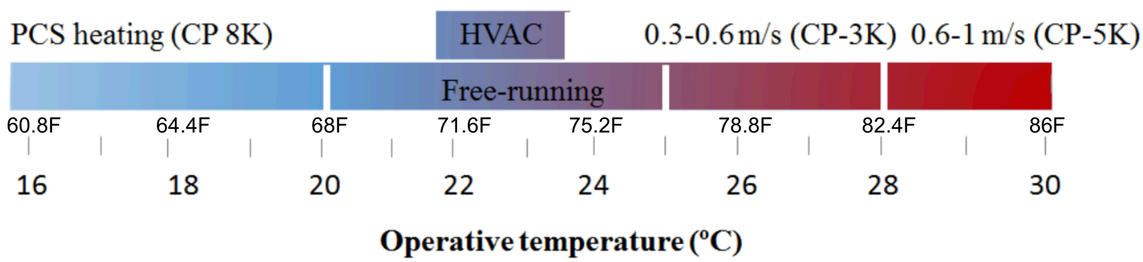
Green plus signs indicate studies using ceiling fans to provide cooling; air speed from front air jets are shown by blue circles and green rectangles represent uniform airflow from box fans.

Credit: Hui Zhang (Zhang, Arens, and Zhai 2015)

The CP index can be used to evaluate both the equivalent change in ambient temperatures caused by fans as well as the changes in subjective responses, such as thermal sensations and comfort. Based on the CP, He et al. (He et al. 2017) proposed the corrective-efficiency-to-power (CEP) index, which describes how much energy is consumed when 1-K CP value of personal comfort systems (PCSs) is achieved. The CEP index provides a detailed but simple calculation method for evaluating the energy-efficiency of PCSs, including fans. Due to the advantages of thermal comfort and energy conservation, fans have become the most successful commercial PCS. Fans are used in offices, classrooms, houses, and other indoor environments.

Figure 10 represents simplified ranges of temperature in which comfort is achievable with PCSs. On the left side, the heating PCS devices (heated chairs, foot and leg warmers) provide positive values of CP by correcting temperatures below the traditional neutral to be comfortable; these therefore have a CP of 7K – 10K from neutral. Heating PCS devices extend the comfort zone down to 16ºC ambient temperature. The cooling side is based on frontal air jets whose CP values are conservative compared to those of ceiling fans and uniform air flow. Air speeds between 0.25 – 1 m/s from ceiling fans are seen to provide comfort up to 33ºC ambient temperatures, and in common practice can be used to 28C (82.4F).

Figure 55: Acceptable Ranges of Operative Temperature with Air Movement



Providing personal control of air speed extend the upper temperature range of the comfort zone.

Credit: Hui Zhang (Zhang, Arens, and Zhai 2015)

CP can also be expressed in terms of comfort votes (CP-C) or thermal sensation votes (CP-S) from the subjects' survey votes, quantified in the scale units of their voting scale. CP-C and CPS quantify the comfort and sensation differences between occupants with PCS and occupants without PCS (the reference condition).

CP can also be determined from electrical manikin tests. In these, CP is determined by directly measuring the Equivalent Homogeneous Temperature (EHT) with and without PCS. The difference is the CP in Kelvin. EHT is a commonly used metric in manikin testing, defined as the uniform ambient temperature at which the manikin's dry heat loss is equal to that under an actual nonuniform environment (in this case the PCS environment).

As an offset to normal ambient room temperature, the CP allows building engineers and operators to modify temperature setpoints and control sequences when PCS is included in their designs.

Review of Thermal Comfort and Fan Use

This project also reviewed fan-use rates in 54 field studies and their effects on thermal comfort, energy conservation, and human productivity (He et al. 2019). The fan-use rate is defined as the percentage of the occupants who are using fans corresponding to an ambient temperature. The goal of this analysis was to isolate the effects of fans on thermal comfort in field studies. The approach entailed a comparison of two groups of field studies: one group with fans and the other without. For the group with fans, studies were conducted in buildings in which at least 70% of the total occupants used fans in warm seasons. Their neutral temperatures (thermal sensation vote (TSV) equals to 0) and upper limits of neutral-zone temperatures (TSV = + 0.5) were analyzed. Choosing TSV = + 0.5 as the upper limit of the neutral zone was based on the suggestions of ASHRAE Standard 55. For the group without fans, studies were selected from buildings in which none of the occupants used fans. The thermal comfort of occupants in air-conditioned (AC) buildings without fans was not included in the analysis because people in AC buildings are less adaptive to warm environments and the comparison would not be influenced by adaptation.

Based on HVAC system operation conditions, the buildings' cooling strategies in the collected literature were divided into three types: air-conditioned (AC), mixed-mode (MM) and naturally-ventilated (NV). In AC buildings, mechanical air-conditioning systems provide cooling. MM buildings have both mechanical cooling and operable windows, and only a fraction of the air-conditioning systems are used or the air-conditioning systems run for only part of the time. NV buildings have operable windows, but either have no air-conditioning systems or the air-conditioning systems are turned off. Therefore, the comfort comparison mainly consists of the results obtained in Mixed Mode (buildings with operable windows and mechanical HVAC systems) and Natural Ventilated (NV) buildings without fans, and AC, MM, and NV buildings with fans. The major findings are:

(1) Currently, fans are more prevalent in MultiMode (MM) and Naturally Ventilated (NV) buildings but not in Air Conditioned (AC) buildings. Despite some fan-use rate differences caused by different cooling strategies (AC, MM and NV) and building functions (residential and office), fan-use rate models in different buildings are mainly decided by environmental temperatures. This result indicates that the main trigger of using fans is the indoor or outdoor temperatures, not building types or functions. Several models were established to present fan-use rates in different buildings correlating with indoor and outdoor temperatures, respectively.

(2) Using fans increases the average neutral temperatures and upper limit of neutral-zone temperatures (using TSV = + 0.5) in buildings by about 3 K from 25.7 °C to 28.7 °C and from 27.5 °C to 30.7 °C, respectively.

(3) Fan-use reduces AC-use in MM buildings. According to the AC-use rate models in this review, the peak reduction of AC-use rate is about 20% when the outdoor temperature is 32.5 °C. When the outdoor temperature is 25 -- 35 °C, the AC-use rate is reduced by more than 15%, which indicates that at least 15% of cooling energy can be saved in MM buildings.

(4) When the temperature rises within 1 K from its comparison temperatures, offering fans to occupants can improve their productivity better than it under the comparison temperatures without fans. As temperature increases more, by 1–3 K from the comparison temperatures, a trend shows that fans can still maintain occupants' productivity at the levels un- der comparison temperature. This 3 K is coincident with the extensions of neutral temperatures and the upper limits of neutral-zone temperatures. As temperature further increases beyond 3 K from the comparison temperature, fan cannot maintain the productivity level from decreasing.

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APPENDIX D:
Final Field Report

EXECUTIVE SUMMARY

Background

As part of the EPIC Fans Project, the research team at the Center for the Built Environment (CBE), at the University of California, Berkeley (in collaboration with TRC, Association for Energy Affordability (AEA), and Big Ass Fans (BAF)) conducted field demonstrations to study the integration of smart Haiku® ceiling fans with SenseME™ control and a smart thermostat through pilot retrofits at four affordable multifamily housing sites in California. The goal of the overall study was to identify optimal configurations for the integration of two newly available technologies: smart ceiling fans and communicating thermostats. This integrated solution has the potential to automate energy savings in ways customers not only accept, but actually seek, for it provides improved comfort and lower energy costs.

These field demonstrations sought to demonstrate the energy saving and improved comfort potential of this integrated solution in retrofit scenarios in residential dwelling unit, office, and shared common space applications.

Intervention

The research team conducted field demonstrations at the following sites and application scenarios:

- Franco Center, Stockton, CA - a five story, 112-unit senior living facility with community spaces and building staff offices on the first floor
  - Two large community activity areas
  - Two private office spaces
  - One reception office space
  - Two support spaces
  - One kitchen preparation area
- Rolling Hills, Newman, CA - a complex consisting of the community center/office building and thirteen tenant buildings containing a total of 52 units
  - One community activity room
  - One kitchen (supporting the community room)
  - One computer lab
  - Two private office spaces
- Parksdale 1, Madera, CA - a complex consisting of the community center/office and twelve tenant buildings containing a total of 48 units
  - One community activity room
  - One kitchen (supporting the community room)
  - One computer lab
  - One lobby / entrance space
  - Two private office spaces

- Parksdale 2, Madera, CA - a complex consisting of the community center/office and twelve tenant buildings containing a total of 48 units
  - One community activity room
  - One kitchen (supporting the community room)
  - One computer lab
  - One lobby / entrance space
  - Two private office spaces
  - Six dwelling units (Three 2-bedroom units, Three 3-bedroom units)

The research team conducted the field demonstrations according to the following schedule:

- July 2017: Installation of monitoring equipment
- July 2017 – June/July 2018: Pre-installation monitoring period
- June/July 2018: Installation of ceiling fans and thermostats
- June/July 2018 – October 2019: Post-installation monitoring period
- December 2019: Removal of monitoring equipment

The research team installed monitoring equipment at each demonstration site to monitor HVAC energy use and indoor environmental quality (IEQ) for pre-installation monitoring period of approximately one year, and a post-installation monitoring period of approximately 16 months. Pre-installation data collection included continuous monitoring of HVAC energy use, temperature, and relative humidity, as well as observations of thermostat settings. Following installations of the ceiling fans and thermostats, the research team also collected data on fan operation and thermostat settings directly from the equipment. Monitored data was transmitted in real-time to the research team via cellular data Wi-Fi hotspots deployed along with the monitoring equipment. In addition, the research team conducted surveys and interviews of occupants on their perceptions of thermal comfort in the demonstration spaces following the equipment installations. Survey and interview respondents included dwelling unit residents, office workers, and occupants in the community activity areas.

The research team coordinated with BAF to develop fan layouts for each site, including CFD analysis to determine air speed potential, and in-person visits to each site to determine ideal configurations, and to resolve any potential conflicts with existing building systems such as structure or plumbing.

A total of 99 ceiling fans and 12 thermostats were installed across the four demonstration sites, including five ceiling fans in each 2-bedroom dwelling unit and seven ceiling fans in each 3-bedroom unit. The research team encouraged the demonstration site occupants to increase cooling setpoints and use the ceiling fans as the first source of comfort cooling. In addition, the ceiling fans were equipped with a custom firmware developed for this demonstration to automatically turn the fans on to meet the occupants' desired comfort level. The fans were also programmed to adjust the target comfort level based on any manual adjustments occupants made in fan use and fan speed.

Results

Overall, the intervention of installing smart ceiling fans and thermostats and educating occupants about potential energy and comfort benefits yielded substantially reduced compressor energy consumption in comparison to the baseline period.

Though the results at individual demonstration locations and applications varied widely, taken as a whole, the field demonstration resulted in 39% energy savings compared to baseline conditions, when normalized for floor area served. However, the savings varied a lot across all 13 compressors spread across the sites. This variability reflects the diversity in building, HVAC system and space types, as well as occupants, their preferences and motivating incentives.

Per the occupant interviews and surveys, all occupants reported high satisfaction with the ceiling fans, and the vast majority noted a preference for the automated operation of those fans. The occupants were given the choice to keep the fan firmware as automatic, or to switch to a fully manual operation at the end of the project, and they all chose to keep the automated operation features. Even in sites where the measured energy data does not show savings, the occupants still used and interacted with the fans regularly. All occupants reported an improvement in comfort compared to before the fans, indicating that even when no savings materialized, there was a secondary benefit to thermal comfort.

The results for the thermostats are more mixed. There was a steep learning curve, that many of the occupants struggled with. There were some issues related to control of the system fan, which had an adverse effect on energy consumption. Additionally, the lack of language support was an issue for many of the occupants, particularly in the residences. Due to the nature of this intervention, we cannot decouple the energy savings of the fans or the thermostats from each other, and it is possible that there was a counteracting effect.

Despite the successes described above, the field demonstrations encountered several challenges implementing the smart ceiling fan and communicating thermostat technologies as originally intended for the study. Development of a custom fan firmware was required to fully implement the automated fan operation as the research team envisioned. Although the measured results of the field demonstrations show substantial energy savings, there is a need for further development to achieve widespread adoption. The technologies could be further simplified, and usability could be further improved. This is particularly the case for the thermostats. The research team also notes that we provided oral and written educational materials that described how the integrated system works, and its potential for energy savings. We also suggested new cooling setpoints for the thermostats, and with occupant permission, implemented those new setpoints when the equipment was installed. Though we made it clear that occupants were free to change these settings at any point during the study (and most did), it is still likely that these interventions had a positive effect on outcomes. These interventions - or similarly effective ones - would likely be needed to maximize the energy savings from a larger scale deployment, and that may be difficult to do at scale.

CHAPTER 1: Introduction

This report combines the Multifamily Common Area Field Study: Final Report and Multifamily Dwelling Unit Field Study: Final Report into a single document. All content in this report applies to both common area and dwelling unit field studies, unless otherwise noted.

Field Demonstrations

This final field demonstration report is the final documentation of the field demonstration tasks. The purpose of this report is to document the process and results of the field demonstrations in multifamily common areas and dwelling units. The content of this report includes information adapted from the three previous interim reports, as well as additional updates and final results from all field demonstration sites.

CHAPTER 2: Demonstration Site Selection

This chapter summarizes the process the research team used to determine the demonstration sites for this project. Though several sites had agreed to participate in the study during the proposal phase, once the project commenced the team conducted a thorough evaluation of each of the sites against the needs of the study.

Site Selection Criteria

The first step in determining suitable demonstration sites was establishing a set of criteria for participating sites. The following sections outline the site selection criteria established by the research team. These include general criteria that apply across all demonstration conditions, and two separate sets of criteria for the common spaces and the dwelling units in the study. In many cases, the research team developed both minimum requirements and preferred conditions.

General Criteria

Site selection requirements began with several general requirements and one desirable condition, as outlined below.

General requirements:

- Must have electrical service provided by an investor-owned utility (SCE, PG&E, or SDG&E)
- Sites must be in an area with a CalEnviroScreen score of at least 75%[16]
- No additional planned retrofits or renovations between now and December 2018

Desirable criteria:

- Existing electrical sub-metering in place

Common Spaces

Criteria for common spaces in the demonstration study are outlined below in Table 3. For each category, the table includes both minimum requirements and preferred conditions, as well as potential sources of data.

[16] A map showing CalEnviroScreen scores for the entire state is available here.

Table 3: Demonstration site selection criteria for common spaces.

Category	Minimum Requirement	Preferred Conditions	Source of data
Planned energy retrofits	No additional energy efficiency retrofits planned from now until December 2018		
Major renovations	No major renovations planned from now until December 2018		
Spaces and Space Types	Multiple spaces and space types at one site	Varieties of occupancy types: possibly including office spaces, conference rooms, exercise rooms/fitness rooms, conditioned lobbies, community meeting rooms, group dining rooms, etc. At least one space that requires multiple fans (> 500 sq.ft.)	Owner survey/email
Ceiling Height	8'-6"	at least 9'	Owner survey/email
Air Conditioning	Must have air conditioning: All common spaces served by dedicated AC system that is separate from the AC system that serves dwelling units.	Must have air conditioning: Multiple single zone AC units for separate common spaces	Review mechanical drawings OR owner survey/email
	HVAC systems with functionality not supported by Nest or ecobee thermostats should be avoided (including, but not limited to, VRF or variable speed heat pump systems). Ideally, AC systems will have a single point of power, and be compatible with conventional residential thermostat signals provided by Nest or ecobee (up to 3-stage input available from Nest).		Review mechanical drawings OR owner survey/email

Category	Minimum Requirement	Preferred Conditions	Source of data
Total Area	> 1,000 sq. ft. of common spaces for retrofit per site	> 2,500 sq. ft. of common spaces for retrofit per site	Owner survey/email
Ceiling Type	Ability to install electrical wiring and fans	Drop ceiling	Owner survey/email
Space occupancy	Space is occupied (offices) and regularly used (meeting, fitness, dining, etc). No plans to not use spaces from now until December 2018		
Lighting Equipment	Lighting can be easily adapted to accommodate fans (combination of lighting and fan must not cause flicker)	Lighting does not need to be modified to accommodate fans	Review electrical/lighting drawings, or photos

Dwelling Unit Spaces

Similar to the common space criteria outlined above, Table 4 below describes the criteria for dwelling units in the study.

Table 4: Demonstration site selection criteria for dwelling units

Category	Minimum Requirement	Preferred Conditions	Source of data
Ceiling Height	8’	at least 8’-6”	Owner survey/email
Planned energy retrofits	No additional energy efficiency retrofits planned from now until December 2018		
Major renovations	No major renovations planned from now until December 2018		

Category	Minimum Requirement	Preferred Conditions	Source of data
Air Conditioning	Must have air conditioning: Dedicated AC systems for each unit; ability to separately meter AC energy for each unit		Review mechanical drawings OR owner survey/email
	HVAC systems with functionality not supported by Nest or ecobee thermostats should be avoided (including, but not limited to, VRF or variable speed heat pump systems). Ideally, AC systems will have a single point of power, and be compatible with conventional residential thermostat signals provided by Nest or ecobee (up to 3-stage input available from Nest).		Review mechanical drawings OR owner survey/email
Dwelling Unit Spaces	Ability to install fans in living room, dining room, all bedrooms, and any other main spaces in each unit to accommodate higher AC setpoint		Review architectural & lighting drawings OR owner survey/email
Lighting Equipment	Permanently installed lighting in all retrofit spaces (see above) in each unit does not interfere with ceiling fans (combination of lighting and fan must not cause flicker)	All retrofit spaces (see above) in each unit have existing ceiling surface or pendant mounted luminaire located near the center of the room that can be replaced with ceiling fan	Owner survey/email
Dwelling unit occupancy	Dwelling unit is currently occupied and not expected to be vacant (except in the case of tenant turnover) from now until December 2018		Ask this question after site is selected, during dwelling unit recruitment

Original Site Commitments and Evaluation

During the proposal phase, the research team secured initial commitments for participation for six sites from three different owners, as follows:

Table 5: Proposal Phase Initial Site Commitments

Owner	Site Location	IOU Service Territory
Self Help Enterprises	Madera, 93638	PG&E
	Newman, 95630	PG&E
Community Housing Works	San Diego, 92113	SDG&E
	Fresno, 93705	PG&E
Domus Development	El Monte, 91733	SCE
	El Monte, 91733	SCE

Following the development of the site selection criteria described above, the research team evaluated each of the committed sites against the established criteria. For various reasons, four of the initially committed sites were not compatible with the study:

- The San Diego site and one of the El Monte sites did not have a sufficient amount of conditioned common area spaces for participation in the study.
- The Fresno site was implementing other energy efficiency retrofits that conflicted with the schedule of the study.
- The other El Monte site uses individual mini-split air conditioning systems in most of the common areas that would have been prohibitively challenging for energy monitoring; and several of the spaces had ceiling conditions and lighting layouts that would have conflicted with optimal ceiling fan placement.

The remaining sites in Madera and Newman were found to be compatible with the site selection criteria.

Additional Site Recruitment and Commitments

Following the evaluation of the original sites, the research team sought out new opportunities to complete the list of demonstration sites. In addition to meeting the site selection criteria described above, additional sites were sought from the following sources:

- Owners of the previously committed sites: Domus Development, Self Help Enterprises, or Community Housing Works
- Existing contacts from utility incentive programs managed by TRC or AEA

Through this process, TRC identified another property owner, Community Preservation Partners (CPP), which was interested in participating in the demonstration project. CPP identified three potential sites. Of the three sites, the most viable option was Franco Center, a senior housing facility in Stockton.

Following the evaluation of the originally committed sites, and recruitment of additional sites, the research team proceeded with the following four sites for participation as demonstration sites:

- Franco Center, Stockton, CA
- Rolling Hills, Newman, CA
- Parksdale Village (two separate sites), Madera, CA

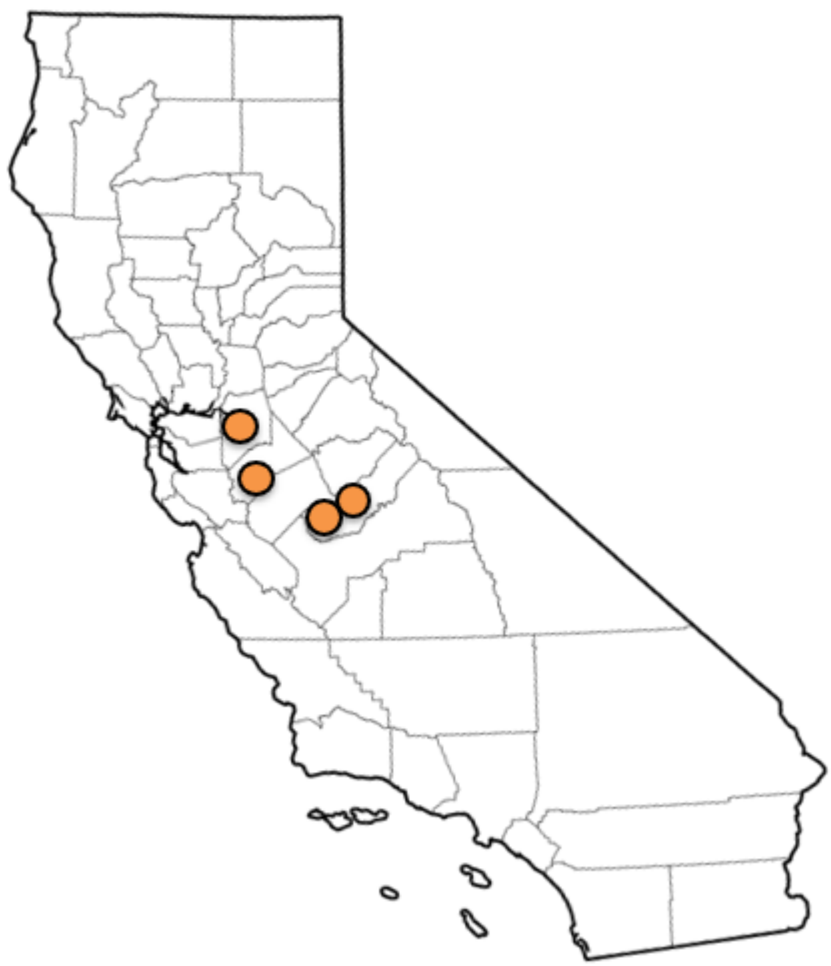
Table 6: Final Selected Site Details

Name	Location	Description	Number of common spaces	Number of dwelling units
Franco Center	Stockton, CA (CA CZ 12)	5 story, Senior housing apartment	Eight spaces: two large community activity areas (at least four to six fans per area), two offices (one fan each), reception office (at least one fan), two support spaces (at least one to two fans each), and kitchen prep area (two fans). Total of at least 18 fans.	
Rolling Hills	Newman, CA (CA CZ 12)	Multifamily townhouse with central community building	Six spaces: open community space (six or more fans), a kitchen (one fan), a computer room (two fans), a lobby (one fan), and two offices (at least one fan each). Total of at least 12 fans.	
Parksdale 1	Madera, CA (CA CZ 13)	Townhouse development with central community building	Six spaces: open community space (four or more fans), a kitchen (one fan), a computer room (at least one fan), an entry (one fan), and two offices (at least one fan each). Total of at least nine fans.	

Name	Location	Description	Number of common spaces	Number of dwelling units
Parksdale 2	Madera, CA (CA CZ 13)	Townhouse development with central community building	Six spaces: open community space (four or more fans), a kitchen (one fan), a computer room (at least one fan), an entry (one fan), and two offices (at least one fan each). Total of at least nine fans.	Six dwelling units (five to eight fans per unit). Total of 39 fans.

The research team also decided to locate all dwelling unit demonstrations at the Parksdale Village sites to allow for better comparison of results across different units. All four sites are described in more detail in the sections below.

Figure 56: Map showing demonstration site locations in California



Dwelling Unit Recruitment

Dwelling unit recruitment flyers describing the study and the financial incentives being offered for participation were sent to the property managers at Parksdale Village. The property manager posted these flyers on residents' doors. Respondents were asked to contact AEA if they were interested in participating. The primary dwelling unit characteristic AEA screened for was its proximity to other units willing to participate in the study. Because the research team used monitoring equipment that transmits data in real-time over a WiFi signal, the objective was to find two groupings of three units each that were close enough to one another that the WiFi signals from the routers could be reliably accessed from within each apartment, thereby reducing the total number of routers required.

The head of household of each of the six apartments included in the study were asked to sign a formal consent form outlining the requirements of their participation.

Franco Center Site Information

Franco Center Apartments is a five story, 112-unit senior living facility located at 144 Mun Kwok Lane in Stockton, CA. The first floor of the building is made up of retail spaces, community rooms (for Franco Center residents), and office space (used by Franco Center staff). The residential spaces (50,565 sf) occupy the second through fifth floors. The unit types are studios and 1-bedroom units on floors two through four, and 2-bedroom units on the fifth floor. The first floor retail and common spaces make up approximately 38,000 sf. Residents of Franco Center Apartments are primarily senior citizens.

Figure 57: Franco Center Apartments

Exterior view of south façade of Franco Center Apartments in Stockton, CA.

Source: Community Preservation Partners (CPP)

Ownership, Management, and Staffing

Franco Center Apartments is owned and operated by WNC & Associates. Midway through the project management operation shifted from John Stewart Company to Quality Management Group. One on-site manager and one janitorial staff lives on the property full time. Franco Center staff manage and occupy the main office, located on the first floor.

Energy Suppliers, Metering, and Electrical Systems

The building receives gas and electric service from PG&E and is a master metered building. No renewable energy sources were present onsite before renovation.

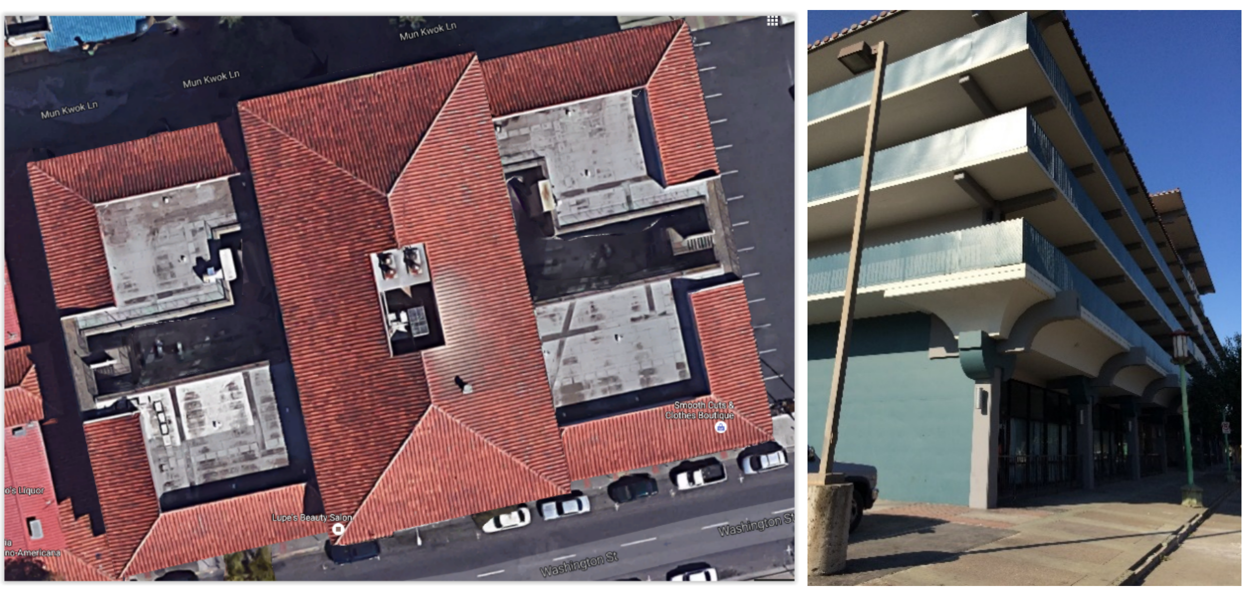
Areas Studied

Monitoring was carried out in the community rooms, offices, and kitchen prep area located on the first floor of the building. Offices are used during standard business hours (9:00-5:00 Monday-Friday), while the community areas are lightly used during the day, with heavier periods of use at mealtimes and during events. No fans or monitoring equipment were installed in the residential spaces.

Building Envelope

The building was constructed in 1967 and renovated in 2007, and is built of solid concrete masonry with no additional insulation (that was verifiable). Roof surfaces on the 1st and 4th floors are flat concrete deck and portions of the fourth and all of the fifth floor is framed attic with tile roofing. Insulation levels were not verifiable onsite.

Figure 58: Franco Center Roof and Building Envelope



Birdseye view of roof (left), and façade detail (right) of Franco Center Apartments.

Credit: Google Maps (left), AEA (right)

Heating and Cooling Systems

The first floor retail, office, and common areas are served by six rooftop-located VRF compressors that provide conditioned refrigerant to eight 3-phase fan coil units (FCUs). The compressor units consist of four 8-ton Mitsubishi models that provide 92 MBtu/hour of cooling and 108 MBtu/hour of heating capacity, and two 24-ton Mitsubishi models that each have two modules providing 144 MBtu/hour of cooling and 160 MBtu/hour of heating capacity. Fan coil units are also Mitsubishi models, with cooling capacities ranging from 0.5-4.5 tons (6-54 MBtu/hr) and heating capacities of 6.7-60 MBtu/hr.

Table 7: Franco Center HVAC Equipment Schedule

HVAC Equipment Schedule					
Location	**Make**	**Model**	**Output Capacity**	**Count**	**Notes**
Roof	Mitsubishi	PURY-P288	288,000 Btu/hr	2	Compressor
Roof	Mitsubishi	PURY-P96	92,000 Btu/hr	4	Compressor
Business Offices	Mitsubishi	PEFY-P06NMAU-E2	6,000 Btu/hr	1	FCU
Leasing Offices	Mitsubishi	PEFY-P24NMAU-E2	24,000 Btu/hr	1	FCU
Community Area	Mitsubishi	PEFY-P36NMAU-E2	36,000 Btu/hr	1	FCU
Community Area	Mitsubishi	PEFY-P48NMAU-E2	48,000 Btu/hr	3	FCU - 1 serves kitchen prep/storage area
Community Area	Mitsubishi	PEFY-P54NMAU-E2	54,000 Btu/hr	3	FCU

Rolling Hills Site Information

Rolling Hills is located at 2110 Prince St, Newman, CA. It is a complex consisting of the community center/office and thirteen tenant buildings containing a total of 52 units (four units each, arranged side by side). Each unit has two or three bedrooms, is one to two stories tall, and is accessible from the ground floor. The central community building is approximately 2,750 sf. Residents of Rolling Hills are a mix of couples and families.

Figure 59: Rolling Hills Community Center

Exterior view of Rolling Hills Community Center building.

Credit: AEA

Building Ownership, Management, and Staffing

Rolling Hills is owned and operated by Self Help Enterprises. One on-site manager and one janitorial staff lives on the property full time. Rolling Hills staff manage and occupy the main office, located in the community center.

Energy Suppliers, Metering, and Electrical Systems

The building receives gas and electric service from PG&E. Units are individually metered while common areas and outdoor spaces are master metered.

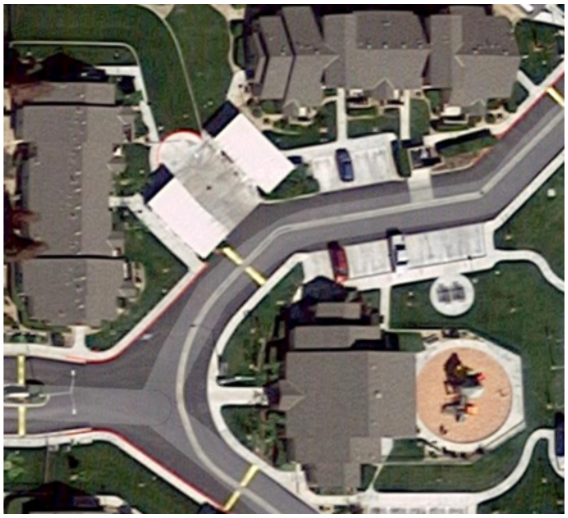
Areas Studied

Monitoring was carried out in the central community building. This building includes an open community space, a kitchen, a computer room, and an office that were all monitored. The building also has a laundry room and maintenance spaces, which are not conditioned and were not monitored. The office is used during standard business hours (9:00-5:00 Monday-Friday), while the community area and kitchen are very lightly used during the day. No fans or monitoring equipment were installed in the residential buildings.

Building Envelope

The buildings were constructed in 2004, and are built of stucco over wood framing. Insulation in the walls was not verified but is likely present given the date of construction. Roof surfaces are angled asphalt shingles, and attics are filled with fiberglass batt insulation, which provides approximately R-19 insulation (not consistently covering roof joists).

Figure 60: Rolling Hills Roof and Insulation




Birdseye view of Rolling Hills Community Building and surrounding dwelling units (left), and view of interior attic space with insulation (right).

Credit: Google Maps (left), AEA (right)

Heating and Cooling Systems

The community building is serviced by two outdoor condensing units for air conditioning and two furnaces installed in the attic for heating. Both the condensing units and furnaces are connected to air handlers located in the attic. The first air conditioning unit and furnace service the office and computer room, while the second service the community room and kitchen. Air conditioners provide 36-60 MBtu/hr (3-5 ton) of cooling, while the furnaces supply up to 42-60 MBtu/hr. Each of the two zones has a separate programmable thermostat.

Figure 61: Rolling Hills Air Conditioning and Heating Equipment

Rolling Hills exterior air conditioning condensing unit (left), and interior attic space with heating and air handling equipment (right).

Credit: AEA

Table 8: Rolling Hills HVAC Equipment Schedule

HVAC Equipment Schedule					
Location	**Make**	**Model**	**Output Capacity**	**Count**	**Notes**
Outside Community Center	Nordyne	FS3BC-060KA	60,000 Btu/hr	1	Compressor
Outside Community Center	Nordyne	FS3BC-036KA	36,000 Btu/hr	1	Compressor
Community Center Attic	Nordyne	C3BA-060C-C	60,000 Btu/hr	1	AHU
Community Center Attic	Nordyne	C3BA-042C-B	42,000 Btu/hr	1	AHU

Parksdale Village Site Information

Parksdale Village consists of two neighboring identical developments (Parksdale 1 and Parksdale 2) of townhome residential units and central common buildings. These are considered two separate demonstration sites for the purposes of this project. This will allow for comparisons between two identical common buildings, with identical HVAC systems, but different users and use patterns to see how the energy impacts of ceiling fans and thermostats differ between the two. In addition, Parksdale 2 will be the location for all six residential unit demonstrations.

The two Parksdale Village properties are located at 13549 and 13600 Wood St, Madera, CA. Each is a complex consisting of the community center/office and twelve tenant buildings containing a total of 48 units (four units each, arranged side by side). Each unit has two, three, or four bedrooms, is one to two stories tall, and is accessible from the ground floor. The central community building is approximately 3,190 sf. Residents of Parksdale Village are a mix of couples and families.

Figure 62: Parksdale 1 Community Building

Exterior view of the Parksdale 1 Community Building, one of two community buildings in the Parksdale Village area.

Credit: AEA

Building Ownership, Management, and Staffing

The Parksdale Village properties are owned and operated by Self Help Enterprises. One on-site manager and one janitorial staff live on each property full time. Parksdale Village staff manage and occupy the main office of each property, which is located in the community center of each property.

Energy Suppliers, Metering, and Electrical Systems

The building receives gas and electric service from PG&E. Units are individually metered while common areas and outdoor spaces are master metered.

Areas Studied

Monitoring was carried out in the central community buildings and at six units of Parksdale Village #2 (13600 Wood St). The community buildings include an open community space, a kitchen, a computer room, and two offices that were all monitored. The buildings also have a laundry room and maintenance spaces, which are not conditioned and were not monitored. The main office of each building is used during standard business hours (9:00-5:00 Monday-Friday), while the second office is rarely used. The community area and kitchen are very lightly used during the day, and the computer room is frequently used.

Residential units either have all spaces on the first floor, or the kitchen, living room, laundry room, and bathroom on the first floor, with three bedrooms and a bathroom on the second floor.

Building Envelope

The buildings were constructed in approximately 2009, and are built of stucco over wood framing. Insulation in the walls was not verified but is likely present given the date of construction. Roof surfaces are angled asphalt shingles, and attics are assumed to be filled with R-19 fiberglass batt insulation, based on similar properties built by the owner.

Heating and Cooling Systems

The community building is serviced by two outdoor condensing units for air conditioning and two furnaces installed in the closet outside the building for heating. Both the condensing units and furnaces are connected to air handlers attached to the furnaces. The first air conditioning unit and furnace service the offices and computer room, while the second service the community room and kitchen. Air conditioners provide 42-60 MBtu/hr (3.5-5 ton) of cooling each, while the furnaces supply up to 80 MBtu/hr. Each of the two zones has a separate programmable thermostat.

Units each have an outdoor compressor for air conditioning and a furnace located in a closet in the rear of the unit. Air conditioners provide 18-24 MBtu/hr (1.5-2 ton) of cooling per hour, while furnaces provide 48 MBtu/hr of heating.

Figure 63: Community Building Air Conditioning and Heating Equipment

Parksdale Community Building exterior air conditioning condensing unit (left), and interior heating and air handling equipment (right).

Credit: AEA

Figure 64: Typical Dwelling Unit Air Conditioning and Heating Equipment

Parksdale typical dwelling unit exterior air conditioning condensing unit (left), and interior heating and air handling equipment (right).

Credit: AEA

Table 9: Parksdale Village HVAC Equipment Schedule

HVAC Equipment Schedule					
Location	**Make**	**Model**	**Output Capacity**	**Count**	**Notes**
Outside Community Center	Carrier	24ABB461W300	60,000 Btu/hr	1	Compressor
Outside Community Center	Carrier	24ABB442W300	42,000 Btu/hr	1	Compressor
Community Center HVAC Room	Nordyne	C6BH-X60C-C	60,000 Btu/hr	1	AHU
Community Center HVAC Room	Nordyne	C6BH-X48C-C	48,000 Btu/hr	1	AHU
Outside Unit	Nordyne	JS4BE-018K	18,000 Btu/hr	1/unit	Compressor. Output ranges from 18,000-24,000 Btu/hr based on unit size
HVAC Closet behind unit	Nordyne	C6BH-X24C-A	24,000 Btu/hr	1/unit	AHU
HVAC Closet behind unit	Nordyne	KG7TA 060C-23A1	39,000-60,000 Btu/hr	1/unit	Furnace

Memorandum of Understanding

Each individual property owner signed a Memorandum of Understanding (MOU) that provided details about the project, its anticipated duration, the level of involvement needed from the owner and their staff, the expected benefits that may arise at their site as a result of their involvement in the project, and confirmed their commitment to participating in the project. Each MOU was also signed by Gail Brager, on behalf of CBE and the research team, and by the appropriate representative for each demonstration site.

The text of the MOU is reproduced in Appendix A.

Monitoring Installation Agreement

AEA was responsible for installing the data monitoring, networking, and temperature/RH sensing equipment, as well as managing and overseeing the installation of the power metering equipment. AEA developed the scope of work for the power metering installations and requested a price proposal from Big Ass Fans (BAF), a licensed electrical contractor and also the research team partner responsible for providing and installing the Haiku's in the next stage of the project. For the sake of consistency throughout the project there was a preference on the part for the research team to have BAF perform the pre-monitoring electrical work. In order to ensure that BAF's labor prices were competitive AEA spoke with three additional local electrical contractors, all of whom agreed to provide AEA with written proposals. However, after numerous attempts at follow up by AEA only one of the three contractors ultimately responded with a formal written proposal. That contractor provided pricing for the Franco project only, which consists of common area metering installations only (no dwelling unit meter installations), that exceeded the estimate from BAF. This partial estimate, along with a verbal cost estimate provided over the phone by one of the other one additional contractors, which were also higher than BAF's, provided the project team with confidence that BAF's prices were competitive.

BAF included each property ownership entity, AEA, TRC, UC Berkeley, and the CEC as "additionally insured" in their installation agreement with AEA.

The full breakdown of installation costs by BAF is below:

Table 10: Proposed costs at each study location for installation by BAF contractors.

	Job Scope	Total Cost for Job Item
1.	**<u>Franco Center</u>** Install 35 fans and controls as specified, configure and group fan controls. Patch and repair as needed. Electrical Permits and Inspections	$23,182.00
2.	**<u>Rolling Hills</u>** Install 13 fans and controls as specified, configure and group fan controls. Patch and repair as needed. Electrical Permits and Inspections	$8,796.00
3.	**<u>Rolling Hills</u>** Provide and install nine (9) Halo 750 6" recessed fixtures.	$1,884.00
4.	**<u>Parksdale 1</u>** Install seven (7) fans and controls as specified, configure and group fan controls. Patch and repair as needed. Electrical Permits and Inspections	$5,827.00

	Job Scope	Total Cost for Job Item
5.	**<u>Parksdale 2 (Community Building)</u>** Install eight (8) fans and controls as specified, configure and group fan controls. Patch and repair as needed. Electrical Permits and Inspections to be added as a pass-thru cost**	$3,910.00**
6.	**<u>Parksdale 2 (Two bedroom Units)</u>** three units total Install fifteen (15) fans and controls as specified, configure and group fan controls. Patch and repair as needed. Electrical Permits and Inspections to be added as a pass-thru cost**	$7,376.00**
7.	**<u>Parksdale 2 (Two bedroom Units)</u>** three units total Provide and install twelve (12) Halo 750 6" recessed fixtures.	$2,512.00
8.	**<u>Parksdale 2 (Three bedroom Units)</u>** three units total Install twenty-seven (27) fans and controls as specified. Configure and group fan controls. Patch and repair as needed. Electrical Permits and Inspections to be added as a pass-thru cost**	$10,541.00**
9.	**<u>Parksdale 2 (Three bedroom Units)</u>** three units total Provide and install twelve (12) Halo 750 6" recessed fixtures.	$2,512.00
10.	BAF to install NEST thermostats provided by others, building maintenance team to provide verification that HVAC system is in working order after t-stat changeout.	

CHAPTER 3:
Site Monitoring Setup

This chapter outlines the monitoring plans and monitoring equipment installation at the demonstration sites.

Field Demonstration Timeline

The overall schedule of the field demonstrations was as follows:

- July 2017: Installation of monitoring equipment
- July 2017 – June/July 2018: Pre-installation monitoring period
- June/July 2018: Installation of ceiling fans and thermostats
- June/July 2018 – October 2019: Post-installation monitoring period
- December 2019: Removal of monitoring equipment

Monitoring Plan

As part of the planning for the site demonstrations the research team developed a general monitoring plan for the project. This monitoring plan is summarized in the sections below.

Pre-Installation Monitoring

The research team installed monitoring equipment at each site to monitor energy use and indoor environmental quality (IEQ) conditions for all common area spaces and each residential unit included in the study. Pre-installation monitoring included approximately one year of data collection before the fans and smart thermostats were installed. Pre-installation monitoring data collection included the following:

- Air-conditioning energy use:
  - Power metering at each air conditioning circuit serving common areas or residential units included in the demonstration study.
  - Collected data was transmitted to the research team in real-time via Wi-Fi.
- IEQ measurements:
  - Temperature and relative humidity were collected in all common areas and in each residential unit included in the demonstration study using Hamilton sensors (www.HamiltonIOT.com).
  - Collected data was available to the research team in real-time, at 20-second intervals.
- Thermostat settings:
  - The research team observed and recorded thermostat settings in common spaces and residential units in the demonstration study during visits to the site

whenever possible. This included asking residential unit occupants about their thermostat use.

- Monitored data communication:
    - The research team installed cellular data Wi-Fi hotspots to provide live communication of energy monitoring and IEQ measurement data.

Post-Installation Monitoring

Following the installation of ceiling fans and thermostats, the research team continued monitoring at all demonstration sites using previously installed monitoring equipment. Monitoring continued for roughly 16 months.

- Air-conditioning energy use:
    - Power metering at each air conditioning circuit serving common areas or residential units included in the demonstration study.
    - Collected data was available to the research team in real-time via Wi-Fi.
- IEQ measurements:
    - Temperature and relative humidity was collected in all common areas and in each residential unit included in the demonstration study using Hamilton sensors.
    - Collected data was available to the research team in real-time via Wi-Fi.
- Ceiling fan operation data: in collaboration with BAF, the research team collected operation and energy use data from each installed ceiling fan through the existing ceiling fan API.
- Thermostat settings: the research team collected thermostat setpoint and operational settings data from each installed thermostat through the ecobee thermostat API.
- Monitored data communication: The research team used the previously installed cellular data Wi-Fi hotspots to provide live communication of all monitored data to the study team.
- Occupant surveys: CBE administered occupant satisfaction surveys to occupants primarily via paper survey. In addition, CBE interviewed occupants.

Monitoring Equipment Installation

AEA and BAF performed the installation of monitoring equipment at all four sites over the course of two weeks at the end of July 2017. Installations typically took between one to two days per site.

DENT PowerScout 3037 power meters were installed on all central HVAC compressors, while dedicated current transducers (CTs) were used to measure amperage for the smaller fan coil units (FCUs) and forced air units (FAUs). Both the DENT power meters and FCU/FAU CTs were connected to Hobo U30s for data storage and wireless data transmission. Power meters read continuously from the compressors sending pulse output signals (1 pulse per 0.1 kWh) to a pulse converter, which outputs readable signals for the Hobo U30 Smart Sensor inputs. Pulse data was stored in the pulse converters which was then pulled by the Hobo U30 at 5-minute intervals. The dedicated CT's were connected to the Hobo U30 through FlexSmart TRMS signal converters and were also sampled at 5-minute intervals.

For the monitoring of space conditions Hamilton temperature and relative humidity sensors were mounted in key locations throughout the conditioned spaces (see photos within each site location description below). The Hamilton sensors were programmed to automatically link to Hamilton border routers within range and send data continuously. Temperature and relative humidity data were stored within the Hamilton border router itself and then transmitted via cell signal through a hard-line Ethernet connection to an Internet router (further described below). The Hamilton border routers were powered by an external power adapter and connected directly to a net extender provided at each site.

Each site was equipped with a cell modem and net extender which provides a continuous 2G internet signal. Each Hobo U30 installed at each site was programmed to connect to the 2G signal output by the net extender. The net extender was in turn connected to the provided cell modem which allowed data gathered on site to be transmitted to a Hobo cloud-based server. The logged data was transmitted from the Hobo U30 every 60 minutes and was also automatically transferred to an AEA hosted FTP site on a daily basis. The Hobo server could be accessed by all members of the research team. A weekly summary of all data was also compiled and shared on the AEA hosted FTP site. The Hamilton sensor data was sent to a cloud-based monitoring platform hosted by CBE via the same net extender and cell modem configuration.

Franco Center

A total of six DENT power meters were installed at Franco Center in order to measure and record energy consumption of the six 3-phase VRF compressors. All six power meters were installed in the primary electrical service room located on the first floor. Each of the power meters were installed in their own dedicated electrical enclosures which were mounted on the wall just below the respective service panels. The pulse outputs of each of those six power meters were connected to a single Hobo U30, also located in the electrical service room, which was powered by a dedicated electrical receptacle installed by BAF.

The six VRF compressors were connected to a total of twenty-four 3-phase fan coil units (FCUs). The project included monitoring of the nine community area and office area FCUs only. These spaces were located directly across from the electrical service room on the first floor. The remaining FCUs were located in the above floors and serve the residential hallways. Magnelab 20A CT's were used to measure and transmit amperage of the FCU's, and spot voltage measurements were taken. These measurements were used to calculate total energy (kWh) consumption of each of the FCU's. The proximity of the community room and the electrical service room allowed the shared use of the required cell modem and net extender which were responsible for making the gathered data available on-line. The project also included the installation of one Hamilton border router and seven Hamilton sensors for the monitoring of temperature and relative humidity of the community/office areas throughout the duration of the project.

The total breakdown of installed equipment can be seen in the summary below:

Table 11: Franco Center Monitoring Equipment Installed

Manufacturer	Model	Function	Count
HOBO	U30	Multi-channel data logger	2
Magnelab	Current Transformers	CT's for air handler/fan coil amperage	9
Onset	FlexSmart TRMS	Convert CT amperage readings to HOBO input signals	9
HOBO	S-UCx-M00- Pulse output converter	Convert power meter pulse outputs to Hobo input signals	6
Dent	Powerscout 3037	Power meter	6
Dent	Current Transformers	CT's for compressor power - (3) per compressor (1 per phase)	18
Verizon	Jetpacks 791L-9925	Cell modem	1
Netgear	AC1900	Network Range Extender	1
Hamilton	Temperature/RH Sensors	Temperature/RH Sensors	7
Hamilton	Border Router	Dedicated Hamilton router	1

Figure 65: Franco Center Monitoring Equipment Installation

Credit: AEA

Rolling Hills

A total of two DENT power meters were installed at Rolling Hills in order to measure and record energy consumption of the two single-phase AC condensing units. Both power meters were installed in the primary mechanical closet located on the exterior southwest corner of the Community Center. Both of the power meters were installed in one dedicated electrical enclosure which was mounted on the wall just below the side-by-side service panels. The pulse outputs of the two power meters were connected to a single Hobo U30 which was mounted above the power meter enclosure. The Hobo U30 was powered by a dedicated electrical receptacle installed by BAF.

The two AC condensing units serve two forced air units (FAUs). Each FAU serves dedicated spaces: FAU 1 – Community Room, Kitchen and Storage; FAU 2 – Office and Computer Room. Magnelab 20A CTs were used to measure and transmit amperage of the FAUs and spot voltage measurements were taken. These measurements were used to calculate total energy (kWh) consumption of each of the FAUs. The AC condenser circuits and FAU circuits were located within the same service panels; therefore AC condensing unit power meters and FAU CTs could be connected to one Hobo U30. The required cell modem and net extender were mounted adjacent to the one Hobo U30 in the same mechanical closet. The project also included the installation of one Hamilton border router and five Hamilton sensors for the monitoring of temperature and relative humidity of the Community Room (two total sensors), Kitchen, Office and Computer Room (one sensor each) which was monitored throughout the duration of the project.

The total breakdown of installed equipment can be seen in the summary below:

Table 12: Rolling Hills Monitoring Equipment Installed

Manufacturer	Model	Function	Count
HOBO	U30	Multi-channel data logger	1
Magnelab	Current Transformers	CT's for FAU amperage	2
Onset	FlexSmart TRMS	Convert CT amperage readings to HOBO input signals	1
HOBO	S-UCx-M00- Pulse output converter	Convert power meter pulse outputs to Hobo input signals	2
Dent	Powerscout 3037	Power meter	2
Dent	Current Transformers	CT's for compressor power - (2) per compressor	4
Verizon	Jetpacks 791L-9925	Cell modem	1
Netgear	AC1900	Network Range Extender	1
Hamilton	Temperature/RH Sensors	Temperature/RH Sensors	5

Figure 66: Rolling Hills Monitoring Equipment Installation

Credit: AEA

Parksdale 1

A total of two DENT power meters were installed at Parksdale 1 in order to measure and record energy consumption of the two single-phase AC condensing units. Both power meters were installed in the primary mechanical closet which is located on the exterior north side of the Community Center. Both of the power meters were installed in one dedicated electrical enclosure which was mounted on the wall just above the electrical service panel. There is one service panel located in the mechanical closet that houses both AC condenser circuits. The pulse outputs of the two power meters were connected to a single Hobo U30 which was mounted adjacent to the power meter enclosure. The Hobo U30 was powered by a dedicated electrical receptacle installed by BAF.

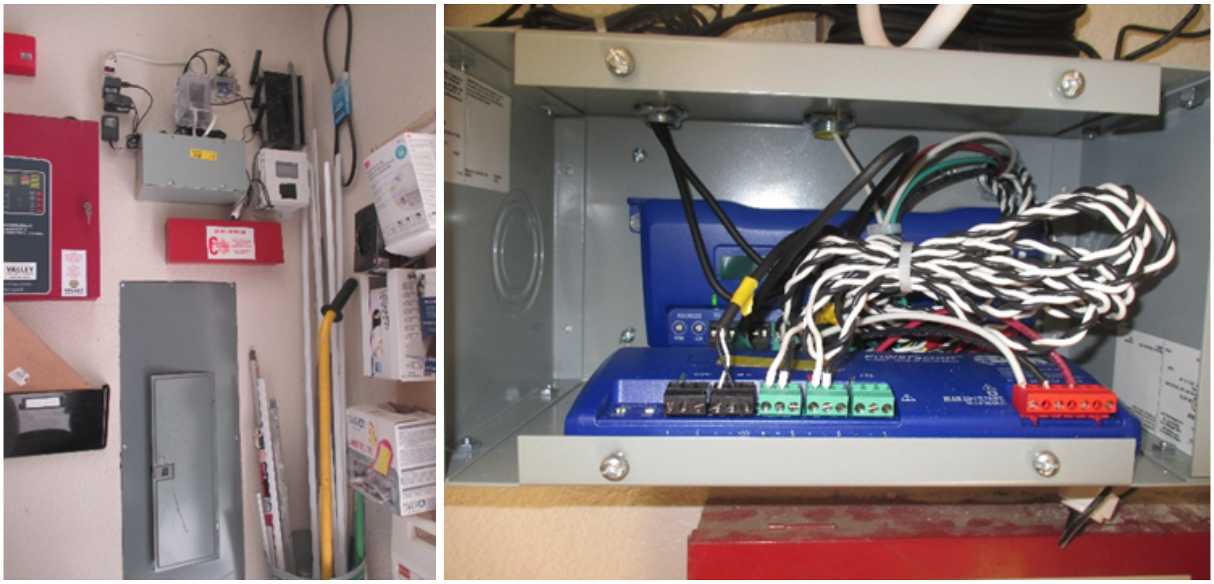
The two AC condensing units serve two forced air units (FAUs). Each FAU serves dedicated spaces: FAU 1 – Community Room, Kitchen and Storage; FAU 2 – Office and Computer Room. Magnelab 20A CTs were used to measure and transmit amperage of the FAUs and spot voltage measurements were taken. These measurements were used to calculate total energy (kWh) consumption of each of the FAUs. The AC condenser circuits and FAU circuits are located in separate areas and so two separate Hobo U30s were required for data logging. The AC condensing service panel is located in the mechanical closet described above and the FAU service panel is located is a storage closet located inside the Community Center. The required cell modem and net extender were mounted in the mechanical closet. The FAU Hobo U30 can communicate wirelessly with the cell modem via the net extender in the mechanical closet. The project also included the installation of one Hamilton border router and two Hamilton sensors for the monitoring of temperature and relative humidity of the Community Room (one sensor) and the Kitchen (one sensor) which were monitored throughout the duration of the project.

The total breakdown of installed equipment can be seen in the summary below:

Table 13: Parksdale 1 Monitoring Equipment Installed

Manufacturer	Model	Function	Count
HOBO	U30	Multi-channel data logger	2
Magnelab	Current Transformers	CT's for FAU amperage	2
Onset	FlexSmart TRMS	Convert CT amperage readings to HOBO input signals	1
HOBO	S-UCx-M00- Pulse output converter	Convert power meter pulse outputs to Hobo input signals	2
Dent	Powerscout 3037	Power meter	2
Dent	Current Transformers	CT's for compressor power - (2) per compressor	4
Verizon	Jetpacks 791L-9925	Cell modem	1
Netgear	AC1900	Network Range Extender	1
Hamilton	Temperature/RH Sensors	Temperature/RH Sensors	2

Figure 67: Parksdale 1 Monitoring Equipment Installation



Credit: AEA

Parksdale 2

A total of eight DENT power meters were installed at Parksdale 2 in order to measure and record energy consumption of eight total AC condensing units. This site is unique in that monitoring occurred on both the Community Center as well as six individual dwelling units.

The Community Center is served by two single-phase AC condensing units. Both required power meters were installed in the primary mechanical closet which is located on the exterior north side of the Community Center. Both of the power meters were installed in one dedicated electrical enclosure which was mounted on the wall just above the electrical service panel. There is one service panel located in the mechanical closet that houses both AC condenser circuits. The pulse outputs of the two power meters were connected to a single Hobo U30 which was mounted adjacent to the power meter enclosure. The Hobo U30 was powered by a dedicated electrical receptacle installed by BAF.

The two Community Center AC condensing units serve two forced air units (FAUs). Each FAU serves dedicated spaces: FAU 1 – Community Room, Kitchen and Storage; FAU 2 – Office and Computer Room. Magnelab 20A CTs were used to measure and transmit amperage of the FAUs and spot voltage measurements were taken. These measurements were used to calculate total energy (kWh) consumption of each of the FAUs. The AC condenser circuits and FAU circuits are both located in the primary mechanical closet and so the use of only one Hobo U30 was necessary. The required cell modem and net extender were mounted in the mechanical closet. The project also included the installation of one Hamilton border router and four Hamilton sensors for the monitoring of temperature and relative humidity on the Community Room, Kitchen, Office and Computer Room (one sensor in each space) which will be monitored throughout the duration of the project.

The total breakdown of installed equipment in the community center can be seen in the summary below:

Table 14: Parksdale 2 Community Center Monitoring Equipment Installed

Manufacturer	Model	Function	Count
HOBO	U30	Multi-channel data logger	1
Magnelab	Current Transformers	CT's for FAU amperage	2
Onset	FlexSmart TRMS	Convert CT amperage readings to HOBO input signals	1
HOBO	S-UCx-M00- Pulse output converter	Convert power meter pulse outputs to Hobo input signals	2
Dent	Powerscout 3037	Power meter	2
Dent	Current Transformers	CT's for compressor power - (2) per compressor	4
Verizon	Jetpacks 791L-9925	Cell modem	1
Netgear	AC1900	Network Range Extender	1
Hamilton	Temperature/RH Sensors	Temperature/RH Sensors	4

Figure 68: Parksdale 2 Typical Dwelling Unit Monitoring Equipment Installation

Credit: AEA

CHAPTER 4: Fan controls development and testing – fan controls and phone app

Key outcomes

- Research team worked with manufacturer (BAF) to specify, implement, and iteratively improve three successive versions of a new ceiling fan control algorithm based on temperature, occupancy, and user interaction, and install it on 100 fans.
    - As intended, occupant interaction did cause fan setpoints to gradually adjust over time
    - All occupants surveyed preferred the temperature-based fan operation with the firmware developed for this study (always with the option of manual override) to reverting to a commercially available version that did not support temperature-based control
    - The specific firmware implementation for this project is proprietary to the manufacturer, however the control logic is specified below
- Manufacturer configured access to allow researchers to analyze high-resolution ceiling fan usage data
- Research team collected and classified examples of different fan control technologies currently commercially available for residential and commercial spaces. Most ceiling fans do not offer temperature-based control. This feature could be encouraged. Globally, at least two other companies manufacture ceiling fans with integrated temperature sensors, and third-party home automation software can also be used to stage a ceiling fan with air conditioning based on indoor temperature.

Key lessons learned

- Some space types, such as bedrooms, require special consideration for controls. For example, occupants sleeping under blankets may have a lower metabolic rate and accordingly desire a higher fan cooling setpoint, and may not be detected by motion or infrared-based occupancy sensors. In addition, blinking LEDs to indicate fan speed are disruptive at night.

Additional project narrative

In conjunction with the recruitment and planning for demonstration sites, the research team also conducted testing of the Haiku ceiling fan and thermostat technologies in a test chamber at CBE. The Haiku Home smartphone app for the ceiling fan allows for integration with smart thermostats from Nest and Ecobee, so one of the early priorities of this testing examined the functionality of the integration of the Haiku fans with both thermostat models. The team chose to use Ecobee thermostats for the demonstration sites due to the ability to download thermostat data for the entire field study period directly through the Ecobee API.

The initial testing also revealed several concerns related to how the technologies will be implemented at the demonstration sites. The Haiku product was designed primarily for use in a single application with a single user (e.g., installation of one fan in a single room in a residence with one individual using the smartphone app to control the fan). However, the goal of the study was to test applications of the Haiku technology in combination with smart thermostats in multi-room, multi-user, and nonresidential applications. The Haiku product functionality and user interface were not optimized for these types of applications. This initial testing at CBE resulted in two primary concerns about the technology functionality at the demonstration sites:

- The Haiku product's automatic "smarter cooling" functionality did not operate in the transition phase (or deadband) between heating and cooling modes on the thermostat, posing problems for systems and locations that may operate in heating mode during cool nighttime and early morning hours and cooling mode during daytime hours. The fan's smarter cooling mode, which automatically increases air movement in a space to match a user's comfort setting, would not be activated until the thermostat switches to cooling mode. This may create a comfort gap if thermostats are set to higher temperatures with the expectation that the fan will provide additional cooling before the AC is triggered.
- The current fan and smartphone interface allows access to fans from any device on the same Wi-Fi network; and smartphone control is only possible when connected to the same network as the fan. This poses challenges for user permissions in common areas, or in shared spaces like offices.

The research team worked directly with BAF to address the issues that were identified through this initial testing, and BAF committed to providing improved fan functionality and smartphone interface to address these issues. The research team worked with BAF to develop a custom version of the fan firmware to better coincide with the field demonstration research goals of the project, as described in the next chapter.

As a result of the issues identified through the technology pilot testing the research team worked directly with BAF to make improvements to the control protocols and smartphone app (Haiku Home) control interface for the Haiku fan product.

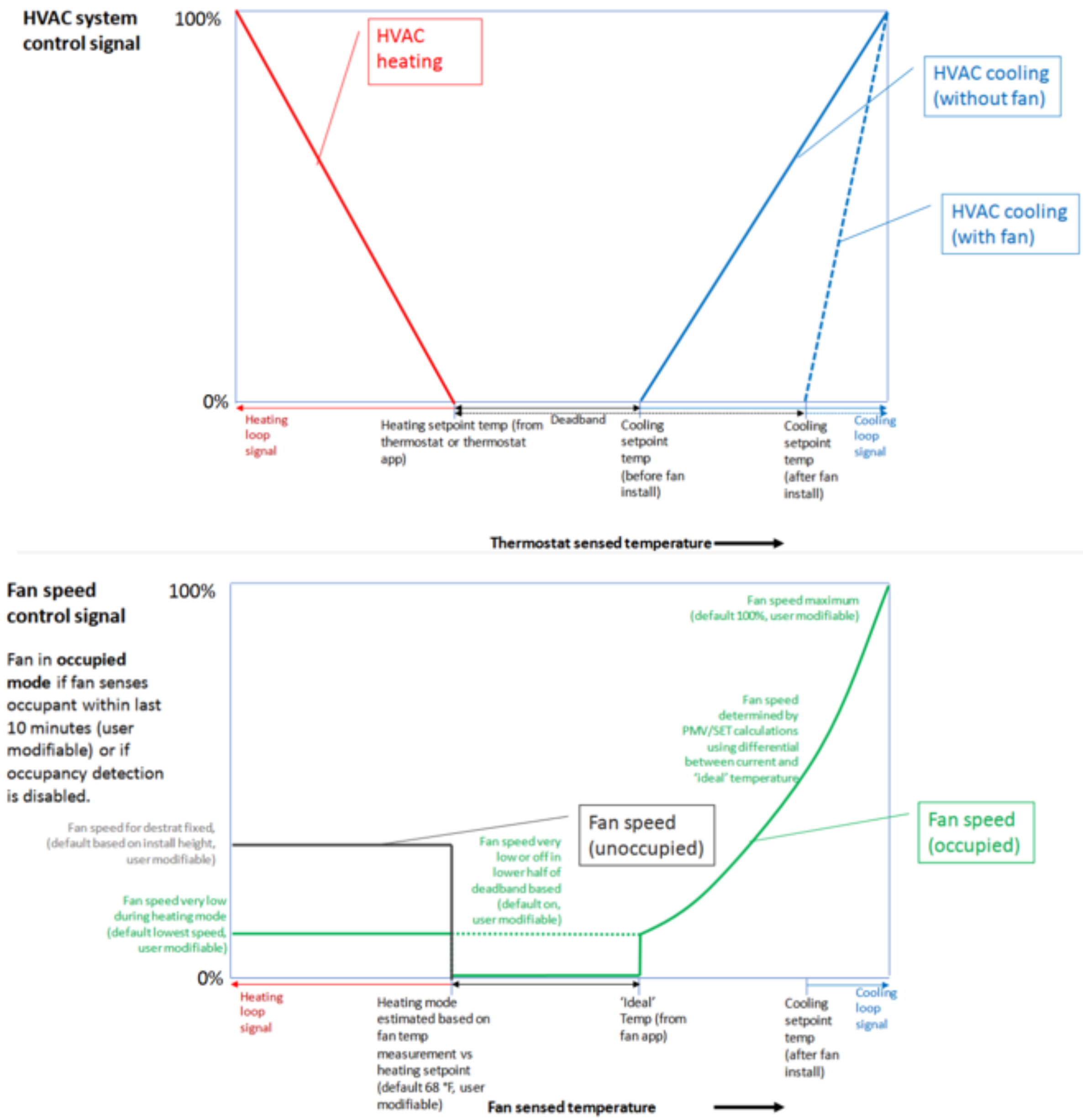
Following the initial testing, CBE and TRC developed the following priorities for updates to the Haiku Home interface:

- Address the switchover between "smarter cooling" and "smarter heating" modes so that ceiling fans will continue to operate to provide comfort cooling as needed in the thermostat deadband between heating and cooling modes, allowing for higher cooling setpoints. This could potentially be resolved by separating the operation and control of "smarter cooling" and "smarter heating" modes from the thermostat settings.
- Limit user access to fans in common areas, public areas, or other shared spaces. Because anyone with the Haiku Home app connected to the same Wi-Fi network as the fans could potentially control the fans in that space, it may be necessary to establish user profiles that could limit controls in public spaces to a facility manager, or limit access to a specific user's space in settings like an office suite with a single shared Wi-Fi network.

- Allow for multiple fans in different rooms to be connected to a single thermostat, especially in instances such as separate rooms within a single dwelling unit. This could also potentially be resolved by separating the function of the “smarter cooling” and “smarter heating” modes from the thermostat settings, as described above.
- Provide easier access to Ecobee thermostat control within the Haiku Home app, potentially including proactive suggestions to adjust thermostat setpoints to increase energy savings, and with more clear communication about what effect the control options and setpoints will have.
- Improve the user interface for setting the smart cooling “ideal temperature,” clarify how the setting works, and how the “learning” functions.

CBE and TRC collaborated directly with BAF to develop solutions for these strategies to provide a fully functioning product for installation in the demonstration sites.

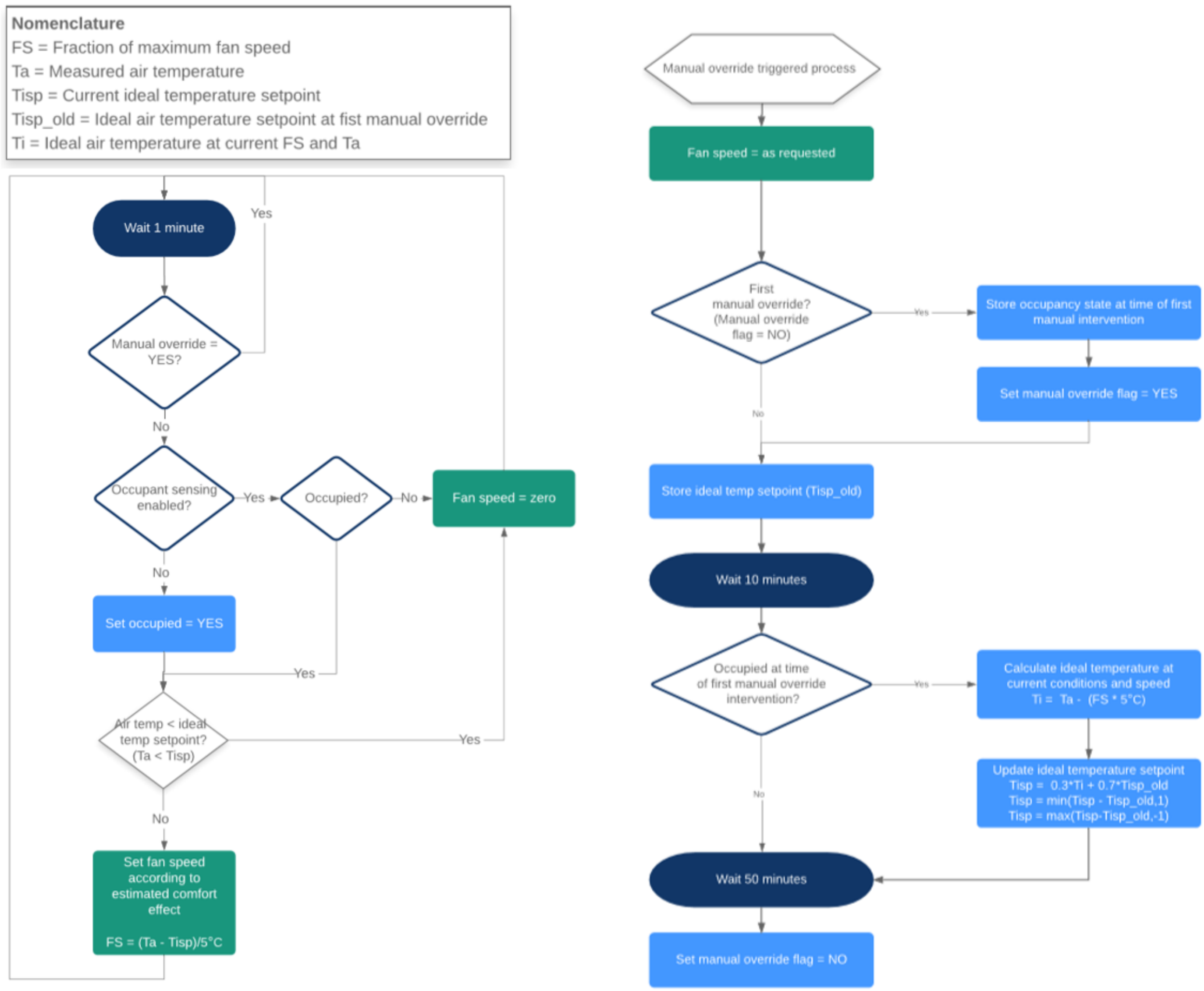
Figure 69: Control sketch for air conditioning and fan operation



When staged with ceiling fan operation, air conditioners are expected to use less energy due to both less overall runtime and reduced cooling loads. Fan operation is based on both temperature and occupancy. A ceiling fan will run if a space is occupied and above a setpoint temperature, and fan speed gradually increases at higher air temperatures up to a defined limit.

Credit: CBE

Figure 70: Logic flowchart for new temperature- and occupancy-based ceiling fan control strategy that adjusts fan setpoint in response to user behavior



The controls above describe logic for both automatic operation and manual overrides via the remote control or phone application. Left: Control logic. Right: Control logic when manual override is triggered. The controls 'learn' user preferences by gradually adjusting the fan setpoint in response to occupant adjustments.

CHAPTER 5: Site Intervention Planning and Installation

The following sections describe the planning and design process for the fan and thermostat installation at the demonstration sites.

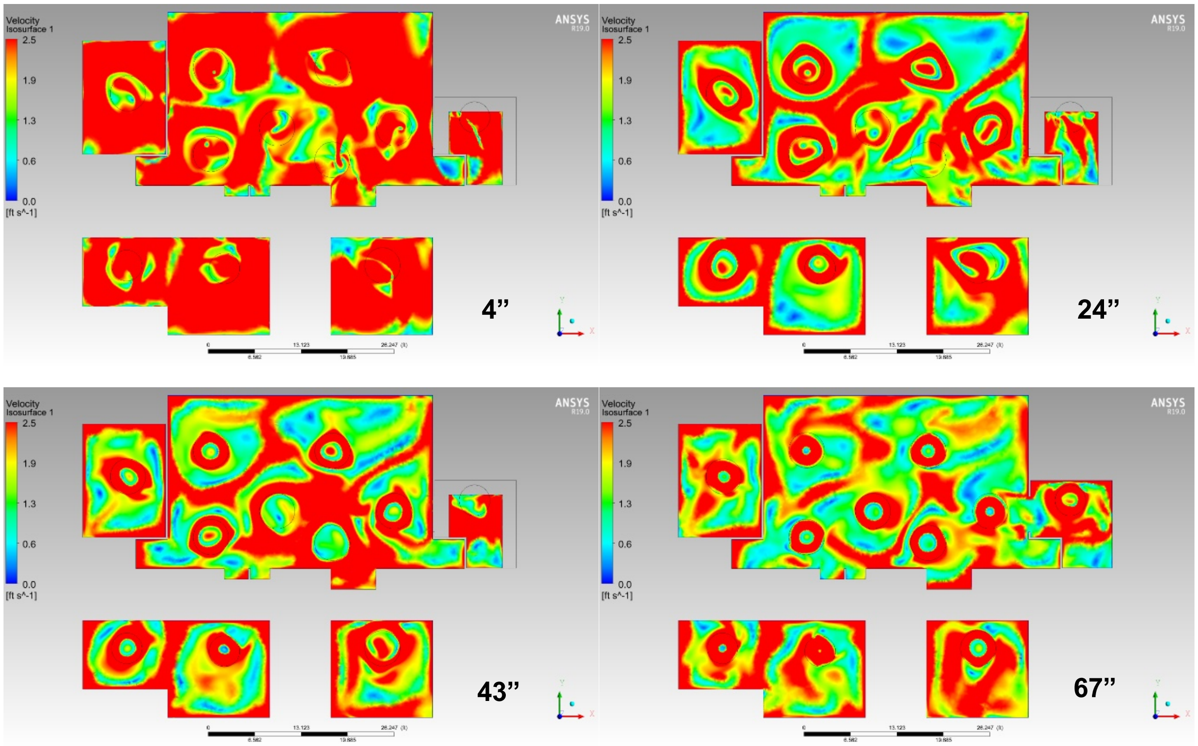
Performance Targets and Initial Design Analysis

Since the goal of the site demonstrations was to test the potential to use ceiling fans to maintain comfort at increased thermostat setpoints, the determination of the fan layout was critical to the overall success of the project. To that end, BAF provided computational fluid dynamic (CFD) simulation to test and develop proposed fan layouts for each site.

The research team developed an overall goal of achieving an average of up to 150 feet per minute (fpm), or 2.5 feet per second (fps), of air flow in each demonstration space. This velocity was determined based on previous studies that found that speeds above approximately 150 fpm start to move papers on desks. As such, this was considered the upper limit air velocity to maximize cooling effectiveness without becoming disruptive. (This air flow target assumes the highest fan speed setting, so occupants could always use the fans at lower speeds to achieve lower air velocities.)

Using this target, BAF ran CFD simulations that measured air flow at four different levels to determine the effectiveness of various fan layouts. The four heights were 4”, 24”, 43” and 67” above the floor. Figure 8, below, shows an example of the CFD analysis results for an initial fan layout plan at the Rolling Hills community building.

Figure 71: Example Rolling Hills CFD Analysis



CFD analysis visualizations for the Rolling Hills Community Building initial fan layout showing air speeds at vertical heights of 4”, 24”, 43”, and 67” above the floor.

Credit: BAF

Based on the results of the CFD analysis, and the existing conditions (light fixtures, fire sprinklers, etc.) at each site, BAF proposed initial layouts for all of the spaces at all four sites.

Pre-Installation Site Visits and Layout Revisions

Prior to finalizing the designs for each of the sites, CBE, TRC, and AEA conducted site visits at each of the demonstration sites with the BAF installation team to become familiar with the spaces in the study, and to confirm the final layouts and details for the fan installations.

Based on these site visits, in order to ensure adequate coverage and air movement from the ceiling fans, CBE and TRC proposed increasing the number of fans for the Franco Center and Rolling Hills community rooms, and in the Parksdale 1 & 2 computer labs, compared to what BAF had initially proposed based on the CFD analysis. In some cases, such as the community rooms at both Parksdale sites, there was a desire to increase the fan coverage, but locations of existing light fixtures and fire sprinklers made revising the proposed fan layouts prohibitive.

In addition to updating fan layouts and quantities, the research team identified areas where lighting changes would be required to accommodate the installation of the fans. These lighting changes are described in more detail below.

Thermostat Selection

The research team had initially planned to use Nest thermostats at the demonstration sites (with the exception of the Franco Center site, where the existing thermostats needed to remain in place to ensure compatibility with the existing HVAC system). However, due to restrictions on the use of thermostat data in Nest's standard terms and conditions, and the inability to come to agreement with Nest on data usage for this research study, the research team instead opted to use Ecobee thermostats. The Ecobee thermostats provide essentially the same functionality and capabilities as the Nest thermostat, so this change did not have a material impact on the overall study.

Final Ceiling Fan Layouts and Installation Design

Based on the CFD analysis and site visits described above, the research team arrived at the final fan layout designs. The final fan layouts from BAF are included below in Appendix D.

In addition to the fan installations, the full installation scope included installing and configuring thermostats (at Rolling Hills and Parksdale sites), and lighting reconfigurations in areas where the fans and the existing lighting would be in conflict.

Lighting changes are not always shown in the figures below, but details are as follows:

- Franco Center:
    - Ceiling fan with light kit replaced existing surface mounted fluorescent fixtures in small office and computer room
- Rolling Hills:
    - Five LED downlights replaced two existing recessed fluorescent troffer fixtures in the Kitchen space to avoid strobe effect from conflict with the ceiling fan
    - Two LED downlights replaced one existing recessed fluorescent troffer fixture in the Computer Lab to avoid strobe effect from conflict with the ceiling fan
- Parksdale 2 Community Building:
    - Relocated one existing surface mounted fluorescent fixture in the Kitchen area to avoid strobe effect from conflict with the ceiling fan
- Parksdale 2 Residential Units:
    - Ceiling fan with light kit replaced existing surface mounted fluorescent fixture in all kitchens, four new LED downlights added to supplement light from ceiling fan
    - In all other spaces, ceiling fans with light kits replaced existing fixtures, where applicable

Demonstration Site Installations

Fan and Thermostat Installation Scope of Work

TRC worked with BAF to develop a detailed installation scope of work that the BAF installation team would follow at the demonstration sites. The scope of work for the BAF installation team included installation and configuration of the fans, replacing existing thermostats with new smart thermostats where applicable, and installing or reconfiguring lighting where applicable. The full scope of work document is included in Appendix B, below.

Programming and configuration of the thermostats was carried out by AEA, in coordination with CBE and TRC, following the installation.

Monitoring equipment installed as described above remained in place for monitoring during the post-installation period.

Installation Schedule

Fan and thermostat installations occurred at the demonstration sites over the following dates:

- Franco Center: June 25-29, 2018 (fan installation only)
- Rolling Hills: July 9-11, 2018
- Parksdale 1 and Parksdale 2: July 12-20, 2018

Overall, the physical installation of the fans and thermostats was successfully completed as designed and on the schedule initially proposed by the BAF installation team. The pre-installation site visits with the BAF installation contractor proved critical to the success of the installations as the information on the drawings provided by the sites did not always match the actual conditions at each site. As a result of the pre-installation visits, all fan locations had already been identified, and potential conflicts with HVAC and lighting systems had been resolved prior to the scheduled installation dates.

Network and Connection Issues

After the physical installation of the fans the research team ran into multiple challenges with getting the fans and thermostats connected to internet networks, and connecting fans to the BAF Haiku app.

The initial intent was to connect all of the new devices to whatever local network occupants used at the site, but this posed several challenges. At some sites the research team was not able to access the same network that on-site staff use due to privacy concerns with tenant records. In addition, the ceiling fans are required to be connected to a password-protected network to function properly, which also limited connection options at the Franco Center site where the public wireless network does not require a password for access.

Separately, the installation team ran into challenges connecting the fans to the Haiku app at several sites, requiring multiple return visits from AEA, and coordination with BAF to resolve the connection problems. These two connection issues were largely been resolved in community spaces with the addition of separate wireless routers and using separate network connections to get all the fans up and running. However, post-installation, some of the occupants of the demonstration residential units experienced problems connecting their personal devices to their existing wireless networks, which were shared with the new fans and thermostats. Residential units at the Parksdale 2 site each use an internet modem/router that is provided by the property for internet access. The project team found that these systems allow a maximum of 15 individual IPs to be registered at any given time. Since each fan and thermostat counted as a separate IP these, in addition to existing smartphones, computers, TVs, and other internet-connected devices frequently exceeded the maximum number of IP addresses. To remedy this AEA installed separate mobile internet hot spots at each unit that were dedicated for the fans, removing them from the residents' networks.

Supplemental Desk Fans and Lighting

In order to ensure personal comfort, and to supplement the ceiling fans in areas where air circulation may be less optimal, the research team decided to provide small desk fans for all office occupants at each site, as well as for each computer lab station at each site. These small fans added nominal cost, but helped support varying thermal comfort preferences at the demonstration sites, especially in shared spaces.

In addition, following the installation at the Franco Center site, the light kit for the ceiling fan was found to not sufficiently meet the lighting needs in the small office and computer lab spaces. To address this issue, the research team provided supplemental desk lighting for each computer station in the computer lab, and a desk light and floor light for the small office to supplement light from the ceiling fan.

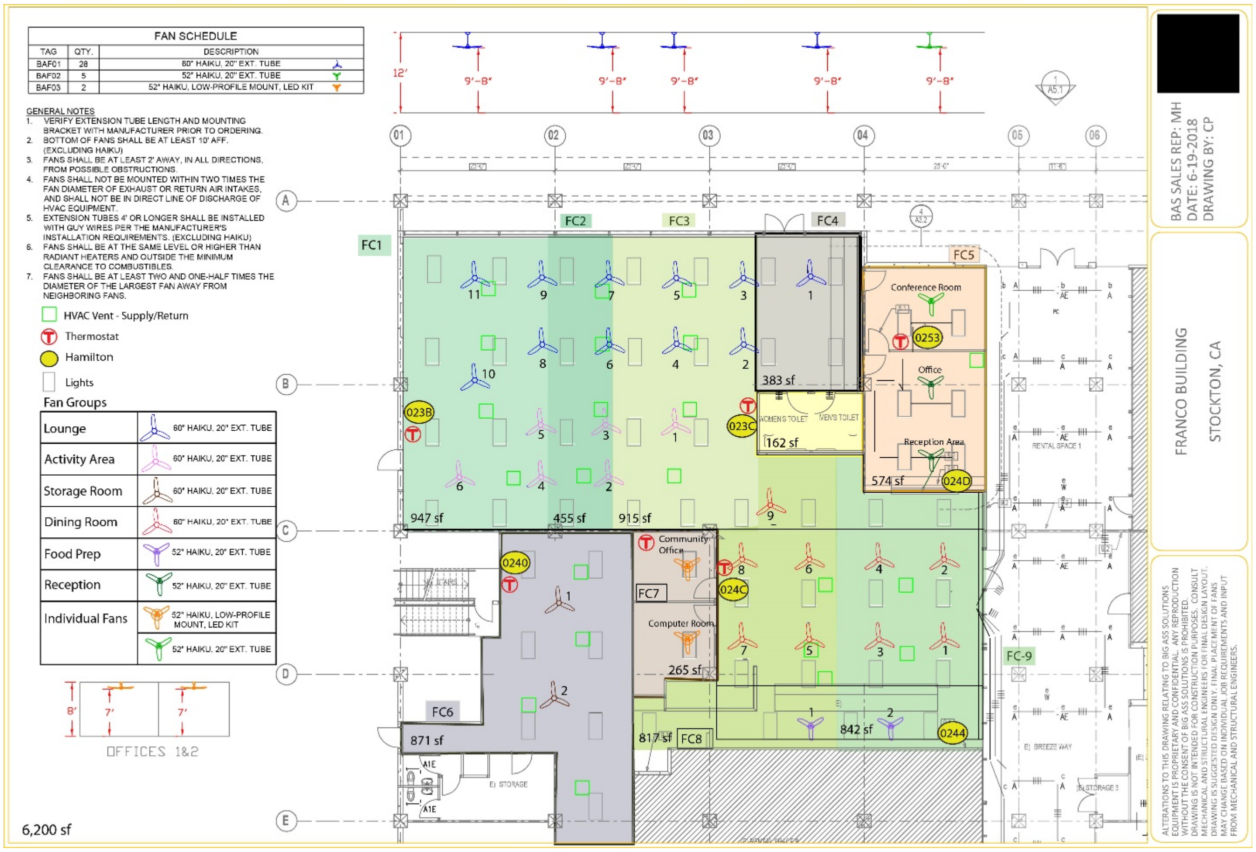
Final Installation Conditions

The figures below show the final installation layouts for the ceiling fans, thermostats, and other equipment installed at the demonstration sites.

In total, 99 ceiling fans were installed across the four demonstration sites, as follows:

- Franco Center: 35 ceiling fans
- Rolling Hills Community Building: 13 ceiling fans
- Parksdale 1 Community Building: 7 ceiling fans
- Parksdale 2 Community Building: 8 ceiling fans
- Parksdale 2 2-Bedroom Unit: 5 ceiling fans each (15 total)
- Parksdale 2 3-Bedroom Unit: 7 ceiling fans each (21 total)

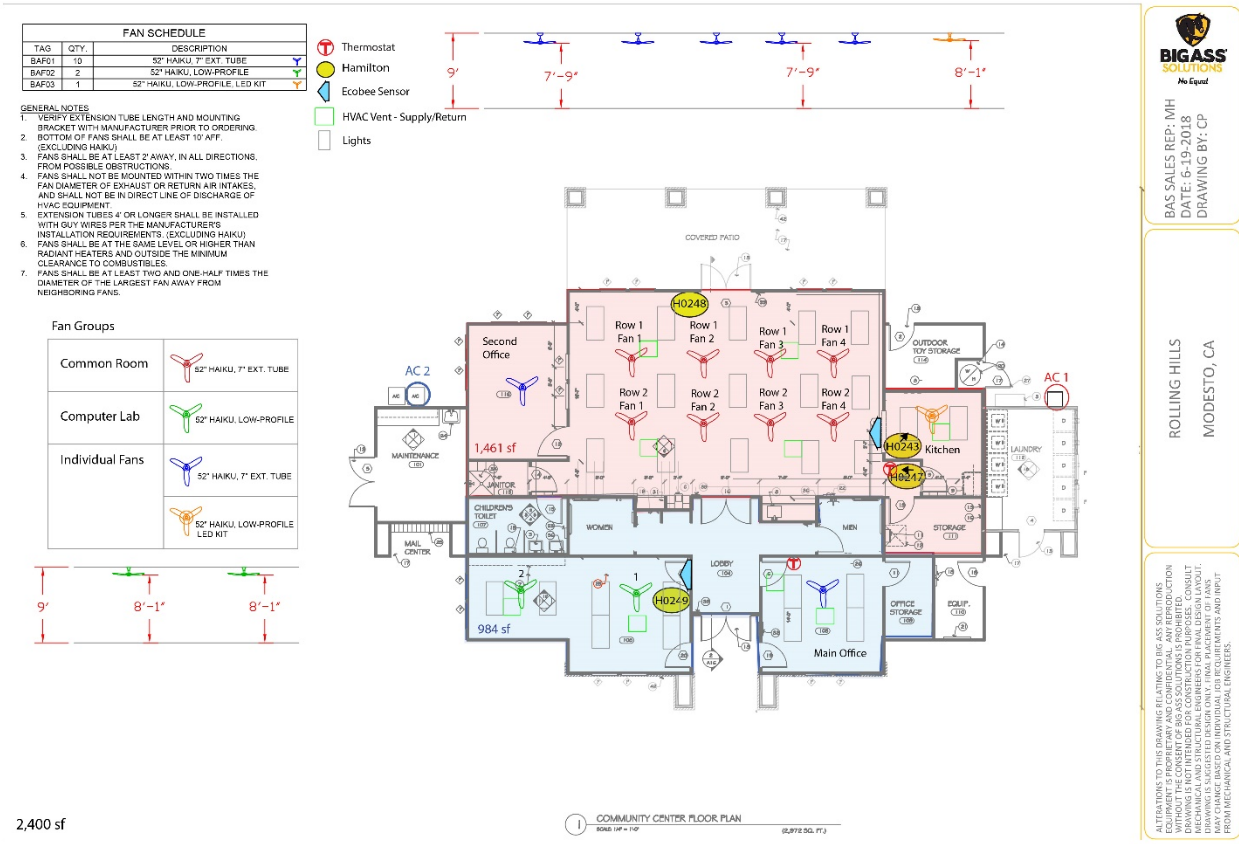
Figure 72: Franco Center Installation Layout



Layout of Franco Center demonstration site showing ceiling fan and thermostat locations, HVAC control zones, Hamilton temperature and humidity sensors, and lighting and HVAC vents.

Credit: TRC

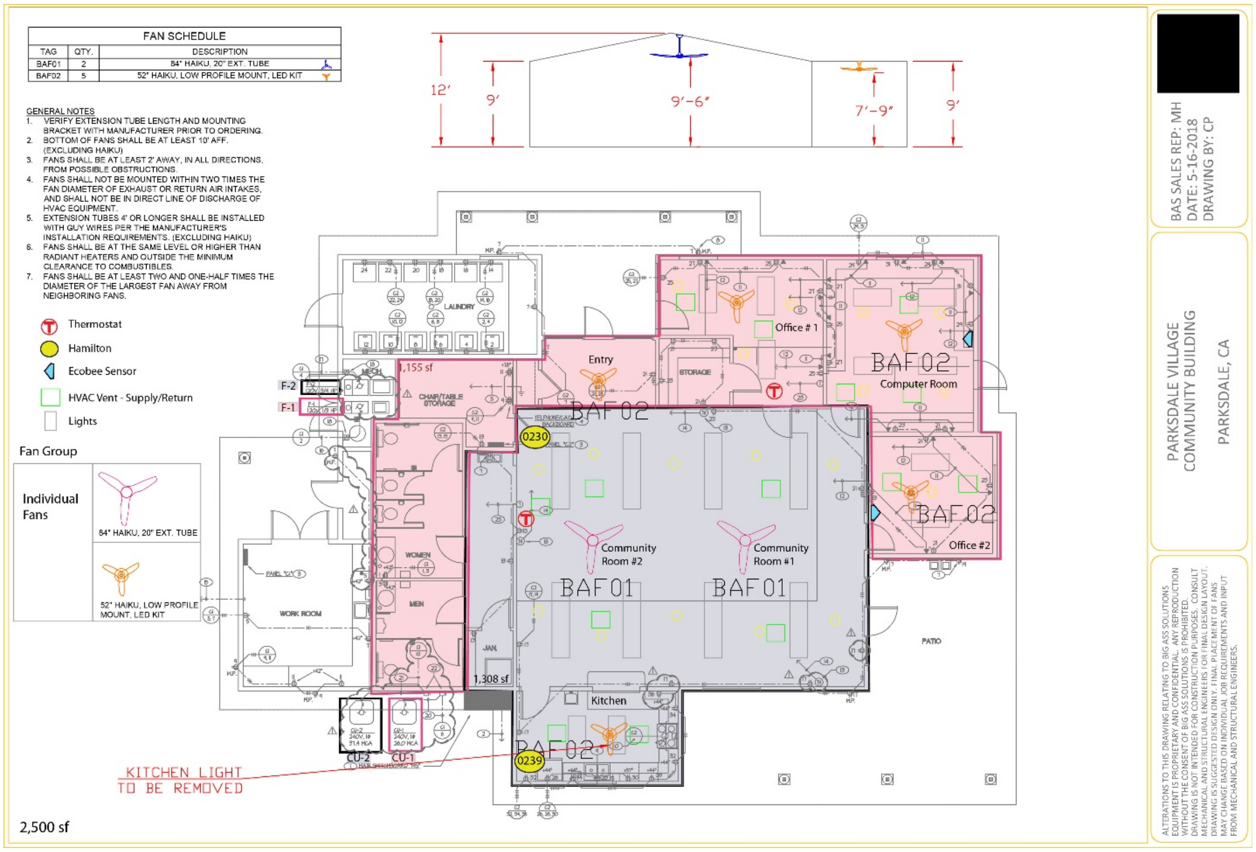
Figure 73: Rolling Hills Community Building Installation Layout



Layout of Rolling Hills Community Building demonstration site showing ceiling fan and thermostat locations, HVAC control zones, Hamilton temperature and humidity sensors, and lighting and HVAC vents.

Credit: TRC

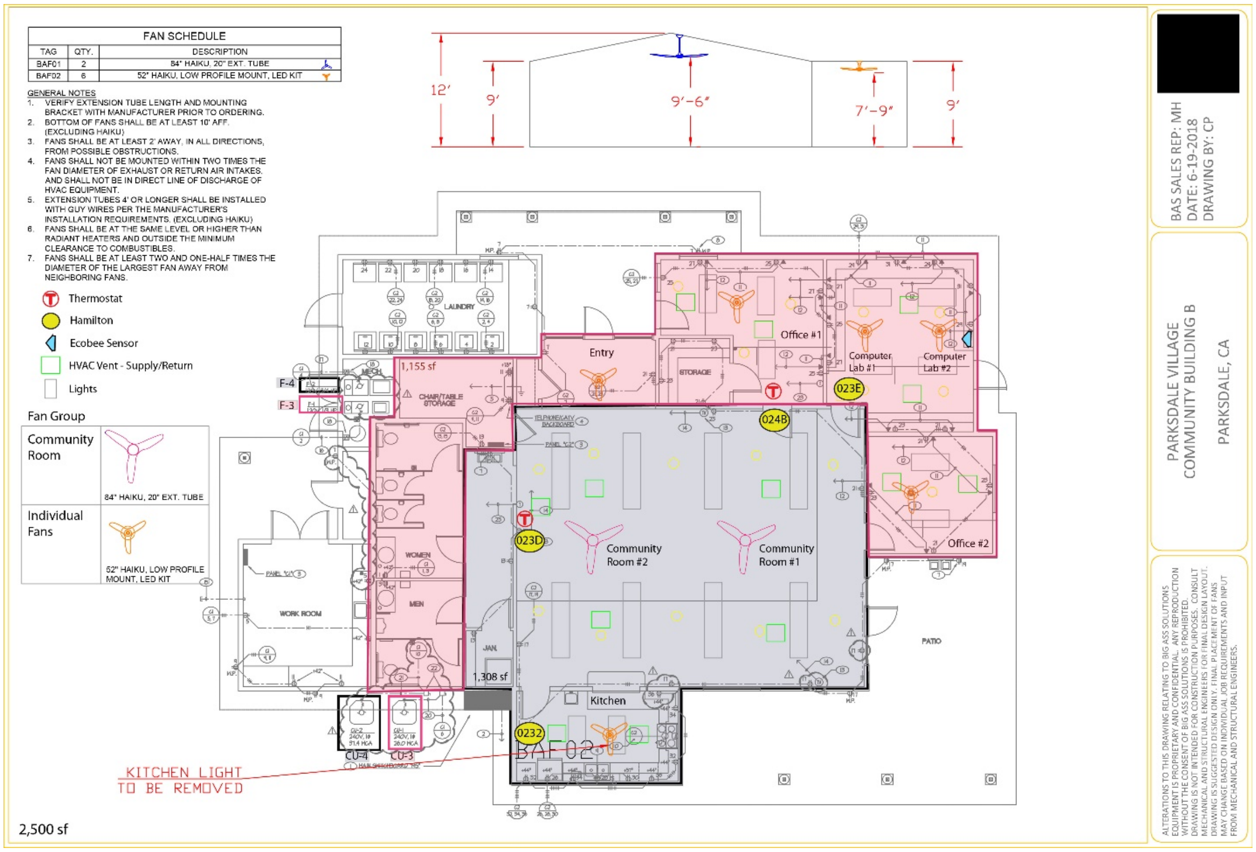
Figure 74: Parksdale 1 Community Building Installation Layout



Layout of Parksdale 1 Community Building demonstration site showing ceiling fan and thermostat locations, HVAC control zones, Hamilton temperature and humidity sensors, and lighting and HVAC vents.

Credit: TRC

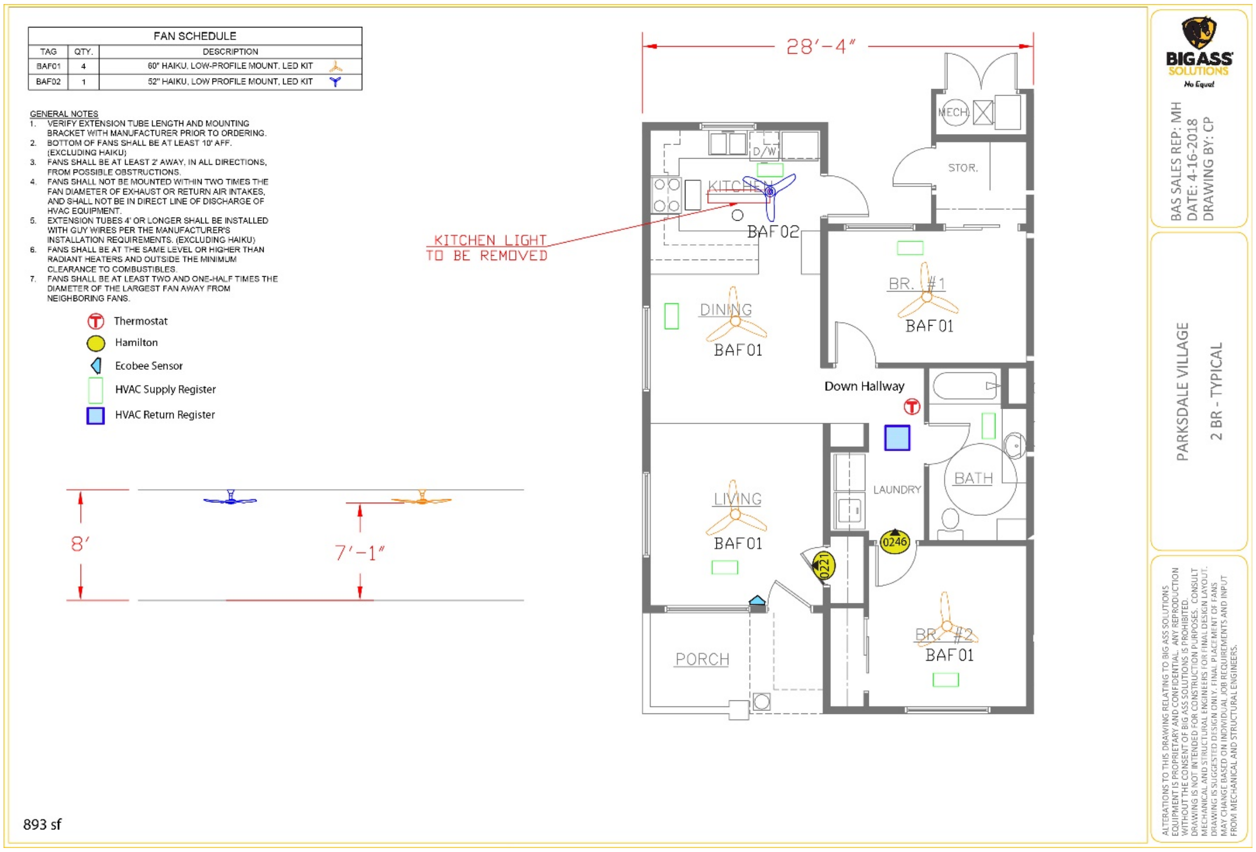
Figure 75: Parksdale 2 Community Building Installation Layout



Layout of Parksdale 2 Community Building demonstration site showing ceiling fan and thermostat locations, HVAC control zones, Hamilton temperature and humidity sensors, and lighting and HVAC vents.

Credit: TRC

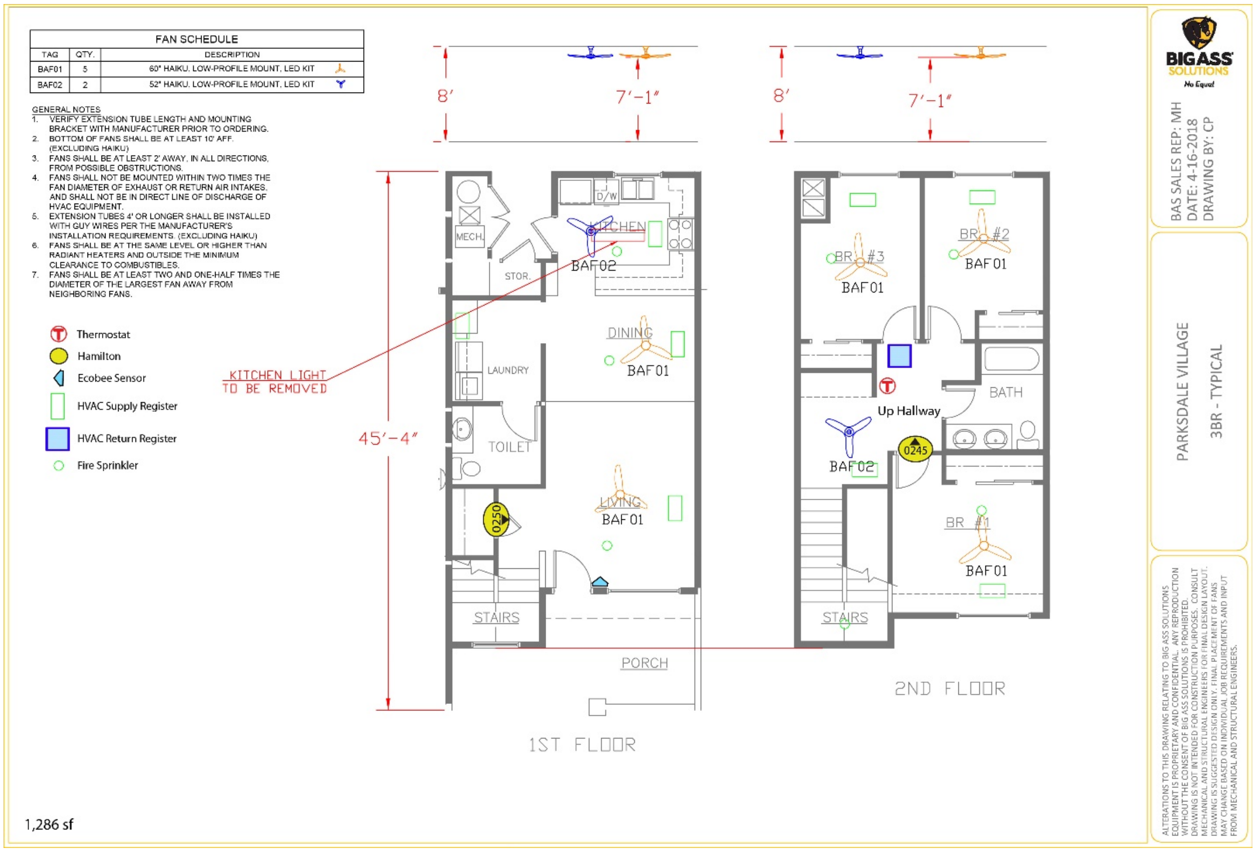
Figure 76: Parksdale 2 Typical 2-Bedroom Unit Installation Layout



Layout of Parksdale 2 Typical 2-Bedroom Unit demonstration site showing ceiling fan and thermostat locations, HVAC control zones, Hamilton temperature and humidity sensors, and lighting and HVAC vents.

Credit: TRC

Figure 77: Parksdale 2 Typical 3-Bedroom Unit Installation Layout



Layout of Parksdale 2 Typical 3-Bedroom Unit demonstration site showing ceiling fan and thermostat locations, HVAC control zones, Hamilton temperature and humidity sensors, and lighting and HVAC vents.

Credit: TRC

The photos below provide examples of the conditions at the site following the installation of the fans.

Figure 78: Franco Center community room with ceiling fans installed

Credit: CBE

Figure 79: Rolling Hills community room with ceiling fans installed

Credit: CBE

Ongoing Maintenance and Demonstration Site Challenges

Post-install visits were frequently required for a variety of concerns and data monitoring issues. All data was uploaded remotely to be visible either in real time or through daily downloads. This allowed the research team to see immediately when there was a problem, but made it difficult at times to diagnose whether a lack of data was due to equipment or the network it was connected to.

For convenience and price, Wi-Fi hotspots used were consumer models with minimal range, requiring a range extending device to be used with each one. For the residential units this equipment, in addition to the data monitoring equipment, was installed in the water heater closets outside the units. During high summer temperatures these closets would become hot enough to cause the range extenders to shut down, so that any equipment connected to them could not transmit data. While the range extenders did restart as the temperature cooled, the research team found that the equipment transmitting HVAC energy use would not reconnect and had to be restarted. This problem was solved by replacing all range extenders submitted to high temperatures with outdoor models built to withstand extreme temperatures.

Wi-Fi hotspots in exterior locations did not shut down in high temperatures, however the regular temperature swings are thought to be the cause of extreme battery expansion in many units, which required battery replacement and sometimes caused loss of power and charging ability.

Ceiling fans were only able to be controlled and adjusted via smartphone connected to the same local area network as the fan, and so required frequent visits. In order to retrieve fan data from the BAF servers properly, all fans needed to be registered under known users, and running firmware tailored to this project. This required visits to register the fans and update firmware. Fans in residential kitchens were found to have an incorrect logic board that did not allow them to be updated to the correct firmware version, and were replaced by BAF installers December 3rd - 4th 2018. Additionally, two of the installed fans at Franco developed problems with the motor, and needed to be replaced by BAF.

Many of the times when equipment lost connection with the network, or the network itself went down, the solution was to restart the item in question, which was only possible manually. To try and avoid this problem AEA installed "smart plugs" where possible, which could be controlled remotely and would automatically turn equipment off and on at least once per week.

One location that Hamilton sensors were installed was at HVAC supply vents, in order to determine whether compressors were in heating or cooling mode, as thermostat data was not available at this site. However, the project team found that being in the changing temperature air streams caused condensation to form on the devices, which was sufficient in some cases to short out the device. To eliminate this problem two methods were used: installing Hamiltons in plastic bags with a desiccant included, and installing separate temperature sensors wired directly into the Hobo U-30 data loggers.

Site Interventions

On April 24-26, 2019 AEA performed interventions in study spaces to set up and prepare for cooling season requirements. With worker/resident approval, thermostat and fan setpoints and scheduling were adjusted to be consistent across sites, at levels that were designed to be comfortable with some fan use, but not aggressive amounts. Fans were set to an ideal temperature of 75˚ F, except in bedrooms where the ideal temperature was raised to 76˚ F based on resident complaints of air movement while sleeping. Temperature setpoints for thermostats were as following:

- 80˚ F during the day while residents/workers were present ("Home" setting on Ecobees)
- 78˚ F during the night in residences ("Sleep" setting on Ecobees)
- 86˚ F while residents/workers were not present ("Away" setting on Ecobees)

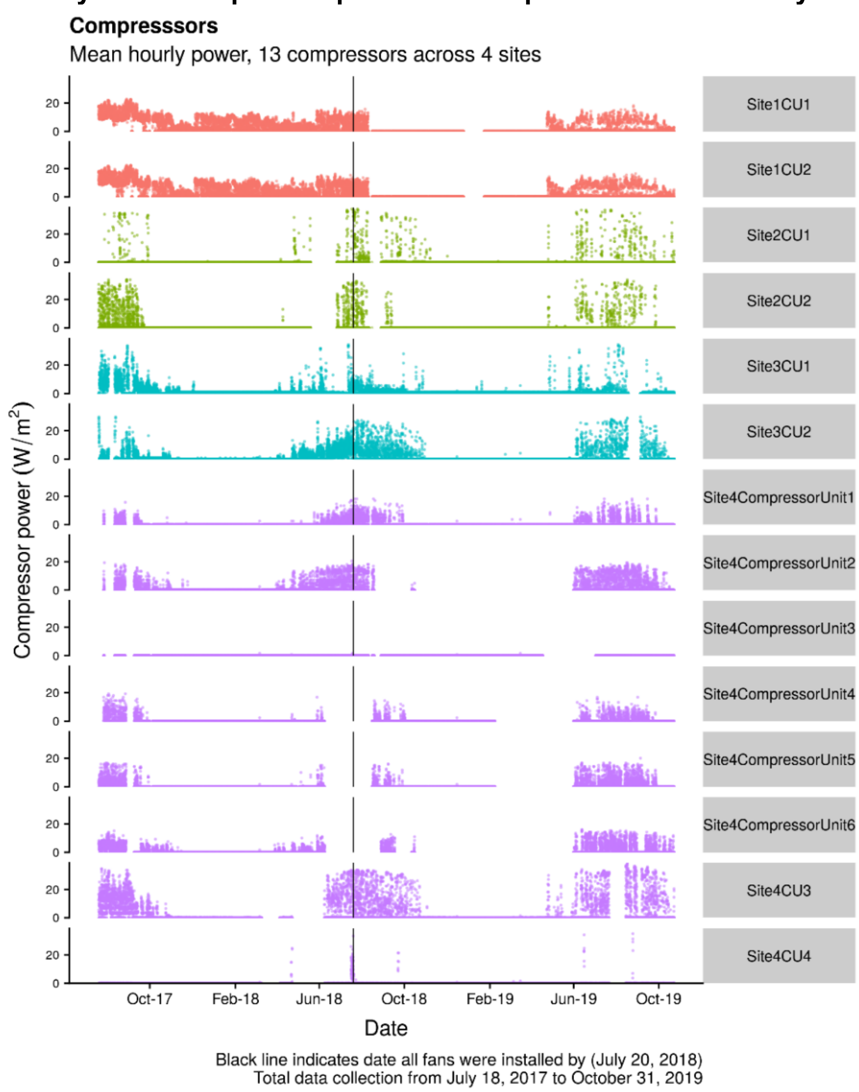
When the setpoints were adjusted, AEA and CBE conducted education to ensure that all residents and workers were comfortable using the fans and thermostats as needed. Education had been carried out at the initial installation, but followup surveys indicated that there was still some confusion on proper use of the equipment. In particular, use of scheduling on the thermostats, temporary vs permanent temperature setpoints, and using fans prior to reducing thermostat setpoints for cooling needed to be emphasized. Education was carried out verbally in person, using an English-to-Spanish translator when needed, and with flyers that were left with each user.

CHAPTER 6:
Energy Monitoring Analysis

Data overview

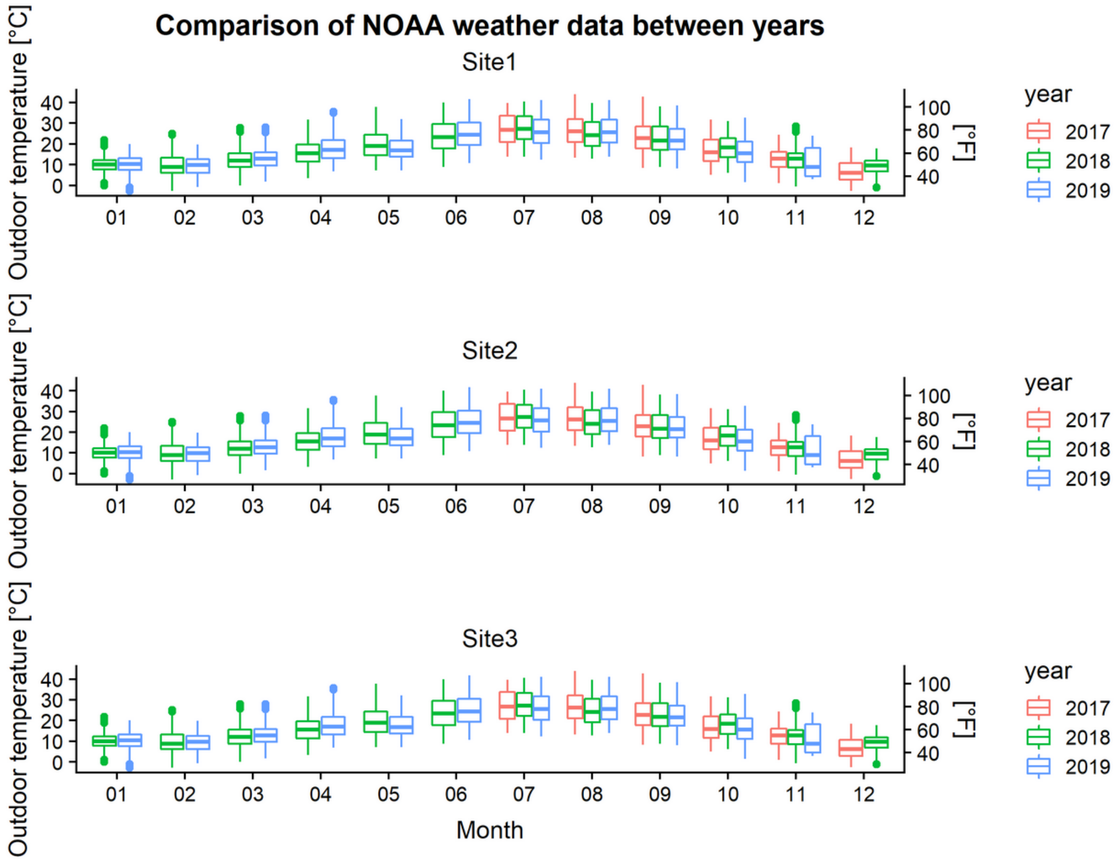
As described above, the research team installed monitoring equipment to measure compressor and system fan energy consumption at each site from July 18, 2017 to October 31, 2019. We also acquired measured weather data for the same period from the NOAA weather station nearest each installation site. Note that, as discussed above in Chapter 5, data acquisition difficulties that resulted in numerous periods of missing data for some of the sites, and in one residential unit, we were unable to measure compressor energy consumption.

Figure 80: Hourly mean compressor power consumption for all field study compressors



Timeseries of hourly average compressor power measured by each datalogger at each site over the study period. Blank periods reflect missing data.

Figure 81: Hourly mean outdoor air temperature for all field study sites



Hourly mean outdoor air temperature at each site over the study period, using data from NOAA Local Climatic Data station nearest to each site.

Compressor use across all sites

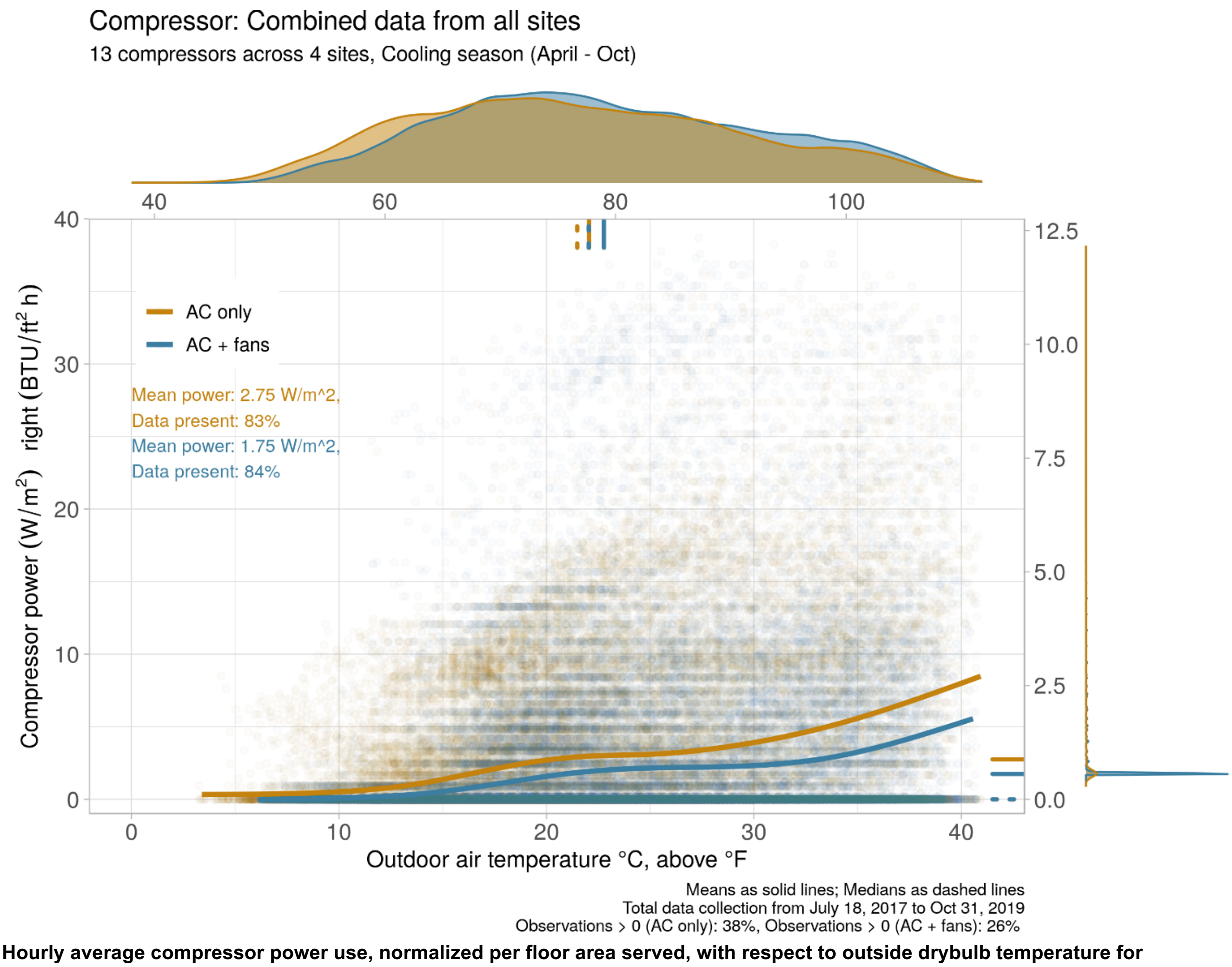
The research team defined our analysis plan in writing prior to generating the final summary plots for compressor energy use and indoor air temperatures below. This is good research practice to reduce potential bias in how results are presented. Figure 16: Hourly Mean Air Conditioning Compressor Power below shows the hourly average compressor power use, normalized by floor area served, for all sites with respect to outside drybulb conditions.

Overall, the intervention of installing smart ceiling fans and thermostats and educating occupants about potential energy and comfort benefits yielded substantially reduced compressor energy consumption in comparison to the baseline period. When considering all of the sites in the study, the average compressor power per floor area served during the intervention period was 36% lower than during the baseline period over the cooling season (defined as April 1 to October 31). If compared to the entire year, mean compressor power per floor area during the intervention period was 30% lower than the baseline.

It is important to note here that the floor area served by each individual compressor varies widely and the size and energy consumption of a compressor correlates with floor area. This is why the research team normalized by floor area – to prevent the larger floor area sites having more of an impact on the percentage savings estimate. The percentage reduction in average power without normalizing by floor area during the cooling season was 49%. This value is higher than the value normalized by floor area since the majority of the savings come from the largest site.

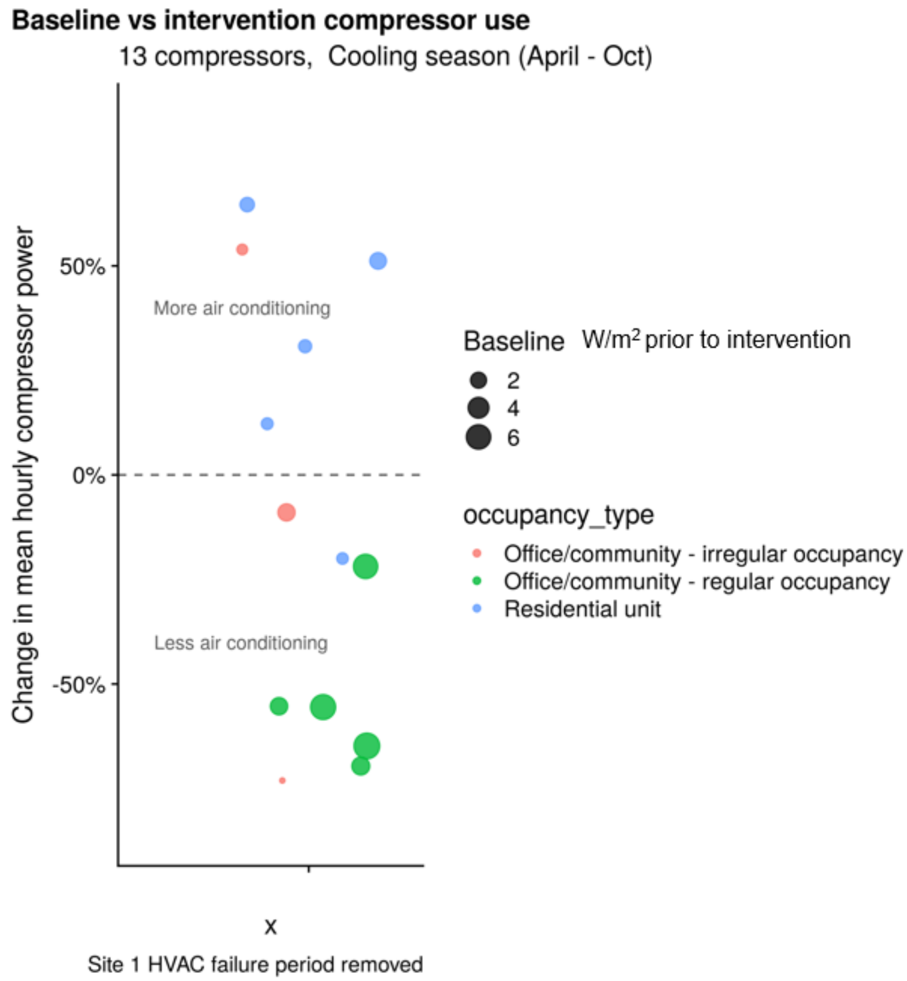
This is the observed savings during the study period without normalizing for weather, since as seen in Figure 16: Hourly Mean Air Conditioning Compressor Power below the measured outdoor air temperatures during the intervention period were comparable or warmer than the baseline period. Weather-normalized results will be discussed in more detail in the final report.

Figure 82: Hourly mean air conditioning compressor power during baseline and intervention periods across all field study sites



Hourly average compressor power use, normalized per floor area served, with respect to outside drybulb temperature for all 13 compressors measured in the project.

Figure 83: Observed energy savings per compressor, by space type



Comparison of observed energy savings per compressor, by space type. Points are sized relative to average compressor energy use during baseline period. Savings are estimated conservatively by excluding the period at Site 1 when the mechanical system failed. Weather-normalized savings will be estimated and compared for the final report.

While the majority of sites had both absolute and weather-normalized energy savings, the savings varied considerably between site, and in some cases, there was no energy savings. All of the commercial spaces with regular occupancy schedules had absolute energy savings in the intervention period, as well as two of the irregularly-occupied commercial spaces and one of the homes. The sites that did not report absolute energy savings were four of the homes and one of the irregularly-occupied commercial spaces, which is likely sue to a combination of both user behavior (eg preferring not to adjust cooling setpoints) and warmer outdoor temperatures during the intervention period that need to be accounted for with weather normalization.

To convey this variability in results, and highlight some of the issues encountered and considerations involved in scaling this technology more broadly, four examples are discussed below, with the full results for each site presented in Appendix C.

Note that we report data from the residences anonymously as the information contains personal data about occupant behavior.

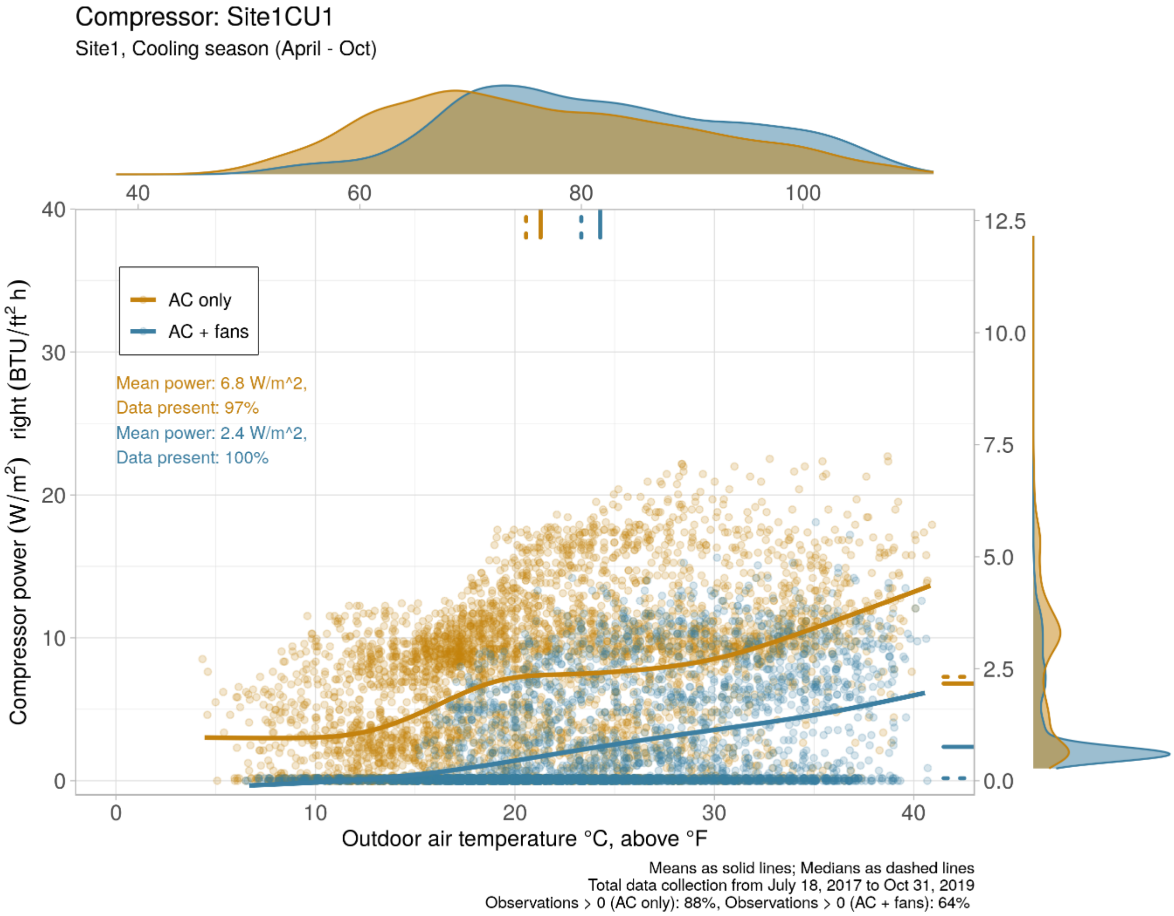
Examples of successful energy savings with fans + air conditioning

1 - Commercial site with largest sustained cooling setpoint change and energy savings

This particular site had a regular occupancy schedule and used relatively fixed setpoints in both the baseline period, and had substantial cooling energy consumption during that period. It also differed from the other sites notably in several ways. It is a high thermal mass building of concrete construction that is conditioned using a VRF heat recovery system that provides both heating and cooling to the space. Additionally, in this particular site we did not replace the thermostats as interoperability with thermostats other than those provided by the VRF manufacturer (such as Ecobee) is not supported. Thus, this is the only site in which we can assess the effect of installing the ceiling fans without the confounding effect of replacing the thermostat. This was also the largest site in the study - 564 m^2 (6070 ft^2).

As shown in Figure 20 below, the savings at this particular site were very substantial (65% reduction in compressor power), without normalizing for warmer weather in the intervention period. This particular site also encountered an extended HVAC failure during the study period due to a failure of the condensation pump system and a failed control board. During this period, the fans were still operating and the research team still collected surveys and data during this period. Despite the high indoor temperatures shown in the following section, the majority of the occupants were comfortable, demonstrating that this solution provides a measure of resilience during mechanical system failures.

Figure 84: Hourly mean air conditioning compressor power during baseline and intervention periods at commercial site with the largest energy savings

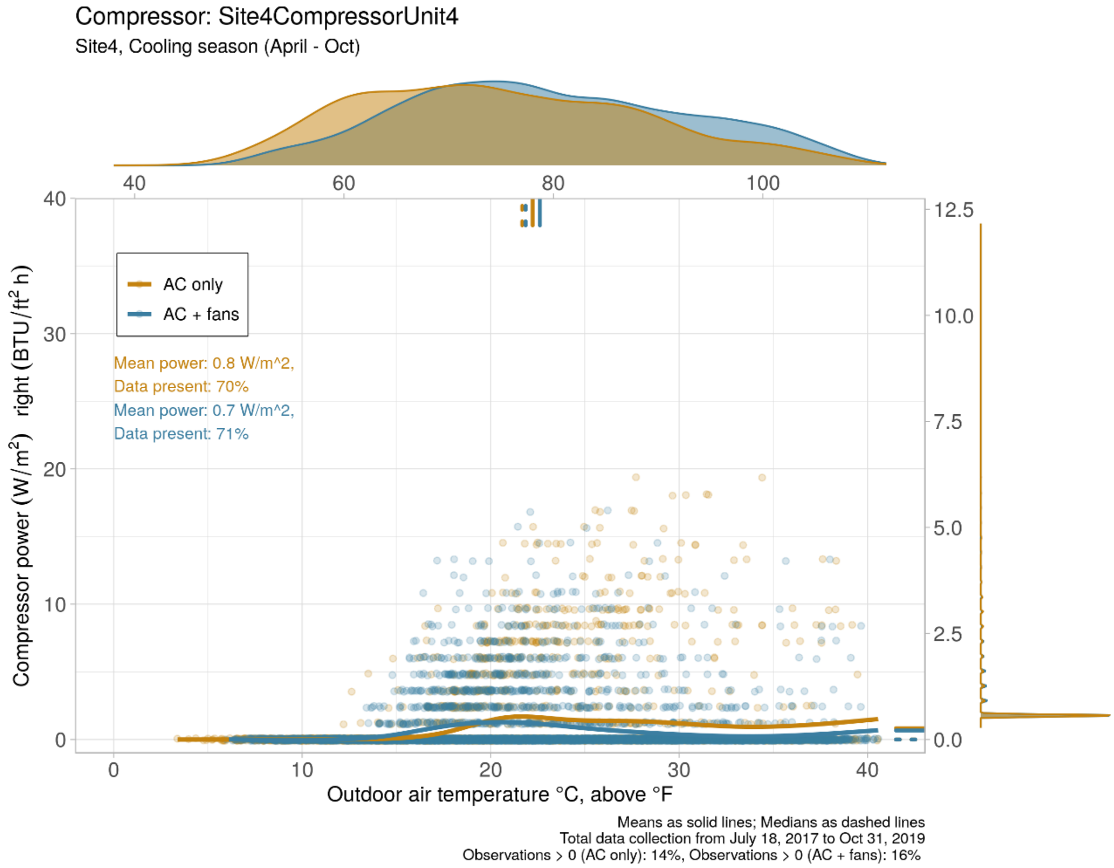


Compressor power use, normalized per floor area served, with respect to outside drybulb temperature for the large zone at Site 1 with both offices and a community room. Raising cooling setpoint temperatures (from ~72 F up to 78 F) resulted in much lower air conditioning energy use, in addition to less hours of runtime.

2 - Residential unit with energy savings

Figure 21 below summarizes energy use in one of the one-story stucco and wood multifamily residential units at Site 4. When the programmable occupancy-sensing thermostat was installed as part of the retrofit, the occupants were encouraged (and agreed to) set their cooling setpoint to 78 F. While the air conditioning compressor ran for a comparable fraction of hours during the baseline and intervention periods (14 % and 16%), the average cooling energy use during the warmer intervention period was slightly lower than the cooler baseline period. While the occupants schedule did not permit an interview for more detailed feedback, thermostat data showed the thermostat was frequently off during summer 2019, and that occupants adjusted the cooling setpoint to 80 and 86 F. While the fan usage data has not been processed yet, this may reflect occupants using fans for cooling before using the air conditioning and therefore not needing to run the air conditioning as often.

Figure 85: Hourly mean air conditioning compressor power during baseline and intervention periods at residential site with energy savings



Compressor power use, normalized per floor area served, with respect to outside drybulb temperature for one multifamily residential unit. Despite higher temperatures during the intervention period, energy use was comparable or lower.

Examples of limitation of retrofit approach

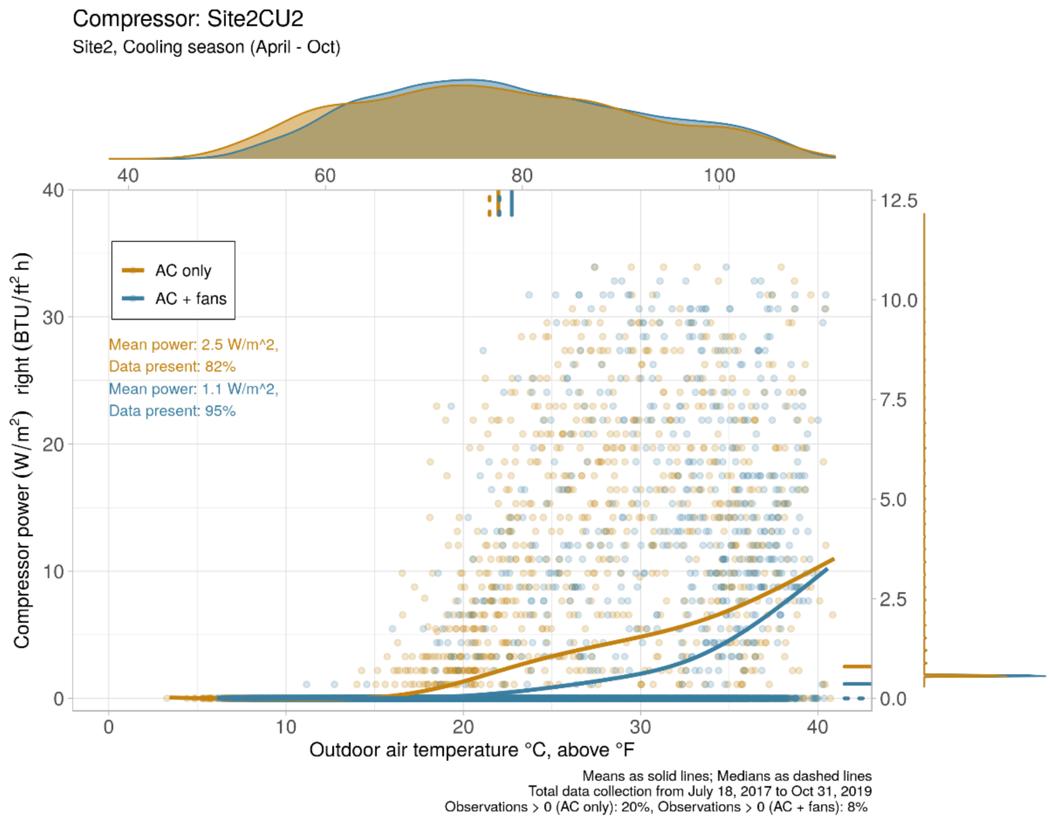
3 - Example of commercial site with infrequent occupancy

Figure 22 below summarizes energy use in the one-story community room at Site 2. While the average energy for air conditioning decreased in the intervention period after the fans and occupancy-sensing programmable thermostats were installed, the space is very infrequently occupied and mechanical cooling was not operated on a regular schedule. This is because unlike the adjoining offices, the community room is primarily used for evening or weekend events booked by residents. The air conditioner compressors used less energy after the fans were installed (an average of 56% less compressor power), with positive feedback from the site manager. However, since the compressors operate for less hours per year than a more frequently occupied space, the total energy savings is less than could have been realized if the initial mechanical cooling use was more frequent.

Reduced potential for energy savings due to infrequent space usage was also an issue in the community room at site 3, where despite small absolute energy savings, the compressor ran for only 2% of total hours in both the baseline and intervention periods.

This is an important consideration for future retrofits considering integrating fans and air conditioning – the potential savings from staging air movement and air conditioning is greatest at sites that have more frequent and/or more intense air conditioning use.

Figure 86: Hourly mean air conditioning compressor power during baseline and intervention periods at commercial site with infrequent occupancy and therefore reduced potential for savings

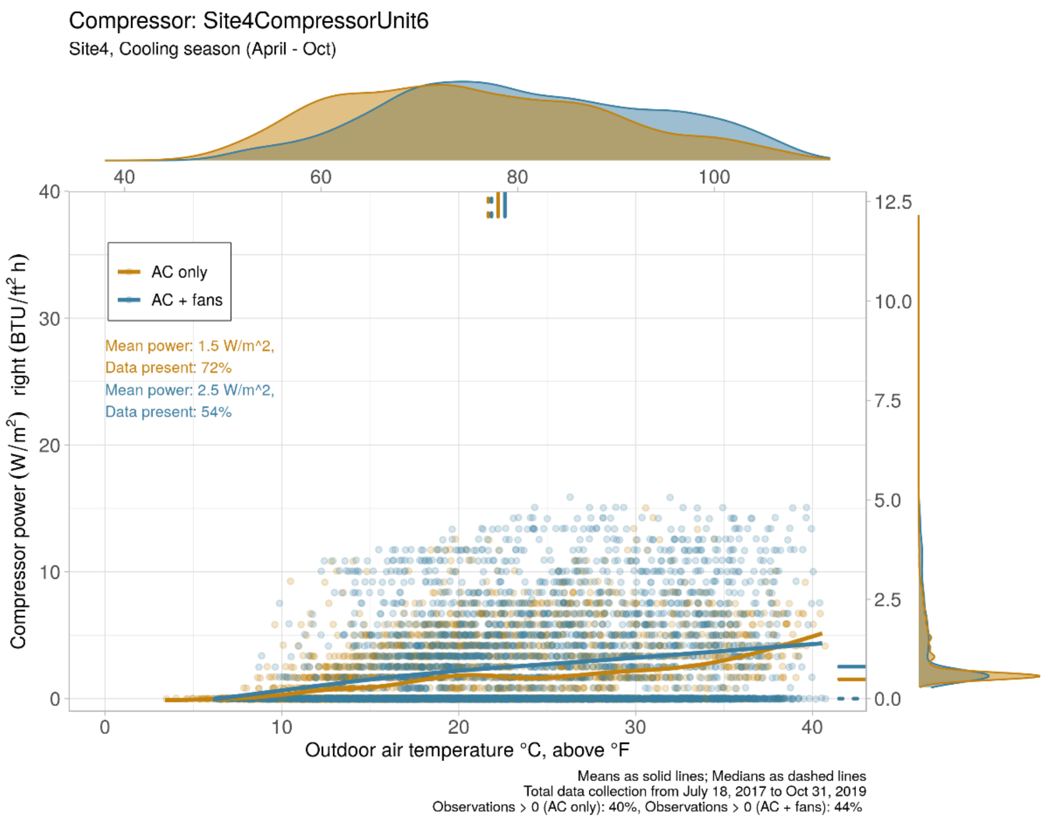


Compressor power use, normalized per floor area served, with respect to outside drybulb temperature for a less-frequently used community room. Across comparable temperatures, the site used less air conditioning energy during the intervention period, but greater savings could have been realized if the space had required more frequent air conditioning.

4 - Residential unit without energy savings (before weather normalization)

Figure 23 below summarizes energy use in one of the two-story stucco and wood multifamily residential units at Site 4. When the programmable occupancy-sensing thermostat was installed as part of the retrofit, the occupants were encouraged to set their cooling setpoint to 78 F, but afterwards typically chose to set lower cooling setpoints of ~ 71 F. This may have been due to personal preference, and the consideration that at least one adult occupant was home most of the day, so there was less potential for setbacks during unoccupied periods. The air conditioning compressor ran for a comparable fraction of hours during the baseline and intervention periods (40 % and 44%), however the intervention period was warmer, with about twice as many 95 F degree hours than the intervention period. Without normalizing for the warmer weather, the observed compressor cooling energy use increased by 66%. In interviews, the occupants reported appreciating the fans. One of the occupants expressed that the fans improved their comfort in the space, particularly in one of the upstairs rooms, and had been excited to have the fans installed and would recommend the fans. So despite not saving energy in this case, likely due to the lower cooling setpoints that the occupants chose to continue to maintain, they reported a comfort benefit.

Figure 87: Hourly mean air conditioning compressor power during baseline and intervention periods at residential site with reduced potential for savings due to low cooling setpoints



Compressor power use, normalized per floor area served, with respect to outside drybulb temperature for one multifamily residential unit that did not realize energy savings. The occupants preferred to maintain relatively low thermostat cooling setpoints (~71 F) after fan installation.

CHAPTER 7: IEQ Monitoring Analysis

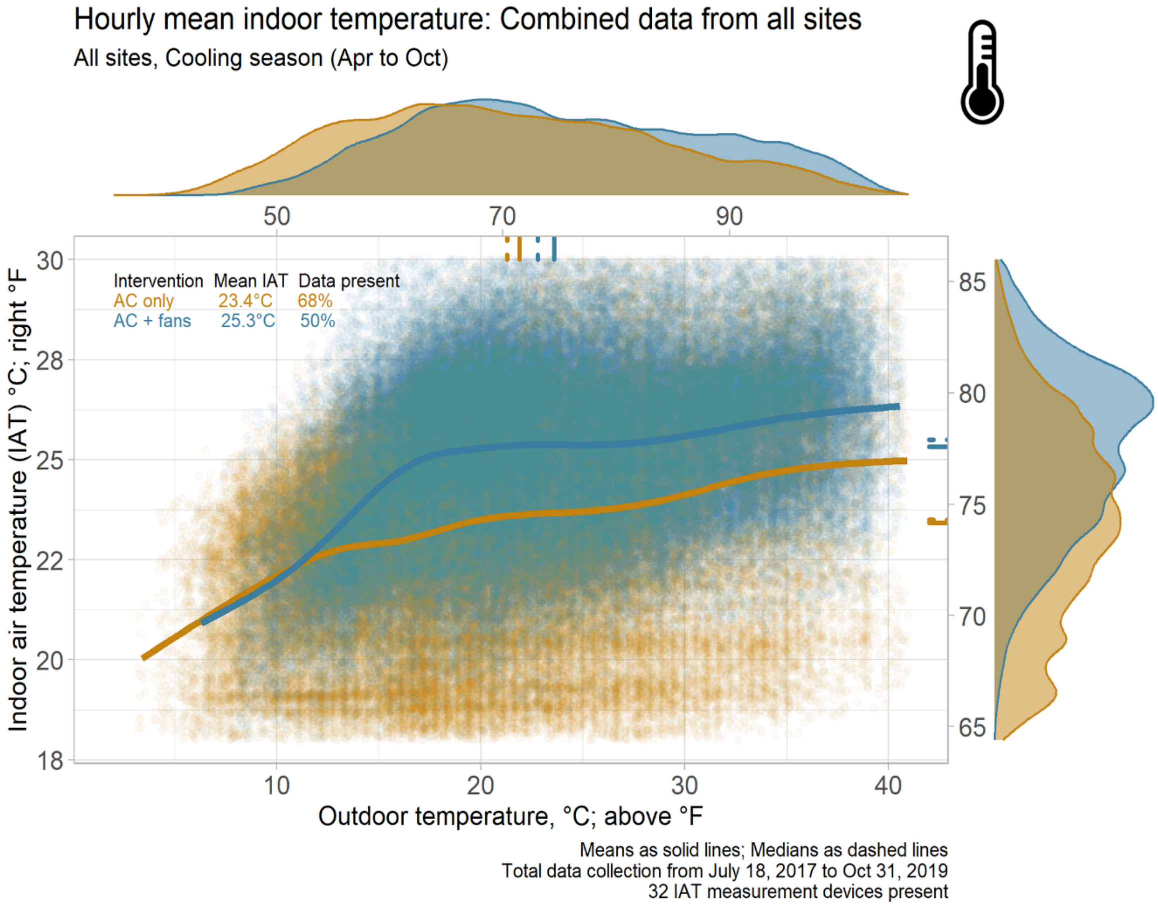
Indoor temperature sensors were installed at each site in summer 2017, one year prior to the retrofit installation of the ceiling fans and new thermostats. Multiple temperature sensors were installed at some sites to capture potential variation in larger spaces (such as a large zone or a two-story residential unit). Due to data transmission issues, some sensors had periods of missing data. In the plots below, temperatures for each HVAC zone are based on the mean hourly temperature from all temperature sensors in each zone, with data for each sensor available in Appendix C.

After the new ceiling fans and thermostats were installed, occupants at each site were encouraged to increase their air conditioning cooling setpoints to account for the cooling effect of the fans through verbal explanations and printed educational materials. In commercial spaces, depending on the previous cooling setpoint the cooling setpoints for the new thermostats were either directly increased to 76 F at install, or gradually raised over a period of several weeks in cooperation with the site. Occupants were free to adjust the thermostat, and were provided with information on how to do so. In residential units, the default cooling setpoints were increased to 78 ˚F during installation. Residents were similarly free to adjust the thermostat and were provided with instructions on how to do so. Based on thermostat usage data, occupants in both commercial and residential spaces adjusted their thermostats, with changes ranging from permanently changing the schedule or default setpoints to temporary overrides.

Consistent with the reductions in air conditioning compressor use and the observed increases in thermostat setpoints, mean measured indoor air temperatures were higher in the intervention period than the baseline period across a similar range of outdoor temperatures. As shown in Figure 88 below, the mean hourly indoor air temperature across all sites increased approximately 2 ˚C (4 ˚F).

The subsequent figures (36 – 40) show the indoor air temperatures for the same four sites compressor usage was shown for in Chapter 6 above (Figures 31 – 34).

Figure 88: Hourly mean indoor air temperature during baseline and intervention periods across all sites



Indoor air temperature across all 32 indoor sensors across all sites compared to outdoor drybulb air temperature

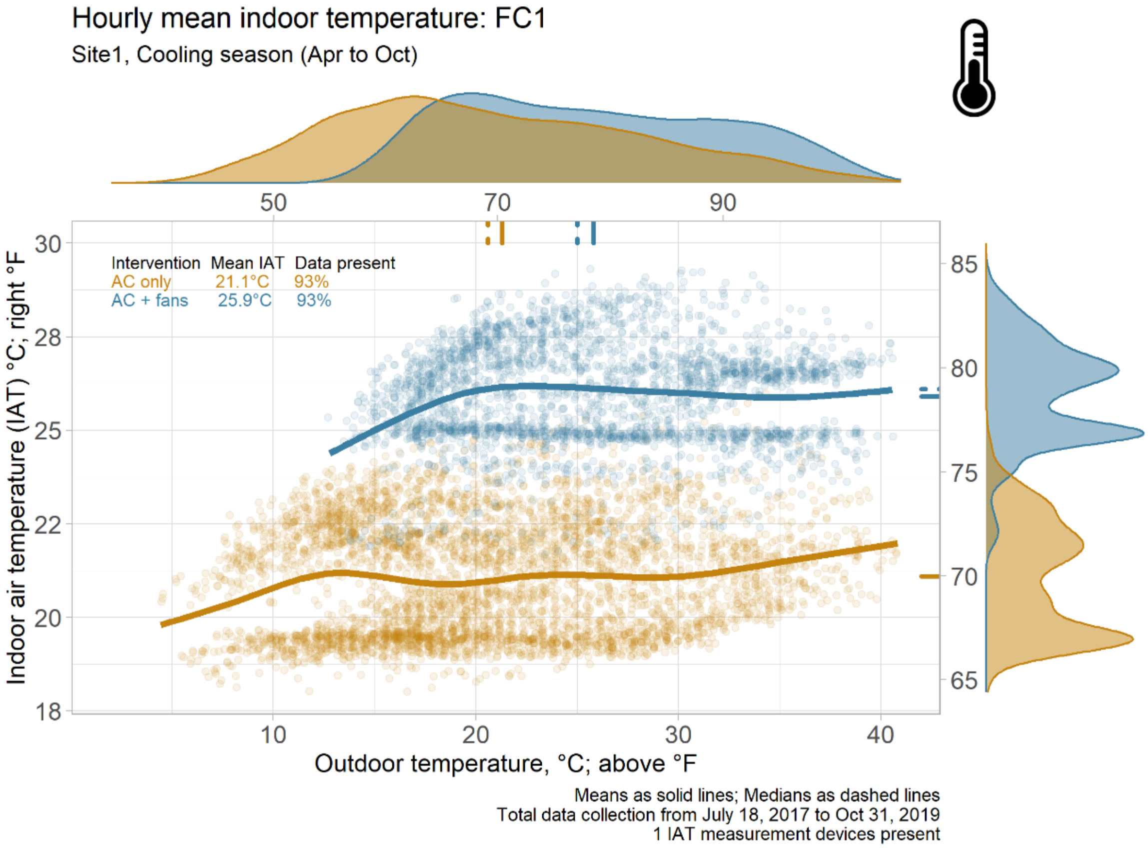
Examples of successful energy savings with fans + air conditioning

1 - Commercial site with largest sustained cooling setpoint change and energy savings

As shown in the previous section, this particular site had substantial savings, at 65% reduction in compressor power use.

Figure 25 below demonstrates that the mean indoor temperatures also substantially increased, by approximately 4.5 ˚C (9 ˚F). The site facilities manager, office staff and occupants had positive feedback about the fans, and right now occupant surveys showed a similar thermal comfort between baseline and intervention periods.

Figure 89: Hourly mean indoor air temperature during baseline and intervention periods at commercial site with the largest energy savings

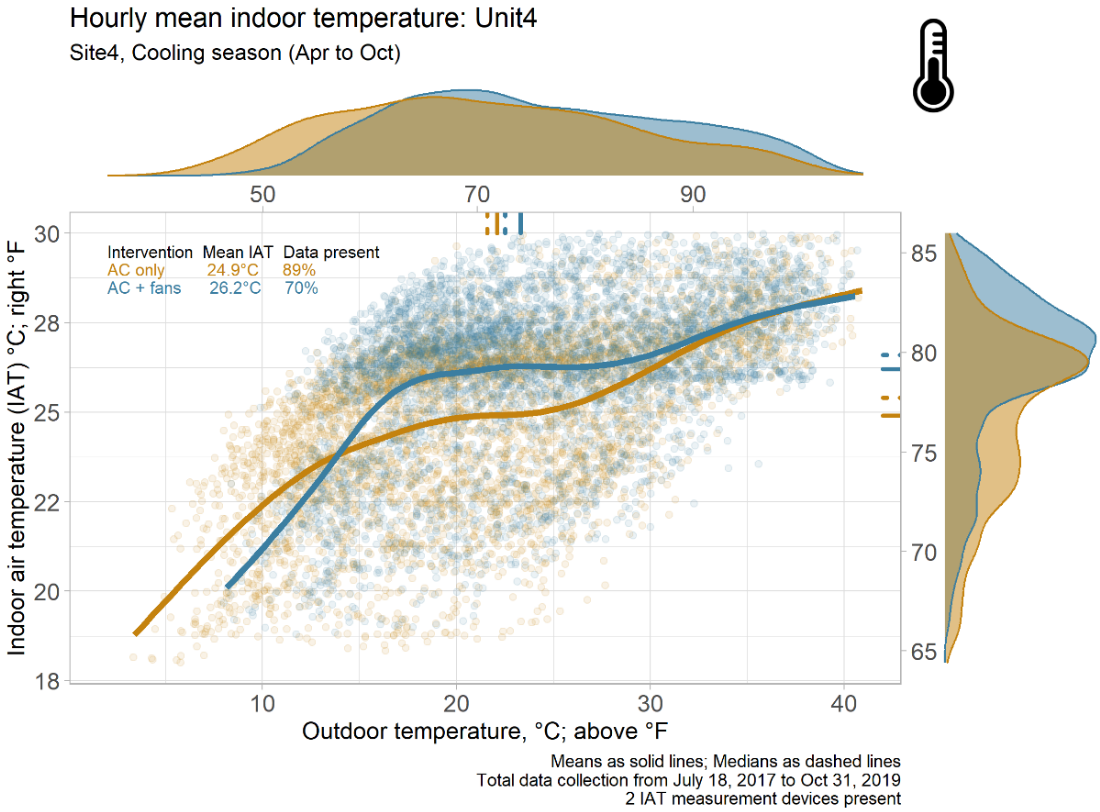


Indoor air temperature compared to outside drybulb temperature for a large zone at Site 1 that increased cooling setpoints from ~ 72 F to ~ 78 F, resulting in higher indoor air temperatures, while maintaining occupant comfort.

2 - Residential unit with energy savings

Figure 26 below summarizes indoor air temperatures in one of the one-story stucco and wood multifamily residential units at Site 4 that used less energy during the intervention period, despite higher outdoor temperatures. Mean and median indoor air temperatures are about 1 ˚C (~ 2 ˚F) higher in the intervention period after fan install, and are most noticeably higher between outdoor air temperatures of approximately 15 and 30 ˚C (60 – 86 ˚F). The data shown is for all hours, which may include unoccupied periods when residents were not at home for extended periods of time. Occupancy data will be discussed in more detail in the final report.

Figure 90: Hourly mean indoor air temperature during baseline and intervention periods at residential site with energy savings



Indoor air temperature compared to outside drybulb temperature for a one-story multifamily residential unit that realized energy savings despite warmer temperatures during the intervention period. Mean and median indoor air temperatures are about 1 °C (~ 2 °F) higher in the intervention period after fan install.

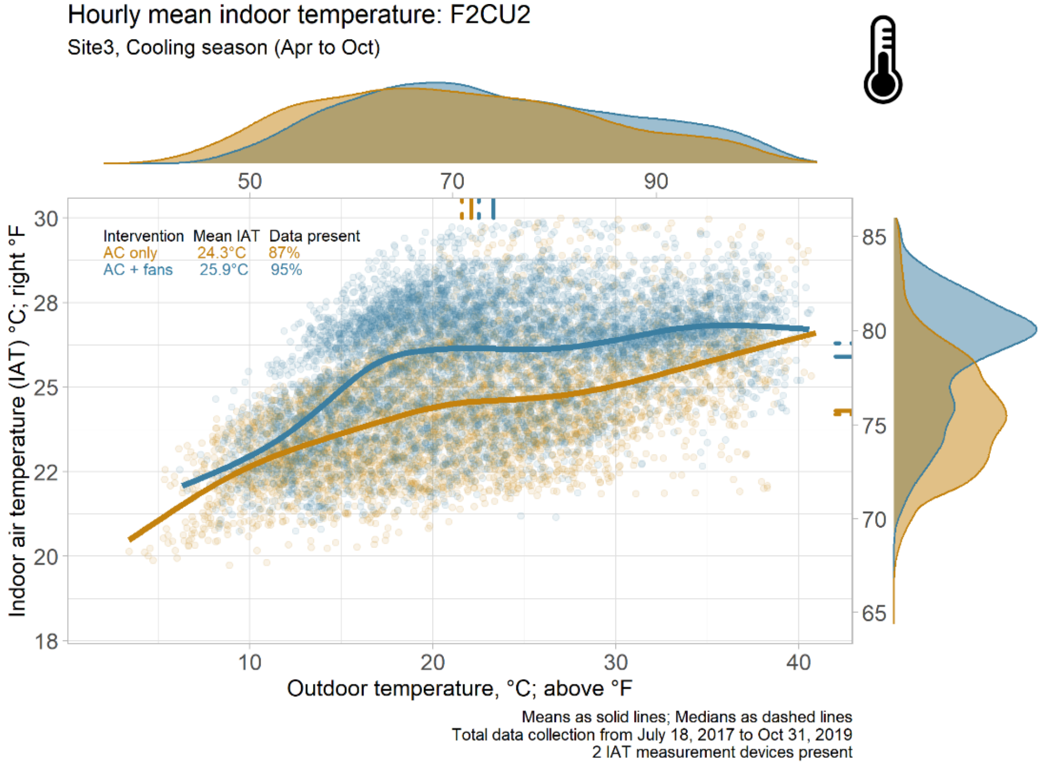
Examples of limitation of retrofit approach

3 - Example of commercial site with infrequent occupancy

As discussed above, this space is infrequently occupied and thus the HVAC system operates infrequently and the total cooling energy savings are relatively low. Despite this,

Figure 27 below shows the combined intervention of the new occupancy-sensing thermostat and ceiling fans appears to have led to higher indoor temperatures in the intervention period (consistent with the reduction in air conditioning use discussed in Chapter 6 above). This is likely due to the new thermostat schedule, setpoints, and occupancy sensing, including an unoccupied cooling setback setpoint of 82 ˚F.

Figure 91: Indoor air temperature compared to outside drybulb temperature for a less-frequently used community room



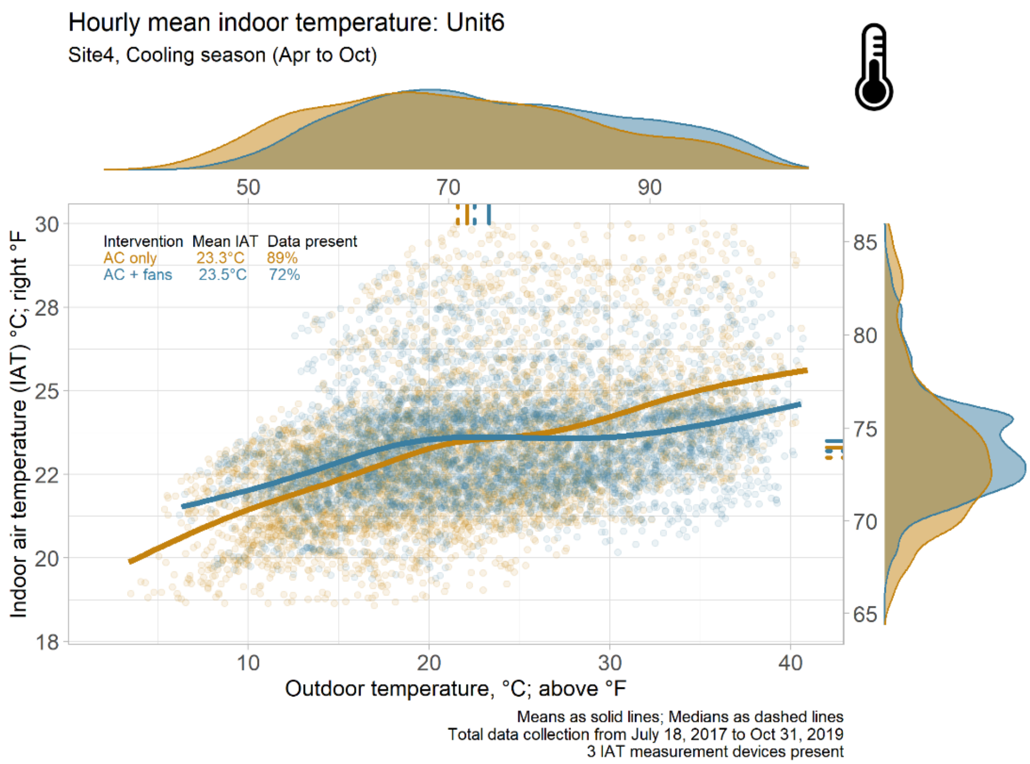
Indoor air temperature compared to outside drybulb temperature for a less-frequently used community room. Across comparable temperatures, the site that higher indoor temperatures during the intervention period, used less air conditioning energy during the intervention period, but greater savings could have been realized if the space had required more frequent air conditioning.

4 - Residential unit without energy savings (before weather normalization)

As discussed in the corresponding section in Chapter 6 above, occupants in this residential unit preferred not to increase the air conditioning cooling setpoints after fan installation, so unsurprisingly mean hourly indoor air temperatures were comparable in both the baseline and intervention periods as shown in Figure 28 below. The occupants received written and verbal information about how increasing cooling setpoints could contribute to energy savings with comparable comfort, but preferred their existing setpoints. At least one adult was home during most of the day, which may also have contributed to this preference.

This highlights the conditional potential for energy savings using air movement – while ceiling fans staged with air conditioning can save substantial amounts of cooling energy, this intervention is only effective if the cooling effect from fans enables occupants raising cooling setpoint temperatures. Numerous personal needs and preferences, including but not limited to differences in indoor activities, clothing levels, and health status all contribute to cooling temperature preferences.

Figure 92: Hourly mean indoor air temperatures during baseline and intervention periods at residential site with reduced potential for savings due to low cooling setpoints



Indoor air temperature compared to outside drybulb temperature for a residential unit that maintained comparably low air conditioner cooling setpoints after the intervention, and therefore did not realize energy savings prior to weather normalization.

CHAPTER 8: Occupant Interviews and Surveys

This chapter examines perceptions and experiences with the installed thermostat and ceiling fans equipment from both resident and office occupants. Feedback was collected using both surveys and interviews across multiple time points. The methodology implemented for both the surveys and interviews, limitations of the current data and methodologies, and the results from each method, by participant type are described below.

Methods

To capture occupant perceptions, the research team collected data with two primary methodologies: interviews and surveys. Interviews were conducted at two time points with both residential and office worker occupants. Surveys were collected mainly during Summer and early Fall 2018 with office workers and at community events, though surveys were also distributed at a final community event in Summer 2019. Details of each method and participants are described below.

Survey tools

All participants were given two surveys: the “Personal Characteristics Survey” and the “Right Now Survey”. The Personal Characteristics Survey asked occupants for their basic demographics and their general perceptions of energy use. Specifically, the survey asked occupants about their age, gender, use of heating and cooling devices, whether they get hot or cold easily, and typical energy-saving behavior. The Right Now survey was a brief 10-item survey aimed at understanding occupants’ perceptions of the space they were in at that given moment the survey was deployed. This survey asked questions around thermal comfort, perceptions of air movement, and perceptions of air quality in situ. Further, it asked what articles of clothing occupants were wearing that day.

Survey protocol and participants

Office Workers

Each office worker was required to be in the space for at least 20 minutes before filling out the surveys. Employees were asked to complete the surveys 2-3 times throughout the day as they were able to over a period of about six weeks. Each time they completed the two surveys, workers were given a $5 gift card. Surveys took approximately three to five minutes to complete.

More specifically, surveys were deployed to office workers at the start of the 2018- cooling season until that November. On five dates between 29th June 2018 and 12th September 2018, a total of 16 survey responses were collected from office workers at two sites. 12 responses were collected at the Franco site; 4 responses were collected at the Parksdale I site. Participant mean age was 48 years (SD = 15), and 13 respondents were female and 3 respondents were male.

Limitations of Office Worker Surveys

Initially the research team left a pile of surveys for office workers to complete as they were able and our research team would aim to pick them up periodically as they were completed. The researchers struggled a great deal in getting employee engagement with the surveys. Often times occupants expressed their lack of time in being able to complete the brief survey. To reduce effort on the employees part, the team replaced the initial surveys with ones that required the least amount of information possible to be filled out by participants, gave them stamped and addressed envelopes for each survey, contacted them with regular reminders, and also offered $5 gift cards for participation. This increased survey completion in a couple of instances, however participation was still quite low making the findings from this data source limited in its generalizability.

Residential Community Events

Surveys were distributed by the research team at a total of three community events for the residents held within the common room at the Franco site. Similar to office worker surveys, participants were required to be in the space for at least 20 minutes before filling out the surveys. Also like office workers, two surveys were given: the Personal Characteristics Survey and the Right Now Survey. Ultimately the researchers reduced the Personal Characteristics Survey after the first round of data collection to help ease participant effort. All of the residents attending these events were elderly citizens some of which had trouble reading the materials. To combat these challenges the team increased the font size of the forms after the first round of data collection. Also, the survey team worked closely with residents by reading the surveys aloud to them to ensure they understood the questions and could physically fill in the survey correctly. Participants were given a $5 gift card each time they completed a survey. Given the surveys were read aloud to participants, they took approximately five to ten minutes to complete.

More specifically, surveys were administered twice, once in June (i.e., Time One) before ceiling fans were installed in the common room space and again in September (i.e., Time Two) after ceiling fans had been installed in the common room space. The surveys were deployed a third and final time in July 2019 (Time Three), in the middle of the cooling season, a year after the equipment had been installed.

During Time One of data collection in 2018, 26 respondents completed the survey (11 females and 10 males; five respondents gave no answer for gender). Mean age for these occupants was 66 years (SD = 13). At Time Two, again 26 participants completed the survey (12 females and 13 males; one respondent gave no answer for gender). And the mean age for Time Two was 65 years (SD = 12). At Time Three 30 respondents completed the survey (15 females, 12 males, and 3 did not respond). The mean participant age at this time point was 65 years (SD = 14.7).

Limitations of Residential Community Event Surveys

These surveys were only conducted at one site (Franco), therefore there are limits in the generalizability in the findings. Further, occupants at this site tended to be older and as a result of age needed a great deal of assistances from the researchers to complete the surveys. The research team aimed to increase usability of the surveys over time by increasing font size, reducing the number of questions asked, and having the team read the survey to the participants and assist them as they filled it out, but there is still possibility that there was unaccounted for error present in participants' responses.

Survey Results

Office Workers

Because recruitment was a challenge to get office workers to complete surveys, little data is available and thus the generalizability of this particular data source is limited. Here the research team focuses on the data collected from the "Right Now" survey. This information is the focus because it provides a quick snapshot of questions most relevant to how the occupant was engaging with the space at the moment of data collection. Below the results reflect a composite of all of the data points collected before and after installation of the fans.

The tables overall show an increase in variation in each response occurred within the post-installation collection points. It is a challenge to conclude though if these findings are meaningful since there was a significant increase in data collected. What these findings do consistently suggest though is that there are likely individual differences across participants that account for shifts in preferences in thermal sensation, air movement acceptability and thermal acceptability. These differences are possibly physiological, psychological, and situationally dependent. There is less variation visible in air quality acceptability, however, there are still likely individual differences in this perception, most likely due to situational circumstances of the space.

More specific insights about the office worker perceptions can be learned from the interview data presented below. However, future research should examine the impact of fans on worker perceptions in a larger sample of participants to increase understanding and generalizability.

Table 15: Office worker responses before and after fan installation

Survey question	Answers before fan installation	Answers after fan installation
Thermal sensation: "How warm or cool do you feel right now?"	Much too warm: 0 Too warm: 1 Comfortably warm: 0 Comfortable: 1 Comfortably cool: 1 Too cool: 0 Much too cool: 0	Much too warm: 0 Too warm: 2 Comfortably warm: 2 Comfortable: 6 Comfortably cool: 3 Too cool: 0 Much too cool: 0

Survey question	Answers before fan installation	Answers after fan installation
Thermal acceptability: "Is this temperature in this space acceptable right now?"	Yes: 3 No: 0	Yes: 11 No: 1 N/A: 1
Air movement acceptability: "Which of the following best describes the air movement right now?"	Unacceptable, too low: 1 Acceptable, but too low: 1 Acceptable: 1 Acceptable, but too high: 0 Unacceptable, too high: 0	Unacceptable, too low: 0 Acceptable, but too low: 1 Acceptable: 12 Acceptable, but too high: 0 Unacceptable, too high: 0
Air quality satisfaction: "How satisfied are you with the air quality (how clean and breathable the air feels) in your space right now?"	Satisfied: 1 Somewhat satisfied: 0 Neutral: 2 Somewhat dissatisfied: 0 Dissatisfied: 0	Satisfied: 9 Somewhat satisfied: 2 Neutral: 1 Somewhat dissatisfied: 1 Dissatisfied: 0

Residential Community Events

Below results focus on examination of residential perceptions of the common room spaces at the Franco site. Specifically, results focus on data collected at three time points: before installation of the fans, and data collected after fan installation at the end of summer 2018 and mid-summer 2019.

Below, results are broken down across each of the three time points for thermal sensation (i.e., thermal comfort), thermal acceptability, air movement acceptability, and air quality satisfaction. Overall, very little change was detected within the survey data from time point to time point. It is important though to understand that this lack of change in perspective is impressive given the average temperature had shifted across each time point. More specifically, at the surveying pre-install, the average indoor temperature was 72 ˚F (22 ˚C). During the second survey, during the mechanical system failure when only the fans were operating the mean indoor temperature was warmer, approximately 80 ˚F (27 ˚C), and at the third survey both fans and the air conditioning were operating as planned and the average indoor temperature was 80 ˚F (26.5 ˚C). What these overall results suggest is that the presence of the fans increased the range of thermal comfort and acceptability across participants.

Further, when examining air movement acceptability, an increase in acceptance can be seen after the installation of the fans at both time points. These results highlight that in addition to increasing one's range of thermal comfort, the fans' presence in the space also seem to have a positive impact on air movement acceptability. Other possible influencers over any variance across time points could include individual differences of the participants (e.g., age, personality, background) and of the circumstances occurring within the physical environment at the time of the data collection. Results also reveal that perhaps future work should explore other questions (like found in the interview methods) that could help detect more of the nuanced variation across participant perceptions.

Thermal sensation: As seen in Table 16, across the three time points, thermal comfort stayed consistent. A slight increase in comfort can be seen after installation of the fans.

Table 16: Resident perceptions of thermal sensation

	Much too warm	Too warm	Comfort ably warm	Comfort able	Comfort ably cool	Too cool	Much too cool	N/A	Overall % Comfort able
Before installation N = 26	1	1	1	13	7	2	0	1	84%
Fans only, without AC Post installation (2018) N = 26	0	2	3	14	3	0	1	3	86%
Fans + AC Post installation (2019) N = 30	2	0	3	20	5	0	0	0	93%

Thermal acceptability: As seen in Table 17, across all three time points, thermal acceptability remained fairly constant. A slight increase in acceptability can be seen at the third time point of data collection.

Table 17: Resident perceptions of thermal acceptability

	Acceptable	Not acceptable	N/A	Overall % Acceptable
Before installation N = 26	24	1	1	96%
Post installation (2018) N = 26	24	1	1	96%
Post installation (2019) N = 30	28	2	0	93%

Air movement acceptability: As seen in Table 18, air movement acceptability was fairly high across all three time points. However, an increase was visible after the installation of the fans at both time points two and three.

Table 18: Resident perceptions of air movement acceptability

	Unacceptable, air movement is too low	Acceptable but air movement is too low	Acceptable air movement	Acceptable but air movement is too high	Unacceptable, air movement is too high	N/A	Overall % Acceptable
Before installation N = 26	2	2	21	0	0	1	92%
Post installation (2018) N = 26	0	2	23	1	0	0	100%
Post installation (2019) N = 30	1	2	24	3	0	0	97%

Air Quality Satisfaction: Table 19 shows there was very little shift overall in occupants' satisfaction with the overall air quality across the three time points. These findings indicate very little shift in air quality perceptions due to the installation of the fans.

Table 19: Resident perceptions of air quality satisfaction

	Dissatisfied	Somewhat dissatisfied	Neither satisfied nor dissatisfied	Somewhat satisfied	Satisfied	N/A	Overall % Satisfied
Before installation N = 26	0	1	1	3	20	1	92%
Post installation (2018) N = 26	0	0	2	2	21	1	92%
Post installation (2019) N = 30	2	2	2	3	22	0	83%

Interview Guide

The purpose of the interviews was to better understand occupants' experiences and perceptions around a number of factors related to the equipment: perceptions and attitudes of the occupants, ease of use, impacts on indoor environmental quality (caused by the equipment), perceived impact on energy costs, and perceived value. Also, at the end of the second interview occupants were asked if they had any feedback on how the research team could have improved the study and answered any questions they had as the study concluded.

Interview protocol and participants

Office Workers

Office workers were recruited at each of the four field sites to complete interviews with the research team. The same interview was completed at two time points just after cooling season—in November 2018— and then again November 2019. Interviews were conducted over the phone and last approximately 20 to 30 minutes. Workers were given a $50 gift card following completion of the interview and both time one and time two.

Limitations of Office Worker Interviews

Interviews were collected in two rounds, both of which were conducted after the cooling season (November 2018 and November 2019). Due to the lag time between the cooling season and the time the interviews were conducted, participants may have had challenges in recalling specific instances about their usage of the fans and thermostats. Also, it should be noted during the first set of interviews (November 2018) the main office worker at Parksdale 1 had just resigned and a new employee had just begun. Since the new employee had not had experience with the equipment during the cooling season, the research team did not interview her in the first round of data collection. During the second round of interviews (November 2019), this same employee was actually interviewed. However, it should be noted that though she was interviewed, her perceptions may also differ due to the fact she had entered the study half way through the field study time period. Further, it should also be considered that at the Franco site, the research team was only able to obtain interviews at both time points by one of the employees. Also, possible bias may have emerged in participant responses due to the fact they were being gifted the equipment and also receiving compensation in the form of gift cards ($50 at both time points) for participating in the interviews.

Residents

Five of the six residents enrolled in the study completed interviews at two time points. The first interview was conducted in May 2019 just before the cooling season, the second was conducted November 2019, just after cooling season. Interviews were conducted in Spanish, in the residents' home at time one, and over the phone at time two for occupant ease. Each interview lasted approximately thirty minutes. Occupants were given gift cards after completing each interview-- $50 for the first, and $100 for the second.

Limitations of Residential Interviews

Interviews were collected in two rounds, both of which were conducted after the cooling season (May 2019 and November 2019). The purpose of the May 2019 interviews was to have participants recall their experiences for the previous summer. Due to the lag time between the cooling season and the time the interviews were conducted, participants may have had challenges in recalling specific instances about their usage of the fans and thermostats. The research team also used this first interview session as an opportunity to clarify any questions the occupants might have about the equipment going into cooling season. Because the team spent time specifically working with the occupants to ensure they understood the usages and benefits of the equipment prior to cooling season, it is possible these interactions could have positively biased participants' perceptions. It should also be noted possible bias may have emerged in participant responses due to the fact they were being gifted the equipment and also receiving compensation in the form of gift cards ($50 in the first round, $100 in the second) for participating in our interviews. It is possible either of these forms of compensation could have swayed occupant perceptions or incentive to answer honestly. Finally, as mentioned previously, only five of the six residents agreed to participate in our interviews, therefore the team was unable to gain full participation.

Interview Results

Equipment Usage and Experiences

Both occupant types were asked questions about their experiences in using both the fans and thermostat equipment. Overall, occupants felt the equipment was easy to use though they did remark in several instances that they felt the Ecobee thermostats to have a steep learning curve. However, each of those respondents explained they eventually felt comfortable with the Ecobee once they understood how to best engage with it. No challenges were expressed in the ease of use of the fans.

The table below (Table 20) shows the number of occupants who reported using the fan remote, the fan mobile app, and the Ecobee browser login. By the end of the study, all participants reported using the fan remote on a regular basis and felt satisfied with that tool. None of the occupants reported use of the mobile app and many described that they did not see the purpose behind the application. The same could be said for the browser login for the Ecobee. Initially one resident was using the login, but had stopped by the end of the study.

When the team inquired about occupants' preferences for the fans to be functioning automatically or manually, at Time One, regardless of occupant type, participants were split in which setting they would prefer. Interestingly though, by Time Two, all office workers reported preferring the automatic setting whereas most (80%) of residential occupants preferred manual usage of the fans. Desire for manual seemed to stem from occupants' desire for more control. Amongst many of the residents they described feeling that the fans in some cases cooled too much or that they did not always enjoy the air movement. Interestingly in the exit interviews office workers also expressed a desire for more control, but several voiced that they actually liked the fact that the fans did the work for them. For instance, one office worker said "They've helped (me) by not having to worry about being too hot or too cold in the office. Because when you're too hot or too warm it's hard to concentrate. By having the fan. it helps me stay focused because I don't have to worry about the temperature".

Difference in preference for manual versus automatic control across these two participant types unveils a couple of possibilities. It seems there is intrinsic motivation across most if not all people to have some sense of control over their environment; however, perhaps there are individual differences across people in one's level of need for control. Second, these results also suggest the activity one is needing to accomplish within their environment may have an effect over that level of need for control. Office spaces, unlike homes, tend to support a specific set of tasks (focus, productivity), whereas homes support a multitude of tasks (working, relaxing, child care, socialization, etc.). Perhaps in spaces where activities vary more heavily, more occupant control (or the perception of control) is more important.

Table 20: User use and experiences with equipment

	Use fan remote	**Use fan mobile app**	**Use Ecobee browser login**	**Prefer automatic operation**	**Prefer manual operation**
Time One:					
Residents (N =5)	**1**	**0**	**1**	**3**	**2**
Office workers (N= 4)	**3**	**0**	**0**	**2**	**2**
Time Two:					
Residents (N =5)	**5**	**0**	**0**	**1**	**4**
Office workers (N= 4)	**4**	**0**	**0**	**4**	**0**

In addition to which pieces of equipment occupants used, the team also asked participants about how the fans impacted their perception of indoor environmental quality (IEQ). Overall, perceptions were quite positive from both occupant groups as they related to IEQ. All participants felt the fans provided adequate cooling, and importantly, none could recall an instance in which the fans did not provide effective cooling in their space. One resident reported the use of an additional portable fan during cooling season, but he explained this was used only in the bathroom (i.e., a space that did not have access to the ceiling fans). Additionally, most (100% of residents, 75% of office workers, one simply did not respond to this question) reported that the fans improved their overall air quality at Time One, and 100% of all participants reported this at Time Two. Further, though two residential occupants reported random hot and cold spots throughout the space at Time One, at Time Two all occupants believe the fans elevated this issue and that the air was evenly mixed. Finally, all residents reported that they felt the fans improved their overall IEQ at both Times One and Two and 50% and 100% (at times One and Two respectively) of all office workers reported that the fans improved their IEQ. (Two office works did not comment on this at Time One).

The researchers also asked occupants whether or not the fans influenced the functionality of other aspects of IEQ specifically: Wi-Fi effectiveness, lighting, noise levels, ceiling clearance, and the safety of occupants. At Time One two residential occupants reported having had issues with Wi-Fi interference due to the fans. The research team worked with those occupants to alleviate this situation with the inclusion of updated technology and the problem was remedied by Time Two. One issue that was also voiced, but not specifically asked by the team, related to occupants' television sets. Two residential occupants reported that the fans interfered with the TV signals forcing them to make a decision between television and fan usage.

Table 21: User perceptions of equipment's impact on environmental quality

	Fans provided adequate cooling	Used portable fans in addition to ceiling fans	Fans improved air quality	Air distribution consistent across space	Improved quality of the indoor environment
Time One:					
Residents (N =5)	5	NA	5	3	5
Office workers (N= X)	4	0	3	2	2
Time Two:					
Residents (N =5)	5	1	5	5	5
Office workers (N= 4)	4	0	4	4	4

Design Perceptions

Fans: Overall, both user groups expressed a lot of enjoyment with the fan equipment. They were all incredibly pleased with its ability to cool the space quickly and effectively. Most users also enjoyed the design of the fans and the ability to adjust the equipment easily and with the remote. Some occupants were troubled by the light on the fans. They believed they were too dim, and then they were also confused by the blue sensor light. All occupants seemed satisfied with the air circulation that the fans provided, though many (especially residents) felt the fans speeds were too high at times.

As can be noted in the previous sections, both groups felt both satisfied and dissatisfied with the automation of the fans. One interpretation of this may be that they are simply craving more desire for perceived control. The fan automation seemed to be appreciated at times, but frustrating to users at others. Frustration seemed most palpable in the resident user group compared to office workers who seemed more accepting and appreciative of the automatic nature of the equipment. This different could be due to the different needs or expectations one has in a workspace compared to a home space.

Below the research team lists a summary of the reported likes and dislikes of the fan equipment by user group.

Fan likes:

Residents:

- Automation
- Lower energy cost
- Provide effective cooling
- Quickly cools the home
- The remote
- Adjustability of the speed
- Easy to control
- The light
- That they prevent the AC from coming on

Office workers:

- Sleek design
- Design that can fit in any space
- That all the fan speeds are synced together
- Adjustable speed
- Air circulation
- Automation
- The remote control

Fan dislikes:

Residents:

- Automation
- Speeds are too high
- Interfered with the Wi-Fi
- Do not like or understand the blue lights on the fans, confused by when they turn on/off
- That the light can only be turned on with the remote
- High speeds are uncomfortable/provide too much air movement
- Collect a lot of dust
- Feel the plastic blades are toxic and would prefer wood

Office workers:

- Originally found light too dim
- Causes papers to blow around on desk
- Don't like them in the winter
- The fact that the fans will stop moving when there is no movement in the space
- Design is "weird and looks like a space ship"
- That the fans go on when there is motion in the space

Thermostats: Consistently, across user types, each reported that they felt the thermostat equipment was challenging to use at first. However, it should be noted that by the second interview, all reported that they felt they had mastered the equipment. This finding suggests that over time the thermostats become understandable, but that there is likely a steep learning curve for users at installation.

Residents reported satisfaction with the lower energy costs from the installation of the fans and the thermostats. Both groups also expressed happiness from their lack of having to use the AC as much as they had prior to having the fans installed. Many users, especially residents also reported appreciation for the look and feel of the thermostat interface.

Below the research team lists a summary of the reported likes and dislikes of the thermostat equipment by user group.

Thermostat likes:

Residents:

- Lower energy cost
- Digital interface
- Easy to find in the dark
- Modern
- Easy to use

Office workers:

- Felt was easy once learned how to use
- That it can easily be turned on and off
- That they rarely turn on

Thermostat dislikes:

Residents:

- Very complicated to use
- Struggled with the programming feature

Office workers:

- Hard to set up and understand

Suggested Design Improvements

Overall, most occupants (regardless of type) did not have any suggestions for design improvements. One resident explained that perhaps having a slower start speed for the fans would be useful. Many occupants explained they felt the phone app was not useful and that they would never use it. And in general, most occupants reported they would keep the design of both the fans and the thermostat equipment exactly as is.

Though occupants did not provide much direct feedback when they were asked explicitly about design improvements, looking through their likes and dislikes of both types of equipment can be useful. For instance, in the case of the thermostats it seems as though some effort should be put forth in either a) user education at time of installation, or b) in making the system more intuitive to use. Some users also mentioned that they would have preferred the thermostat interface to be available in Spanish (only English and French were available on the Ecobee). Over time, occupants seemed to effectively learn how to use the thermostat, but almost unanimously it was mentioned that they were initially a challenge to understand. As for the fans, one issue that came up a couple of times across occupant groups was the light. Occupants seemed to want more control over the light in both their ability to adjust it and its level of brightness. Also, both occupant groups mentioned the speed being a struggle at some time and expressing interest in having the ability to have an even lower speed option than what currently exists.

Overall Value and Perceptions of Energy Use

During each interview the team asked participants what their perception had been prior to the study around whether or not fans use more or less energy than air conditioning systems. Results revealed that overall most occupants from both groups were unsure. As Table 22 shows, one resident and one office worker believed they used less energy, and one office worker believed they used more. Below results from both time points can be seen, however, the data from Time Two is likely less reliable due to the fact the team asked occupants to recall across a year and a half time frame after numerous points of education they received from the study intervention.

Table 22: User perception of energy use

	Didn't know how much energy was used	Thought fans used more energy	Thought fans used less energy	Thought fans used same as AC
Time One:				
Residents (N =5)	4	0	1	0
Office workers (N= X)	2	1	1	0
Time Two:				
Residents (N =5)	1	0	2	1
Office workers (N= 4)	2	1	1	0

The team also asked homeowners if they noticed a difference in their energy bill once the fans had been installed. (Office workers were excluded from this question as they did not have access to the energy bills). At both time points one of the residents explained that her spouse handled the bills so she did not have access to that information. At Time One each resident who did have access to this information reported their energy bill went down. At Time Two all but one participant reported a decrease. The reported increase was said to have occurred at one point when the thermostat stopped working and the fans were the only source of cooling for the occupant.

Finally, occupants were also asked whether or not they would recommend the fans to family and friends. At both time points, all occupants (minus one employee who did not respond to this at Time One) reported that they would recommend. Further, at the end of the exit interview most of the office workers also expressed that they wished they had the fans in their own homes.

Table 23: Perceptions of overall value of the fans

	Perceived change in energy bill			Would recommend to others
	No change	Increased	Decreased	
Time One:				
Residents (N =5)	0	0	4	5
Office workers (N= X)	NA	NA	NA	3
Time Two:				
Residents (N =5)	0	1	3	5
Office workers (N= 4)	NA	NA	NA	4

CHAPTER 9: Field Demonstration Close-Out and Handover

Equipment Removal

At each site, all energy monitoring equipment was scheduled to be removed, in addition to networking equipment that had been added by the installation team, and accompanying mounting hardware (boxes, cables, etc). All BAF ceiling fans and Ecobee thermostats that were installed as part of the study were to remain, along with supplemental desk fans supplied to office workers and computer labs.

Equipment was scheduled to be removed in two phases: (1) Electrical work, and (2) Hardware removal and handover. An outside electrician was hired to open electrical panels and remove CTs, and so for convenience this was completed at all sites in one day. A follow-up visit was then scheduled with each site to remove the remaining hardware items, conduct any repairs necessary (primarily patching screw-holes in walls), and conduct handover to residents and workers.

Handover to Sites

Through the course of this study the TRC, CBE, and AEA teams acted as technical support as much as possible to all the project sites with regard to the fans and thermostats that were installed and, to a lesser degree, existing HVAC systems. When the project completed it was necessary for the users of the equipment to be able to properly make use of the capabilities of the systems and know who can be contacted for repairs and to answer questions.

At closeout, the research team needed to prepare both the users and the equipment itself. To prepare users, the research team provided in-person training to each resident with fans installed and workers at the sites. This training repeated typical use instructions that had been given previously, but also expanded to include setting up equipment on the users' own wifi networks and basic troubleshooting that AEA had handled previously. Additionally, documentation was developed by the research team and provided to each user that listed out basic use instruction for fans and thermostats, in addition to information on who to contact in case of equipment problems.

Equipment was handed over to the sites and residents by disconnecting fans and thermostats from WiFi networks that had been installed by the project team, and disconnecting the email/user profile that had been created for the project from each item. Basic fan and thermostat functionality is possible without WiFi connection, and so all systems were left disconnected as the default. If users desired the project team was able to help with initial setup to the users' own networks. For the fans, each user was given the option of continuing to use the firmware that was installed for this project (including adaptive comfort temperatures) or adjust to the standard commercially available firmware.

Close Out & Handover Challenges

Since all the equipment used in this study was chosen for its network integration and smart functionality, both fans and thermostats require being connected to a network to provide all features. Removing equipment from the networks reduced the features available to the users unless they reconnected to their own networks, which isn't guaranteed. Additionally, network control and usage by the users was limited during the study so that the research team could control, update, and monitor equipment as needed. However, this means that residents and workers had limited knowledge coming in to the close out of how to set up and use these additional features. While training and handouts were made available, most of the users were not interested.

CHAPTER 10: Discussion and Conclusions

Based on the results of the field demonstrations as described above, the research has identified the main conclusions outlined in the following sections.

Note that due to the specific circumstances of this study, results are difficult to generalize to a broader population of buildings. The demonstration sites represent a small sample with very different building types, space types, and occupancy patterns. Occupants did not have uniform incentives as not all occupants were responsible for energy costs. In addition, the research team had extensive interaction with occupants, and actively encouraged desired thermostat setpoint and fan use behaviors.

Field demonstrations resulted in substantial overall energy savings, however the savings varied very widely. Overall, the field demonstration resulted in 39% measured compressor energy savings during the April–October cooling season compared to baseline conditions, across all sites and normalized for floor area served. Over all months of the year, mean measured compressor power per floor area during the intervention period was 30% lower than the baseline period. The floor area served by each individual compressor varied more than six-fold, and the size and energy consumption of a compressor correlates with floor area. Thus, the research team normalized reported energy savings by floor area to avoid sites with larger floor area unduly weighting the percentage savings estimate, particularly since these sites had some of the highest savings. Without normalizing by floor area, the total project percentage savings during the cooling season was 48%.

When additionally normalized for weather due to warmer outdoor conditions during the intervention compared to the baseline period, energy use per zone varied from an increase of 36% to savings of 71% across all 13 compressors across four sites, with **median per-compressor weather-normalized savings of 15%.** This variability reflects the diversity in buildings, mechanical systems, prior operation settings, and space types, as well as occupants' schedules and preferences. **All commercial spaces with regular occupancy schedules (as well as two irregularly-occupied commercial spaces, and one home) had measured energy savings on an absolute basis before normalizing for warmer intervention temperatures, and 10 of 13 sites showed energy savings on a weather-normalized basis.** Zones where indoor air temperatures did not increase (occupants did not raise air conditioning setpoints) did not realize energy savings. The zones with the largest increase in air conditioning temperature setpoints and largest increase in indoor air temperatures realized the largest energy savings.

Occupants were generally satisfied with the technologies, though many usability concerns remain.

Per the occupant interviews and surveys, all occupants reported high satisfaction with the ceiling fans, and the vast majority noted a preference for the automated operation of those fans. The occupants were given the choice to keep the fan firmware as automatic, or to switch to a fully manual operation at the end of the project, and they all chose to keep the automated operation features. Even in sites where the measured energy data does not show savings, the occupants still used and interacted with the fans regularly. All occupants reported an improvement in comfort compared to before the fans, indicating that even when no savings materialized, there was a secondary benefit to thermal comfort.

The results for the thermostats are more mixed. There was a steep learning curve, that many of the occupants struggled with. There were some issues related to control of the system fan, which had an adverse effect on energy consumption. Additionally, the lack of language support was an issue for many of the occupants, particularly in the residences. Due to the nature of this intervention, we cannot decouple the energy savings of the fans or the thermostats from each other, and it is possible that there was a counteracting effect.

Technology improvements are needed to achieve widespread implementation.

Despite the successes described above, the field demonstrations encountered several challenges implementing the smart ceiling fan and communicating thermostat technologies as originally intended for the study. Development of a custom fan firmware was required to fully implement the automated fan operation as the research team envisioned. Although the measured results of the field demonstrations show substantial energy savings, there is a need for further development to achieve widespread adoption. The technologies could be further simplified, and usability could be further improved. This is particularly the case for the thermostats. The research team also notes that we provided oral and written educational materials that described how the integrated system works, and its potential for energy savings. We also suggested new cooling setpoints for the thermostats, and with occupant permission, implemented those new setpoints when the equipment was installed. Though we made it clear that occupants were free to change these settings at any point during the study (and most did), it is still likely that these interventions had a positive effect on outcomes. These interventions - or similarly effective ones - would likely be needed to maximize the energy savings from a larger scale deployment, and that may be difficult to do at scale.

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APPENDIX A: Memorandum of Understanding

The full text of the Memorandum of Understanding (MOU) agreed with each demonstration site is reproduced in full below:

Dear [Site Representative]:

On behalf of our research team at CBE, I would like to thank you for agreeing to participate in the above-named project sponsored by the California Energy Commission. The purpose of this letter is to provide you with a few more details about the project, its anticipated duration, the level of involvement needed from your site managers or facilities staff, the expected benefits that may arise at your site from your involvement in the project, and to confirm your commitment to participating in this project.

The overall objective of this project is to conduct field demonstrations to advance technology readiness and support market adoption of smart ceiling fans and smart thermostats to reduce HVAC energy use while maintaining occupant comfort. The field demonstration at your site will involve installing Haiku ceiling fans and communicating thermostats in selected common areas and public spaces, as well as selected dwelling units. The research team will work with site managers or facilities staff to maximize energy savings from the thermostats and ceiling fans while maintaining occupant comfort.

The collaborative research team is made up of three organizations: (1) Center for the Built Environment (CBE) at UC Berkeley, (2) TRC Energy Services, and (3) Association for Energy Affordability (AEA).

The field study will entail the following primary components:

- Pre-installation energy and environmental monitoring for building common areas and select dwelling units
- Installation of ceiling fans and thermostats in building common areas and select dwelling units
- Post-installation energy and environmental monitoring for building common areas and select dwelling units
- Occupant surveys
- The anticipated level of involvement from staff at your site is summarized below:
- Facilitate communication between site management and research team, with timely responses to requests and inquiries.
- Facilitate access to selected common areas, public spaces, and electrical and mechanical rooms, as necessary, to allow installation and removal of energy monitoring equipment, and installation of ceiling fans and thermostats
- Facilitate ongoing periodic access to monitoring equipment during study period

- Post informational flyers on site and assist in soliciting and selecting a limited number of dwelling units to participate in the study and receive demonstration installations
- Facilitate communication with residents of study dwelling units to provide access, as necessary and with sufficient advance notice, to residential units and electrical panels, to allow installation and removal of energy monitoring equipment, and installation of ceiling fans and thermostats
- Facilitate connection between research team and key building contacts for brief, voluntary interviews about aspects of the space and design features. Compensation will be provided via gift cards that will be distributed amongst the group of participants.
- Facilitate connection between research team and occupants to engage in brief, voluntary surveys addressing occupant perceptions of functionality and use of fans in the residential units as well as the common areas of the facility. Compensation will be provided via gift cards that will be distributed amongst the group of participants.

The benefits to your company and your buildings for cooperating and giving our research team access to your buildings will be to see first-hand the potential energy savings and comfort improvements resulting from the innovations being tested. Your buildings and residents will also enjoy the long-term benefits and comfort improvements from the installation of the ceiling fans and communicating thermostats after the study concludes. Fans, thermostats, and installation labor are provided at no cost to you and are yours to keep after the completion of the research project, scheduled to end June 30, 2020. Following the completion of the project, Self-Help Enterprises will be responsible for all ongoing maintenance or removal of installed ceiling fans and thermostats.

All work on the buildings will be carried out by licensed contractors. Contractors will be procured by, overseen by, and obligated to AEA. AEA and TRC will bear all costs for study related construction, including, but not limited to, installation of energy monitoring equipment, installation of ceiling fans and thermostats, and any necessary supporting work. [Site Owner] will not be responsible for any costs related to installations and construction in support of this research effort.

This letter and the details outlined above confirms a mutual understanding between the Research Team, led by CBE, and [Site Owner], and your company’s involvement at the participating project sites. Please confirm your commitment to participating in the study by signing below in the space provided.

APPENDIX B:
Fan and Thermostat Installation Scope

The installation scope of work TRC developed for the BAF installation team is included in full below.

436 14th Street
Oakland, CA 94612

510.368.4427 PHONE

June 10, 2018

MEMORANDUM

To: Chris Meikle, Daniel Abboud (Big Ass Fans)

Cc: Andy Brooks, Sebastian Cohn, Mitch Greene (AEA)

From: David Douglass-Jaimes, Gwelen Paliaga (TRC)

Re: Proposed EPIC Fans Project Installation Scope

EPIC Fans Project Installation Scope

Outlined in the sections below is the proposed installation scope for each of the four demonstration sites for the EPIC Fans project, for the purpose of pricing the installation services from Big Ass Fans installers.

For the purposes of pricing the installation activities, please include the following:

- Price quotes for installation must use prevailing wage rates (see: https://www.dir.ca.gov/Public-Works/Prevailing-Wage.html)
- Price all lighting-related activities (e.g., lighting procurement, new can light installation, fixture relocation, etc.) separately from fan installation work

Franco Center

Franco Center, 144 Mun Kwok Lane, Stockton, CA

- For all fans:
  - Add new sensor covers to fans, as needed (to be shipped separately from fans)
  - Update fan firmware to new EPIC research app version specification
- Resident Activities Area
  - Install (26) new 60" Haiku fans in existing 2' x 4' grid ceiling, in locations as marked on site (supporting layout diagram to be provided by TRC)
    - Fans to be mounted roughly centered within square molding on ceiling panels
  - Configure fans for "Smarter Cooling" mode
  - Group fans into three zones (to be indicated in supporting layout diagram, to be provided by TRC):
    - Dining Hall Zone
    - Activities Zone

- Lounge Zone
- Install wall-mounted remote control (quantity and mounting location to be determined)

- Reception
  - Install (2) new 52" Haiku fans in existing 2' x 4' grid ceiling, each to be mounted centered between a pair of existing light fixtures, one above the desk/work area and one above the waiting area (supporting layout diagram to be provided by TRC)
  - Configure fans for "Smarter Cooling" mode
  - Group fans into a single zone
  - Install wall-mounted remote control (mounting location to be determined)
- "Manager" / Meeting Room
  - Install (1) new 52" Haiku fans in existing 2' x 4' grid ceiling, to be roughly centered in the room
  - Configure fans for "Smarter Cooling" mode
  - Install wall-mounted remote control (mounting location to be determined)
- "Counter" / Food Preparation Area
  - Install (2) new 52" Haiku fans in existing 2' x 4' grid ceiling, each to be mounted between existing light fixtures
  - Configure fans for "Smarter Cooling" mode
  - Group fans into a single zone
  - Install wall-mounted remote control (mounting location to be determined)
- Storage Area (labeled on plans as "Rental Space")
  - Install (2) new 60" Haiku fans in existing 2' x 4' grid ceiling (supporting layout diagram to be provided by TRC)
  - Configure fans for "Smarter Cooling" mode
  - Group fans into a single zone
  - Install wall-mounted remote control (mounting location to be determined)
- Office
  - Replace existing ceiling surface mounted light fixture with new 52" Haiku fan with low-profile mount and LED kit
  - Configure fan for "Smarter Cooling" mode
  - Replace existing lighting wall switch with wall-mounted remote control
  - Patch and paint as needed where previous light fixture was removed
- Office / Computer Lab
  - Replace existing ceiling surface mounted light fixture with new 52" Haiku fan with low-profile mount and LED kit

TRC Results you can rely on

- Configure fan for “Smarter Cooling” mode
- Replace existing lighting wall switch with wall-mounted remote control
- Patch and paint as needed where previous light fixture was removed

Rolling Hills

Rolling Hills, 2110 Prince Street, Newman, CA

- For all fans:
  - Add new sensor covers to fans, as needed (to be shipped separately from fans)
  - Update fan firmware to new EPIC research app version specification
- Replace (2) existing thermostats with new Nest thermostats
- Community Room
  - Install (8) new 52” Haiku fans in existing 2’ x 4’ grid ceiling, each to be mounted centered between four existing light fixtures (supporting layout diagram to be provided by TRC)
  - Configure fans for “Smarter Cooling” mode
  - Group fans into a single zone
  - Install wall mounted remote control (mounting location to be determined)
- Kitchen
  - Install (1) new 52” Haiku fan with low profile mount and LED kit in existing 2’ x 4’ grid ceiling, roughly centered in Kitchen area
  - Configure fans for “Smarter Cooling” mode
  - Replace existing light fixtures with five new recessed can LED luminaires (supporting layout diagram to be provided by TRC) (Halo 750 6 inch recessed housing and LT56 LED Kit, or equivalent)
  - Add new ceiling tiles as needed, match existing
  - Install wall mounted remote control adjacent to light switch
- Storage (labeled on plans as “Headstart Office”)
  - Install (1) new 52” Haiku fan in existing 2’ x 4’ grid ceiling, roughly centered in the space between existing light fixtures
  - Configure fans for “Smarter Cooling” mode
  - Install wall mounted remote control adjacent to light switch
- Office
  - Install (1) new 52” Haiku fan in existing 2’ x 4’ grid ceiling, centered between existing light fixtures, adjacent to existing diffuser
  - Configure fans for “Smarter Cooling” mode
  - Install wall mounted remote control adjacent to light switch

- Computer Lab
  - Install (2) new 52" Haiku fans with low profile mount (supporting layout diagram to be provided by TRC)
  - Replace two existing light fixture with four new recessed can LED luminaires (supporting layout diagram to be provided by TRC) (Halo 750 6 inch recessed housing and LT56 LED Kit, or equivalent)
  - Group fans into a single zone
  - Add new ceiling tiles as needed, match existing
  - Configure fans for "Smarter Cooling" mode
  - Install wall mounted remote control adjacent to light switch

Parksdale 1

Parksdale 1, 13549 Wood Street, Madera, CA

- For all fans:
  - Add new sensor covers to fans, as needed (to be shipped separately from fans)
  - Update fan firmware to new EPIC research app version specification
- Replace (2) existing thermostats with new Nest thermostats
- Community Room
  - Install (2) new 84" Haiku fans at peak of vaulted ceiling (supporting layout diagram to be provided by TRC)
  - Group fans into a single zone
  - Configure fans for "Smarter Cooling" mode
  - Install wall mounted remote control (mounting location to be determined)
- Entry
  - Install (1) new 52" Haiku fan with low profile mount and LED kit, roughly centered on entry door, and half way between existing sprinkler and beginning of sloped ceiling (supporting layout diagram to be provided by TRC)
  - Group fan into a control zone with fans in Community Room
  - Configure fan for "Smarter Cooling" mode
- Kitchen
  - Install (1) new 52" Haiku fan with low profile mount and LED kit, roughly centered between existing light fixtures
  - Configure fan for "Smarter Cooling" mode
  - Install wall mounted remote control adjacent to existing light switch
- Office

  - Install (1) new 52" Haiku fan with low profile mount and LED kit, centered between two of the existing light fixtures (supporting layout diagram to be provided by TRC)
  - Configure fan for "Smarter Cooling" mode
  - Install wall mounted remote control adjacent to existing light switch
- Computer Room
  - Install (1) new 52" Haiku fan with low profile mount and LED kit, roughly centered between the four existing light fixtures
  - Configure fan for "Smarter Cooling" mode
  - Install wall mounted remote control adjacent to light switch
- Office 2 / Music Room
  - Install (1) new 52" Haiku fan with low profile mount and LED kit, roughly centered between existing light fixtures
  - Configure fan for "Smarter Cooling" mode
  - Install wall mounted remote control adjacent to existing light switch
- Patch and paint as needed in all spaces

Parksdale 2

Parksdale 2, 13600 Wood Street, Madera, CA

- For all fans:
  - Add new sensor covers to fans, as needed (to be shipped separately from fans)
  - Update fan firmware to new EPIC research app version specification

Community Building

- Replace (2) existing thermostats with new Nest thermostats
- Community Room
  - Install (2) new 84" Haiku fans at peak of vaulted ceiling (supporting layout diagram to be provided by TRC)
  - Group fans into a single zone
  - Configure fans for "Smarter Cooling" mode
  - Install wall mounted remote control (mounting location to be determined)
- Entry
  - Install (1) new 52" Haiku fan with low profile mount and LED kit, roughly centered on entry door, and half way between existing recessed can light and beginning of sloped ceiling (supporting layout diagram to be provided by TRC)

- Group fan into a control zone with fans in Community Room
- Configure fan for "Smarter Cooling" mode

- Kitchen
  - Move the existing light fixture closest to the stove to the opposite end of the existing ceiling diffuser to new location roughly over the stove
  - Install (1) new 52" Haiku fan with low profile mount and LED kit in place of the relocated light fixture
  - Configure fan for "Smarter Cooling" mode
  - Install wall mounted remote control adjacent to existing light switch
- Office
  - Install (1) new 52" Haiku fan with low profile mount and LED kit, centered between two of the existing light fixtures (supporting layout diagram to be provided by TRC)
  - Configure fan for "Smarter Cooling" mode
  - Install wall mounted remote control adjacent to existing light switch
- Computer Room
  - Install (2) new 52" Haiku fans with low profile mount and LED kit (supporting layout diagram to be provided by TRC)
  - Group fans into a single control zone
  - Configure fan for "Smarter Cooling" mode
  - Install wall mounted remote control adjacent to light switch
- Office 2
  - Install (1) new 52" Haiku fan with low profile mount and LED kit, roughly centered between existing light fixtures
  - Configure fan for "Smarter Cooling" mode
  - Install wall mounted remote control adjacent to existing light switch
- Patch and paint as needed in all spaces

Three Bedroom Units (three units total)

- Replace existing thermostat with new Nest thermostat
- Living Room
  - Install new 60" Haiku fan with low-profile mount and LED kit, roughly centered in the space
  - Pull power from upstairs bedroom outlet adjacent to closet
  - Configure fan for "Smarter Cooling" mode
  - Install wall mounted remote control (mounting location to be determined)

- Dining Room
    - Replace existing light fixture with new 60" Haiku fan with low-profile mount and LED kit
    - Configure fan for "Smarter Cooling" mode
    - Install wall mounted remote control in place of existing light switch
- Kitchen
    - Replace existing surface mounted light fixture with new 52" Haiku fan with low-profile mount and LED kit
    - Install four new recessed can LED light fixtures (Halo 750 6 inch recessed housing and LT56 LED Kit, or equivalent)
    - Power kitchen fan from constant power line to exterior light fixture, and power new can lights from existing lighting switch leg
    - Configure fan for "Smarter Cooling" mode
    - Install wall mounted remote control adjacent to existing light switch
- Bedrooms (three total)
    - Replace existing light fixture with new 60" Haiku fan with low-profile mount and LED kit
    - Configure fan for "Smarter Cooling" mode
    - Install wall mounted remote control in place of existing light switch
- Hall
    - Replace existing light fixture at top of stairs with new 52" Haiku fan with low-profile mount and LED kit
    - Configure fan for "Smarter Cooling" mode
    - Install wall mounted remote control in place of existing light switch
- Patch and paint as needed in all spaces

Two Bedroom Units (three units total)

- Replace existing thermostat with new Nest thermostat
- Living Room
    - Install new 60" Haiku fan with low-profile mount and LED kit, roughly centered in the space
    - Pull power from upstairs bedroom outlet adjacent to closet
    - Configure fan for "Smarter Cooling" mode
    - Install wall mounted remote control (mounting location to be determined)
- Dining Room
    - Replace existing light fixture with new 60" Haiku fan with low-profile mount and LED kit
    - Configure fan for "Smarter Cooling" mode

TRC Results you can rely on

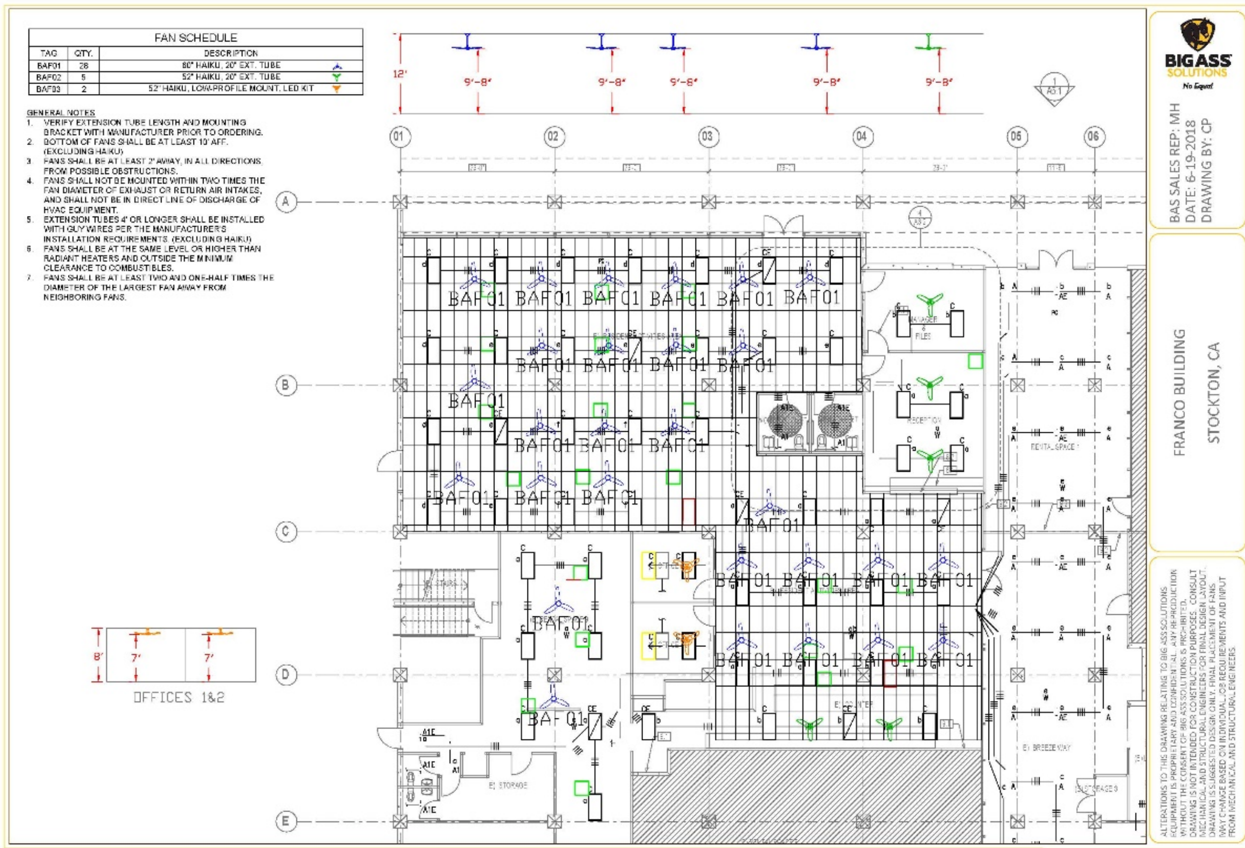
- Install wall mounted remote control in place of existing light switch

- Kitchen
  - Replace existing surface mounted light fixture with new 52" Haiku fan with low-profile mount and LED kit
  - Install four new recessed can LED light fixtures (Halo 750 6 inch recessed housing and LT56 LED Kit, or equivalent)
  - Configure fan for "Smarter Cooling" mode
  - Install wall mounted remote control adjacent to existing light switch
- Bedrooms (two total)
  - Replace existing light fixture with new 60" Haiku fan with low-profile mount and LED kit
  - Configure fan for "Smarter Cooling" mode
  - Install wall mounted remote control in place of existing light switch
- Power supply to Living Room and Kitchen fans to be confirmed on site. Attic access above ceiling should be available for all two bedroom units
- Patch and paint as needed in all spaces

APPENDIX D:
Final Fan Layouts from Big Ass Fans

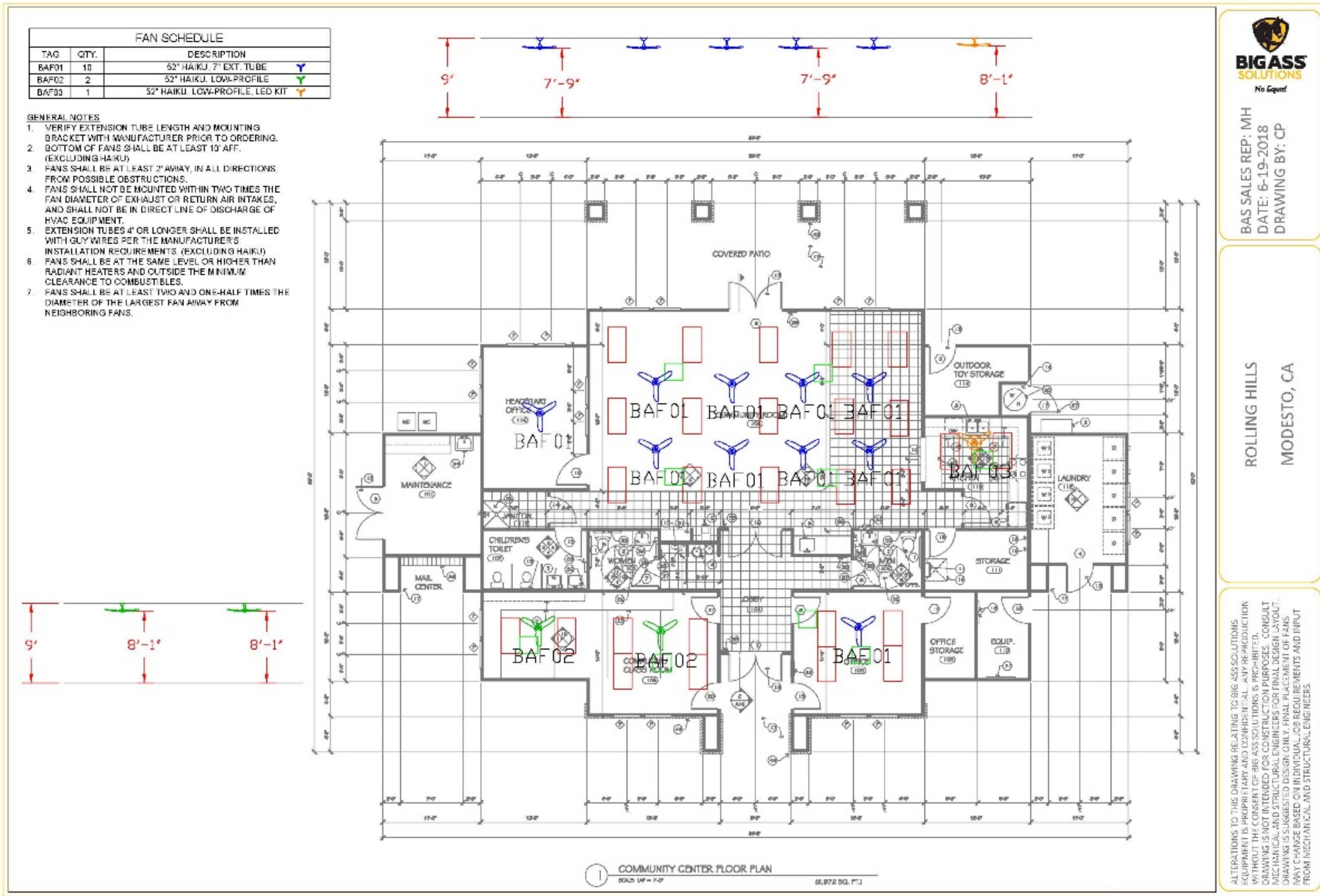
Final fan layouts for each site are shown in the images below.

Figure 93: Final fan layout design for Franco Center site



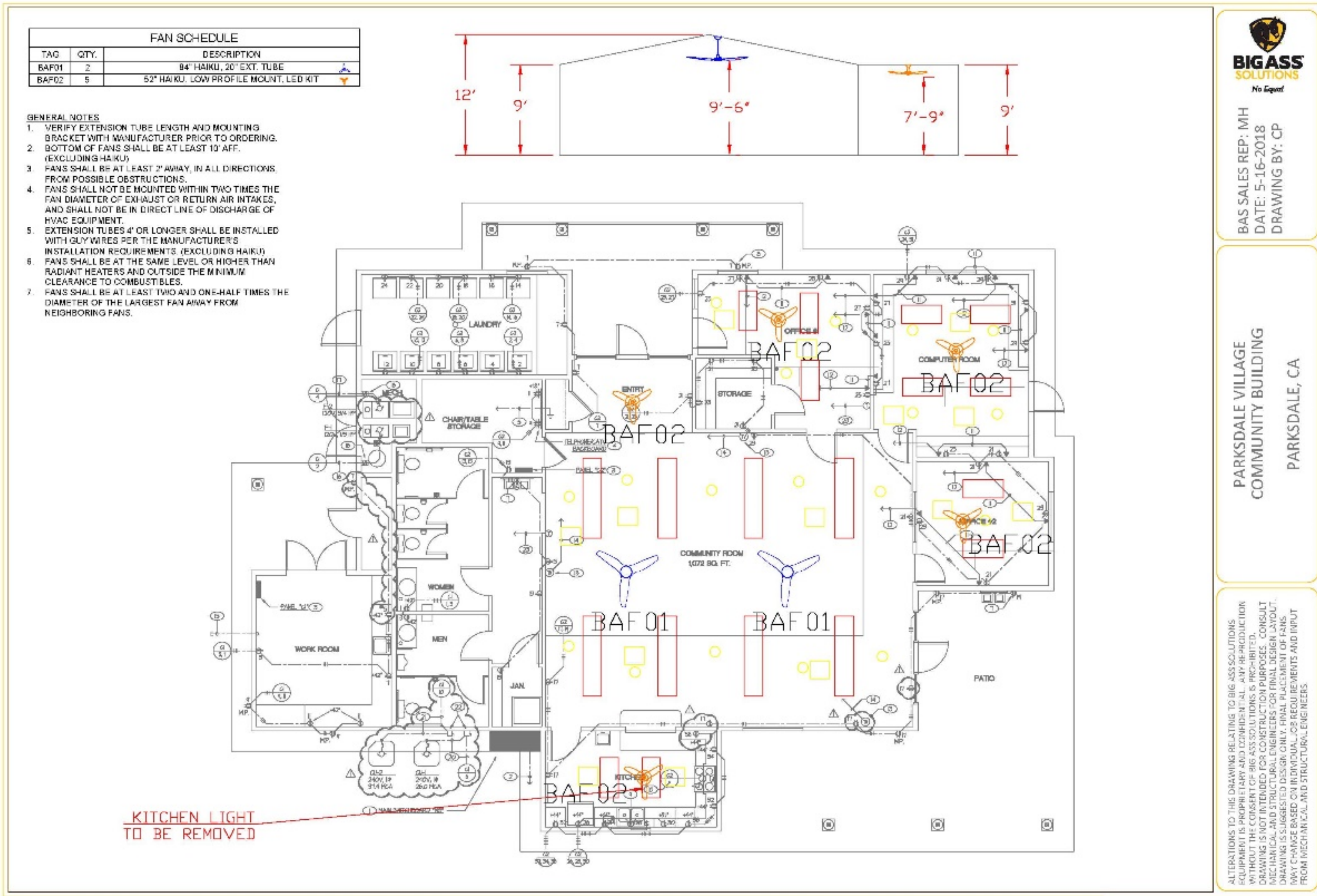
Credit: BAF

Figure 94: Final fan layout design for Rolling Hills community building site



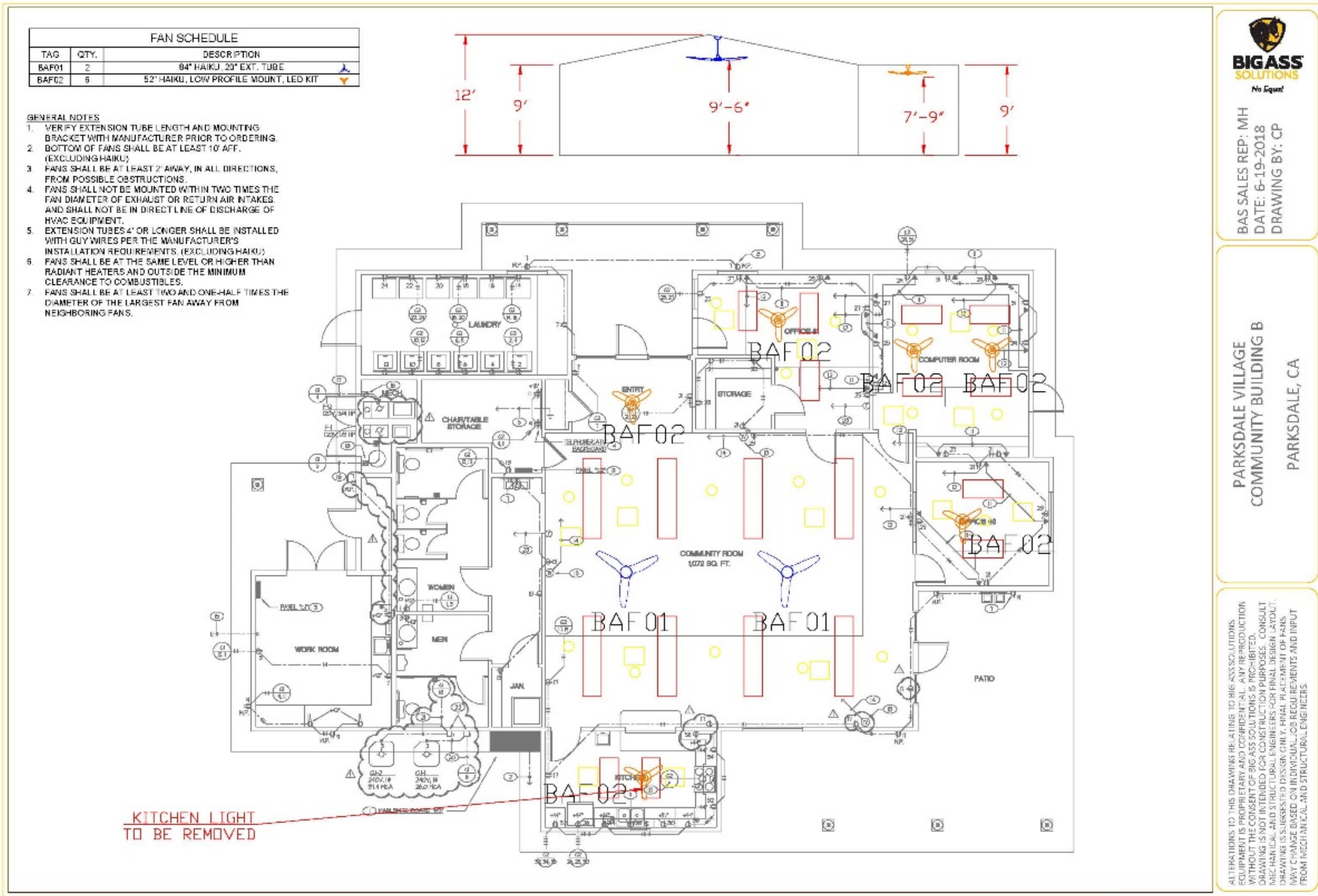
Credit: BAF

Figure 95: Final fan layout design for Parksdale 1 community building site



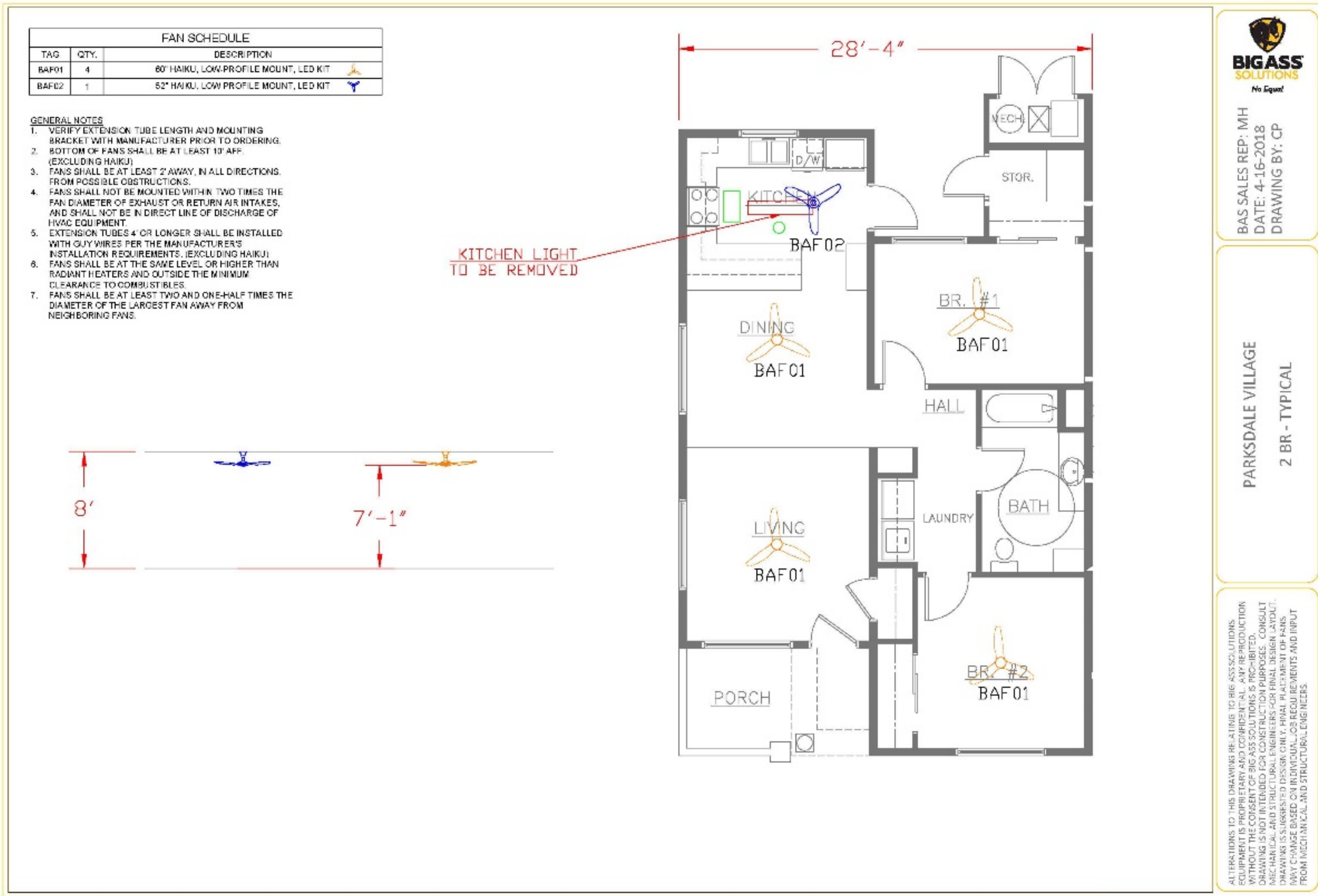
Credit: BAF

Figure 96: Final fan layout design for Parksdale 2 community building site



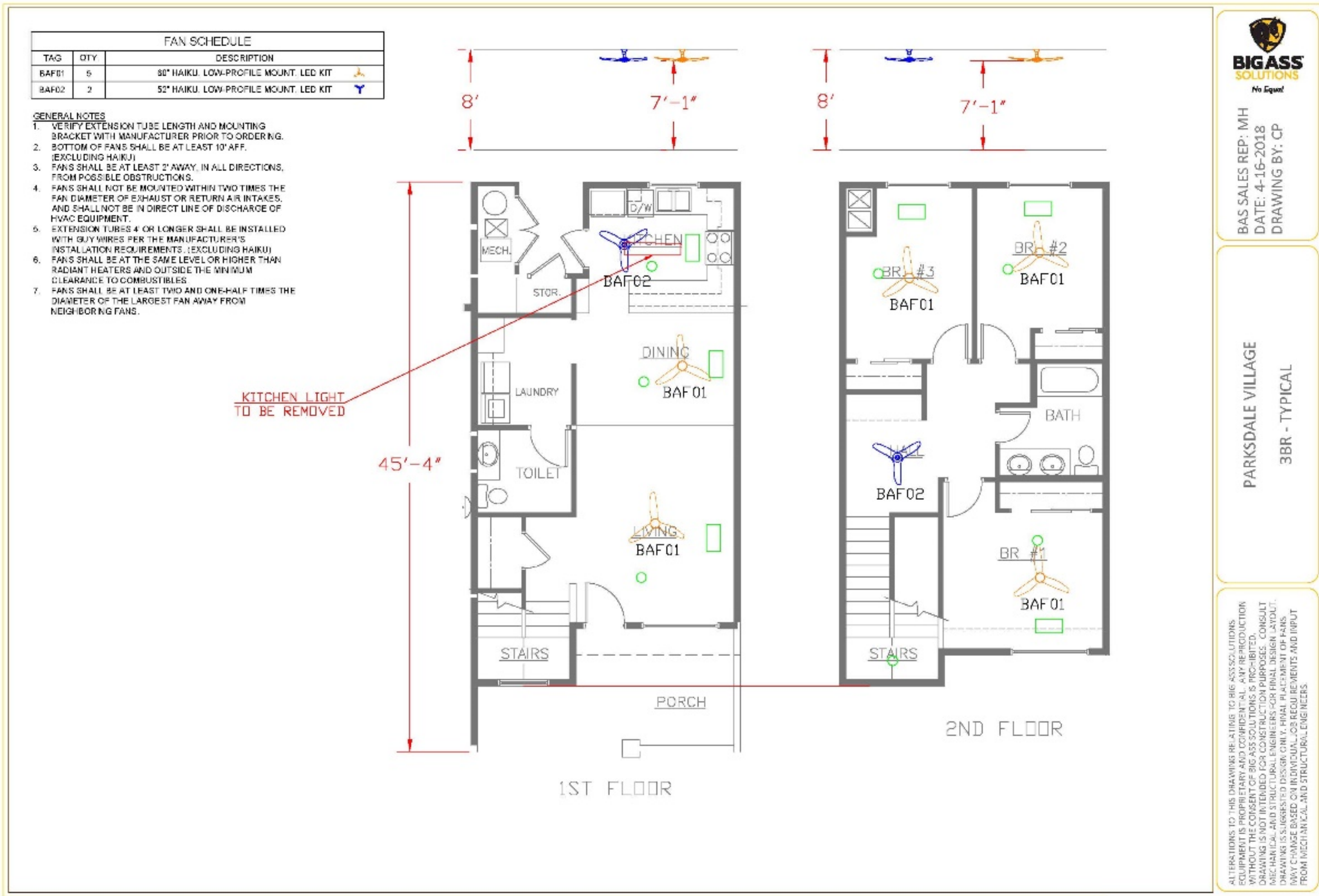
Credit: BAF

Figure 97: Final fan layout design for Parksdale 2 typical two-bedroom unit



Credit: BAF

Figure 98: Final fan layout design for Parksdale 2 typical three-bedroom unit



Credit: BAF

APPENDIX E:
Monitoring Equipment Installation Photos

Figure 99: Franco Center DENT Power Meter Installation

Credit: AEA

Figure 100: Franco Center HOBO U-30 Meter Installation and DENT Connection

Credit: AEA

Figure 101: Franco Center Example of Hamilton Sensor Installation in Office Spaces

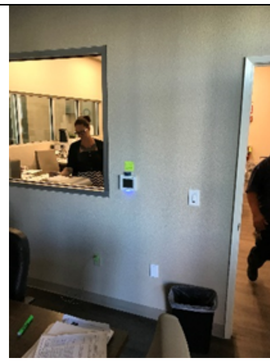
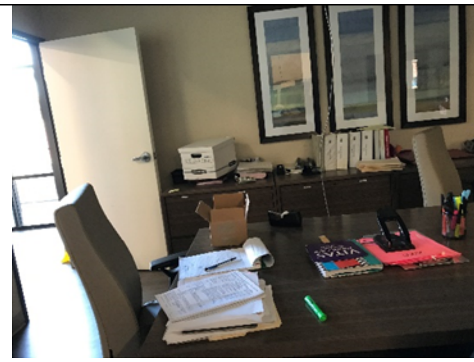
Sensor Number	Sensor Location	View from Sensor
		
		

Figure 102: Rolling Hills DENT Power Meter Installation

Credit: AEA

Figure 103: Rolling Hills Border Router for Hamilton Sensors

Credit: AEA

Figure 104: Rolling Hills Example of Hamilton Sensor Installation in Community Room Spaces

Sensor Number	Sensor Location	View from sensor
		
		

Figure 105: Parksdale 1 Example of Hamilton Sensor Installation in Community Room and Kitchen

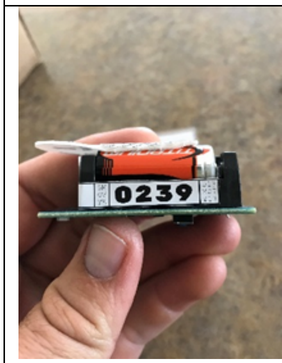
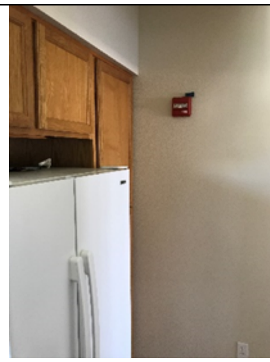
Sensor Number	Sensor Location	View from Sensor
		
		

Figure 106: Parksdale 2 Community Building Monitoring Equipment Installation

Credit: AEA

Figure 107: Parksdale 2 Community Building Hamilton Sensor Installation

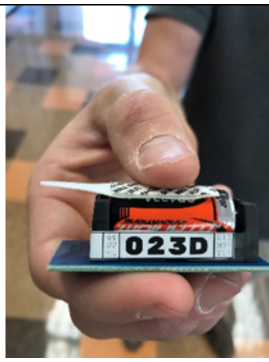
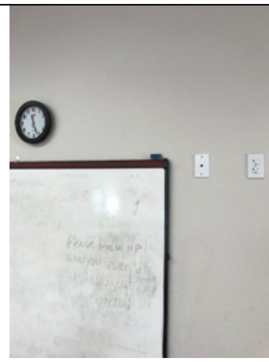
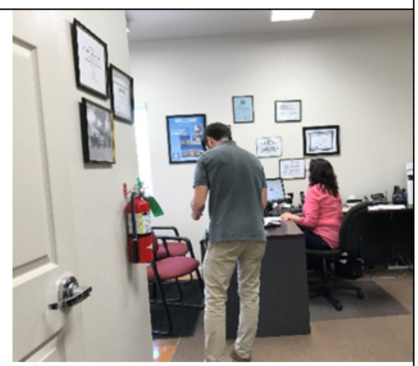
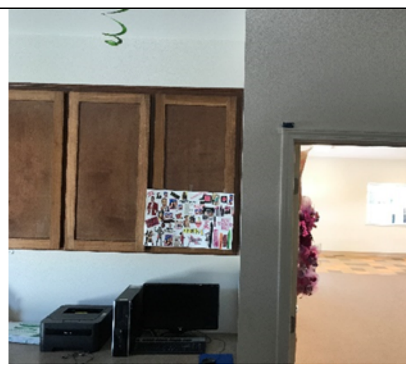
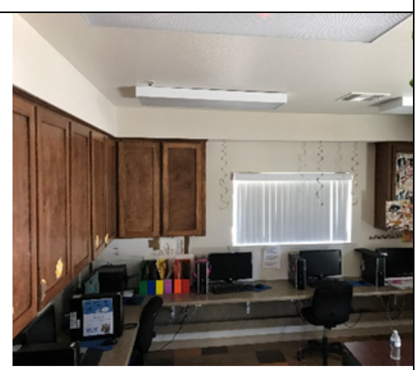
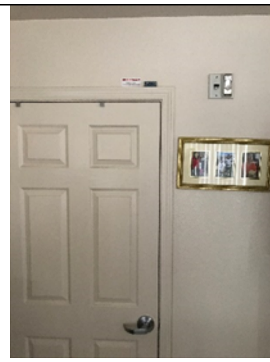
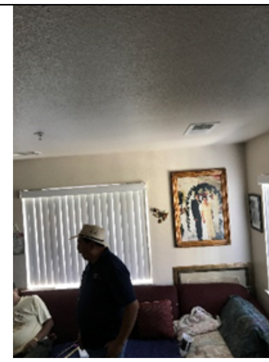
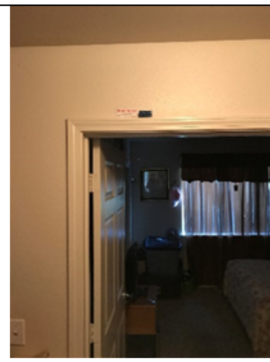
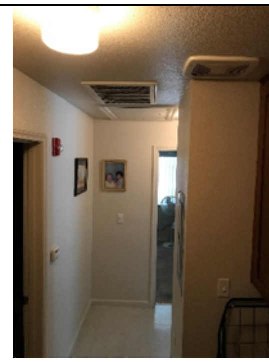
Sensor Number	Sensor Location	View from Sensor
		
		
		
		

Figure 108: Parksdale 2 Typical Dwelling Unit Hamilton Sensor Installation

Sensor Number	Sensor Location	View from Sensor
		
		

APPENDIX E:
Case Study of Ceiling Fan Automation

EXECUTIVE SUMMARY

The purpose of the Case Study of Ceiling Fan Automation is to support the Technology Readiness Task (Task 5), which is to evaluate the current landscape of technologies similar in nature to the proposed demonstration, evaluate the current installations of these technologies and the market opportunities and barriers to the technologies. The contents of the Case Study of Ceiling Fan Automation:

- Includes interviews with owners and designers to determine design features, control approach and owners' perceptions of technology
- Includes spot measurements using CBE Building Performance Toolkit to determine typical air speeds with automated control settings
- Describes challenges and successes of planning and executing retrofits
- Discusses lessons learned.

CHAPTER 1: Summary

Ceiling fans are a traditional approach for increasing occupant comfort and are well-established in residential application in many parts of the world. However, they are infrequently included in commercial spaces even though they have the potential to bring benefits including increased occupant comfort and decreased energy use either through raised setpoints in cooling or destratification[17] in heating. This study provides practical insights into the case of ceiling fans in commercial spaces. The research team at CBE conducted 13 interviews with architects, engineers, and facilities managers from California and around the country to compile common themes of experience. These professionals provided lessons learned from 20 operational projects that include ceiling fans serving a wide set of functions in commercial spaces. Understanding the challenges they faced and the lessons they learned from these projects will facilitate prioritization of research and communication efforts. The researchers also took in-situ airspeed measurements at five of the projects to provide insight into real-world conditions in commercial buildings with ceiling fans. For these, the ceiling fans' operation results in generally relatively low airspeeds, often under 0.2 m/s. The researchers also found just 25% of the 20 projects discussed by interviewees had any type of automation in the ceiling fan controls. This study serves as a resource for designers and for the wider industry, to frame a path forward for the inclusion of ceiling fans in commercial buildings.

The full report is in Appendix A.

The research team at CBE conducted interviews with two architects, eight engineers, and three facilities managers focused on 20 operational commercial building projects that incorporated ceiling fans, and also took a total of 65 in situ airspeed measurements across five sites. The purpose was to better understand common motivations and applications, control strategies, barriers to market adoption, best practices, and airspeeds.

[17] Destratification refers to dispelling the natural thermal stratification of air where in heating environments, the hot air rises to the ceiling. Destratification would mix the room’s air so make better use of the hot air.

Figure 109: A Tree of Sensors Replaces a Chair at a Conference Table.

Left: In situ air flow measurements of one of the sites.

Credit: Elaina Present, CBE

Although interviewees revealed many challenges and barriers during the design process, their feedback about the fans is generally positive once installed. Occupants often choose to have the ceiling fans on even when the resulting airspeeds are too slow to create an appreciable cooling effect. This aligns with findings from the interviews, that ceiling fans provide benefits not only for comfort conditioning and energy use reduction, but also provide individual control, non-thermal benefits (such as perceived and measurable air quality), or an aesthetic choice not only in their own right, but sometimes as a way to eliminate visible ductwork.

The use of ceiling fans in commercial spaces that have mechanical ventilation and/or cooling systems is still a relatively uncommon practice. The benefits of fans in commercial spaces will be adopted more widely in the coming years as one better understands best practices. Furthermore, though the encountered-on-site fan settings and resulting airspeeds were low, it is important to note that these zones were already operating within ASHRAE 55 comfort conditions in the absence of air movement. Higher airspeeds would have overcooled the occupants unless one also increased the zone temperature. This indicates a potential opportunity to reduce HVAC energy consumption by increasing zone cooling setpoints and running ceiling fans faster to provide the first stage of comfort cooling.

Among the projects studied, there were few applications of automatic control, and interviewees did not offer a consensus about whether manual or automated control was preferable, seeing pros and cons of each. A viable option is that of occupancy- and temperature-responsive automated controls that can be configured and temporarily overridden by occupants— similar to current best practice in the lighting industry.

As with many strategies that aim to improve building performance, best practices start with an integrated design process where different stakeholders communicate early in the process and coordinate decision making. This would facilitate overcoming many of the identified barriers to implementing ceiling fans, such as perceived concerns about noise, maintenance, or papers blowing; ability to clearly explain the benefits of fans to building owners or other design team members; cost tradeoffs; and lack of design guidelines. It's also important that the process does not end with design but is maintained through occupant education so that users fully understand the range of performance characteristics of ceiling fans (i.e., cooling vs. destratification), so the benefits are fully realized.

This study found substantial uncertainty around designing with ceiling fans despite the significant potential benefits. Lack of design guidance and measured performance is a significant barrier to downsizing HVAC equipment based on ceiling fan inclusion. Designers would benefit from outside support, such as from industry, government, or academia. The most significant support would be in the form of design guidance, backed by laboratory testing, CFD, and field studies, for commercial spaces with ceiling fans. This would make designers less reliant exclusively on manufacturers' guidance, and improve communication regarding the abilities and design goals of ceiling fans, and make the designers more confident that their designs would perform as intended. Another need is an expansion of the set of available standardized product test specifications, which would allow designers to more directly compare ceiling fan products. This will require industry effort; though ASHRAE is currently working on Standard 216, Methods of Test for Determining Application Data of Overhead Circulator Fans, which would meet most of this need. Industry could also better support ceiling fan products that can easily communicate with building automation systems or, ideally, that are BACNET-capable. In general, a more standardized design process would reduce several of the barriers to implementation. Members of the research team are continuing to work to better understand the needs of the design community in regard to designing with ceiling fans and intend to create a publicly-accessible design tool in the next two years.

Appendix A:

Building and Environment 147 (2019) 241–257

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Ceiling fans in commercial buildings: In situ airspeeds & practitioner experience

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ARTICLE INFO

Keywords:
Ceiling fans
Air movement
Natural ventilation
Airflow
Design
Case study

ABSTRACT

Ceiling fans are a traditional approach for increasing occupant comfort and are well-established in residential application in many parts of the world. However, they are infrequently included in commercial spaces even though they have the potential to bring benefits including increased occupant comfort and decreased energy use either through raised setpoints in cooling or destratification in heating. This study provides practical insights into the case of ceiling fans in commercial spaces. We conducted 13 interviews with architects, engineers, and facilities managers from California and around the country to compile common themes of experience. These professionals provided lessons learned from 20 operational projects that include ceiling fans serving a wide set of functions in commercial spaces. Understanding the challenges they faced and the lessons they learned from these projects will facilitate prioritization of research and communication efforts. We also took in situ airspeed measurements at five of the projects to provide insight into real-world conditions in commercial buildings with ceiling fans. For these, the ceiling fans' operation results in generally relatively low airspeeds, often under 0.2 m/s. We also found just 25% of the 20 projects discussed by interviewees had any type of automation in the ceiling fan controls. This study serves as a resource for designers and for the wider industry, to frame a path forward for the inclusion of ceiling fans in commercial buildings.

1. Introduction

Ceiling fans are common appliances for providing air movement for thermal comfort, and have been studied extensively regarding their cooling effect (for historical summaries, see Refs. [1] and [2]). Elevated air movement increases the rate of the body's cooling [3], and decreases perceived air temperature, causing people to feel comfortable in warmer temperatures than they would be in still air. Multiple lab studies have validated this effect in office, educational, workout, and other environment types [3–7]. One study found this “corrective power” to range from 1 to 6 °C (2–11 °F) [8]. Others have reported comfort conditions as high as 28 °C (82 °F) [9].

ASHRAE 55 establishes thermal environmental conditions for human occupancy, yet most buildings are not currently meeting its comfort criteria [10], with cooling setpoints typically set lower than necessary to maintain comfort [11]. This means that even in still air conditions, typical set points can be raised without increasing occupant discomfort. The addition of air movement from fans allows even higher set points, and can provide an effectively instantaneous means of comfort control. The highest acceptable setpoints occur when air movement is under personal control [9], and warmer setpoints can also increase the range of climates in which passive strategies and compressor-less cooling are possible [12].

Air movement is often considered desirable separate from its cooling effect. Building occupants consistently want *more* air movement rather than *less*, even when reporting a ‘neutral’ thermal sensation [13–15]. Ceiling fans may also be incorporated into projects for benefits of increased individual control [16], alliesthesia [17], or improving perceived [18] and measured indoor air quality [19].

Modern ceiling fans use very modest amounts of energy; often less than 35 Watts even at the highest speed. The ENERGY STAR list of certified ceiling fans includes 16 models of roughly 1.5 m (5 ft) diameter, all of which are rated below 350 CFM/W (595 m^3/h/W) at design flow [20], and are much higher-performing at lower speeds due to the cubic fan power law. Building energy consumption can be reduced when ceiling fans are used to replace for more energy-intensive cooling strategies, such as conventional air conditioners and heat pumps [21–23]. Simulations reveal potential for substantial cooling energy use reductions by utilizing air movement from ceiling fans or other devices, up to 65% [21,22,24–26]. However, this requires a two-step process. While the air movement affects people, it does not directly impact the air temperature, which is the signal a thermostat responds to. To save

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https://doi.org/10.1016/j.buildenv.2018.10.012
Received 14 August 2018; Accepted 5 October 2018
Available online 11 October 2018
0360-1323/

energy, one must increase the thermostat set point or otherwise cause the alternate cooling technology to run less [27,28]. The exception to this, where the energy savings can be more direct, is in radiant or high thermal mass cases where ceiling fans are used to enhance heat transfer between room surfaces and air [10,29].

Ceiling fans can also be useful when buildings are in heating mode [30–32]. In spaces with high ceilings or with certain types of ventilation systems, the air can become thermally stratified and require an excessive amount of heating energy to maintain comfort in the lower occupied zone [33,34]. In these cases, fans can run at velocities so low they do not cool the body, but still mix the room air. This creates a more even temperature throughout the space, maintaining comfortable temperatures in the occupied zone while using less energy since the thermostats now respond to the warmer measured temperature [32,35–37].

Despite these benefits, limited information exists on how to appropriately design with ceiling fans, or in what cases they should be considered. A small number of laboratory studies provide some information. In one study, participants preferred 0.3 m/s-0.5 m/s airspeeds at 24 °C (75 °F) regardless of activity level [38]. For the same temperature, but for exercise conditions with correspondingly higher metabolic rates (MET), research subjects preferred airspeeds of 0.67 m/s (at 2 MET), 1.09 m/s (4 MET), and 1.79 m/s (6 MET) [5]. Another study focused on discomfort due to draft at the ankles, suggesting maximum velocities of 0.22–0.57 m/s at the lower and higher ends of the thermal neutrality range, respectively, to maintain dissatisfaction below 20% [39].

Data in field locations is especially limited. One case study with manually-controlled ceiling fans found that people turned fans *on* based on indoor temperature, but *off* based on occupancy (e.g. when they left for the day) [40]. In two other buildings, occupant satisfaction with the ceiling fans was high (83% and 100%) with the limited dissatisfaction caused by papers blowing, lack of access to the fans, airspeeds too high, or visual distraction. One of these survey buildings had a cooling setpoint of 28 °C (82 °F) [40].

The industry standard ASHRAE 55–2017 currently requires average airspeeds below 0.20 m/s when the temperature is below 23 °C (73.4 °F), increasing to 0.8 m/s based on a Standard Effective Temperature curve for temperatures over 25.5 °C (77.9 °F). There is no airspeed limit for cases where the airspeed is under the occupants' local control, or when the MET is above 1.3 [12]. Two standardized methods of test for measuring power and volumetric air flow for ceiling fan products exist: DOE requirements for fans under 7 ft (2.1 m) in diameter [41] and AMCA 230-15 for greater diameters [42]. However, these methods do not provide the airspeeds used to calculate comfort criteria in accordance with ASHRAE 55–2017.

There is also limited information on the extent to which ceiling fans are incorporated into commercial buildings. As part of the Residential Energy Consumption Survey (RECS), the EIA found that over 80% of single-family homes and 40% of apartments had ceiling fans in 2015 [43], but ceiling fans are not included in the parallel Commercial Building Energy Consumption Survey (CBECS). One of the goals of this paper is to better understand why ceiling fans, while prevalent in residential buildings, are not more commonplace in commercial buildings.

This limited available design guidance is part of a larger feedback challenge in the building industry. Designers rarely get the opportunity to find out how their building is performing in the years following occupancy, unless something goes wrong. As published in a recent report on the state-of-the art of post-occupancy evaluation (POE), only 4 of the 13 documented protocols include airspeed measurements [44]. This could be due in part to the high cost of accurate airspeed sensors. Currently, most ceiling fan airspeed data is taken in empty rooms [45–48]. While some lab studies examine the effects of furniture on ceiling fan air distribution [49], we could not find relevant field data in fully furnished and occupied spaces.

In the current study we are investigating what it takes to get ceiling fans into commercial buildings in cool, moderate, or hot/dry climates (i.e., we did not extend the study to the particularly challenging hot/humid climates), and what the airspeeds are once the ceiling fans are in place. We interview designers and managers of existing commercial buildings with ceiling fans to assess common applications, control approaches, barriers to market adoption that have been overcome, best practices, and resultant airspeeds. This work does not separate out successful from less successful applications of ceiling fans, or identify reasons why ceiling fans were left out of projects. We are strictly characterizing instances where ceiling fans have been included; therefore, barriers that proved insurmountable were possibly not captured. Additionally, we are providing a preliminary step towards feedback and field measurements in the form of a limited number of on-site spot airspeed measurements.

2. Methods

2.1. Interviews

We conducted interviews with architects, engineers, and building managers to gain insights from commercial buildings where ceiling fans were used. We aimed to understand the goals that led to the use of ceiling fans, the process of selecting and designing for them, and the outcomes. We asked especially about barriers to the use of ceiling fans, and best practices and lessons learned from completed projects.

To select participants, we recruited through the Center for the Built Environment's extensive network, seeking professionals who had designed or managed currently-operational commercial spaces with ceiling fans. Our interview guide (Appendix A) included 32 questions focusing on specific thematic areas: project overview, why ceiling fans, design, systems integration, operation, impact on further work, and market trends and obstacles. All interview protocols were reviewed and approved through our campus Institutional Review Board process.

We conducted 13 interviews during August–December 2017: 8 with engineers, 2 with architects, and 3 with buildings or facilities managers. Each interview lasted an average of 47 min and was audio-recorded with the formal consent of all parties. Researchers made transcripts of each discussion, and followed up with clarifying questions by email as needed. We analyzed the interviews looking for common themes and unique perspectives (but it should be noted that we did not try to independently verify the information provided by the interviewees).

2.2. In situ spot measurements

The research team conducted in situ spot measurements in selected commercial buildings varying in type and spatial layout to characterize typical airspeeds and distributions. We took measurements in typically occupied spaces, directly at workstations or conference room tables by moving the chair and replacing it with the anemometer tree (Fig. 1). Additional locations included lecterns, in front of whiteboards, and in corridors, as opportunity allowed. Because the goal was to capture typically experienced airspeeds, we encouraged normal activity to continue in the surrounding areas, and measured the fan speed settings in place when we arrived. When testing in unoccupied areas with no information regarding typical fan speed settings, the research team selected settings for testing, generally bracketing a slow but perceptible airspeed with a second, faster airspeed that was still beneath the paper-blowing threshold.

Wherever possible we took airspeed measurements at three or four locations per space type per site, and two fan speed settings. We measured at a 2-s sampling rate over 3 min, using four omnidirectional anemometers mounted on a tree at 0.1, 0.6, 1.1, and 1.7 m heights to allow for averaged seated- and standing-height airspeed per ASHRAE 55 [12], though only the seated-average calculation is presented here. The anemometer system, manufactured by Sensor Inc., is designed for the typically low airspeeds in room flow with an accuracy of ±

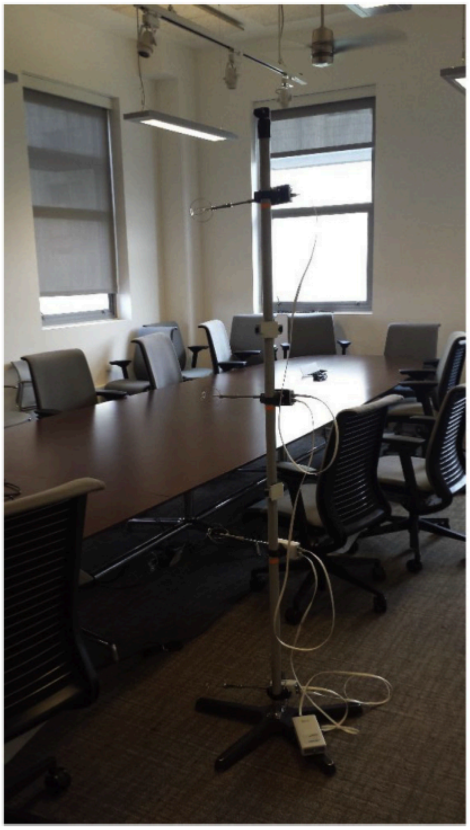


Fig. 1. The anemometer tree replacing a chair at a conference table.

0.02 m/s or 1% of reading (0.05–5 m/s).

We processed the airspeed logs per ASHRAE 55–2017, including averaging temporally across the 3-min data acquisition period, and spatially among the three specified heights for seated (0.1, 0.6, and 1.1 m) and standing (0.1, 1.1, and 1.7 m). These averages are reported for each measured location and condition.

3. Results

3.1. Interviews

Project characteristics. The professionals we interviewed provided insight on a total of 20 projects that used ceiling fans as part of the building comfort system. Of these, 17 were in California and 3 were elsewhere in the U.S. All were completed within the last 10 years. The 20 buildings represented a range of different space types and ceiling fan use cases. Four incorporated ceiling fans as part of tenant improvement work, one as part of a retrofit of an existing building, and the remaining fifteen as part of new construction. Some of the described attributes are characterized in Table B1 (Appendix B). Because each interviewee had different experience, not every interview question was answered for every building.

Practical themes. While discussing best practices, lessons learned, and barriers encountered, the most-mentioned topics by the interviewees (see Table 1) include cost and value engineering (mentioned by 8 of the 13 interviewees), aesthetics (7), ceiling coordination (6), lack of clarity over who on the design team is responsible for the ceiling fans (4), difficulty communicating and gaining trust in the benefits of the fans (4), and lack of readily available ceiling fan product information (5). These and other themes are explored below in the Discussion.

Target airspeeds. Four interviewees provided the targets they used during the design process (and we compare these with in situ measurements in the Discussion). These were equivalent to:

- 0.5–0.8 m/s for some space types and > 0.8 m/s for others
- 0.5–1.3 m/s
- 0.9–2.2 m/s
- 6000 cfm (10,194 m^3/h)

Other interviewees stated that airspeed goals were not a driving factor in ceiling fan selection and design, saying that maximum airspeed for most ceiling fans is too high to be useful, and design drivers instead included aesthetics, weight, mounting options, etc.

In the spaces where fans had automated controls, speeds were set using a variety of methods. In two cases without other cooling available, the setting was selected based on temperature up to some maximum speed that is less than the fan's maximum (in one of these the manual override allows the higher speeds). In another case where there was also radiant cooling, the controls are on/off and the on speed is determined based on occupant feedback, largely related to noise. We were not able to collect controls information for the fourth.

3.2. In situ spot measurements

Table 2 summarizes the five buildings in which we took measurements, providing a snapshot of conditions in the space on a single day, at locations and fan settings that were readily available.

Fig. 2 shows all of the in situ airspeed measurements, separated by those taken at speeds set by the researchers (Fig. 2a), or the building occupants/operators (Fig. 2b), or with the fans off (Fig. 2c). All measurement locations are shown on the y-axis, indicated as XY_Z, where X is the site number (1–5), Y is the space (a-d), and Z is the measurement location within the space. At each location, we measured airspeed at four heights, which Fig. 2 shows alongside the seated-average airspeed. The shaded regions represent airspeeds below what ASHRAE 55–2017 characterizes as "elevated" (i.e., 0.2 m/s (40 fpm)).

The median, lower quartile, and upper quartile of all seated-average airspeeds from encountered fan speed settings (sites 3, 4, and 5) were 0.15 m/s, 0.12 m/s, and 0.16 m/s, respectively. For measurements taken with the fans off (sites 1, 2, and 3), these corresponding numbers were 0.10 m/s, 0.05 m/s, and 0.19 m/s. The remainder of this section goes through these results site by site.

3.2.1. Site 1: unoccupied conference room with three fans and a central table (Fig. 3)

The characteristics of the space and measurements were:

- Conference room with a single large table
- Unoccupied room; no guidance available regarding typical fan speed settings
- Three ceiling fans above table (model unknown, approximately 1.5 m (4–5 ft) diameter, 3 m (9 ft) mounting height).
- Air temperature approximately 21 °C (69 °F).
- Measurements at five locations:
  - o (1a_1) chair along the table
  - o (1a_2) just in front of the white board on the long side of the room
  - o (1a_3–5) three horizontal distances below the ceiling fan not above the table: directly under, half a meter out, and 1 m out from the fan, respectively
- Measurements at all three fan speed settings available on the wall controller, in addition to the fan off at two of the locations.

Fig. 3 shows that all seated-average airspeeds are above 0.25 m/s whenever the fans are on. The lowest measurement height has the slowest or near-average airspeed of the four heights at locations 1a_1

Table 1
Topics brought up by interviewees in discussing best practices, obstacles overcome, and lessons learned.

Theme	Engineers								Facilities			Architects	
	E1	*E2*	*E3*	*E4*	*E5*	*E6*	*E7*	*E8*	*F1*	*F2*	*F3*	*A1*	*2A*
Best Practices													
Get fans in the plan early							X					X	X
Decide and communicate purview			X	X	X							X	
Fan-by-Fan control									X			X	
Creative pitching												X	X
Dense fan coverage				X	X				X				
Space type: high met					X	X							
Space type: high ceilings			X										
Space type: radiant systems	X							X					
Barriers													
Fan connectivity/automation		X	X		X		X						
Perception: maintenance (malfunction, dust)					X	X		X					
Perception: paper blowing/distraction	X			X			X						
Perception: durability				X	X		X						
Communicating benefits/Fan won't perform concerns		X	X					X				X	
Cost	X		X	X	X	X	X					X	X
Aesthetics	X		X		X	X		X				X	X
Guesswork in design/Reliance on venders: General						X	X						X
Guesswork in design: Lack of standardized performance ratings				X	X		X						X
Guesswork in design: Red List information availability		X											
Guesswork in design: Lack of standard recommended control scheme				X									
Guesswork in design: CFD is expensive						X							
Ceilings too low						X				X			X
Ceiling coordination		X		X	X	X						X	X
Running electrical for retrofits									X		X		
Post-installation: wobbling	X											X	
Post-installation: noise or distraction							X		X			X	
Post-installation: occupant association with cooling									X				
Education						X			X	X			

Table 2
Summary of five sites with in situ measurements.

Site	Space Type	Occupancy	Fan Type	Fan Speed Settings[b]	Measurement Locations
1a	Meeting Room	Vacant	Traditional	FR	5
2a	Auditorium	Vacant	HVLS[a]	FR	3
2b	Meeting Room		Modern		2
2c	Office		Traditional		2
3a	Open Office	Partially Occupied	Traditional	AE/FR	4
4a	Open Office	Occupied	HVLS	AE/FR	4
5a	Open Office	Occupied	Traditional	AE	4
5b	Open Office				2
5c	Open Office				3
5d	Open Office				2

[a] HVLS is high volume low speed, these tend to be larger fans that rotate slowly but move a lot of air.
[b] FR (set by Field Researcher); AE (As Encountered).

and 1a_2, which were nearer obstructions, and fastest of the four heights at 1a_5, which was the least obstructed with furniture and walls.

3.2.2. *Site 2: large lecture room with HVLS fans; conference room with two fans: and two-person office with one fan (Fig. 4)*

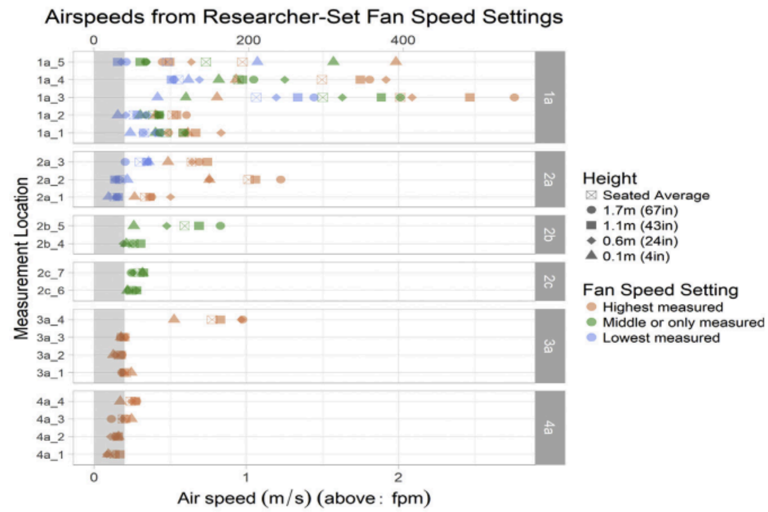
The characteristics of the space and measurements were:

- Newly-constructed site, occupied less than a month
- Three unoccupied spaces; no guidance available regarding typical fan speed settings
- Air temperature approximately 22 °C (72 °F).
- Space 2a:
  - o Large meeting space, can seat approximately 70 people lecture-style, podium and rows of long tables and chairs.
  - o Four Big Ass Fans (BAF) Essence 2.4 m (8 ft) diameter HVLS fans laid out in a grid at approximately 3.5–4.5 m (12–15 ft) mounting height.
  - o Measurements at three locations:
    - ▪ (2a_1) chair near the center of the room, not under the fan
    - ▪ (2a_2) chair under one of the fans
    - ▪ (2a_3) behind the podium at the front of the room.
  - o Measurements with the fans off and at two speeds, approximately 19 and 51 RPM (although this fan model is capable of up to 158 RPM).
- Space 2b:
  - o Conference room with a table layout that seats 22, and a sloped ceiling
  - o Two BAF Haiku fans, 1.5 m (5 ft) in diameter, mounted at approximately 2.7–3.7 m (9–12 ft) in height.
  - o Measurements at two locations:
    - ▪ (2b_4) a chair at the center of the conference table
    - ▪ (2b_5) by the whiteboard.
  - o Measurements with the fans off and at speed 3 (of 7, where 7 is the fastest).
- Space 2c:
  - o Office set up to be shared by two people
  - o Single Hampton Industrial 1.5 m (5 ft) diameter ceiling fan in the center mounted at approximately 2.1–2.7 m (7–9 ft).
  - o Measurements at the two chair locations
  - o Measurements with the fan off and at the 2nd of 4 available speeds.

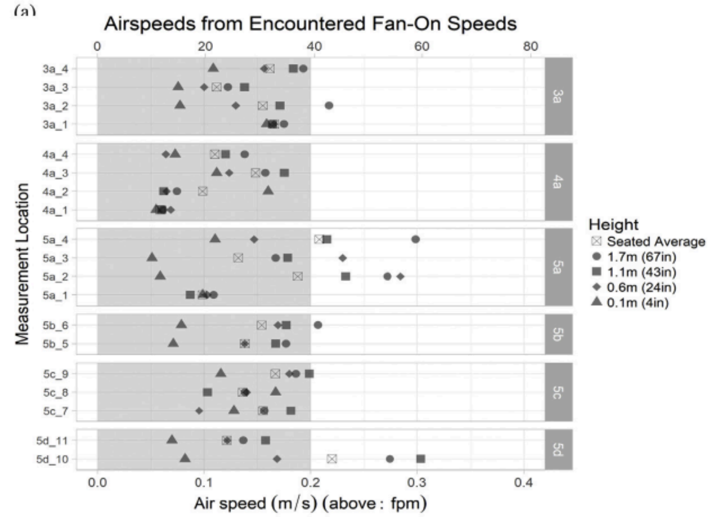
Fig. 4 shows that at the 19 RPM setting, the 0.1 m height has the fastest air velocities in the 2a space, but at the 51 RPM setting it has the slowest airspeed.

3.2.3. *Site 3: open office with multiple small fans (Fig. 5)*

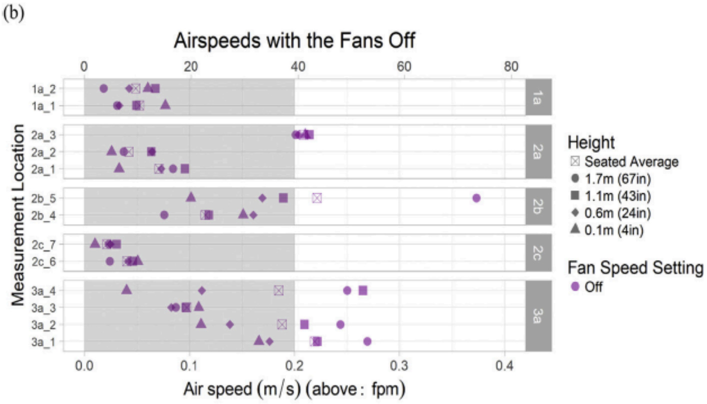
The characteristics of the space and measurements were:



(a)



(b)



(c)

Fig. 2. Overview of in situ measurement results grouped by (a) fans on at speeds the researchers set themselves, (b) fans at speeds encountered on site, and (c) fans off. The grey shaded region indicates airspeeds below the ASHRAE 55–2017 threshold for "elevated airspeed".

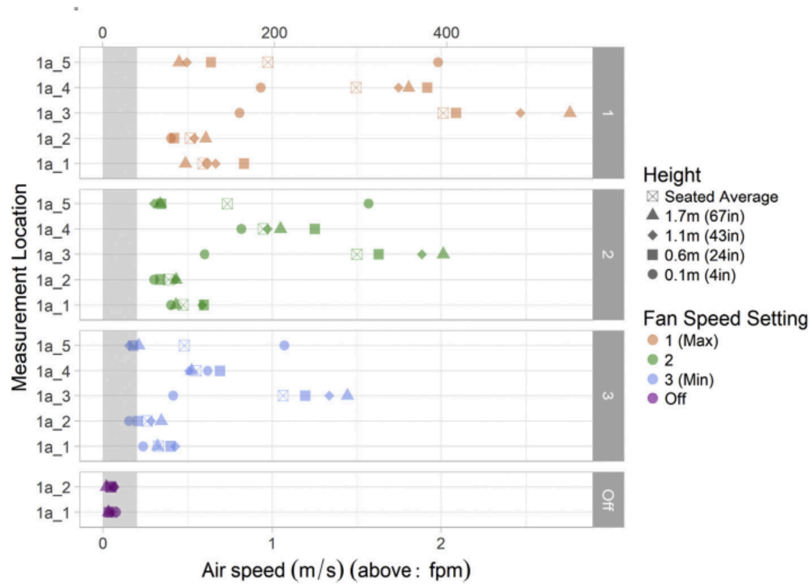


Fig. 3. Site 1 airspeed measurement results by fan speed setting. All fan speeds selected by research team.

- Large open office area with very high ceilings
- Fans of roughly 1.5 m (5 ft) diameter, model unknown, located at 7 m (23 ft) height and spaced 6 m × 9 m (20 ft × 30 ft) on center. There is one fan for every set of 16 (4 by 4) desks.
- Air temperature approximately 23 °C (74 °F).
- Measurements at four unoccupied chair locations (other nearby chairs were occupied at the time) at the following distances from the center of the nearest fan:
  - o (3a_1) 5.8 m (19 ft)
  - o (3a_2) 6.1 m (20 ft)
  - o (3a_3) 4.0 m (13 ft)
  - o (3a_4) within the fan diameter, about 0.6 m (2 ft) from the center.
- The fan control was a slider with an off and three other positions. The first non-off position (not measured) caused roughly half of the fans to slowly rotate and did not obviously affect the other half. The other two fan-on speed settings were measured.

Fig. 5 show that there is no notable air movement (or, correspondingly, cooling effect) from the ceiling fans at the locations measured, at any fan speed setting, except for at the maximum fan setting at location 3a_4, which is directly under a fan. This lack of a measurable increase in air speed in most locations is likely due to the exceptionally high ceilings in this space, the fan mount height (7 m), and the relatively large spacing between fans. The higher fan settings are generally associated with a smaller spread in the airspeeds at different heights, but the seated-average airspeeds are not meaningfully faster at higher fan settings, or faster at all in some cases. The uniformity is also very uneven. At the max speed, some occupants would experience seated-average airspeeds below 0.2 m/s, and others would experience above 0.75 m/s. It is possible that these ceiling fans, though not useful for cooling, are useful in air mixing, destratification, or other purposes which we did not examine. Across all measurements with the fans on, the 0.1 m height has the most consistent and slowest airspeeds.

3.2.4. *Site 4: open office with a central HVLS fan moving slowly (Fig. 6)*

The characteristics of the space and measurements were:

- Occupied open office with a relatively high ceiling
- Single centrally-located 2.4 m (8 ft) diameter BAF Essence HVLS fan mounted at approximately 3.5 m (12 ft). This is the same fan model as in site 2a, with a maximum RPM of 158.
- Air temperature approximately 23 °C (74 °F).
- Measurements at four locations:
  - o Three at desks in the open office:
    - (4a_1) not in the same row as the fan, roughly 3.4 m (11 ft) from the fan center
    - (4a_2) near the row at the center of the fan, roughly 5.5 m (18 ft) from the fan center and near a wall
    - (4a_3) in the same row as the fan, roughly 2.3 m (7.5 ft) from the fan center
  - o (4a_4) in a walkway and within fan diameter, roughly 0.8 m (2.75 ft) from the center
- Measurements at 11 RPM (encountered when the researchers arrived, minimum fan speed setting available) and also 18 RPM (11% of the maximum available, as a second speed slow enough not to risk distracting the occupants seated directly underneath the fan.)

Fig. 6 shows that all seated-average airspeeds are below 0.25 m/s, though faster at every measurement location at the 18 RPM speed than the 11 RPM speed. Additionally, although the temperature was above the 23 °C (73.4 °F) ASHRAE threshold for elevated air movement, the measured airspeeds were not technically elevated – all of the seated-average airspeed measurements taken at 11 RPM and all except one of the 18 RPM measurements are at or below 0.20 m/s and would not be classified as elevated airspeeds by ASHRAE 55–2017.

3.2.5. *Site 5: an open office with automatically-controlled ceiling fans blowing upward (Fig. 7)*

The characteristics of the space and measurements were:

- Open office space, large total floor area > 9000 m^2 (100,000 ft^2).
- Hampton Bay 526012 ceiling fans, 5′ diameter, 2.7 m (9 ft) mounting height, spaced at 6 m (20 ft) intervals
- Fans blow upwards (only project of the 20 to have the fans blowing upwards for cooling goals.)
- Automated ceiling fans in most zones, controlled through the building management system (BMS). Control is solely on/off, and each zone has its own fan speed setting used for all fans in that zone

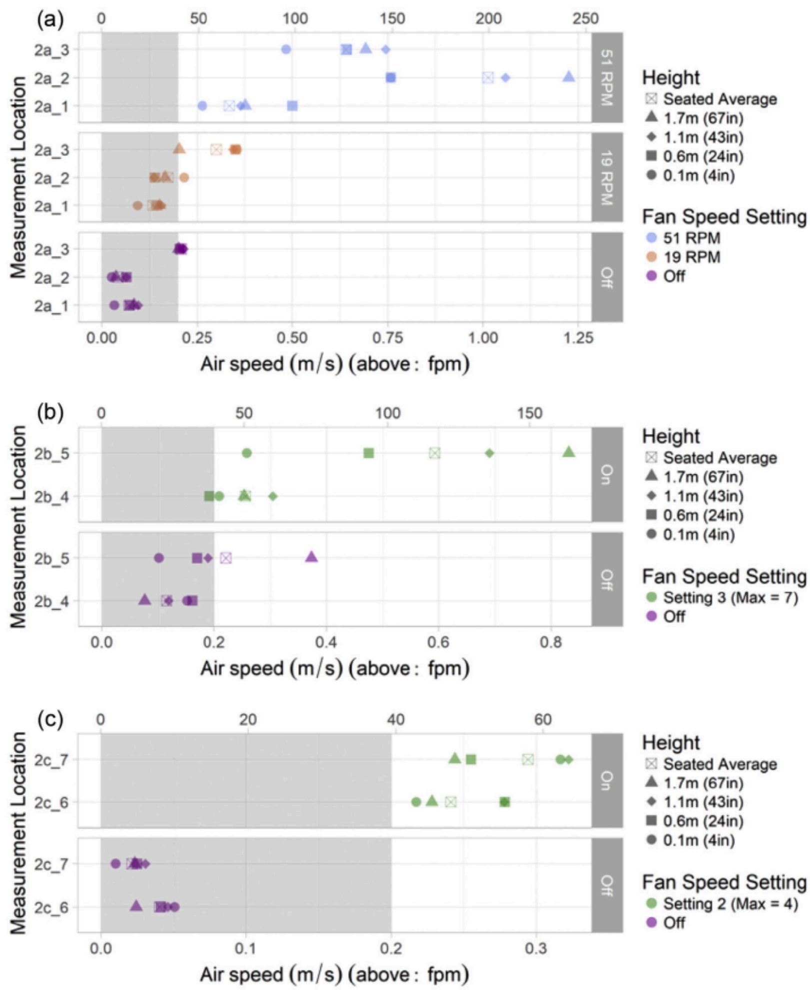


Fig. 4. Site 2 airspeed measurement results in (a) the 70-person lecture room, (b) the conference room, and (c) the two-person office. All fan speed settings selected by research team.

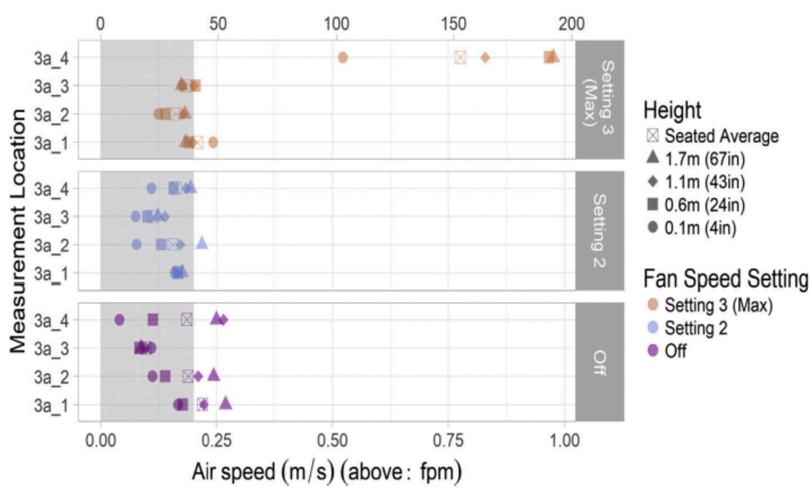


Fig. 5. Site 3 airspeed measurement results grouped by fan speed setting. Setting 2 was encountered, other settings selected by research team.

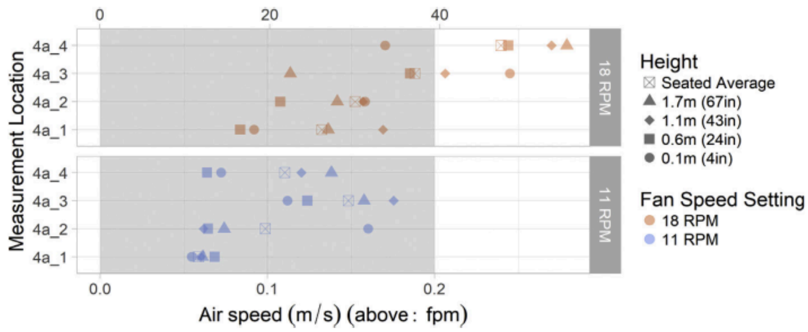


Fig. 6. Site 4 in situ airspeed measurement results grouped by fan speed setting. The 11 RPM speed was encountered and the 18 RPM was selected by the research team.

whenever they are on.

- Speeds and upward direction were established by facility managers over time based on anecdotally collected occupant feedback related to noise and comfort.
- Air temperature approximately 24 °C (75 °F)
- Measurements in four different zones (a-d)
- Measurements at each zone's established fan speed setting (not identical across spaces).

Fig. 7 shows that most of these seated-average airspeeds are in the 0.15–0.20 m/s range and are not characterized as elevated by ASHRAE 55–2017. The 0.1 m height has much slower comparative airspeeds than in the other locations. It is the slowest airspeed in 8 of the 11 locations across Site 5, in many cases by over 0.05 m/s.

4. Discussion

4.1. Ceiling fan applications and motivations

Applications. Interviewees were most likely to use ceiling fans in a few specific types of designs. The first are designs that do not use traditional cooling systems. This includes buildings with radiant systems, whose heat transfer effects are enhanced by ceiling fan air movement [10]. It also includes buildings without mechanical cooling (i.e., no refrigerant cycle), such as those that use economizer-only cooling, natural ventilation (daytime or thermal mass with night flush), or no cooling besides the ceiling fans. Ceiling fans might be implemented to make up the small difference needed to provide comfort on the hottest days of the year, or to provide the first few degrees of comfort cooling before other systems switch on, or to be operated manually independent of other cooling systems. Several interviewees discussed the value of ceiling fans in school districts in milder climates that expressly prohibit the use of compressor-based cooling in classrooms. The second are spaces with higher metabolic rate activities, such as gyms and dance studios, where there are fewer concerns about nuisance issues such as noise or blowing papers. Higher airspeeds are generally welcomed in these types of spaces, allowing greater adaptability to different activity levels. The third are spaces with high ceilings, where ceiling fans are popular for use in air mixing and destratification in heating mode.

Motivations. The reasons designers used ceiling fans in commercial spaces varied. Most cited goals such as comfort cooling or air mixing for destratification. Another recurring theme was a desire to increase occupant control, with one common example being to give teachers more individual control over their classrooms when they may not have thermostats. At least one interviewee mentioned that some of the benefits of occupant control may be psychologically motivated. One interviewee noted that personal USB-powered fans can be a better option in open office type settings, where ceiling fans will affect multiple people. The research team believes personal desk fans may also be a useful supplement to ceiling fans in shared spaces. Air movement was also reported as its own goal without thermal considerations, perhaps for reasons of improved perceived or measured air quality in the breathing zone or alliesthesia (thermal delight associated with temporal or spatial variability).

Aesthetics were also a recurring theme, with many stating that for ceiling fans to be incorporated at all they need to be beautiful. Aesthetic motivations either referred to liking the look of the ceiling fans, or that ceiling fans eliminated the need for visible ducts. The ceiling fans mixed

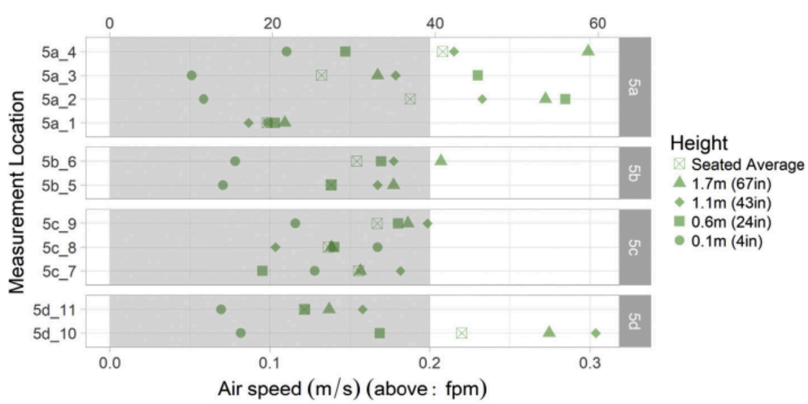


Fig. 7. Site 5 in situ airspeed measurement results. Fan speeds were as encountered in each zone. Note that the encountered fan speeds varied between zones and that the fans blow upwards in this space.

the ventilation air, thus reducing the number of diffusers needed and removing the need for any ducts in the space. A similar opportunity exists through increased design cooling setpoint, reducing the required cooling airflow to the point where side wall diffusers are sufficient, without requiring ducts or diffusers in the space itself.

4.2. Automatic versus manual control

There was considerable discussion about whether automated or manual control is preferable. Only four of the 20 projects have primarily automatic controls, with one having easily-accessible manual overrides. One additional project has manual control with occupancy sensors that turn fans off when the office is empty, and then back on to the previous speed when re-occupied. The other 15 projects have manual control only.

Manual control has the benefit of giving occupants a direct say in ceiling fan operation. Several interviewees said that manual control is their preference whenever possible because of the discretion it gives to occupants, which is both a practical and psychological benefit, and that this approach works best when one person had clear agency in a space, such as in a private office or for the teacher in a K-12 classroom. Even with manual controls, interviewees thought it would be nice to have automatic control as a back-up (e.g. with an occupancy sensor).

The interviews revealed two main challenges associated with manual control. The first occurs when it's hard to establish ownership over the fans, such as spaces with transient occupancy or shared open office plans. People's individual preferences can vary significantly, and airspeeds can vary spatially throughout the zone, so negotiating control can be challenging. The second is that many occupants do not even know about stratification or how ceiling fans help with heating. When an occupant is chilly, and sees that the fan is on, the first response is often to turn it off regardless of the speed or the ceiling height, thus limiting the effectiveness of ceiling fans for destratification. Several designers planned trainings or placards for occupants, but reported that these had mixed success.

Automatic control of the ceiling fans can solve some of these issues, but with its own concerns. The primary challenge is that most ceiling fans are not readily controlled by the BMS, or the BMS isn't BACNET capable, requiring custom solutions in most cases. Four interviewees named difficulties with ceiling fan connectivity as a barrier to ceiling fan use.

Site 5, where fans are intended only for comfort control, not destratification, offered the greatest information about automated control. This building had a large number of fans and active on-site facilities management who were able to adjust the fan speed settings manually or control when the fans switch on using the BAS. Fig. 8 describes the fan control algorithm they have established over several years. In each zone the ceiling fans are either off, or on at a designated speed that has been set for that particular zone taking noise and occupant preferences into account. The ceiling fans run in 'reverse', blowing upward, and the spatial variation of airspeeds in the occupied zone is far less than in cases where the fans were blowing downwards.

4.3. Best practices and lessons learned

Incorporate fans in the plan early. Three interviewees felt that early consideration meant that ceiling fans were more likely to be appreciated as an integral part of the system, and less likely to be removed from the project at a later stage or to create issues.

Have a coordination plan. Four interviewees mentioned that there was confusion or excessive time spent establishing who was in charge of the specification, design, drawings, and eventual installation of the ceiling fans. There is no industry standard for who should do this. In some cases, the architect could address how fans are a component of the aesthetics of the space, or the lighting and electrical team needs to integrate the fans into the ceiling design and power distribution, or the mechanical team needs to consider fans as part of the thermal comfort system. Whatever is right for a specific project, the decision should be made early and communicated clearly.

Fan-by-fan control. Two interviewees explained that their projects only allowed for multiple ceiling fans to be controlled together, and if done again they would have included a mechanism for each fan to be controlled individually.

Pitch creatively. Both interviewed architects had developed strategies for pitching ceiling fans to clients, including focusing on comfort and individual control, or bundling the ceiling fans into a larger package of solutions such as efficient envelope strategies. Several other interviewees also noted that ceiling fans were less likely to be cut late in the process if they were being relied on as a critical part of the cooling, ventilation-mixing, or other comfort systems.

Dense coverage. Three interviewees reported that projects required fairly dense ceiling fan coverage to get appropriate air movement throughout the space. In at least one case, the number of fans was value engineered down and the result was less satisfactory.

4.4. Barriers to ceiling fans in commercial buildings

Some barriers encountered were very minimal and easily overcome,

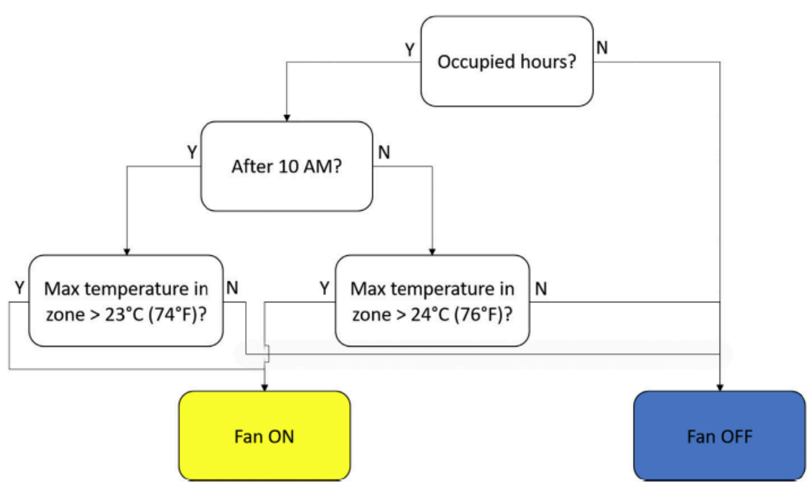


Fig. 8. An on/off control sequence for automated ceiling fans established over time for Site 5.

while others created much more substantial obstacles. Below are eleven the research team feels are worth calling out. Because we intentionally limited our interviews to designers and operators of commercial buildings with ceiling fans, all of these obstacles were evidently overcome in at least some of the projects. Conversely, because we did not ask questions about projects in which ceiling fans were *not* implemented, we recognize that there may be additional, more prohibitive, obstacles that were not necessarily identified.

Perceived Concerns. Our interviewees often had to deal with concerns from other architects and engineers, building owners, and facilities teams. These often included the ceiling fans being noisy or causing maintenance issues, air movement causing papers to blow, or that the fans would not have the necessary durability. For example, in a classroom setting, blowing papers became an issue at lower airspeeds than anticipated because student worksheets were often extremely lightweight. In other examples, a facilities manager and multiple engineers made adjustments to ceiling fans or even replaced some to address noise issues. However, the general opinion was that perceived concerns about maintenance, durability, dust, and other practical considerations have not been problems in the (admittedly short) lifetime of these projects.

Communicating benefits. Four interviewees told us they struggled to effectively communicate the benefits of ceiling fans to others during the design process, and they lacked a set of commonly-understood terminology. As one architect put it, "... you can't say 'perceived comfort' or 'perceived temperature' because that's not a real thing for many engineers." Or an engineer said "It's always a bit of a challenge to try to educate and explain the benefits of ceiling fans, that you can have two spaces exactly the same temperature but you can markedly improve the thermal comfort of one space by increasing air movement."

Cost. Over half of the interviewees mentioned cost as a barrier, more than any other single theme, centered on three points. 1) The installed cost for an existing space is often much higher than the ceiling fan itself and can be prohibitive. 2) The difference in cost between a basic fan and a larger or modern engineered fan of the same diameter can be an order of magnitude or more, which can be difficult to justify, or can be at risk for swap-out by contractors. 3) The most prevalent comment was about ceiling fans being seen as a 'bonus' or 'amenity', making them a prime target for being value engineered out of the project, or reduced in number below what designers would prefer, especially in projects where large numbers of fans are called for.

Aesthetics. Interviewees emphasized that ceiling fans form part of the visual impression of the space, and they are only going to incorporate fans that work aesthetically with the overall design of a space. One interviewee added that some desired aesthetic elements, such as "clean, uncluttered" open ceilings or uplighting, are at odds with most ceiling fans.

Guesswork in design and reliance on vendors. Multiple interviewees stated that designing with ceiling fans continues to be a matter of trial and error or guesswork. They find CFD modeling too expensive, and a lack of available design tools and guidelines, and therefore either use their own educated guesswork or rely on manufacturers' assistance. Only a few interviewees reported being able to easily find the performance information they wanted. Multiple interviewees expressed the desire for more standardized performance information in addition to independent design resources.

Ceilings too low. Three interviewees explained that even in spaces that are otherwise good candidates for ceiling fans, ceiling height limitations can prohibit or limit their use. One interviewee told us that he has found this to be an issue in some fitness spaces, since the extra height added by people standing on exercise equipment can make ceiling fans a safety hazard.

Ceiling coordination. Almost half of interviewees mentioned the challenges of coordinating the ceiling fans with lighting or other equipment so that they did not interfere with each other in terms of their physical placement, allowing each to serve its purpose unobstructed without flicker or sway. Along these lines, other ceiling components must also be taken into consideration, including ventilation and fire sprinklers. Ceiling fans, especially larger ones with splay wires, greatly increases the effort required.

Furniture. No interviewee reported having an established furniture layout prior to designing for the ceiling fans that was *not* changed later in the process. For example, certain activity areas might get different spacings of fans, or fans would be centered over walkways rather than desks. Those areas then ultimately may or may not end up being set up in that layout.

Running electrical for retrofits. Several building managers mentioned that adding additional ceiling fans would be a prohibitive task due to the need to run electrical service through existing ceilings. In one case, this was an issue primarily due to the location being a public education facility with limited funding available. In another, it was due to a radiant slab ceiling.

Post-installation challenges. Relatively few of our interviewees were significantly involved with the projects after occupancy. Those that were cited several specific challenges, especially related to noise or wobbling, but these were generally addressed soon after occupancy by either replacing the fan with another of the same model or using fan settings to limit the maximum operational speed.

Education. Several interviewees discussed steps to educate building occupants on the best practices for using the ceiling fans in their spaces. At least two projects provided placards or informational sheets either mounted near the controls or given to each employee. In another case, design team members gave a presentation to the employees at the time of occupancy. Building occupants generally associate ceiling fans with cooling, and there can be challenges getting the fans to be used appropriately for destratification or air mixing in heating.

4.5. *In situ spot measurements*

Encountered airspeeds. The seated-average encountered airspeed measurements from Sites 4 and 5 ranged from 0.07 to 0.23 m/s, well below the target airspeed ranges reported by interviewees for several other sites. This was not necessarily a detriment to comfort, however, given that the buildings were operating around 23-24 °C (74–75 °F), warm enough that ASHRAE 55–2017 permits elevated airspeeds but considered thermally comfortable regardless of added air movement. This indicates a potential opportunity to reduce HVAC energy consumption by increasing zone cooling setpoints and using the ceiling fans for the first stage of comfort cooling.

Comparing our measurements at the 1.1 m (3 ft 6 in) height to some found in the literature, our measured range of 0.06–0.3 m/s was noticeably slower than the 0.3–0.4 m/s preferred airspeed reported by Zhai et al. for office activity at 24 °C (75 °F) [38]. Yet they were more comparable to the 0.15 m/s and 0.25 m/s measured at 1.09 m in Rohles' classic paper [50] (Fig. 9). Rohles reports that even a 0.15 m/s airspeed measured with the fans on showed significant impacts in thermal sensation over a 0.06 m/s airspeed measured with the fans off. Rohles refers to this 0.15 m/s speed as "extremely low" and "probably ... unable to be perceived". He suggested that the benefit may have been a placebo effect, but we believe it is also possible that there are air quality or alliesthesia factors to consider. Whatever the cause, even with minimal cooling effect, the building occupants in both Site 4 and Site 5 had elected to have the fans on, indicating they found some benefit (psychological, air quality, thermal comfort, or otherwise) present even at these low airspeeds. Note that site 5 has a large number of occupants, zones and fans, and as such is not a small sample size. Note also that the encountered fan speed in site 4 was very low (7% of maximum fan speed).

Uniformity in the Space. The range of encountered airspeeds was smaller for Site 5 (multiple fans blowing upward) than for Site 4 (single HVLS fan blowing down). The proposed standard ASHRAE 216P

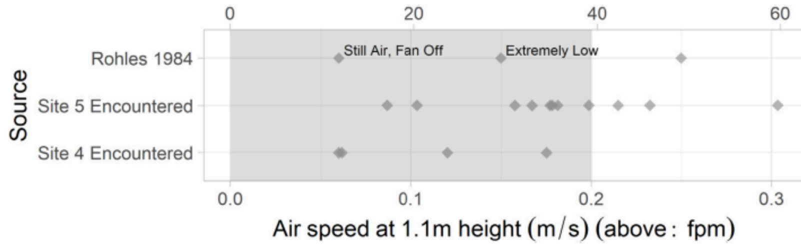


Fig. 9. Comparison of Site 4 and 5 Encountered seated-average airspeeds with the three lower airspeeds from Rohles 1984.

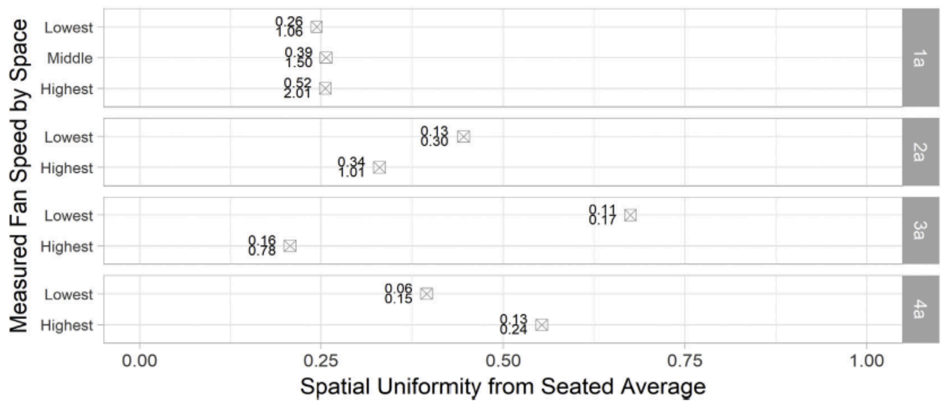


Fig. 10. Spatial uniformity calculations from spot measurements, annotated with the minimum and maximum seated-average airspeed in m/s.

contains a uniformity metric of $U_{Seated} = 1 - \frac{V_1 - V_2}{V_1}$ where V_1 is the second highest seated-average air velocity in a space and V_2 is the second lowest. Because this is designed for much larger sets of airspeeds, we will use the same approach but with the fastest and slowest seated-average airspeeds in each space, for each fan speed setting measured.

While we took different numbers of measurements in each space, and at different distances from the fan, measurements are still roughly comparable across fan settings at the same site (Fig. 10). The spatial uniformities are somewhat consistent in spaces 1a, 2a, and 4a across multiple fan speed settings, indicating that uniformity may not be strongly dependent on fan speed setting. Space 3a is an outlier, likely due to the exceptionally high ceiling and fan mount height; the air movement was perceptible only at the medium speed and directly under the fans.

Height-based variation. Of the four heights we measured, the literature suggests that the fastest airspeeds outside of the ceiling fan diameter are often at the 0.1 m height [47,49]. However, only six of the 65 airspeed measurement sets showed this, and in only 20 was the airspeed at the 0.1 m height faster than the seated-average airspeed (Fig. 11). In many more measurement cases the 0.1 m measurement had the slowest airspeed recorded. The greatest height-based difference was at site 1a_5, at the most open area, not near a workstation, table, or wall. It is possible that these result are due to disruption from our sensor support structure, or 'tree', which has a heavy pronged base near the center with airflow obstructions rising approximately 4 cm (1.5 in) high (Fig. 12). It is also possible that the furnished, occupied environments we studied have more obstructions near the floor than the open environments from the literature.

Representativeness. Our field sites were representative of real-world environments in terms of furniture layout, acoustic and lighting obstacles, ductwork, ventilation diffusers, and other physical objects in the space. The HVAC systems were also operating as they normally would. In most cases, the outdoor temperatures were not particularly warm and, according to ASHRAE 55, the indoor temperatures would have been considered comfortable even without the use of ceiling fans. At Site 5, the cooling setpoint used for controlling the HVAC in Site 5's spaces (24 °C (75 °F)) indicates that these zones are unlikely to get warm enough for the occupants to desire a significant cooling effect due to air movement. This suggests a lost opportunity for energy savings.

Controllers. Fig. 13 shows a selection of the different ceiling fan controllers in these buildings, ranging from labeled remotes left loose in the space or mounted on the wall to unlabeled sliders on a control panel along with lighting controls. The large round controls (a and b) are for BAF HVLS fans: rotating changes speed, and pushing turns on or off. The remote (f, wall mounted or floating) is for BAF Haiku fans. Most other types of fans had vertical sliders, with or without labeling of any kind (c, d, e). Overall, the controls were not straightforward. When controls were numerically labeled, higher numbers could be either faster or slower fan speed settings. None of the controls explicitly say they are for the ceiling fan, and some of the sliders start at the fastest speed. In some cases, the controllers are located far from the fans they control or in obstructed locations.

5. Conclusion

We conducted interviews with 2 architects, 8 engineers, and 3 facilities managers focused on 20 operational commercial building projects that incorporated ceiling fans, and also took a total of 65 in situ airspeed measurements across five sites. The purpose was to better understand common motivations and applications, control strategies, barriers to market adoption, best practices, and airspeeds. Although interviewees revealed many challenges and barriers during the design process, their feedback about the fans is generally positive once installed. Occupants often choose to have the ceiling fans on even when the resulting airspeeds are too slow to create an appreciable cooling effect. This aligns with findings from the interviews, that ceiling fans provide benefits not only for comfort conditioning and energy use

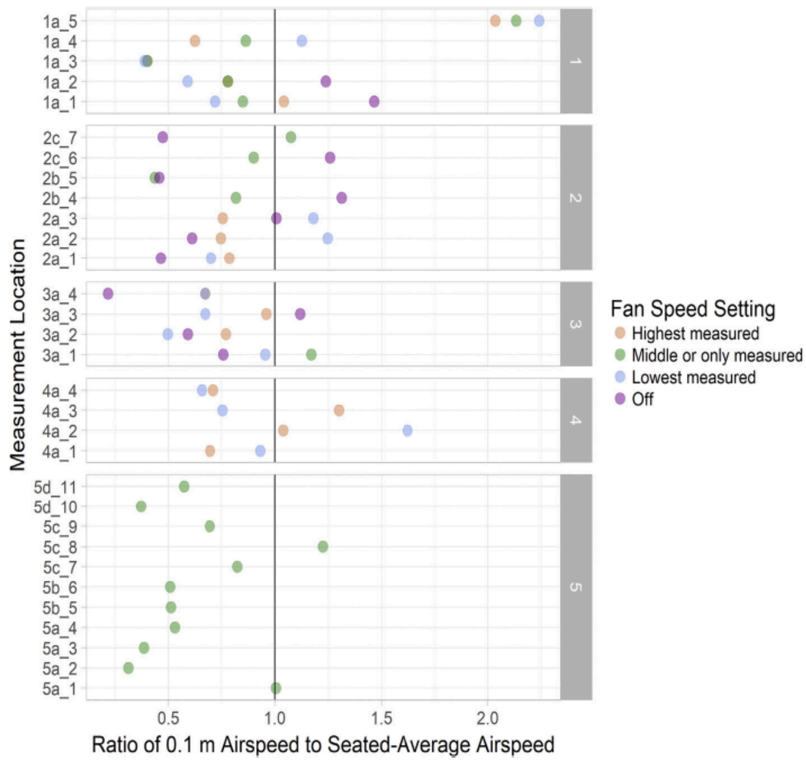


Fig. 11. Ratio of airspeed at 0.1 m height to seated-average airspeed at each measurement location. Points to the right (or left) of 1.0 have 0.1 m airspeeds that are higher (or lower) than the seated average airspeed, respectively.

Fig. 12. Base of measurement tree.

reduction, but also provide individual control, non-thermal benefits (such as perceived and measurable air quality), or an aesthetic choice not only in their own right, but sometimes as a way to eliminate visible ductwork.

The use of ceiling fans in commercial spaces that have mechanical ventilation and/or cooling systems is still a relatively uncommon practice. We believe that the benefits of fans in commercial spaces will be adopted more widely in the coming years as we better understand best practices. Furthermore, though the encountered-on-site fan settings and resulting airspeeds were low, it is important to note that these zones were already operating within ASHRAE 55 comfort conditions in the absence of air movement. Higher airspeeds would have overcooled the occupants unless one also increased the zone temperature. This indicates a potential opportunity to reduce HVAC energy consumption by increasing zone cooling setpoints and running ceiling fans faster to provide the first stage of comfort cooling.

Among the projects we studied, there were few applications of automatic control, and interviewees did not offer a consensus about whether manual or automated control was preferable, seeing pros and cons of each. We believe that a viable option is that of occupancy- and temperature-responsive automated controls that can be configured and temporarily overridden by occupants— similar to current best practice in the lighting industry.

As with many strategies that aim to improve building performance, best practices start with an integrated design process where different stakeholders communicate early in the process and coordinate decision making. This would facilitate overcoming many of the identified barriers to implementing ceiling fans, such as perceived concerns about noise, maintenance, or papers blowing; ability to clearly explain the benefits of fans to building owners or other design team members; cost tradeoffs; and lack of design guidelines. It's also important that the process does not end with design but is maintained through occupant education so that users fully understand the range of performance characteristics of ceiling fans (i.e., cooling vs. destratification), so the benefits are fully realized.

This study found substantial uncertainty around designing with ceiling fans despite the significant potential benefits. Lack of design guidance and measured performance is a significant barrier to downsizing HVAC equipment based on ceiling fan inclusion. Designers would benefit from outside support, such as from industry, government, or academia. The most significant support would be in the form of design guidance, backed by laboratory testing, CFD, and field studies, for

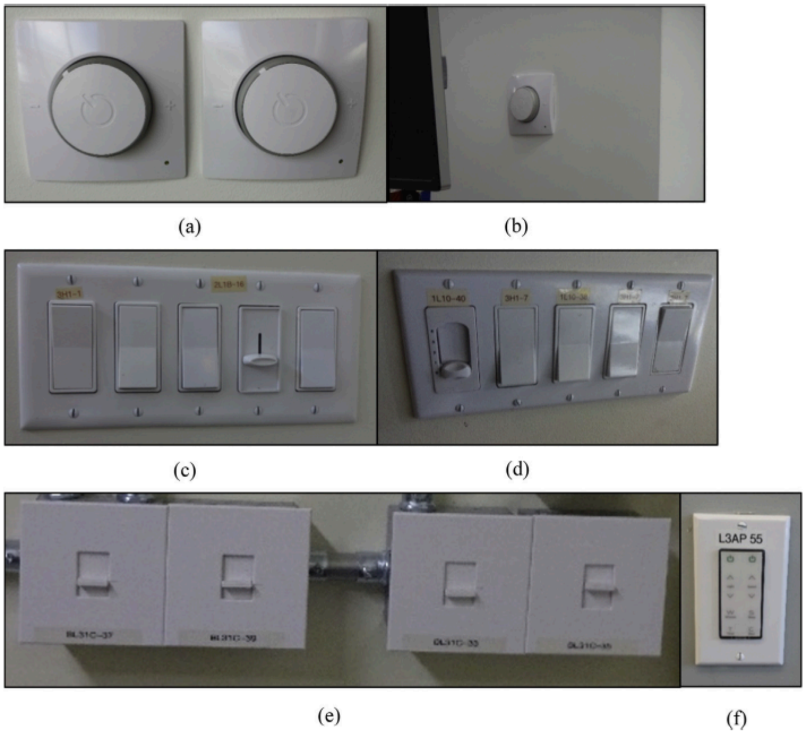


Fig. 13. A selection of ceiling fan controls from in situ measurement sites.

commercial spaces with ceiling fans. This would make designers less reliant exclusively on manufacturers' guidance, and improve communication regarding the abilities and design goals of ceiling fans, and make the designers more confident that their designs would perform as intended. Another need is an expansion of the set of available standardized product test specifications, which would allow designers to more directly compare ceiling fan products. This will require industry effort; though ASHRAE is currently working on Standard 216, *Methods of Test for Determining Application Data of Overhead Circulator Fans*, which would meet most of this need. Industry could also better support ceiling fan products that can easily communicate with building automation systems or, ideally, that are BACNET-capable. In general, a more standardized design process would reduce several of the barriers to implementation. Members of the research team are continuing to work to better understand the needs of the design community in regard to designing with ceiling fans and intend to create a publicly-accessible design tool in the next two years.

Acknowledgements

This work was supported by the California Energy Commission (CEC) Electric Program Investment Charge (EPIC) Grant Award # 031322-022 and the Center for the Built Environment (CBE). Elaina Present holds a Career Development Grant from American Association of University Women (AAUW). Thank you to Therese Peffer for her help in preparing the manuscript and to Arfa Aijazi and Carlos Duarte for their feedback on some of the figures.

Appendix A. Interview guide

Project overview

- Was this a new or retrofit project?
- What was your role on the project?
- Over what time period were you involved on the project?

Why ceiling fans/getting ceiling fans on the table

- Why did you choose ceiling fans on this project? (Comfort? Energy savings? Destratification?)
- What led to the decision to move forward with ceiling fans? What alternatives were considered?
- What types of HVAC systems are in the areas where fans are used? Setpoints?
- Why did you choose the ceiling fan and controls technologies that were installed? Did you consider any other options?
- What, if any, barriers were there to specifying or installing ceiling fans on this project?

Design

- What resources assisted you in specifying fans on this project – guides, tools, performance specifications, standards, etc.?
- Was adequate performance information available for you to choose a fan? What information was unavailable (or difficult to find)?
- Did you have specific airspeed targets?
- Was fan power consumption or efficiency a consideration in the selection process?
- How did you determine the locations for the fan(s) within the space?
- Was the furniture layout fixed at the time when you finalized the fan selection/design? If not, were there multiple options on the table, or was there simply no information at that point in time?

The system

- How many ceiling fans were used, in what types of spaces and with what spacing? How was this decided?
- How are the ceiling fans controlled? Who has control of the ceiling fans? What is the hierarchy of control?

Operation

- How long has the ceiling fan system been in operation? Have any changes or updates been made?
- How well are the fans and controls working? Are they achieving the intended effect? What is working well? What is not working well? Have there been any surprises?
- What has the response from occupants been? (Do they like the fans, or have there been complaints? How have any complaints been addressed?)
- Has there been a difference in the responses of those with more versus less control?
- Have there been any issues with maintenance (perceived concerns, or actual failures) of the fans since install?
- Have you noticed whether or not the occupants have used the fans as intended? Have the fans been moved or adjusted in any way since installation?
- Adjustment to set points?

Impact on further work

- Have you considered/specified/installed ceiling fans in any subsequent projects? Why or why not?
- What lessons learned from this project have you applied to subsequent projects?

Market trends and obstacles

- In your experience, has the number of ceiling fan products on the market increased or decreased?
- How have costs for ceiling fans and ceiling fan controls changed over time?
- Are there any specific design or control strategies you would recommend?
- Are there specific products you would recommend over others, either hardware, controls systems, or design or specifying resources?
- What, if any, improvements to the products or control strategies would you like to see?
- What kinds of product or control changes would encourage you specify or install more fans in the future?
- What, if any, barriers are there to specifying or installing ceiling fans on future projects?

Wrap-up

- What should we have asked that we did not ask?

Appendix B. Project characteristics

Table B1
Project characteristics.

Project/ Site#	Location	Space type with Ceiling Fans	Ceiling fan Goals	Cooling in Ceiling Fan Spaces	Interviewee(s)	Controls	# Ceiling fans	Ceiling fan spacing	Fan diameter (Approx.)
1	Berkeley, CA	Conference rooms Common areas Open offices Private offices	Energy savings LEED certification	Other compressor-based	Building manager	Manual (mostly grouped)	Varies	Varies	NA

(*continued on next page*)

Table B1 (*continued*)

Project/ Site#	Location	Space type with Ceiling Fans	Ceiling fan Goals	Cooling in Ceiling Fan Spaces	Interviewee(s)	Controls	# Ceiling fans	Ceiling fan spacing	Fan diameter (Approx.)
2	Santa Cruz, CA	Large seminar room (SR) Conference rooms (CR) Private and shared offices (O)	Cooling Destratification (SR) Occupant control (O) Aesthetics (SR - no ducts)	Operable windows No compressor cooling VAV central air handler with no cooling coil, economizer cooling only	Mechanical engineer	Manual (SR) Manual (proprietary remotes) (CR) Manual with occupancy (O)	1 per office 4 in SR 1–2 in CR	NA	HVLS 2.4 m (8 ft) (SR) 1.5 m (5 ft) (CR) 1.5 m (5 ft) (O)
3	Emeryville, CA	Open Office	Destratification Air movement Cooling	Other compressor-based	Architect, Facilities	Manual	Array	6 m (20 ft) on center x 9 m (30 ft) on center	1.5 m (5 ft)
4	San Francisco, CA	Open office	Destratification Air movement Aesthetics	VRF fan coil units	Tenant Engineering Consultant	Manual (wall)	1	~Centered	HVLS 24 m (8 ft)
5	Sacramento, CA	Open office	Comfort cooling Air movement	Radiant cooling Night pre-cooling	Building manager/ Controls implementer	Automatic	10/open office zone	6 m (20 ft) on center	1.5 m (5 ft)
6	Woodside, CA	Maker space (MS) Preschool	Occupant control Comfort	NA	Architect	Manual	1 HVLS in MS Array in preschool	Varies	NA
7	Finland, MN	Housing common area	Destratification Cooling on warmest days	Whole-house fan No compressor cooling	Mechanical engineer	Manual (proprietary remote)	1	~Centered	1.3 m (52 in)
8	Saratoga, CA	Maintenance shops	Cooling on warmest days	No compressor cooling	Mechanical engineer	Manual	6 (1 per shop)	NA	HVLS 2.4 m (8 ft)
9	Watsonville, CA	Lab spaces Conference room Offices (private & open)	Occupant control Enhance radiant	Radiant cooling	Architect	Manual	NA	Varies	1.5 m (5 ft)
10	Santa Rosa, CA?	Multi-use spaces Offices (private) Classrooms Kitchen Specialty Areas	Comfort User control Destratification Flexibility Enhance radiant	Radiant cooling	Architect	Manual	12 in dining room 1 per office Other: varies	Varies	Varies (some HVLS)
11	Menlo Park, CA	Open office Private office Dining rooms	Extend comfort cooling range Enable/enhance radiant (Comfort and efficiency)	Radiant cooling Chilled sails/ fan coils Operable windows	Mechanical engineer	Manual (wall)	~60 1 per office Arrays elsewhere	3.7–4.6 m (12–15 ft) on center	1.2 m (4 ft)
12	Atherton, CA	Classrooms Library	Occupant control Cooling Eliminate AC	Other compressor-based	Architect	Manual (grouped)	12 in library 1 per classroom?	Varies	1.5 m (5 ft)

(*continued on next page*)

Table B1 (*continued*)

Project/ Site#	Location	Space type with Ceiling Fans	Ceiling fan Goals	Cooling in Ceiling Fan Spaces	Interviewee(s)	Controls	# Ceiling fans	Ceiling fan spacing	Fan diameter (Approx.)
13	Basalt, CO	Open office Kitchen Atrium Convening room	Comfort cooling Air movement	No compressor cooling	Architect	Automatic	Array	6 m (20 ft) on center	1.2 m (4 ft)
14	Seattle, WA	Open office Conference room	Added air movement Thermal comfort improvement	Radiant cooling Natural ventilation Operable windows Thermal mass	Mechanical engineer	Occupant control (proprietary remotes)	8 in open office 2 in conference room	every structural bay (~6 m (20 ft) on center)	1.5 m (5 ft)
15	Oakland, CA	Classrooms (C) Assembly area (A) Indoor courtyard (IC) Private offices (O)	Cooling Air mixing Destratification Assist with night pre-cool	Thermal mass Night pre-cooling	Project engineer, Mechanical engineer/ Commissioning agent	Automatic Manual override	1/(C) 1/(O) 2/(IC, A)	~Centered	HVLS 5.5 m (18 ft) (A, IC) HVLS 3.7 m (12 ft) (C) HVLS 1.8 m (6 ft) (O) 1.5 m (5 ft) (O, Phase II)
16	Newport Beach, CA	Semi-enclosed, semi-exterior lounge space	Cooling on warmest days	No compressor cooling	Mechanical engineer	Automatic (temperature - based)	2	NA	HVLS 2.4 m (8 ft)
17	San Jose, CA	Open office	Destratification Air movement	Water source heat pumps	Mechanical engineer	Manual (touchscreen, grouped)	4	NA	HVLS 1.8 m (6 ft)
18	Sacramento, CA	Open office	Destratification Air movement	Packaged unit	Mechanical engineer	Manual	1 HVLS 3 smaller	NA	HVLS 2.4 m (8 ft) 1.3 m (52 in)
19	Northridge, CA	Fitness rooms Gym area	Comfort cooling	Campus VAV	Mechanical engineer	Manual	30	NA	1.2 m (4 ft)
20	Pomona, CA	Fitness studios Gym area	Occupant control Comfort cooling	Campus VAV	Mechanical engineer	Manual	30	NA	1.3 m (52 in)

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APPENDIX F:
Spatial Uniformity of Thermal Comfort from Ceiling Fans Blowing Upwards

Spatial Uniformity of Thermal Comfort from Ceiling Fans Blowing Upwards

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ABSTRACT

Air movement from fans is an effective way to deliver thermal comfort in warm air temperatures. We measured air speeds in a shared office at 15 sites where an occupant would typically be located. The fan speed and direction were changed to operate in either the upwards or downwards direction. Mean air speeds in the occupied zone were higher when fans were blowing downwards, but the spatial distribution across the space was less uniform. When fans are blowing upwards, thermal comfort estimates using SET indicate less risk of discomfort from high airspeed locations directly under the fans compared with the downward case. Vertical air speed gradients showed higher air speeds at head height and lower air speeds at ankle height in the upwards direction, but the opposite profile for fans blowing in the downward direction. The positive vertical gradient in the upwards direction is favorable to reduce the potential for draft at the ankles. These results suggest that despite lower air speeds, fans blowing upwards can provide more spatially uniform thermal comfort under elevated air movement, requiring less consideration of occupant and furniture placement relative to the fan.

INTRODUCTION

Ceiling fans are a common component of a thermal comfort strategy for building designs aiming for higher energy efficiency (Arens et al. 2009; He et al. 2019). This is particularly true for warmer climates, where cooling from fans can enhance occupant comfort while allowing setpoint temperatures to be widened to reduce energy expenditure (Rohles et al. 1982; Tanabe and Kimura 1989; Lipczynska et al. 2018). In cooler conditions, draft is one of the common sources of local thermal discomfort (Toftum 2004) and elevated air movement is discouraged in ASHRAE 55-2017 for buildings where indoor operative temperatures are below 23°C (73.4°F). Aside from operative temperature, the placement of ceiling fans in relation to occupants and office furniture represents a potential design challenge due to spatial inhomogeneity of the resulting air movement (Liu et al. 2018; Gao et al. 2017; Ho et al. 2009). Incorrectly positioning ceiling fans may lead to excessive air movement for occupants directly under a fan while their colleagues sitting further away experience insufficient air movement.

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There is evidence that fans blowing in the upward direction may offer a simple solution to this issue of spatial variation in air speeds from ceiling fans (Raftery et al. 2019). By reversing the rotation direction of the motor, the patterns of air movement within the space are altered in a way that can improve the uniformity of comfort conditions for occupants irrespective of furniture and layout. This can be beneficial in some applications like commercial offices

where occupants cannot freely and easily move around the space. This is considered an important step in promoting the use of ceiling fans in contemporary commercial offices. Accordingly, the aims of this paper are:

1. Measure the air speed field of fans blowing in both the upward and downward directions
2. Evaluate the uniformity of thermal comfort conditions from spatial variations in air speed within a typical office environment with ceiling fans.

Method

We conducted field measurements of air speeds from ceiling fans in a single-zoned office in Sacramento, California in May (spring) 2018. The office building, shown in Figure 1, has radiant heating and cooling delivered by thermally active building system (TABS). It is LEED Platinum certified with numerous energy efficiency strategies. Ceiling fans are distributed throughout the zone for occupant comfort and to supplement the dedicated outdoor air system (DOAS) with overhead air distribution for ventilation. The space is a mix of cubicle-style workspaces, and print and archival areas. A floorplan of the office space is shown in Figure 5.

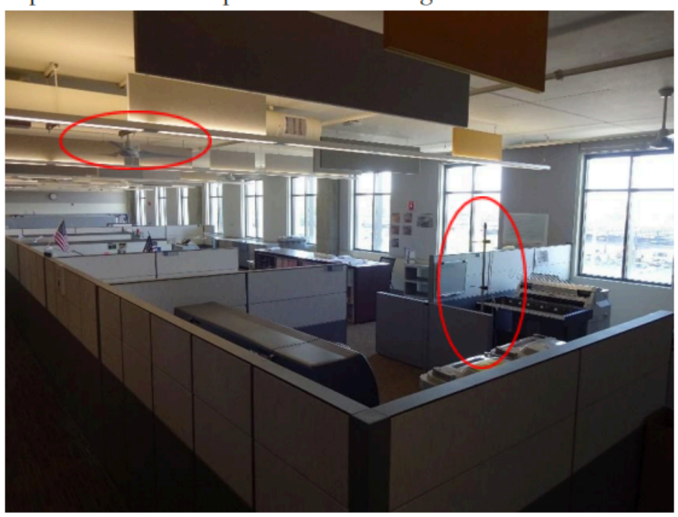

Figure 1 Photo of the field site where measurements were performed. Red circles highlight the anemometer stand used to measure air speed at four heights, and one of the seven ceiling fans.

Ceiling fans installed in the space have three blades with a 60” diameter, an airflow rating of 9,602 cfm, and a maximum motor speed of 247 RPM. Fan speeds are set using a rotary dial on a controller located in a locked utility space. As required for all ceiling fans sold in the USA, the fans can be switched to operate in reverse direction. The field study involved in situ spot measurements of air speeds at multiple sites within the occupied zoned with the fans at two different speeds – nominally “medium” (~155 RPM) and “high” (~237 RPM) – blowing in both the upward and downward direction. The location of the measurement sites were at least 6” away from any furniture, and are shown along with a floorplan in Figure 5. Air speeds were also measured when the ceiling fans were off to establish baseline conditions. All fans in the zone had approximately the same settings during the tests, resulting in five different test conditions (off, up medium, up maximum, down medium, down maximum).

Measurements

Air speed measurements were taken at 15 sites within the space that were considered representative of typically occupied areas. A stand with omni-directional anemometers (5100SF, Sensor Electronic, Poland) mounted at four different heights (0.1 m, 0.6 m, 1.1 m, 1.7 m; 0.33 ft, 1.97 ft, 3.61 ft, 5.58 ft) measured both air speed (±0.02 m/s ±1.5%; ±3.94 fpm ±1.5%) and air temperature (±0.2°C; ±0.36°F) in accordance with ASHRAE 55-2017. For the calculation of thermal comfort indices, operative temperature was assumed to be equal to air temperature, relative humidity was assumed to be 50%, and the personal factors were set for an office worker in summer (1.1 met, 0.5 clo).

Analysis

We used the open source R statistical computing language (R Core Team 2018) with tidyverse (Wickham 2017) for all analysis, and additional software packages comf (Schweiker et al. 2019) for thermal comfort calculations, imager (Barthelme 2019) for some graphics, and here (Müller 2017) for file path management.

RESULTS AND DISCUSSION

Summary statistics of the measured air speeds and air temperatures for each test condition are shown in Table 1. Air speeds were highest when the fans were blowing in the downward direction. The mean air temperature was stable and identical across all tests, but the resulting predicted mean vote (PMV) and standard effective temperature (SET) are markedly different between test cases. A PMV of -0.6 in the initial case with fans off suggests the space is slightly cool, likely due to the assumed value of clothing and metabolic rate. Both PMV and SET decrease as the mean air speed increases. This shows the significance of the cooling effect of elevated air movement on the predicted thermal comfort of occupants.

Table 1. Summary Statistics Across all Measurements Sites (Mean and Standard Deviation)

	Physical Measurements		Thermal Comfort Indices	
Test	**Air Temperature °C (°F)**	**Air Speed m/s (fpm)**	**SET °C (°F)**	**PMV**
Off (off)	23.6 ± 0.0 (74.5 ± 0.0)	0.09 ± 0.04 (17.72 ± 7.87)	22.8 ± 0.1 (73.0 ± 0.2)	-0.6 ± 0.1
Up Medium (upmed)	23.6 ± 0.0 (74.5 ± 0.0)	0.20 ± 0.07 (39.37 ± 13.78)	22.3 ± 0.5 (72.1 ± 0.9)	-0.9 ± 0.2
Up Maximum	23.6 ± 0.0 (74.5 ± 0.0)	0.30 ± 011	21.7 ± 0.7	-1.1 ± 0.2

(upmax)		(59.06 ± 21.65)	(71.1 ± 1.3)	
Down Medium (downmed)	23.6 ± 0.0 (74.5 ± 0.0)	0.46 ± 0.28 (90.56 ± 55.12)	21.1 ± 1.1 (70.0 ± 2.0)	-1.3 ± 0.4
Down Maximum (downmax)	23.6 ± 0.0 (74.5 ± 0.0)	0.76 ± 0.50 (149.61 ± 98.43)	20.3 ± 1.3 (68.5 ± 2.3)	-1.6 ± 0.4

The mean air speed was different between tests, with large spatial variation between measurement sites across the zone. Mean air speeds across the four heights for different measurement sites ranged from 0.21 m/s (41.34 fpm) to 1.20 m/s (236.22 fpm) in the downmax test, and 0.17 m/s (33.46 fpm) to 0.43 m/s (84.65 fpm) in the upmax test. This is mostly due to the smaller mean air speeds measured in the upwards blowing tests. However, we observed generally more uniform spatial distribution when the fans were blowing upwards. Figure 2 shows the mean air speed for each test by measurement site under sitting (excluding 1.7 m measurements) and standing (excluding 0.6 m measurements) configurations. There is much larger difference in air speeds experienced by a seated occupant compared to standing. The trends in air speed between sites was different in the downwards and upwards tests - in other words, the locations of the highest and lowest airspeeds vary depending on the direction the fan is blowing.

Measured air speeds were much lower when fans were blowing upwards compared to downwards. It was recently shown by Raftery et al. (2019) that the various parameters governing air movement in the occupied zone from ceiling fans can be used to predict the resulting air speeds. We performed a simplified version of that approach in Figure 3 that shows an approximately linear relationship between fan speed setting and mean air speeds for both the upwards and downwards blowing directions. This suggests that the modelling approach used by Raftery et al. (2019) may also apply in the case of upward blowing fans if a rated airflow was available for the upwards direction, as is currently required for all ceiling fans sold in the USA for the downwards direction.

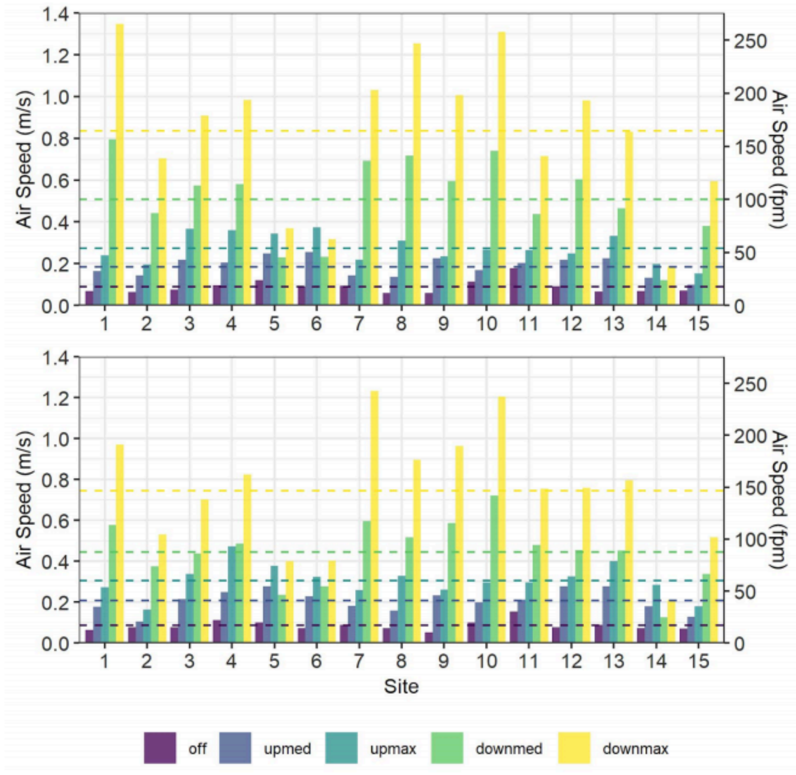

Figure 2 Mean air speeds of measurement sites for each fan test for sitting (top) and standing (bottom) measurements. Dashed lines represent the group mean.

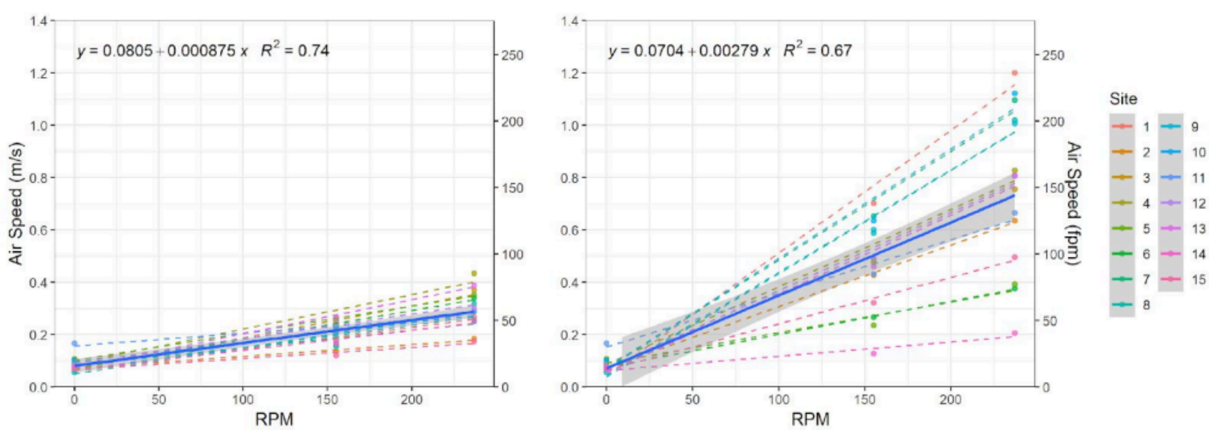

Figure 3 Mean air speeds by site for the off (0 RPM), medium (~155 RPM), and maximum (~237 RPM) speed settings in the upwards (left) and downwards (right) direction. The solid blue line is the mean for all sites and shading shows the confidence interval of the linear regression.

Vertical Air Speed Gradient

Mean air speed is an important parameter for determining occupant thermal comfort when using popular models like PMV and SET. However, the magnitude of local air movement at different body sites has been shown to exert a large influence on overall comfort due to draft sensation. ASHRAE 55-2017 generally estimates that 10% of all thermal dissatisfaction arises from some kind of local discomfort. It is for this reason that vertical air speed gradients are an important consideration for thermal comfort under elevated air movement. Figure 4 shows the distribution of all air speed measurements (0.5 Hz) from each test at the four heights. There is much larger variance in air speeds in the downward blowing direction, similar to what was observed when summarizing the data by site in Figure 2. There is an approximately normal distribution of air speeds in the upwards blowing tests, with the downwards blowing direction exhibiting a bimodal or multimodal distribution that suggests more inhomogeneity across measurement sites.

The key finding in Figure 4 is that the vertical air speed gradient is flipped when the fans are blowing in the downwards and upwards directions. Under normal operation, fans blowing downwards will create a negative vertical gradient where air speeds are fastest at the ankle height of occupants, and slowest at head height. In contrast, air speeds from upwards blowing fans are highest at the head and lowest at the ankle. This has very important consequences for overall comfort due to the sensitivity of the ankles to draft (Schiavon et al. 2016). In fact, natural temperature gradients across the body mean that cooling in warm conditions is best targeted at the head level rather than the feet. This is in line with the neutral vertical temperature gradient ("ideal piste") by Wyon et al. (1989) and consistent with the idea of thermal pleasure arising from cool stimuli applied to warm body sites described by the spatial alliesthesia hypothesis by Parkinson and de Dear (2015).

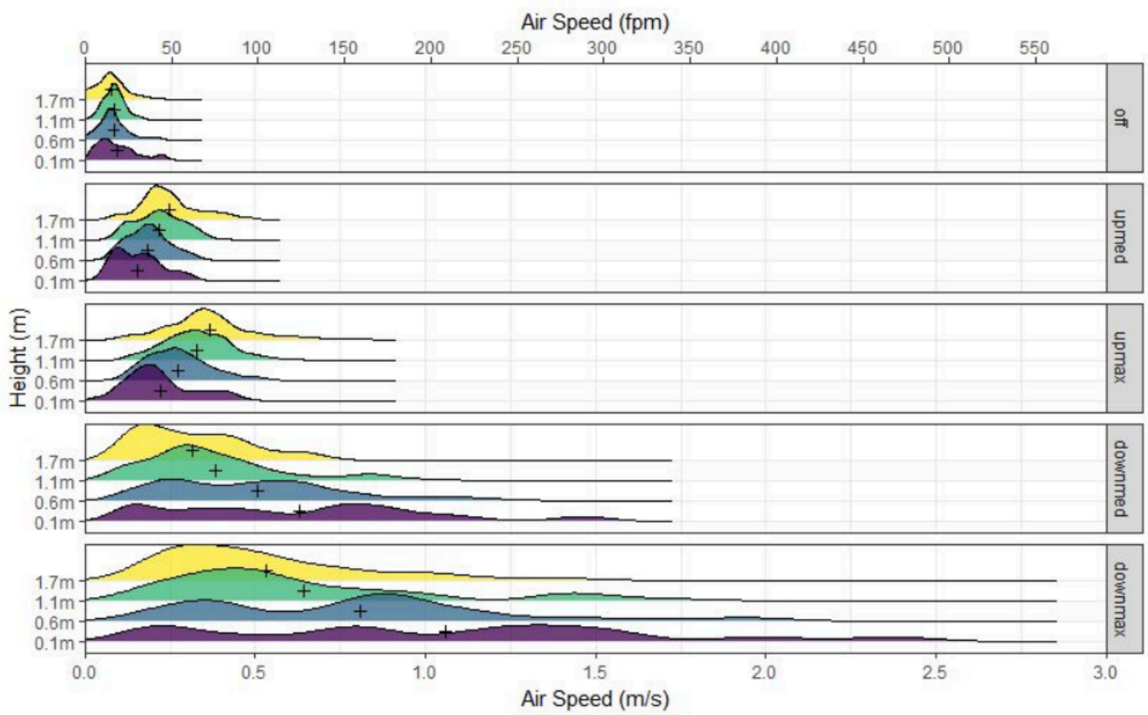

Figure 4 Distribution of measured air speeds for each test at the four measurement heights using the raw data (0.5 Hz). The '+' symbol marks the mean air speed at each height across all measurement sites.

Spatial Uniformity of Thermal Comfort

The vertical air speed gradient from upward blowing fans is likely to have positive benefits for occupant thermal comfort. Another key advantage of upward blowing fans is a more spatially uniform distribution of air speeds across the floorplate, as shown earlier in this section. To visualize the implications of this uniformity of air speed on thermal comfort, the mean air speed across the four heights was used to determine the neutral operative temperature for the space in the upmax and downmax tests – 27.0°C (80.6°F) and 28.6°C (83.5°F) respectively – where SET was 25°C (77°F) and PMV was 0 for a standard office worker in summer (50% relative humidity, 1.1 met, 0.5 clo). Thus, these fans allow for neutral comfort conditions at an operative temperature that is 2°C and 3.6°C higher than the still air case respectively for the upwards and downwards direction tests. This has significant energy savings potential reducing HVAC energy consumption by approximately 30% and 40% respectively for upwards and downwards respectively in this climate zone using the simulation data from Hoyt et al. (2014). The results are shown in Figure 5 along with a floorplan of the office space showing the placement of ceiling fans and office furniture in relation to the measurement sites.

Figure 5 Mean SET and air speeds at each measurement site for the upmax (top) and downmax (bottom) test conditions. The SET calculation used an operative temperature corresponding to thermal neutrality based on the mean air speed of each test as a way to normalize the cooling effects of elevated air movement across the upwards and downwards blowing tests. The background is the floorplan showing the location of fans (blue symbols), office furniture (grey squares) and partitions (solid grey lines). Note the fan in the lower right was not able to be reversed

and was off for all tests.

Figure 5 shows the variability in air speed in the tests when the fans are blowing downwards, and the implications of that variability on thermal comfort conditions across the zone. Even after being corrected for mean air speed, the SET under the downward blowing fans varies across the different sites. In some cases (e.g. site 14 and 6) there is significant likelihood of warm discomfort, while occupants of other sites located under the ceiling fans (e.g. site 1 and 10) could be experiencing cool discomfort. When the fans are blowing upwards there is a smaller difference in SET across the zone, with the greatest cooling effect at sites positioned near the convergence zone of two fans (e.g. site 4 and 13). The greater uniformity of air speeds when fans are blowing upwards would make it easier for a designer to ensure thermal comfort for all occupants of the space without having to know the position of the fans and the occupants, or the furniture layout which is likely to change more often than the position of ceiling fans. Even if the upwards case was designed with faster fans such that the average air speed matched the downwards case, the resulting air speed distribution would still be more uniform.

CONCLUSION

We measured air speeds at multiple spots across a single zone within an office building while ceiling fans were operating in an upwards or downwards direction at different speeds. The purpose was to determine the spatial uniformity of air speeds from ceiling fans and assess the impact on thermal comfort at different positions within the occupied zone. Mean air speeds were lower when fans were set to blow in the upwards direction. We found less spatial uniformity in mean air speed measurements (averaged over 3 or 4 heights) across the zone when fans were blowing downwards, with the highest air speeds observed directly below the fans. In contrast, the highest air speeds when blowing upwards were spots positioned in the convergence zone between two fans. The vertical air speed gradient reversed when the direction of the fans was switched, with the positive gradient when blowing upwards less likely to result in local thermal discomfort from draft. These results show that fans blowing upwards can provide more spatially uniform thermal comfort under elevated air movement. Although this is a small-scale study, we believe this is an important finding as it suggests that designers can more reliably predict thermal comfort when ceiling fans are operating in the upward direction regardless of occupants' location in the zone, the position of the fans, or the placement of furniture.

ACKNOWLEDGMENTS

This work was supported by the California Energy Commission (CEC) Electric Program Investment Charge (EPIC) Grant Award #031322-022 and the Center for the Built Environment (CBE). Thomas Parkinson is supported by the Republic of Singapore's National Research Foundation Singapore through a grant to the Berkeley Education Alliance for Research in Singapore (BEARS) for the Singapore-Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST) Program. BEARS has been established by the University of California, Berkeley as a center for intellectual excellence in research and education in Singapore. Elaina Present held a Career Development Grant from American Association of University Women (AAUW).

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APPENDIX G: Codes and Standards Support

As part of the *Integrating Smart Ceiling Fans and Communicating Thermostats to Provide Energy-Efficient Comfort* (EPIC Fans) research project, the research team has been supporting and researching a variety of issues related to building codes and standards. This document summarizes those activities and findings.

Codes and Standards support activities, as described in the sections below, include:

- Development of a new ASHRAE Standard 216 – Methods of Test for Determining Application Data of Overhead Circulator Fans
- Proposed Addendum C to ASHRAE Standard 55 defining Thermal Environmental Control Classification Levels for certain compliance options
- A description of barriers and opportunities for ceiling fans in the California Building Energy Efficiency Standards
- A discussion of building code considerations for ceiling fans, including a description of fire code requirements, and opportunities for additional clarification of the code requirements related to ceiling fans

Development of ASHRAE Standard 216

As part of this research study, members of the project team are also supporting the development of the proposed ASHRAE Standard 216, titled "Methods of Test for Determining Application Data of Overhead Circulator Fans." Gwelen Paliaga of TRC is serving as chair of the standard development committee, and several other members of the research project team from CBE, TRC, and Big Ass Fans are also serving on the committee or supporting the development of the standard.

This standard was created to provide standardized performance data for the application of overhead circulation ceiling fans in indoor spaces. The room airspeed distribution test results can be used to calculate occupant thermal comfort and to demonstrate compliance with the thermal comfort requirements of ASHRAE Standard 55. This standard includes requirements for test instrumentation, the features of test rooms, and measurement procedures. It also includes calculation procedures for a number of performance metrics relevant to thermal comfort application of overhead circulator ceiling fans such as uniformity, room average cooling effect, heating draft risk, and comfort cooling efficacy.

Once adopted, this standard will provide a consistent, industry-standard practice for determining ceiling fan performance characteristics. In conjunction with the proposed Addendum C to ASHRAE Standard 55 (described in the next section), this new standard will support the implementation of ceiling fans as thermal comfort features in buildings.

As of this writing, the proposed Standard 216 is still in draft form pending final adoption. Additional details of the final adopted Standard will be provided in subsequent reports for this research project.

Proposed Addendum to ASHRAE Standard 55

In conjunction with this study, several members of the research team are supporting an effort to revise ASHRAE Standard 55 – Thermal Environmental Conditions for Human Occupancy. Per the description from ASHRAE, “Standard 55 specifies conditions for acceptable thermal environments and is intended for use in design, operation, and commissioning of buildings and other occupied spaces.”[18] The proposed addendum will define increased air speed (through devices such as ceiling fans or desk fans), among other strategies, as a potential measure for thermal comfort control.

The proposed Addendum C to Standard 55 would modify Section 6 “Design Compliance” to require projects following certain compliance paths to specify a “Thermal Environmental Control Classification Level” for each space type within the building.[19] The proposal defines five Thermal Environmental Control Classification Levels, summarized as follows:

- Level 1 – two or more control measures for each occupant
- Level 2 – one control measure for each occupant
- Level 3 – two or more multi-occupant control measures for each room or thermal zone
- Level 4 – one multi-occupant control measure for each room or thermal zone
- Level 5 – no occupant control

The proposal notes that control measure options may include thermostat control, ceiling fans, desk fans, foot warmers, or other devices, and requires that all control measures be readily accessible to occupants. For desk fans, cooled chairs, heated chairs, and footwarmers, the proposed addendum sets minimum requirements for each to allow prescriptive compliance as a control measure. For all other potential control measures, the proposed Addendum defines minimum PMV, temperature, or air movement requirements for eligibility.

The proposed addendum is currently in the public review and comment phase, and is expected to be finalized and adopted in 2020. Once adopted, this addendum will provide significant support for ceiling fans as a thermal comfort feature from a building standards perspective.

Barriers and Opportunities in California Building Energy Efficiency Standards

To date, ceiling fans have not been included in the California Building Energy Efficiency Standards (Title 24, Part 6) as a compliance option for thermal comfort control. Although ASHRAE Standard 90.1 has some options for increasing assumed cooling setpoints in conjunction with strategies such as ceiling fans, this strategy has not yet been included in the California Energy Standards. There have been previous proposals for Codes and Standards Enhancement (CASE) studies to develop options for residential compressorless comfort in some coastal climate zones in California. These proposals use cooling load avoidance strategies as a

[18] https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy

[19] Public review draft of Addendum C to ASHRAE Standard 55

first priority, including passive solar strategies, advanced envelopes, and night cooling, supplemented by non-compressor-based cooling strategies, such as ceiling fans, when needed. This proposal was most recently presented as part of the 2013 Standards development process, but has never been pursued by the CEC or the California investor-owned utilities.

Although the strategies proposed for residential compressorless comfort remain viable, there are several barriers to adoption in the Energy Efficiency Standards. One of the primary barriers has been a lack of widely accepted standards for measuring cooling effect from compressorless strategies such as ceiling fans. Without accepted methods for modeling the cooling load avoidance, or measuring the cooling effect of compressorless strategies, there has been no reliable method for determining the potential energy savings or cost effectiveness in accordance with standard CASE proposal procedures.

However, the development of new standards such as ASHRAE Standard 216, and updates to existing standards such as the proposed addendum to ASHRAE Standard 55, described in the sections above, will help to address this barrier. With the development of industry standards for measuring performance characteristics of ceiling fans (ASHRAE 216) and defining the use of ceiling fans as a potential thermal comfort control strategy (proposed addendum to ASHRAE 55), California has new resources to cite in developing compressorless cooling comfort models. These new standards re-open the opportunity to develop compressorless comfort compliance options in future revisions to the Energy Efficiency Standards.

Building Code Considerations

In addition to the more fan-specific issues addressed in the sections above, there are also more general building code requirements that apply to ceiling fan installations.

The following sections summarize these issues and related requirements, as well as several opportunities for clarifications in the code to better address ceiling fan installations. The requirements and considerations outlined below are derived from model codes that have been adopted as part of the California Building Code. Other states may have different code requirements, and municipalities within California may have additional code requirements beyond the statewide building code. Always consult local codes to confirm requirements as they apply to a specific project.

Fire Code Requirements

The primary concern with ceiling fans in relation to the fire code is the interaction with fire sprinklers. For the most part, standard ceiling fans in typical residential and commercial applications have few limitations in relation to fire sprinklers, while larger HVLS fans require a higher degree of integration with fire suppression systems.

The California Fire Code (Title 24, Part 9) cites the requirements of National Fire Protection Association's NFPA 13, "Standards for the Installation of Sprinkler Systems,"[20] and NFPA 13R,

[20] https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=13

"Standard for the Installation of Sprinkler Systems in Low-Rise Residential Occupancies,"[21] with some minor exceptions, to govern the use of fire sprinklers in buildings.

Per NFPA 13 in most nonresidential applications, ceiling fans less than 60 inches (1.5m) in diameter that are at least 50% open in plan view, fire sprinklers can be located without regard to the fan blades.[22] Since the above requirement specifically calls out "fan blades," there may be cases where other parts of the ceiling fan, such as motor housing or mounting pendants, are considered obstructions to fire sprinklers. In most cases, for any motor housing, mounting pendant, or other part of the fan that is 18" or less below the level of the sprinkler deflector, the so-called "rule of three" applies, where sprinklers must be placed away from the obstruction a minimum distance of three times the maximum dimension of the obstruction, up to 24".[23] In other words, if the motor housing of a ceiling fan is 7" in diameter, any fire sprinklers should be located at least 21" from the motor housing. In the 2019 version of NFPA 13, for extended coverage sprinklers and residential sprinklers, this requirement is increased to a distance of four times the maximum dimension of the obstruction, up to a maximum of 36".[24]

For low-rise residential applications, NFPA 13R requirements are more explicit about sprinkler locations in relation to obstructions such as ceiling fans. In these cases, the standards require pendant sprinklers to be a minimum of 3 feet from any ceiling fan[25], and sidewall sprinklers to be at least 5 feet from any ceiling fan.[26] Though the standards do not explicitly state where those distances are measured from, this is typically interpreted at being the distance from the center point of the ceiling fan.

For larger format high velocity low speed (HVLS) fans, NFPA 13 lays out more detailed requirements as follows:[27]

- HVLS fans must be no more than 24 feet in diameter
- Each fan must be approximately centered between four adjacent sprinklers
- The vertical distance from fan blade to sprinkler deflector must be at least 3 feet
- All fans must be interlocked to shut down immediately upon receiving a waterflow signal from the alarm system in accordance with the requirements of NFPA 72 (the waterflow and alarm system interlock wording is slightly different in the 2019 version for applications in storage areas and buildings, section 20.6.7.1, but the requirement is roughly the same)

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[21] https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=13R

[22] NFPA 13 2016 sections 8.6.5.2.1.10, 8.7.5.2.1.6, 8.8.5.2.1.9, 8.9.5.2.1.6; NFPA 13 2019 sections 10.2.7.2.1.10, 11.2.5.2.1.9, 12.1.10.2.1.9

[23] NFPA 13 2016 section 8.6.5.2.1.3; NFPA 13 2019 section 10.2.7.2.1.3

[24] NFPA 13 2019 sections 11.2.5.2.1.3 and 12.1.10.2.1.3

[25] NFPA 13R 2016 and 2019 section 6.4.6.3.4.1

[26] NFPA 13R 2016 and 2019 section 6.4.6.3.5.1

[27] NFPA 13 2016 sections 11.1.7 and 12.1.4.1; NFPA 13 2019 sections 19.2.7 and 20.6.7.1

While this section covers requirements as they apply in the California Fire Code, adapted from NFPA Standards, specific requirements may vary by local jurisdiction.

Areas for Clarification in Fire Code Requirements

As ceiling fan installations in non-residential applications increase, it will become increasingly important that they are adequately addressed in building standards such as the NFPA codes. With that in mind, we have identified several areas of the Standards where there are opportunities for further clarification on how they apply to the installation of ceiling fans:

- The requirements for standard ceiling fans only apply to fans less than 5 feet in diameter, and the NFPA defines an HVLS fan as, "A ceiling fan that is approximately 6 ft (1.8 m) to 24 ft (7.3 m) in diameter with a rotation speed of approximately 30 to 70 revolutions per minute."[28] This combination of factors create a gap in the Standards for the standard ceiling fans on the market that are more than 5 feet in diameter. Future editions of the Standards should address applications of standard ceiling fans of 5 feet or more in diameter, and clarify the distinction between standard ceiling fans and HVLS fans, potentially by citing other accepted standards for fan definitions such as UL 507 Standard for Electric Fans.
- While NFPA 13 specifically notes that sprinklers may be placed without regard to the location of fan blades in most cases, the Standards to do not explicitly address whether other parts of a fan should be considered obstructions, and how those obstructions should be considered in relation to sprinklers. Future editions of the Standards should clarify which parts of a ceiling fan should be considered obstructions, and how those obstructions should be addressed.
- NFPA 13R specifies specific minimum distances sprinklers must be from ceiling fans and light fixtures, but the Standards do not specify where those distances are measured from. Future editions of the Standards should clarify how to determine these minimum distances.

Seismic Considerations

In many applications, standard ceiling fans attached directly to a structural ceiling do not require any further seismic bracing or restraint. However, applications with larger fans or HVLS fans, suspended ceilings, long suspension rods, or other special conditions may require additional seismic support.

Seismic considerations and requirements are especially relevant for installations of ceiling fans in California. Per the California Building Code, nonstructural components that are permanently attached the structure, such as ceiling fans, must be installed to resist the effects of earthquake motions in accordance with the ASCE 7 standard (from the American Society of Civil Engineers).[29] The exact requirements in ASCE 7 will vary depending on the size, weight, and configuration of the fan, the strength of the expected seismic forces for the area, and the building type where it is installed.

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[28] NFPA 13 2019 section 3.3.93

[29] 2016 California Building Code, Part 2 Volume 2, Section 1613.1

In addition to the specific requirements in ASCE 7, there are some general best practices for all applications and scenarios. The Federal Emergency Management Agency's (FEMA) document, "Reducing the Risks of Nonstructural Earthquake Damage – A Practical Guide" recommends that all suspended fixtures, such as lighting and ceiling fans, have positive attachment to the structure to avoid falling hazards.[30] Ceiling fans should never be supported on a suspended ceiling grid or ceiling tile. In addition, the California Department of the State Architect (DSA) has issued code interpretations pertaining to suspended fixtures such as ceiling fans, stating that fixtures with rigid suspension pendants must be attached to the structure using a device allowing movement in any direction (i.e., a ball and socket joint),[31] and requiring bracing where any pendant fixture passes through a suspended ceiling.[32] Some manufacturers, such as Big Ass Fans, also suggest lateral restraint using guy wires that are at least ¼ inch (6.35 mm) in diameter for HVLS fans.

As always, consult local building codes to determine specific requirements.

Areas for Clarification in Seismic Standards

In some cases, including the FEMA guide and the DSA interpretations, ceiling fans are grouped with suspended light fixtures for the purposes of seismic bracing requirements. This has the potential to cause confusion as suspended light fixture and ceiling fans typically have very different characteristics and mounting configurations. Whenever possible, seismic bracing standards should address ceiling fans independently from suspended light fixtures.

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[30] Section 6.4.9.3 https://www.fema.gov/media-library-data/1398197749343-db3ae43ef771e639c16636a48209926e/FEMA_E-74_Reducing_the_Risks_of_Nonstructural_Earthquake_Damage.pdf

[31] DSA IR 16-9, section 2 https://www.dgs.ca.gov/DSA/Publications

[32] DSA IR 25-2, section 3.1 https://www.dgs.ca.gov/DSA/Publications

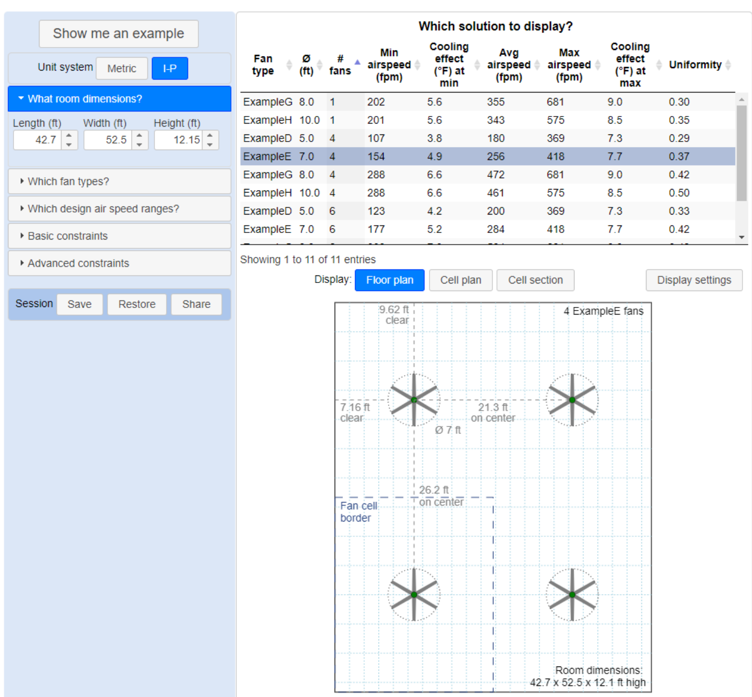
APPENDIX H:
CBE Ceiling Fan Design Tool

To help determine optimal ceiling fan arrangements, CBE developed an online Ceiling Fan Design Tool, available at cbe.berkeley.edu/fan-tool.

The tool allows users to input room dimensions, design air speed ranges, and other parameters to determine optimal ceiling fan placement. The tool includes characteristics for a range of default ceiling fan options, or users can input specific details of other ceiling fan models to determine appropriate layouts. In addition to providing recommended fan layouts, the tool provides estimate for airspeeds (minimum, average, and maximum), cooling effect (minimum and maximum), and airspeed uniformity for each proposed layout, as shown in the figures below. The tool also provides visualizations for the overall ceiling fan plan for the space, as well as ceiling fan "cell" plan and section showing details on airspeeds within each fan cell, and ideal mounting heights, as the figures below illustrate.

The CBE Ceiling Fan Design Tool takes into account many of the design factors discussed in the CBE Ceiling Fan Design Guide. For more details on how the tool functions, please consult the online User Guide, https://github.com/CenterForTheBuiltEnvironment/fan-tool/wiki/User-Guide.

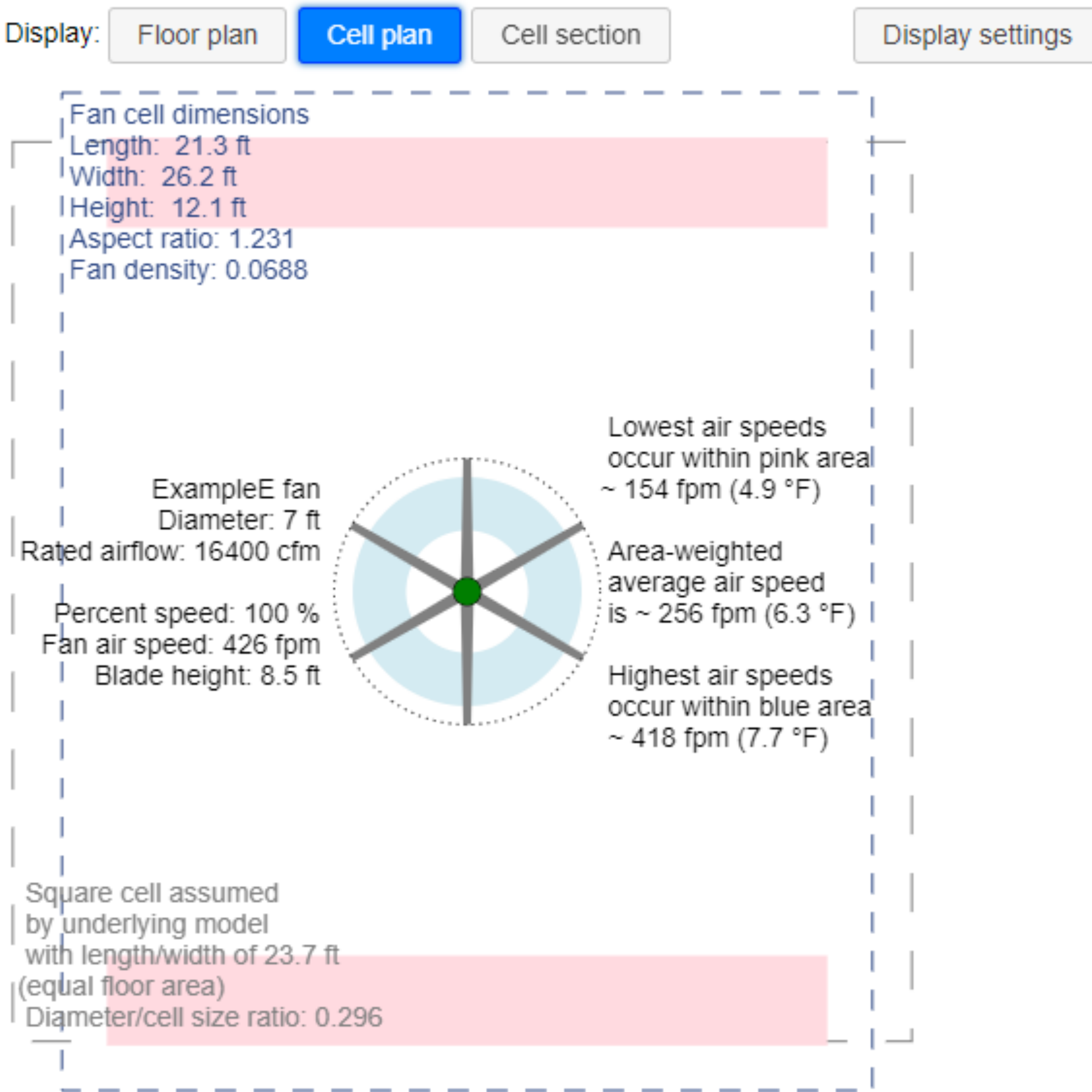
Figure 110: Example CBE Ceiling Fan Design Tool outputs



An example screenshot of the online CBE Ceiling Fan Design Tool showing room dimension inputs and the tool's optimal fan configuration layout result for four 7-foot diameter ceiling fans.

Credit: CBE Ceiling Fan Design Tool

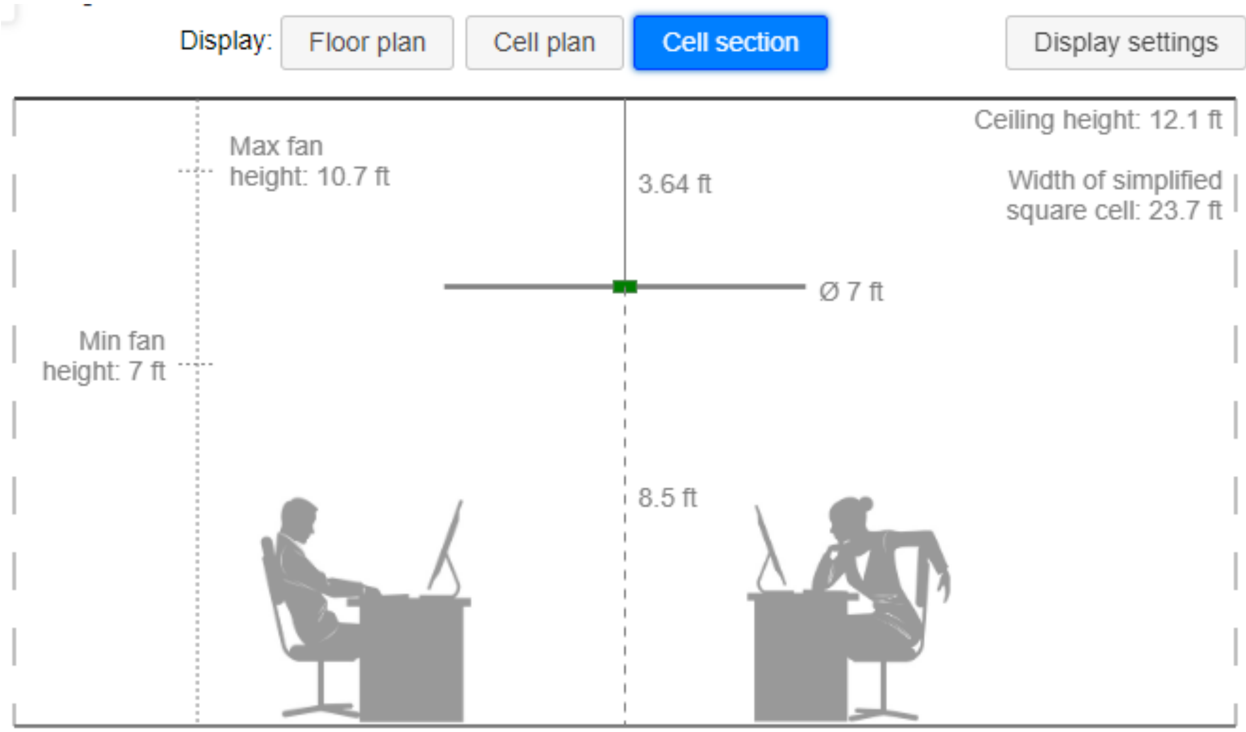
Figure 111: Example cell plan from CBE Ceiling Fan Design Tool



An example screenshot of the online CBE Ceiling Fan Design Tool showing a typical fan cell outputs, including cell dimensions, fan performance characteristics, and expected airspeed results for an example 7-foot diameter ceiling fan.

Credit: CBE Ceiling Fan Design Tool

Figure 112: Example cell section from CBE Ceiling Fan Design Tool



An example screenshot of the online CBE Ceiling Fan Design Tool an example fan cell section outputs, including ceiling height, fan mounting height, and distance from the ceiling for an example 7-foot diameter ceiling fan.

Credit: CBE Ceiling Fan Design Tool

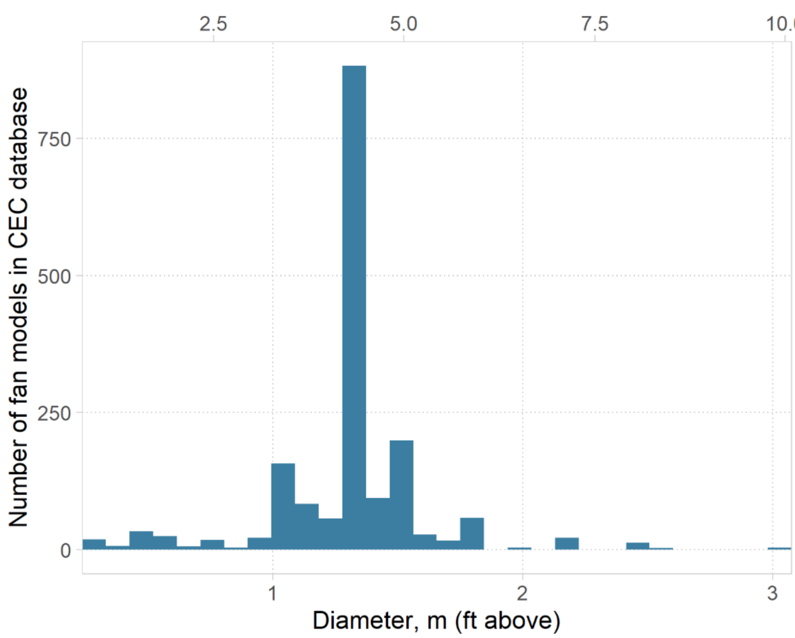
APPENDIX I:
Technology Readiness Report

The technology readiness report discusses both ceiling fans in general, and automated or "smart" ceiling fans more specifically.

Current ceiling fan product availability

Ceiling fans are a commonly available appliance type, with a wide variety of products on the market. The California Energy Commission (CEC) maintains the Modernized Appliance Efficiency Database System (MAEDbS), which contains a large dataset of information on a variety of appliances, including ceiling fans. The MAEDbS currently includes data on over 13,000 ceiling fan models, though some of those models may no longer be in the market. Similarly, recent searches on big box home improvement store websites returned results for over 4,000 ceiling fan models at one store, and 1,700 ceiling fan models at another.

Figure 1: Distribution of fan diameters in a random sample of ceiling fans in the CEC MAEDbS



○

Distribution of a random sample of ceiling fans in the CEC MAEDbS shows the vast majority of fans in the 3- to 5-foot diameter range.

Data source: CEC MAEDbS

Ceiling fans are available in a variety of sizes, configurations, and styles. Available diameters range from very small fans, approximately 18 inches in diameter, to very large fans, up to 24 feet in diameter. However, as the data in Figure 31, above, shows, the bulk of ceiling fans are concentrated in the three-to-five foot diameter range, aimed primarily at a residential market.

Fans are also available with different quantities of blades, typically ranging from two blades up to eight blades (higher bladed quantities are typically found on larger diameter fans).

The United States Department of Energy (DOE) defines several types of ceiling fans[1], but the bulk of ceiling fan products fall into two main categories:

- **Standard ceiling fan –** any ceiling fan with a diameter greater than 18 inches but no more than 7 feet, and with the lowest point of the fan blades more than 10 inches below the ceiling, and that meets the speed and airflow criteria outlined by the DOE.
    - For spaces with lower ceilings, the DOE also defines **Hugger ceiling fans**, which are otherwise equivalent to standard ceiling fans, except that the lowest point on the fan blades is less than or equal to 10 inches from the ceiling.
- **Large-diameter ceiling fan** – any ceiling fan that is greater than seven feet in diameter. These are often also known as High Volume Low Speed (HVLS) fans.

Though standard ceiling fans are often thought of in their residential applications, they are equally effective for comfort cooling in practically any nonresidential application (including offices, classrooms, gyms, hospitality, etc.) where they can be positioned near the occupants. Large-diameter ceiling fans require higher ceilings (typically at least 11 ft) and larger spaces free from obstructions to accommodate their increased diameter. As a result, large-diameter ceiling fans are most often found in nonresidential commercial and industrial applications.

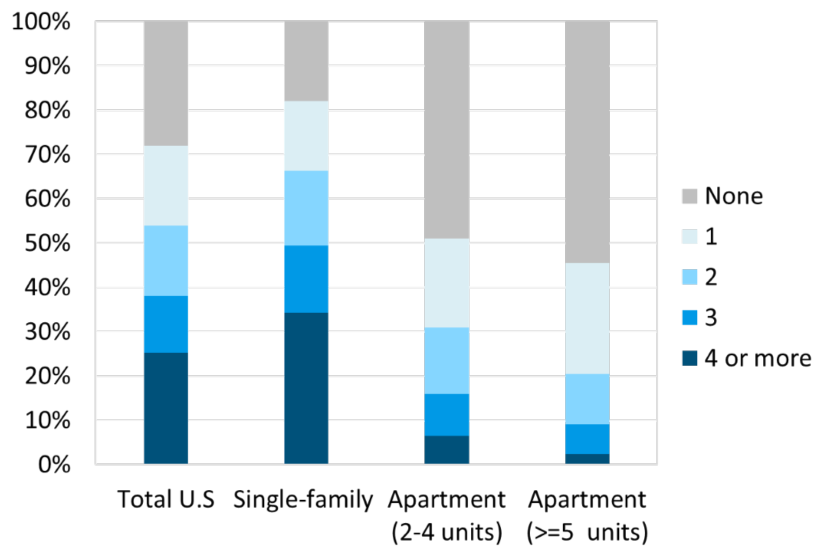
While there are thousands of models of ceiling fans available on the market, only a subset of those thousands are capable of any sort of automated, programmed, or "smart" control. A survey of several large retail websites found roughly 5-18% of available ceiling fans listed as "smart", "smart home compatible", or "WiFi connected" depending on the retailer. However, not all "smart" fans are equivalent, and these categories likely included a wide variation in capabilities, from simply being able to control the fan through a smartphone app on the more basic end, to more complex capabilities to automatically control and adjust fan speeds based on built in occupancy and temperature sensors, and learning occupant comfort preferences from previous use patterns. In interviews with architects, engineers, and facility managers for 20 advanced buildings with ceiling fans, the research team found that only about 25% of those buildings used any kind of automation for the ceiling fans.

Large-diameter fans tend to be more likely to have more advanced control capabilities than standard ceiling fans, in part because of their use in nonresidential applications. Especially in unconditioned applications such as warehouse and industrial buildings, large-diameter fans may be programmed to turn on at a certain temperature threshold. Alternatively, large diameter fans can often be integrated with building automation systems (BAS) to coordinate with HVAC controls and temperature sensors. In addition, fire codes often require large-diameter fans to be interconnected with a building's fire sprinkler system, to automatically shut off fans in the event of a fire to prevent interference with sprinklers.

Estimated current market penetration

Ceiling fans are widespread in residential applications in the United States. As Figure 32 below shows, over 70% of all U.S. households have at least one ceiling fan, including over 80% of single-family homes, and over 40% of multifamily units. However, while ceiling fans are widespread in residential applications, they may present limited effectiveness in deterring air conditioning use if fans are only installed in one or two spaces within a home.

Figure 2: Ceiling fans per household by housing unit type



Over 70% of U.S. households have at least one ceiling fan, including over 80% of single-family homes, and over 40% of apartment units

Data source: U.S. Energy Information Administration 2015 Residential Energy Consumption Survey

In contrast to the residential market penetration, the research team expects that ceiling fan market penetration in nonresidential applications is very low. To date, no publicly available data sources have tracked ceiling fan use in nonresidential buildings, but known applications tend to be limited to a small subset of building types. Applications of large-diameter ceiling fan have been increasing in some building types such as warehouse and industrial applications (especially when unconditioned), but retrofit scenarios for large-diameter fans may be limited by potential conflicts with other building systems such as lighting and structure.

Though ceiling fans, when implemented appropriately, present a significant energy savings opportunity for nearly any building type through increased air conditioning setpoints, actual applications in most nonresidential applications remains near zero.

Motivations and barriers to adopting ceiling fans

As part of this study, the research team interviewed 13 architects, engineers, and facility managers from California and around the U.S. on their experiences designing or managing 20 operational nonresidential buildings with ceiling fans implemented as an energy saving measure.

The interviewees identified three key motivations for using ceiling fans in these projects:

- **Effective comfort strategy for spaces without compressor-based cooling** – interviewees reported they were most likely to use ceiling fans in buildings that lacked traditional compressor-based cooling systems, such as to supplement cooling in buildings with radiant systems.

- **Increase occupant control** – interviewees reported that ceiling fans were an effective strategy to provide occupants greater control over thermal comfort conditions in their spaces.
- **Preferable aesthetics** – interviewees noted that ceiling fans effectiveness for air mixing and distribution minimized the need for traditional ducts and diffusers, and that ceiling fans were considered more aesthetically pleasing than ducts and diffusers.

Despite the benefits noted above, the interviewees in this study identified a wide range of barriers to implementing ceiling fans in nonresidential buildings:

- **Whose scope is it?** – interviewees reported that one of main challenges with implementing ceiling fans in nonresidential buildings is the lack of clarity on whether ceiling fan design responsibility belongs to the architect, electrical engineer or mechanical engineer.
- **Perceived concerns** – interviewees note that occupants and owners may have concerns about long-term use of ceiling fans, including maintenance, durability, loudness, and papers being blown away. However, in practice, many of these did not end up being problematic. (The research team found that at many sites operational air speeds from the ceiling fans were under 0.2 m/second, or barely noticeable as elevated air speed. While these low air speeds are unlikely to result in adverse effects, they also provide very limited, if any, cooling effect.)
- **Lack of information** – though the interviewees understood the benefits of ceiling fans, they often reported difficulty conveying those benefits to owners and occupants, largely due to a lack of standardized data and terminology.
- **Aesthetic limitations** – despite the fact that ceiling fans are often considered aesthetically preferable to ducts and diffusers, interviewees reported that architects and engineers may only consider ceiling fans that work with the aesthetics of the building overall, limiting potential options.
- **Cost** – interviewees noted that costs can be prohibitive. Installation costs often exceed the price of actual fan, and the most effective engineered fans can be an order of magnitude more expensive than more traditional ceiling fans.
- **Trial-and-error** – interviewees reported too much uncertainty in designing with ceiling fans, describing it as a trial-and-error or guesswork process. They also reported that more reliable methods, such as CFD modeling, are too expensive.
- **Safety hazards** – some interviewees noted that ceiling fans in spaces with lower ceilings may pose safety hazards, or the perception of safety hazards.
- **Coordination challenges** – implementation of ceiling fans requires careful coordination with other objects on the ceiling, an already crowded surface for interviewees, including systems such as lighting, ventilation, and fire sprinklers
- **Conflicts with electrical service** – some interviewees noted that providing electrical service for ceiling fans through certain ceiling types can cause further complications, especially in the case of radiant slab ceilings.

- **Perceptions barriers may limit effectiveness** – some interviewees reported that occupants' association with using ceiling fans for a cooling effect may create confusion if ceiling fans are also used for destratification during heating periods, limiting the usefulness of ceiling fans.

Though the experts that the research team interviewed identified a wide range of potential barriers to ceiling fan implementation in nonresidential applications to date, the results of this research project can also serve to directly address some of these concerns. For example, the results of the field demonstrations provide concrete evidence of the energy benefits of ceiling fans when paired with increased cooling setpoints. In addition, new resources resulting from this project, including the Ceiling Fan Design Tool, Ceiling Fan Design Guide, and forthcoming ASHRAE Standard 216, provide resources for designers that include reliable outputs to gauge the effectiveness of various ceiling fan design choices.

Increasing market share through utility programs and codes

Two potential mechanisms for increasing market penetration for ceiling fans is through utility efficiency programs and building energy standards. The sections below outline potential opportunities and strategies for both.

Utility program opportunities for ceiling fans

The research team utilized data from the demonstration portion of the research study to test a Normalized Metered Energy Consumption (NMEC) approach to evaluating energy savings from the combination of ceiling fans and increased air conditioning thermostat setpoints (see memo immediately following this report). In addition, the team is developing a straw-man program design using this NMEC approach geared toward residential applications (see second memo following this report.

Building energy standards opportunities for ceiling fans

To date, ceiling fans have not been included in the California Building Energy Efficiency Standards (Title 24, Part 6) as a compliance option for thermal comfort control. Although ASHRAE Standard 90.1 has some options for increasing assumed cooling setpoints in conjunction with strategies such as ceiling fans, this strategy has not yet been included in the California Energy Standards. There have been previous proposals for Codes and Standards Enhancement (CASE) studies to develop options for residential compressorless comfort in some coastal climate zones in California, but these proposals have not yet been pursued for adoption into the Standards.

The energy savings results of the field studies as part of this research project, as well as new standards for assessing thermal comfort and ceiling fan performance, such as updates ASHRAE Standard 55 – Thermal Environmental Conditions for Human Occupancy, and the in-development ASHRAE Standard 216 – Methods of Test for Determining Application Data of Overhead Circulator Fans, have generated renewed interest in opportunities to integrate ceiling fans in the California Standards as a thermal comfort control option. In addition, states like Florida and Hawaii have already adopted "Tropical Zone" compliance options that require ceiling fans in every bedroom and the largest non-bedroom space, in combination with limiting air conditioning and heating and requiring operable fenestration, among other requirements.

Although the residential market already has relatively high adoption of ceiling fans, including ceiling fans as a compliance option in the Building Energy Standards still has the potential to increase market penetration. Fans need to be installed in most or all regularly occupied spaces to provide an adequate alternative to mechanical cooling, as exemplified by the Tropical Zone compliance option described above. While over 80% of single-family homes in the U.S. have at least one ceiling fan, one ceiling fan can only provide thermal comfort benefits in one space. Roughly 50% of single-family homes have at least three ceiling fans, and only about 35% of homes have four or more, suggesting a potential to increase market penetration by providing ceiling fans in more spaces throughout a home.

Furthermore, a compliance option for ceiling fans in the nonresidential Building Energy Standards has the potential to significantly increase market share in nonresidential building types where ceiling fans are currently almost nonexistent. However, even with building code mechanisms to encourage ceiling fan adoption, market penetration would be expected to increase relatively slowly at first, as the design and building industries navigate the market barriers noted above. However, utility efficiency incentive programs, like the example described in the previous section, could help to bridge those barriers and prepare the industry for more widespread adoption.

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March 31, 2020

MEMORANDUM

To: Adel Suleiman (California Energy Commission)

Cc: Therese Peffer (Center for the Built Environment)

From: Lake Casco, Brandon Yamasaki, Dhananjay Mangalekar, David Douglass-Jaimes (TRC)

Re: NMEC analysis of data from the Integrated Smart Ceiling Fans and Communicating Thermostats EPIC Research

NMEC ANALYSIS OF CEILING FAN ENERGY SAVINGS

To further the findings in the *Integrating Smart Ceiling Fans and Communicating Thermostats to Provide Energy-Efficient Comfort* TRC conducted an NMEC analysis of one of the residential units from the study's field demonstration. TRC used an tool called RMV2.0, an NMEC analysis tool developed by Lawrence Berkley National Lab (LBNL) that uses piecewise linear time-of-week and temperature (TOWT) or machine learning gradient boosting machine (GBM) modeling strategies. Tools like this on apply learning algorithms based on a combination of indoor air temperature and relative humidity measurements as well as manual occupant settings.

Data

TRC reviewed data from the residential site "Unit4" (for more information see details in Field Demonstration Report and Final Report for this research project). Evaporator, compressor, and ceiling fan usage data were given in 5-minute intervals for the pre and post install cases. Outdoor air temperature was supplied in hourly intervals.

Data was sorted into hourly bins to show usage and temperature relationships. Evaporator, compressor, and ceiling fan data were summed over the 12 5-minute periods for each hour. However, there were several periods of the demonstration project where data was unavailable. The analysis tool RMV2.0 analyzes the input data and the percentage of missing data is charted in the same manner as the table below. The program sees both 0 and NA values as "missing" data.

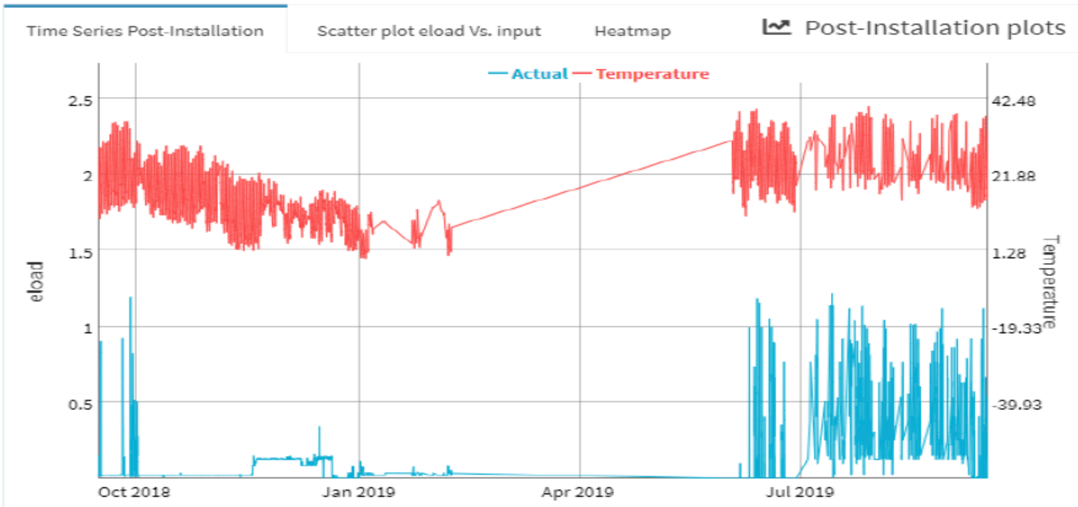

Figure 1. Usage and temperature time-series plot showing the March-May 2019 missing data

RMV2.0

TRC determined the relationship between total energy (the sum of evaporator, compressor, and ceiling fan energy) and outdoor air temperature using RMV2.0. RMV2.0 is an NMEC analysis tool developed by Lawrence Berkley National Lab (LBNL) that uses piecewise linear time-of-week and temperature (TOWT) or machine learning gradient boosting machine (GBM) modeling strategies. RMV2.0 is used to build a predicted (training) model for the baseline and compare it to actual metered post case data. Savings are generated by the normalization of the predicted model to a common parameter. In this case, that parameter is post-case weather data. Goodness-of-fit for the baseline model can be seen in the following table.

R-Squared	CVRMSE
.99	.12

Figure 2. R-Squared and CVRMSE values

R-Squared is how closely the data points fit the regression line. An R-squared of 1 means each point is on the regression line. The closer the R-Squared value is to 1 also implies a stronger correlation between the two variables. A value of .99 implies a very high correlation between predicted and actual usage.

CVRMSE is the Coefficient of Variation Root-Mean-Squared-Error. It is the normalized squared difference between the predicted and actual usage. Per ASHRAE Guideline 14, a CVRMSE of and below .25 indicates a good model fit with acceptable predictive power. Thus, a CVRMSE value of .12 is reliably predictive.

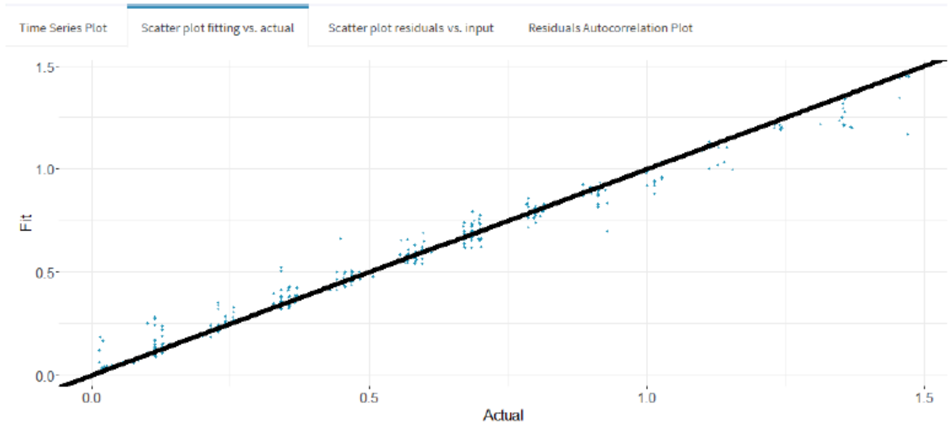

Figure 3. Predicted baseline vs actual baseline usage with line of best fit

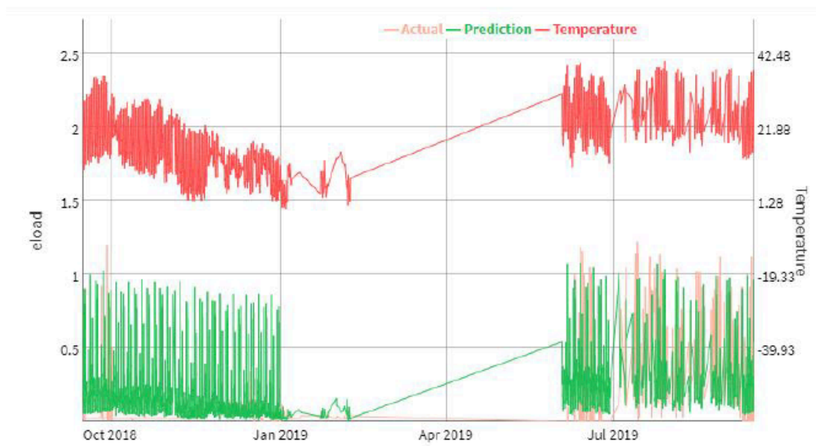

Figure 4. Postcase time-series plot of predicted and actual usage with outside air temperature

RMV2.0 generated savings with the given baseline and post case data. Savings are calculated by taking the base case model, normalized to the post case outdoor air temperature profile, and subtracting by the actual post energy usage.

Fractional savings (FS) is the result of savings per predicted post-case energy usage – it is another way of interpreting savings; it is expressed in percent.

Savings (kWh)	Fractional Savings (%)
368	47.2%

Figure 5. Savings calculated from RMV2.0

The exported savings represent only the time periods where data was available. However, the results of the RMV2.0 analysis (47% savings) is roughly consistent with research team analysis of the same data that found a weather-normalized energy savings of 39% for the cooling season period of April-October (note that the RMV2.0 analysis included a period beyond just the cooling season).

While these results are limited to a single residential unit of the larger demonstration project, this test indicates that these tools may be a reliable way to measure NMEC savings, and that these types of approaches can help support new types of program offerings such as the demonstration project integrating smart ceiling fans and learning thermostats to provide energy savings.

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March 30, 2020

MEMORANDUM

To: Adel Suleiman (California Energy Commission)

Cc: Therese Peffer (Center for the Built Environment)

From: Siobhan McCabe, John Brown, David Douglass-Jaimes (TRC)

Re: Utility Program Opportunities to expand on the findings of the Integrated Smart Ceiling Fans and Communicating Thermostats EPIC Research

PROGRAM OPPORTUNITIES FOR CEILING FANS

To further the findings in the *Integrating Smart Ceiling Fans and Communicating Thermostats to Provide Energy-Efficient Comfort* study and expand the potential for energy savings, TRC recommends developing a targeted program offering, in combination with in-unit HVAC system retrofits in multifamily units to maximize savings and opportunity. Although multifamily properties and projects often require additional time for planning and approval, due to multiple stakeholders and various sizes, multifamily dwelling units offer an economy of scale in testing potential and savings opportunity. Demonstrating success in multifamily applications, a scenario featuring a complex customer-type and access and site coordination challenges, would indicate widespread viability in other sectors and buildings.

A potential starting point for a program integrating smart ceiling fans and communicating thermostats is in combination with a heat pump pilot program TRC tested as part of PG&E's Multifamily Upgrade Program. This combination compounds the benefits of energy savings and resident comfort from both measures. Last year, TRC completed a small pilot incentivizing in-unit gas wall furnace replacements for heat pumps through the Multifamily Upgrade Program, a whole building retrofit incentive program that TRC implements. Through this program, TRC estimates that 30% of multifamily properties have in-unit gas wall furnaces.

The pilot targeted wall furnaces because they are inherently inefficient, with maximum efficiency around 65% Annualized Fuel Utilization Efficiency (AFUE) in pre-1978 models. Since then, efficiency has only increased to about 70% AFUE in modern wall furnaces. Moreover, they lose a lot heat energy through the flues and do not effectively distribute heat throughout a dwelling unit. TRC recognized that there is no in-kind retrofit that would significantly improve efficiency and conditions, and the better option would be to replace with heat pumps, resulting in the following:

- Increased indoor air quality due to the removal of an in-unit combustion device
- Better distribution of heat through a living unit
- Reduced danger of natural gas leaks or back drafting of carbon monoxide into living units, which can place residents at risk without them even being aware of it
- Reduced annual greenhouse gas emissions

- Decreased maintenance and expense of having to perform combustion appliances safety (CAS) testing

However, replacing the furnaces with heat pumps introduces a further complication of fuel switching and added electrical load. That said, there are still potential savings with proper system use and resident education. Then, when coupled with the measures and results of the EPIC Integrated Smart Ceiling Fans and Communicating Thermostats Project, energy savings and resident satisfaction could be even further enhanced. Indeed, the savings potential of the ceiling fans could substantially offset the added electrical load of a heat pump retrofit.

To date, exploration and understanding of fuel switching savings is limited. In addition, these retrofits are cost-prohibitive, especially in multifamily to scale for all the units, without utility program incentives.

A significant challenge is the increased cost and retrofit complexity of changing from a gas to an electrical system. Mini-split heat pumps can operate at 15 amps or more, requiring a professional electrician to upgrade a property's electrical infrastructure to allow the safe use of a heat-pump system. Removal of a wall furnace also requires the removal or safe capping of the natural gas line used for the wall furnace.

Survey results from the pilot program indicate the extra time and added costs were worth it – residents reported extreme satisfaction with their new heat pumps. Residents in the pilot's properties have observed no to nominal increases in energy bills; those that have had increased total utility charges said the increase is worth it. All the residents in the unit are vastly more comfortable, air distribution is superior, and ambient noise has reduced.

Similarly, the EPIC fan study observed that the fans increased energy savings at most sites, and that regardless of the energy savings, residents felt the fans made their living spaces more comfortable. The study also found positive examples demonstrating that the fans improve resident comfort when combined with air conditioning systems, even when the mean indoor temperature is increased.

The project facilitators believe that the wide variability of energy savings seen across sites is due to the variety of building, living space, and HVAC system types, as well as the many different types of people the inhabit the living units. A targeted program like the one proposed could help reduce the variability and refine findings within a building sector and HVAC system.

Despite some challenges, the EPIC Fans Project illustrated that ceiling fans are a successful intervention to increase residential energy savings. Those savings could increase from addressing both the heating and cooling. Adjusting the setpoints and improving air distribution in general apply to both seasons, and savings realized throughout the year financially and environmentally justify the project. Also, the challenges are not mutually exclusive to heating or cooling systems. Combining these interventions in one program would help mitigate inefficiencies and challenges of entering units multiple times for separate interventions, training maintenance staff and educating residents from improving the in-unit HVAC systems holistically.

The proposed program allows the state, administrators and implementors to deepen energy savings potential and validate savings behind the meter, and further explore topics such as bill impacts, fuel switching, cost effectiveness and workforce opportunities. By continuing the study's and pilot's efforts, more data can be collected to refine findings and bolster meter-based savings efforts, including normalized metered energy consumption, and even conduct bill analyses. Findings and conclusions would inform better programs, offerings, and incentives or rebates tailored to the property, project, and users. Current programs are a key mechanism in market adoption, but can be hampered by limited knowledge, regulatory policies, and energy modeling challenges. Improving overall offerings and experiences could improve uptake while actualizing real, validated savings.

Particularly, programs need to address fuel switching in order to advance decarbonization goals, but programs are still beholden to cost effectiveness requirements (even with the three-prong test revision). Today, program portfolios are designed around a complex cost effectiveness test that ultimately constrains what administrators and programs can offer. In a narrow sense, after doing fundamentally the same variable analysis, all the most cost effective programs would be the same. However, the most cost effective programs may not yield the most savings, the greatest grid impact, or even the best opportunity for a property or customer. This is not to say cost effectiveness should be discounted. The problem is the cost effectiveness defined for the industry is a yardstick that can prevent administrators from incorporating new opportunities like the now-approved fuel switching into existing program portfolios.

Another area for opportunity is workforce development. All these interventions discussed involve newer technology that requires some training, which is crucial to both quality installation and persistent savings. To provide the data necessary for cost effectiveness tests, studies addressing workforce impacts on projects and energy savings would drive programs to adopt workforce requirements and even measures defined as operations and maintenance trainings or the like. Again, the value of trainings and developing workforce is acknowledged, but not well documented. To equip administrators with the data they need to enhance their programs, they need to have such data available.

Hence, pilots and program extensions like the combination of heat pump retrofit and smart ceiling fans proposed here would be critical within the current program portfolio landscape. Program administrators need latitude to explore a new feature like fuel switching without cost effectiveness looming. More work is needed to better understand the challenges and costs inherent to fuel switching. Programs will need to test and trial these types of interventions now to collect and analyze more data to support broader implementation in the future.