Energy Research and Development Division
FINAL PROJECT REPORT

CHANGING THE RULES:

Innovative Low-Energy Occupant-Responsive HVAC Controls and Systems

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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ABSTRACT

The overall goal of this Project was to create a new occupant-based paradigm for Heating, Ventilation, and Air Conditioning (HVAC) control that will reduce HVAC energy use in buildings while improving occupant comfort. The Project explored integrating low-energy personal comfort systems (PCS) into HVAC operations, advanced variable-air volume (VAV) control algorithms, and innovative open-source software for monitoring and control. The Project investigated deployment of commercially available occupant-vote based ambient temperature control technology alongside the other innovations. To accomplish this the research team developed, tested and demonstrated, through the performance of three detailed case studies, new products and HVAC control & operation practices, and performed work to identify market transformation potential for these innovative technologies in standards, codes, and common practice.

Key research activities and findings are summarized below.

- Fifty low-energy heated and cooled chairs (PCS) with wireless internet connectivity were designed and fabricated for use in the demonstration field studies.
- A method of test using a thermal manikin was developed to determine personal heater efficiency (PHE). Experiments on 12 personal heaters found that conductive heaters (heated chairs or foot-warmers) are far more efficient than radiant or convective heaters.
- Three demonstration field studies were conducted to study the project innovations. Two were in office buildings with conventional VAV reheat with overhead air distribution: (1) San Mateo County (SMC) office building in Redwood City, and (2) Sutardja Dai Hall (SDH) on the UC Berkeley campus. A third was in an office building with advanced low-energy space conditioning: (3) Integral Group office building in San Jose, which uses radiant slab heating and cooling.
- The SMC field study involved PCS chairs alongside occupant vote-based HVAC control (Comfy[tm]). Key results showed that the PCS chair users have high thermal satisfaction across the investigated setpoint range of 20.5-24.5°C (69-76°F). Occupant and management response to voting-based temperature control (Comfy[tm]) was positive, although we were unable to directly confirm energy use reduction resulting from expanded temperature deadbands.
- The SDH field study focused on implementation and testing of advanced VAV control strategies in combination with occupant vote-based HVAC control. Detailed field trials were completed for two promising advanced VAV control strategies: (1) time-averaged ventilation (TAV) and (2) cost-based supply air temperature (SAT) reset. TAV testing showed a reduction in fan (15%), reheat (41%), and chilled water (23%) energy. A cost-based SAT reset testing showed an additional reduction in total HVAC energy costs of 29%.
- The most successful energy-saving and immediately applicable innovative technology demonstrated in the Project was time-averaged ventilation (TAV) for VAV reheat air distribution systems. As a result, TAV has been incorporated in ASHRAE Guideline 36,

which when published later in 2017, will reach a wide audience and encourage widespread adoption.

- Innovative open-source software can enable the development and integration of the occupant-based HVAC technologies explored by this Project. Applications included the connectivity of PCS chairs, underlying technology for commercially available occupant voting-based temperature control, and deployment of advanced VAV control algorithms.
- The research team evaluated and identified code change potential for Personal Comfort Systems and VAV controls at both the state energy code level (Title 24 Building Energy Efficiency Standards, Title 20 Appliance Efficiency Standards), as well as national energy and comfort standards (ASHRAE Standards 90.1, 189.1 and 55).

Keywords: Personal comfort systems, thermal comfort, Internet of Things, variable air volume (VAV) systems, building system controls, sequences of operation, occupant-responsive controls, field study, occupant surveys, whole building energy simulation.

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EXECUTIVE SUMMARY

Introduction

The radical improvements in building energy efficiency now being called for by the State of California will be difficult to meet if the focus is only on improving buildings and energy efficiency; we need to change the relationship between energy use and comfort. Heating, Ventilation, and Air-Conditioning (HVAC) industry standards call for modern buildings to provide satisfactory comfort for 80 percent of their occupants. Some buildings do better than this, and many do worse. Designers, engineers, owners, operators, and occupants expect more. One of the difficulties is that different occupants have different requirements for comfort; some like it cooler, some like it warmer, some prefer more air movement, others less. The same occupant may have different preferences at different times of day, when wearing different clothing, or perhaps after having just walked up a few flights of stairs.

The Project seeks to create a new occupant-based paradigm for HVAC control, integrating low-energy personal comfort systems (PCS) into HVAC operations, investigating advanced control algorithms, and exploring innovative software for integration of control and monitoring. The Project also looked at commercially available occupant voting-based temperature control along side the other technology innovations. This control paradigm applies equally to existing buildings as well as new designs. These new strategies have the potential to dramatically improve traditional levels of energy efficiency, increase occupant satisfaction and thermal comfort, and increase the flexibility and useful life of the conditioning systems. They require new operation approaches, a reexamination of how comfort performance is quantified in standards and design tools, and training for the building professions.

Project Purpose

This Project developed, integrated, and demonstrated HVAC control and PCS technologies. This work was accompanied by steps potentially leading to adoption, including development of proposed changes to standards and codes. The project synthesized three innovative components that provide an integrated, comprehensive approach to correcting frequently occurring control problems in buildings that improve both occupant comfort or energy efficiency. The technologies included: (1) low-energy personal comfort systems (PCS) that provide direct local heating and cooling to building occupants and methods of test for assessing efficiency of PCS; (2) innovative control improvements to VAV systems, including lower minimum zone airflow rates and cost-based supply air temperature reset; and (3) information technology in the form of open-source software for implementing control logic across a full range of existing direct digital control (DDC) systems. The project explored commercially available occupant voting-based controls along side these innovations.

The specific objectives of this Project were:

1. To further develop and demonstrate new low-energy, localized personal comfort systems, and to develop methods of test for certifying their efficiency.

2. To develop and demonstrate innovative improvements to VAV control systems.
3. To explore open-source information technology software for implementing actuation control logic across a full range of DDC systems.
4. To explore deployment and commercialization planning for the above innovations in occupant-based HVAC controls.
5. To demonstrate integrated applications of above innovations in occupant-based HVAC controls.
6. To enable implementation of the results in Standards and Codes (e.g. Title 24, Title 20, ASHRAE 90.1, ASHRAE 55, etc.), and to perform other technology transfer activities to enable adoption in common practice.

Project Results

Personal Comfort Technology

Personal comfort system (PCS) chairs

In the early stages of the Project, the research team finalized the design and arranged for the fabrication of 50 low-energy heated and cooled chairs for use in the demonstration field studies. Additional work was done to develop a new controller for the PCS chairs that provided the capabilities to collect and store data (e.g., cooling or heating intensity, temperature, relative humidity and occupancy status) and communicate wirelessly with the internet to enable real-time access to and use of the chair data. Using the newly developed (version 1) digital PCS chairs, we then conducted developmental testing in Sutardja Dai Hall. The purpose of this field study was to test the performance and reliability of the new digital PCS chairs and to evaluate our field study protocols in preparation for the major demonstration field study at the San Mateo County (SMC) office building.

Additional analysis on the PCS chair data led to the development of a new personal comfort model (PCM) that uses direct feedback from individuals along with physical measurements of local conditions to characterize person-specific comfort needs/desires. The new PCM consistently outperforms conventional comfort models across all tested subjects and algorithms with the overall prediction accuracy of 74%.

Several lessons were learned from the developmental testing in Sutardja Dai Hall (SDH) on the UC Berkeley campus. Field use of the chairs revealed that the smartphone-based controller was not the most intuitive way to control PCS chairs. Based on this learning, we designed the next version of the digital controller (version 2) to have a physical user interface (UI) with LED lights to indicate control intensity. We deployed the digital PCS chair v.2 with a physical UI at the demonstration study at SMC.

Personal heater efficiency index

We created a classification of personal heaters and a draft of a method of test. We tested 12 personal heaters using a thermal manikin to assess the personal heater efficiency (PHE). We found that conductive heaters (heated chairs or foot-warmers) are far more efficient than radiant or convective heaters. A transition toward use of conductive heaters can be a game changer because up to 95% of the energy currently used on personal heaters can be saved, and personal heaters allow buildings to reduce their heating setpoint during winter months by approximately 2°C.

Demonstration #1: San Mateo County (SMC) Office Building

After completing the developmental testing in SDH, we selected the San Mateo County office building located in Redwood City, CA, for the first demonstration field study site. In this field study, we deployed Internet-connected PCS chairs alongside occupant vote-based HVAC control (Comfy™) in an office building with a conventional VAV system—evaluating the effect on comfort and energy use. An initial 4-month baseline operations period was conducted with only occupant voting-based temperature control installed, during which the zone temperature deadband was set at the nominal installation float range of 21-23 °C (70-74°F). Beginning in July 2016 the project implemented a progressive expansion of the default float range for occupant-based HVAC controls. This was simultaneous with PCS chair deployment in parts of the building. The default float range was expanded in steps, reaching 20.5-24.5°C (69-76°F) at the end of August 2016. This demonstration is different from the typical deployment of occupant voting-based temperature control, which can have a much tighter baseline deadband (often a single setpoint). The typical deployment expands the default deadband to the base case for this demonstration.

There were no noticeable changes in occupants' usage of the voting-based control and discomfort complaints due to this float range expansion (please see Section 2.3). Anecdotes from the PCS field study suggest that the PCS chairs played a role in maintaining the high degree of occupant satisfaction—by providing individual control for cases where challenging physical characteristics of the space or conflicting comfort preferences did not allow establishment of consensus set points. The chairs helped maintain high thermal satisfaction when the range of operative temepratures within the zones exceeded the range of deadband control. Overall, the response of occupants and management to the voting-based control was positive, as evidence by management's decision to continue their service contract with Comfy™ after the Project ended.

The Project attempted to obtain direct measurement of energy use reduction resulting from the expanded range of temperature setpoints enabled by the occupant-based HVAC controls and the PCS chairs. The results did not conclusively show whether the intervention saved energy or not. However, based on a past study on the prediction accuracy of Measurement & Verification methods in a large set of buildings, it is likely that if savings were present, they were less than 10% of HVAC energy consumption in this building. This is consistent with the limited shifts in temperature setpoints, 0.5°C (1°F) for the lower setpoint and 1°C (2°F) for the upper setpoint. The SMC building had just recently undergone a control system upgrade and recommissioning so that the building was operating with current best practice controls (dual max control logic and reduced zone minimum airflows). It is likely that the savings potential of expanding setpoints would be lower in this type of system.

Demonstration #2: Sutardja Dai Hall (SDH)

The research team implemented several advanced VAV control strategies in SDH often using the open source sMAP architecture and the pybacnet package, without directly interfacing with the proprietary building management system software. This in itself is novel, potentially enabling scalable lower-cost deployment regardless of the BMS. Occupant voting-based HVAC control operated alongside advanced VAV control strategies in SDH, indicating these technologies can be compatible with minimal integration.

Detailed field demonstrations with energy impact measurements were completed for two advanced strategies: (1) time-averaged ventilation (TAV) and (2) cost-based supply air temperature reset.

Time-averaged ventilation (TAV)

For most building systems, VAV box flow minima are higher than the ventilation minimum required by current code (Title 24 and ASHRAE 62.1). To resolve this issue, we developed a TAV strategy that cycles the airflow from 0% (i.e., a fully closed damper) to a higher value, defined by the larger of either 30% of the design maximum airflow or the maximum airflow required to avoid stratification at the design heating condition. The results of the intervention study showed the following:

- Hourly average airflow accurately met the required ventilation rates in each zone.
- A reduction in fan (15%), reheat (41%), and chilled water (23%) energy.

Cost-based supply air temperature reset

The current best practice in operation in many VAV buildings today is a demand-based reset that constrains the range of possible SAT setpoints based on the outside air temperature. We developed a new supply air temperature control reset strategy for multi-zone variable air volume systems. The strategy is intended to be implemented either with open source software or directly within existing building management systems. At 5-minute intervals, the strategy estimates the cost of fan, heating and cooling energy at three different supply air temperatures, and chooses the lowest cost as the setpoint. We implemented this strategy in Sutardja Dai Hall and compared the energy costs to the industry best practice control strategy in a randomized (daily) controlled trial over a 6-month period. We showed that the new control strategy reduced total HVAC energy costs by approximately 29%, when normalized to the typical annual climate data for this location and operating only during typical office hours. These results are additive with the reduced energy use for time-averaged ventilation. We also describe the new control strategy in language common to the industry (see sequence of operations included as supplemental material in the appendix) so that readers may easily specify and implement this immediately, in new construction or controls retrofit projects.

Demonstration #3: Integral Group Office Building

The demonstration field study in the Integral Group office in San Jose was undertaken to explore how many of the innovative technologies developed in this project would integrate with a building that used an advanced HVAC system (in this case, radiant slab heating and cooling) instead of a more conventional VAV reheat air distribution system. Major findings and lessons learned were as follows:

- The quick-responding PCS heated and cooled chairs, along with other PCS devices (desktop fans and footwarmers), were able to provide an improved thermal acceptability of 82% compared to the baseline acceptability (pre-PCS) of 71%. This improvement occurred for all testing periods during which the room temperature setpoints were expanded to cover the range of 67°F to 79°F.
- The advantage of PCS is in its ability to provide fast-responding conditioning to occupants when they desire it. The research team believes this capability is particularly well-suited for buildings involving low-energy radiant slab systems. Thermally massive radiant systems are unable to make quick changes in response to load or control changes.
- Measured HVAC energy savings in the building due to widening of the temperature setpoints were modest because the building is already extremely energy efficient. The main benefits were in terms of comfort, as described above.
- The installation of Comfy^{tm} in the Integral Group office confirmed that occupant voting-based temperature control technology, particularly the "blast" mode, is not compatible with a radiant slab system.

Commercialization

Advanced VAV control strategies

Two advanced variable air-volume (VAV) control strategies were developed and demonstrated by this project:

- Time-Averaged Ventilation (TAV)
- Live Cost-Based Optimization of Supply Air Temperature

This project has created algorithms that actively produce pulse width modulation of dampers to explicitly control ventilation rates and form the basis for TAV controls. The project has demonstrated programming of these algorithms using an open source software package (sMAP and pybacnet) and the existing building automation system controller and network infrastructure. Per Section 3.1.1 a paper describing TAV implementation has been published by this project.

This project field tested a new air temperature reset algorithm based on estimating the dynamic cost of chilled water, reheat, and fan power, and then selecting the SAT that yields the minimum cost, subject to comfort constraints. The implementation is designed around the specific configuration of the demonstration site. Prior to commercialization efforts more development and field test activities are needed in buildings with variations in equipment.

Both the TAV and cost-based SAT reset approaches will likely be incorporated in ASHRAE Guideline 36 (anticipated to be published later in 2017)—which will provide broad distribution and encourage widespread application. Another eventual technology transfer venue would be inclusion in future versions of advanced VAV design guides.

Personal comfort systems

This Project continued demonstrations of personal comfort systems (PCS), primarily the low energy heated and cooled chair, often alongside other technologies. The results are consistent with significant potential for energy savings as well as improved occupant comfort. The results also illustrate the importance of the user interface and communications capabilities for low energy heated and cooled chairs. Commercialization efforts will benefit from feeding this information into ongoing product improvement efforts.

There is a marketing opportunity for PCS in conjunction with sophisticated HVAC control based on occupant requests. Vendors of the control technologies may seek to increase the occupant satisfaction percentage even more, approaching 100% with PCS. This is envisioned as a deployment of PCS limited to a small residual percentage of dissatisfied occupants, or occupants in zones that have a disproportionately high impact on HVAC energy use, as opposed to a universal deployment of PCS.

HVAC control based on occupant requests

Cloud-based software is commercially available to enable sophisticated HVAC temperature control at the zone level—enabling building occupant requests for heating and cooling, responding to requests with immediate heating or cooling, aggregating requests as votes, and using machine learning to establish space temperature settings including dead bands. Space temperatures are typically allowed to float to establish relatively wide dead bands based on occupant preference.

The product described here and deployed in the project demonstrations is Comfy™. This product is marketed as a subscription service to increase personal thermal comfort of commercial building occupants. Marketing targets high-level executives concerned with multiple aspects of employee wellbeing. Though energy use reduction is asserted in marketing materials, no guarantees are made and no accounting of energy use is provided as a part of the service. Customer service and fulfillment is focused on occupant satisfaction around thermal comfort and interaction with the product.

This vendor has observed the market for software-based energy management services, noting two important things: 1) there is intensive effort involved in validating energy savings claims to fulfill explicit energy management assertions, and 2) this is a highly competitive market with as many business failures as successes among these vendors. This vendor is able to successfully market, generate revenue, and grow at the desired rate with the comfort-only offering.

Commercialization might be accelerated for HVAC control based on occupant requests by advancing building labling credit for occupant control and/or monitoring (e.g., LEED™)—in a way that takes advantages of the synergies between comfort and energy efficiency.

Enabling information technology

Innovative open-source software can enable the development and integration of the occupant-based HVAC technology explored by this Project. The simple Measurement and Actuation Protocol (sMAP) supported the field research on the PCS chairs with similar data management capability likely playing into integrating with other HVAC technology. sMAP is an underlying technology for the commercially available occupant voting-based temperature control product. sMAP provides a means to deploy advanced VAV control algorithms that offered advantages over direct implementation through a BMS.

This technology is itself evolving with UC Berkeley Electrical Engineering and Computer Science Department researchers creating a different archiver in the eXtensible Building Operating System or XBOS (Fiero et al. 2015), replacing powerdb with the high performance Berkeley Tree Database or BTrDB (Andersen et al. 2016), and providing drivers with distributed authentication and authorization through BOSSWAVE. sMAP/XBOS provides utility by providing a consistent interface to link data from various sources to flexible and extensible control code, enabling interoperability (Peffer et al 2016). Addressing portability between buildings and establishing viable business models are among the remaining milestones on the path to commercialization for this enabling technology

Standards and Codes

The research team evaluated and identified code change potential for Personal Comfort Systems and Variable Air Volume System Controls at both the state energy code level (Title 24 Building Energy Efficiency Standards, Title 20 Appliance Efficiency Standards), as well as national energy and comfort standards (ASHRAE Standards 90.1, 189.1 and 55).

Title 24 Code Change Options

Allow different temperature setpoints when equivalent comfort is demonstrated through the use of PCS devices, compared to traditional setpoints used by building codes and operators.

Develop a compliance option for occupant feedback systems that allows different temperature setpoints when equivalent comfort is demonstrated through the use of Occupant Feedback Systems, compared to traditional setpoints used by building codes and operators.

With the development and validation of an effective control sequence to implement time-averaged ventilation (TAV), the prescriptive requirements in Title 24 could be revised to eliminate the 20 percent airflow criterion when in deadband and to prescriptively require the use of TAV when the required ventilation is less than 20 percent of the peak airflow.

The prescriptive code sections that require supply air temperature reset in Title 24 and Standard 90.1 could be revised to require reset based on zone and energy cost feedback for systems with DDC to the zone.

Title 20 Code Change Options

This project developed a personal heater thermal manikin based method of test and implemented one test procedure. However, more work will be needed to compare the new test with alternative methods for measuring the personal heater efficiency. Based on the study results to date, the efficiency levels may need to be set based on the mode of heat transfer (conductive, convective, radiative).

Based on results of this project, as well as related studies being conducted by CBE, a performance index called 'corrective power' (CP) has been proposed. CP is defined as difference between two ambient temperatures at which equal thermal sensation is achieved - one with no PCS (the reference condition), and one with PCS in use. Further work is necessary to establish methods of test to calculate and verify CP of various PCS devices.

ASHRAE Standards 90.1/189.1 Code Change Options

The proposed code changes for ASHRAE Standards 90.1 and 189.1 are similar in nature to those proposed for Title 24.

ASHRAE Standard 55 Code Change Options

Recent updates and enhancements to Standard 55 support the assessment of PCS comfort benefits associated with air movement under personal control (for example, desktop or ceiling fans). During the course of this project, the following work was done on Standard 55 provisions for air movement: raising the still air zone threshold to 0.2 m/s, and eliminating the upper airspeed limit when the airspeed is under group/individual control. In addition, a User's Guide has been prepared for Std. 55 by TRC with CBE as a participant. Within the User's Guide, the role of air movement on comfort is addressed for the full range of operative temperatures and humidity using the ASHRAE/CBE Thermal Comfort Tool. The User's Guide was published by ASHRAE in 2016.

Update Standard 55 requirements and assessment methods to explicitly address PCS in their ability to provide occupant thermal comfort at conditions that may be different than those of the ambient environment due to user adaptation and localized comfort provided by PCS.

Proposed new comfort classes based on PCS represent a new approach to evaluating the potential of occupants to regulate environmental conditions to attain thermal comfort in buildings based on the level of personal occupant controls available to the occupants. In principle, a building with a higher level of personal control will get a higher classification designation.

Project Benefits

We updated the potential California impacts and benefits of Project HVAC control innovations—based on project results, as well as more recent and comprehensive floor area estimates and more recent energy prices:

- 15 million therms per year of natural gas savings
- 560 million kWh per year of electricity savings
- $100 million per year of energy cost savings (at rates of $0.95 per therm & $0.16 per kWh)
- 260,000 tons of CO_2e emissions per year avoided (at 11.7 lbs per therm and 0.624 lbs per kWh)
- 67 tons/year of NO_x emissions avoided (from elimination of on-site natural gas use (Loyer and Alvarado 2012))

- 20 tons/year of NOx emissions avoided (assuming California gas-fired electr. Generation (Loyer and Alvarado 2012))
- 58 MW of avoided peak electric demand
- Weighted average technical potential of 0.05 therms/yr-sf and 1.7 kWh/yr-sf of heating ventilation, and air-conditioning savings in retrofit or new construction
- Weighted average technical potential of 29% of natural gas and 28% of electricity for heating, ventilation, and air-conditioning in retrofit or new construction

The energy use reduction estimates are based on three primary modes of optimized HVAC control:

1. Advanced optimization of supply air temperature (pending reference).
2. Reduction in variable air volume box minimum airflow settings to levels necessary for adequate ventilation—based on recent advances in understanding of practical operating constraints and innovation in TAV (Taylor et al. 2012, Kaam et al. 2017).
3. Widening of the ambient temperature dead band (Hoyt et al. 2015) in conjunction with occupant-based innovations including: a) Low-energy heated and cooled PCS chairs; b) Low-energy science-based fans and foot warmers; and c) Occupant surveys or polling as input to HVAC control.

Based on project results, energy use reduction estimates per unit floor area decreased for expansion of temperature set point deadbands and increased for advanced VAV control algorithms.

Energy savings estimates are based on technical potential in three Commercial End Use Survey (CEUS) sectors: a) Large Office (technical potential to impact 90% of building stock); b) Small Office (technical potential to impact 60% of building stock); and c) College (technical potential to impact 30% of space—primarily offices). Energy savings are estimated in three end-use types: a) Heating (natural gas and electricity); b) Cooling (natural gas and electricity); and c) Ventilation (electricity). Total floor area is adjusted upward by 50% reflecting the difference between the 2006 CEUS and more current California Energy Demand Forcast estimates

Other assumptions and methodology includes: a) 25% market penetration of buildings with technical potential over a six-year period; and b) Minimal energy use of PEC and PCS Units accounted for and included in estimates—distinguishing low-energy technologies from higher-energy technologies currently in common use (e.g., "space heaters").

Both natural gas and electricity savings are anticipated from each of the project innovations. Widening of the ambient control dead band will decrease the need for both heating and cooling. The CEUS database identifies a significant amount of natural gas cooling in both the large office and college sectors. Control innovations will reduce simultaneous heating and cooling (reheat), avoiding both natural gas and electricity use.

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CHAPTER 1:
Personal Comfort Technologies

Heating, Ventilation, and Air-Conditioning (HVAC) industry standards call for modern buildings to provide satisfactory comfort for 80 percent of their occupants. Some buildings do better than this, and many do worse. Designers, engineers, owners, operators, and occupants expect more. One of the difficulties is that different occupants have different requirements for comfort; some like it cooler, some like it warmer, some prefer more air movement, others less. The same occupant may have different preferences at different times of day, when wearing different clothing, or perhaps after having just walked up a few flights of stairs.

The concept of a Personal Comfort System (PCS) is equipment that individuals can use to provide the environment they prefer at any particular moment, right where they are. With PCS, potentially 100 percent of the people in a building can be comfortable.

Fundamental lab studies at CBE on thermal comfort led to the concept of providing localized conditioning. Practical PCS have been in development for some time under different names, such as Task-Ambient Conditioning and Personal Environmental Controls. At present, the PCS components consist of foot warming devices, leg warming devices, chairs that provide both heating and cooling, and small desk fans (Figure 1.1). All of these PCS devices are relatively low-energy, using as little as 1 W for a small fan up to a maximum of about 50 W for the foot warmer. Other components are under consideration, and all of the current devices are in active development at CBE.

Zhang et al. (2015) discuss a variety of PCS devices and present the "corrective power," defined as the difference between two ambient temperatures at which equal thermal sensation is achieved - one with no PCS (the reference condition), and one with PCS in use. Holt et al. (2015) present simulated central HVAC energy savings associated with extending air temperature setpoints in buildings enabled by the application of PCS devices.

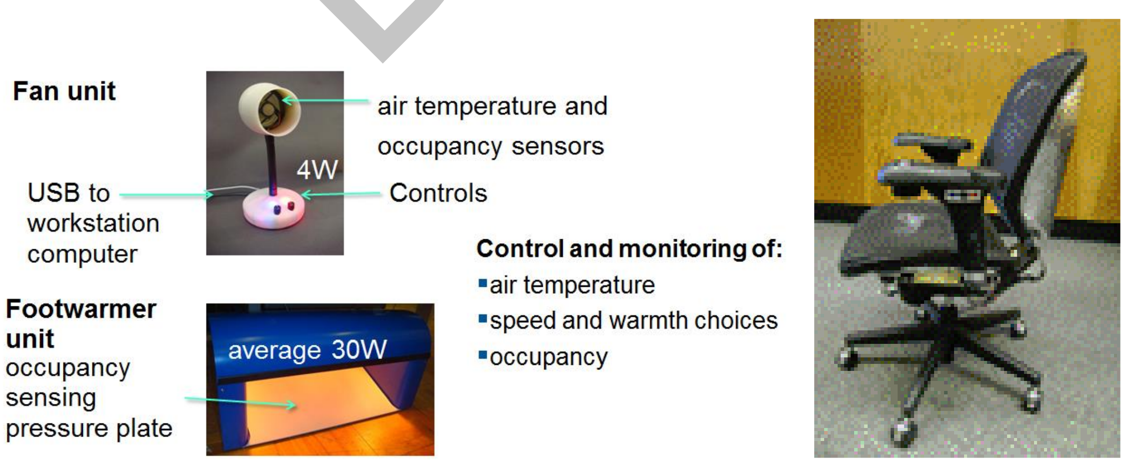

Figure 1.1. PCS desktop fan and footwarmer (left) and PCS chair (right)

1.1 Development of a Personal Heater Efficiency Index

Personal heaters are portable devices built to convert electrical energy to heat in order to provide thermal comfort to people while indoors. There is no standard for the assessment of the efficiency of these heaters. We created a classification of personal heaters and a draft of a method of test. Personal heaters can be classified as radiant heaters (heating output 50% or more as radiant heat), convective heaters (heating output 51% or more as convective heat), and conductive heaters (relies on physical contact to transfer heat).

We developed a new measurable figure of merit named, Personal Heater Efficiency (PHE), to assess the efficiency of personal heaters. PHE can be used to compare personal heaters. Personal Heater Efficiency is defined as the ratio between the Heating Effect (HE) and the power of the heater. It is measured in °C/kW.

We tested 12 personal heaters using a thermal manikin to assess the Heating Effect. We found that conductive heaters (heated chairs or foot-warmers) are far more efficient than radiant or convective heaters. Heaters that rely on physical contact to transmit heat are approximately 20 times as energy-efficient as convective heaters, and over 10 times as energy-efficient as radiant heaters. A transition toward use of conductive heaters can be a game changer because up to 95% of the energy currently used on personal heaters can be saved, and personal heaters allow buildings to reduce their heating setpoint during winter months by approximately 2°C.

A full description of this research, including (1) classification of personal heaters, (2) definition of personal heater efficiency index and method of test, and (3) analysis of test results for a selection of personal heaters, is contained in Appendix 1.1. Development of a Personal Heater Efficiency Index.

1.2 Ceiling Fans and Other PCS Devices

1.2.1 Evaluation Index "Corrective Power" for PCS Devices

PCS Devices have the potential to satisfy individual comfort requirements while offering opportunities to save HVAC energy in buildings. The potential to save energy is based on the ability of PCS devices to widen the range of temperatures that building operators consider necessary for maintaining occupant comfort. We reviewed literature on human subject and manikin tests for evidence about the comparative comfort performance of PCS. We assembled and evaluated data from (mostly) laboratory studies performed over many years in order to:

- Quantify the thermal comfort levels that have been found from particular types of PCS.
- Suggest appropriate temperature setpoint ranges that are possible when PCS is included in a building.
- Examine evidence of alliesthesia—whether the satisfaction with non-uniform PCS may exceed that of the neutral uniform conditions traditionally considered ideal.
- Inform the design of future PCS.

Based on this review, and as a way to measure the comfort-producing effectiveness, we coined the index 'corrective power' (CP) (Zhang et al. 2015). CP is defined as the difference between two ambient temperatures at which equal thermal sensation is achieved - one with no PCS (the reference condition), and one with PCS in use. CP represents the degree to which a PCS system may "correct" the ambient temperature toward neutrality. CP can alternatively be expressed in terms of thermal sensation and comfort survey scale units.

Published studies of PCS were reviewed to extract their CP values. Cooling CP ranges from -1K to -6K, and heating CP from 2K to 10K. Deeper understanding of PCS will require new physiological and psychological information about comfort in local body segments and sub-segments, and about spatial and temporal alliesthesia. These topics present many opportunities for productive future research.

Specific to the use of fans as PCS devices, we conducted laboratory studies and human subject tests. One issue with fan performance is that the presence of furniture such as tables and partitions affect the air flow distribution. In the lab, we have been doing a series of lab testing for ceiling fan velocity profiles with a table at different locations and with two types of partitions. This work will be continued and will be our future next step. CBE also performed a series of human subject tests to evaluate comfort effectiveness of ceiling fans for sedentary people, people with slightly higher metabolic level (representing people working with standing table), and people with ergonomic bikes (representing people in exercise facilities). The tests show that the ceiling fan CP can reach to 6K (Zhai et al. (2015a, 2015b)).

The comfort studies with ceiling fans for slightly higher metabolic rate and for exercise people in gyms provide valuable information for the Standard 55 applications for standing people. The team's work helped to push forward a new proposed ASHRAE Standard 216P: Methods of Test for Determining Application Data of Overhead Circulator Fans.

1.2.2 ASHRAE Standard 216P

ASHRAE Standard 216P is currently in development and represents a professional activity that will lead to a practical method of test for the evaluation of ceiling fans. The committee was formed by ASHRAE on January 22, 2014 at the annual meeting in New York. The approved Title, Purpose, and Scope of the standard are:

TITLE: Methods of Test for Determining Application Data of Overhead Circulator Fans

PURPOSE: The purpose of this standard is to specify the instrumentation, facilities, test installation methods, and procedures to determine circulator fan application data for occupant thermal comfort in a space.

SCOPE: This standard applies to overhead circulator ceiling fans.

The SPC-216 committee is a consensus committee made up of designers, consultants, manufacturers, and testing labs. Members of this research team have contributed to the development of the standard during the project term, including Gwelen Paliaga serving as chair and Stefano Schiavon serving as a voting member. CBE contributed to the measurement instrumentation specification and has supplied laboratory test results that informed the standard.

The SPC-216 committee has subtantially completed sections of the standard covering: Definitions, Classification of Parameters, Symbols and Units, Instrumentation and Apparatus, Test Conditions and Procedures, Measurements and Measurement Locations. The following sections are in development: Calculations, Reporting. The committee hopes to vote on a first public review draft in June 2017.

Standard 216 is a method of test that will support innovative occupant responsive comfort solutions that save energy. Ceiling fans are a form of PCS that are widely available and understood, although lack a method of quantifying their comfort impact. The intent of ASHRAE 216 is to provide standardized design data for the application of overhead circulation fans in indoor spaces that comply with the thermal comfort requirements of ASHRAE Standard 55.

1.2.3 References

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CHAPTER 2: Demonstration #1 – San Mateo County Office Building, Redwood City, CA

In this Chapter of the final report, we present our findings from Task 3.1, Demonstration #1. The goal of this task was to conduct a demonstration field study involving the integration of project innovations in an existing building with a conventional VAV overhead air distribution system. We selected the San Mateo County office building located in Redwood City, CA, for the demonstration field study site. In this field study, we deployed Internet-connected PCS chairs alongside occupant vote-based HVAC in an office building with a conventional VAV system—evaluating the effect on comfort and energy use.

2.0.1 Building Description

The San Mateo County (SMC) Office Building is a 5-story building, plus basement and underground garage, which was constructed in 1999 and comprises about 142,000 gross square feet (Figure 2.1). The building primarily houses County services and administrative offices. The SMC building is conditioned by a VAV reheat system, with two evaporatively cooled rooftop units (RTU) serving the north and south portions of the building. Reheat zones are served by a hot water plant, and data rooms on each floor are served by water-cooled heat pumps and an auxiliary condenser water system. The original HVAC control system was replaced in early 2015, as part of a separate unrelated project, with a Distech (BACnet) system and a Tridium Niagara AX front end. The BAS retrofit updated the control sequences to include current state-of-the-art sequences, including demand-based supply air temperature and duct static pressure reset, dual maximum VAV zone airflow control, and demand controlled ventilation. The recent completion of the BMS retrofit made the SMC building a good location for a field demonstration.

2.0.2 Demonstration Timeline

Table 2.1 presents the timeline for our demonstration field study in the SMC office building. Abbreviations are defined in the legend below the table.

Preparation for the demonstration field test began with installation of fan and air conditioning compressor electricity metering and trending software in the last quarter of 2015. Preparation continued with the installation of commercially available occupant-based HVAC control[1] in the first quarter of 2016, as well as planning toward deployment of low-energy heated and cooled chairs.

[1] The Comfy vendor's company name, originally Building Robotics, now reflects the product name.

Figure 2.1. San Mateo County office building, Redwood City

Table 2.1. Demonstration timeline: San Mateo County Office Building

Period	2014 Oct-Dec	2015 Jan-Mar	2015 Apr-Jun	2015 Jul-Sep	2015 Oct-Dec	2016 Jan-Mar	2016 Apr-Jun	2016 Jul-Sep	2016 Oct-Dec	Future
M&V				F Pwr C Pwr Trndr	F Pwr C Pwr Trndr	F Pwr C Pwr Trndr Cx	F Pwr C Pwr Trndr	F Pwr C Pwr Trndr	F Pwr C Pwr Trndr	
Occupant-Based HVAC Control					Install	Voting Blast	Voting Blast	Voting Blast	Voting Blast	Voting Blast
Personal Comfort Systems					Prep	C Chrs	C Chrs	C Chrs	C Chrs	
Integration Observations								DB Exp		

Legend

M&V

F Pwr—Fan Power

C PWR—Compressor Power

Trndr—Data Acquisition Software by Comfy™

Cx—Occupant-based HVAC control identified faults

Occupant-Based HVAC Control by Comfy™

Install—Technology Installed

Voting—Preference expressed for warmer/cooler temperatures, control dead band adjusted per votes

Blast—Instant "blast" of heating or cooling upon request (available once every 10 minutes)

Personal Comfort Systems

Prep—Preparatory steps

C Chrs—Low energy heated and cooled chairs with communication capability

Interactions Observed

DB Expansion—Default dead bands expanded from SMC 70-74°F to 69-76°F

2.0.3 Background: Occupant-Based HVAC Control

Occupant vote-based ambient temperature control is commercially available as cloud-based software that operates at the zone level— enabling occupant requests for heating and cooling, responding to requests with a "blast" of immediate heating or cooling, aggregating requests as votes, and using machine learning to establish space temperature settings and a dead band within limits of a float range. The blast mode is defined as an immediate 10-minute period during which warm or cool air is supplied at increased volume to the zone having the occupant request. More detailed description of this technology is provided in sections 2.3 and 3.3 in the context of implementation of two of the Project demonstrations and in Chapter 6 in the context of commercialization planning.

The commercially available occupant-based HVAC control (Comfy[tm]) deployed for the demonstration field study is cloud-based software that operates at the zone level—enabling occupant requests for heating and cooling, responding to requests with a "blast" of immediate heating or cooling, aggregating requests as votes, and using machine learning to establish space temperature settings and a dead band within limits of a float range. The float range determines the starting temperature set points for all zones in a building and is unique to each installation, established in consultation with the customer. Our understanding is the typical float range is 70-74°F. This is wider than some traditional practice (e.g., a single set point or tight range of 2°F), but not as wide as comfort standards suggest. The vendor indicates they tend to have the greatest success both increasing comfort and reducing energy use when the baseline condition is over-cooling in summer or over-heating in winter. In such cases letting occupant votes establish heating and cooling set points and a deadband within a 70-74°F float range may represent a substantial relaxing of temperature control with significant energy savings potential.

Though some assertions of energy savings are made for the technology, the product is increasingly marketed on the basis of potential improvement in occupant comfort (GSA 2015[2], Intel 2015[3], Comfy[tm] 2016a[4], Comfy[tm] 2016b[5], Comfy[tm] 2016c[6], Comfy[tm] 2017a[7]). The intent is to maximize occupant satisfaction, with the strategy informed by customer experience indicating that occupants dislike a tight year round single setpoint or tight (e.g., 2°F) deadband, over-cooling in the summer, or over heating in the winter.

This approach is thought to have the potential to reduce energy use, particularly in scenarios with tight baseline conditions described above, or with low space utilization or low occupancy. However, no accounting of energy use is provided as a part of service and the compact with the customer is increasingly focused on occupant satisfaction.

The product is marketed as a subscription service to increase thermal comfort of commercial building occupants. Marketing targets high-level executives concerned with multiple aspects of employee well-being. Customer service is focused on occupant satisfaction around thermal comfort and interaction with the product. Engagement with building operation or energy management personnel is necessary during installation, but is not a central part of engagement with the customer afterwards.

Occupant interaction with the service is through a web page or smart device app. Product integration with the HVAC system is limited to zone temperature controls, avoiding interaction with other aspects of HVAC control (e.g., supply air temperature control at air handlers).

2.0.4 Similarities and Differences with Typical Deployment

The installation of occupant-based HVAC control resembled a typical product deployment in some ways and differed in others. The technology deployment was nominal, with control approaches that are the standard product offering.

[2] GSA 2015. *Socially Driven HVAC Optimizing*. GSA Public Buildings Service GPG-25. Downloaded from Comfyapp.com March 2016.

[3] Intel 2015. *Controlling Office Temperature with Building Robotics*. Intel® IOT Smart Building Solution Brief. Downloaded form Comfyapp.com January 2017.

[4] Comfy 2016a. Case Study: *Facility Manager's Perspective.* Downloaded from Comfyapp.com March 2016.

[5] Comfy 2016b. Comfy Case Study: *Comfy Software and Glumac LA Pioneering New Technologies in the Living Building Challenge*. Downloaded from Comfyapp.com March 2016.

[6] Comfy 2016c. Case Study: Johnson Controls, Inc. Downloaded from Comfyapp.com March 2016.

[7] Comfy 2017a. Comfy Product and Spec Sheets. Downloaded from comfyapp.com January 2017.

The customer engagement was different—focusing on the building manager, and with the research team in the loop. This is different from the typical customer engagement with a client company executive. During the implementation, the customer engagement moved toward the typical case as the vendor phased out an interface for the building operator and took even more responsibility for occupant hot and cold calls.

The baseline operations included a dead-band already at the nominal installation float range of 70-74°F. The occupant participation rate of 41% is within the typical range according to the vendor (Comfy™ 2017c[8]). It is lower than three posted case studies of deployment of the technology at 50+%, 85%, and 77% (GSA 2015, Comfy™ 2016b, Comfy™ 2016c).

The occupant-based HVAC control was activated in February 2016. The default float range for the heating and cooling set points was established at 70-74°F, equivalent to the pre-installation baseline set points. Until the end of July set points were managed based on occupant votes within this range—creating dead-bands equivalent to or tighter than the baseline. This established our baseline usage database for comparison with subsequent measurements under expanded dead band conditions (see below). For more detail please refer to the analysis of occupant-based HVAC control operations in Section 2.3.

Initiation of occupant-based HVAC control operations resulted in the identification, diagnosis, and resolution of commissioning issues with Building HVAC controls.

2.0.5 PCS Chairs

Low-energy communicating PCS heated and cooled chairs were deployed in the building beginning in March 2016. For more detail please refer to the analysis of PCS chairs in Section 2.1.

2.0.6 Default Float Range Expansion

Beginning at the end of July 2016 the project implemented a progressive expansion of the default float range for occupant-based HVAC controls. This was simultaneous with PCS chair deployment in parts of the building. The default float range was expanded in steps, reaching 69-76°F at the end of August 2016.

There were no noticeable changes in occupants' usage of the voting-based control and discomfort complaints due to this expansion (please see Section 2.3). Anecdotes from the PCS field study suggest that the PCS chairs played a role in maintaining the high degree of occupant satisfaction—by providing individual control for cases where challenging physical characteristics of the space or conflicting comfort preferences did not allow establishment of consensus set points (please see Section 2.1).

This simultaneous deployment of occupant-based HVAC control and PCS, with PCS supporting occupant satisfaction for challenging situations, is one of the two ways it has been suggested the two technologies might complement each other. The vendor agrees with the potential of this

[8] Comfy 2017c. Correspondence with Steve Schwartz 18 January 2017.

technology synergy, indicating they see promise for using the PCS chairs as a part of their product offering[9]. Both the experience of this project and the vendor vision emphasize the importance of communications ability for the PCS chairs. Please see Chapter 6 for more discussion of commercialization issues.

Due to limited availability of the PCS chairs it was not possible to explore the other way in which the two technologies might work together— deployment of chairs to all occupants to allow an even wider expansion of the default float range and the potential for even wider dead bands.

2.0.7 Energy Use Evaluation

Assertions of energy use reduction by the occupant-based HVAC controls technology have so far been supported only by observations of expanded control dead bands combined with modeling of energy use reduction expected to be associated with these temperature set points. As a part of this demonstration field study the project attempted to provide the first direct measurement of energy use reduction by the occupant-based HVAC controls. Please see Section 2.4 for the details of this analysis. This evaluation could not confirm energy use reduction from the technology, with observed shifts within the uncertainty of the measurement.

2.0.8 Discussion

Actual energy use reduction is likely to have been less than asserted for typical applications of the technology—below the threshold detectable within the uncertainty of the measurement. Possible reasons for this result are:

- The baseline conditions, including a set point dead band equivalent to the default float range of 70-74°F, were not as energy intensive as sometimes encountered (e.g., single set points, winter overheating, summer over cooling).
- Space utilization and/or occupancy is more intensive than sometimes encountered.
- The actual set points resulting from occupant votes are tighter than the default float range more often than anticipated, and/or "blast" requests use more energy than anticipated.
- Actual energy use is different from modeled energy use because of issues with VAV controls.

The latter explanation would suggest that the advanced HVAC control strategies explored by this project may be complementary to the occupant-based HVAC control technology. Time averaged ventilation or live-cost optimizing HVAC control may reduce energy use associated with wider temperature dead bands. Please see sections 3.1.1 and 3.1.2 for descriptions and analyses of the advanced VAV control strategies.

Concurrent deployment of the technologies may be relatively simple without the need for complex integration. This is because the occupant-based HVAC control operates at the zone level, avoiding interaction with air handler and other HVAC controls. The advanced VAV control strategies play out interactions with both zone-level and other HVAC controls—but

[9] Comfy 2016. Interview with Lindsay Baker. December 2016.

experience in the SDH demonstration field test suggests the two technologies operate compatibly beside each other at the zone level. (For more information please see sections 3.1.1 and 3.1.2). More difficult complexity might manifest if both technologies were interacting at both levels.

2.1. Field Study of Occupant Comfort and Behavior with Internet-Connected PCS Chairs

A separate report was prepared focusing on the PCS chair aspects of the demonstration field study in the San Mateo County office building. This report is contained in Appendix 2.1. Field Study of Occupant Comfort and Behavior with Internet-Connected PCS Chairs. The report includes the following: implementation of the Demonstration Plan, deployment of PCS heated and cooled chairs, results and discussion of all data collection and occupant surveys, and research and development work on information/integration technology to support the development and deployment of the Internet-connected PCS chairs.

Key findings from the demonstration field study with the PCS chair are listed below:

- Our results show that the PCS chair users have high thermal satisfaction; over 95% acceptability across all exposed operative temperature of 20.5-24.5°C (69-76°F), far exceeding the ASHRAE 55 Standard’s minimum 80% satisfaction threshold.
- When control is given, people use it to address their comfort needs; therefore, behavior can describe their comfort preference. The chair data can be traced back to individuals and is available in real-time with digital PCS chairs. Hence, there is an opportunity to use individuals’ chair behavior to understand their comfort needs in real time.
- People are exposed to different thermal conditions even within the same VAV zone. Our results show the variation of up to 2.9°C (5.2°F) in mean exposed air temperature across different chair locations. The PCS chairs maintained high thermal satisfaction when operative temperatures within the zone had a wider range than the temperature setpoints.
- The general feedback about the digital PCS chairs was positive. The overwhelmingly positive satisfaction ratings from short surveys confirm this. The design of chair control via rheostat knobs was intuitive, and the subjects quickly learned how to use it after a short (5-10-min) in-person training. The vast majority of benefits to the occupant come from the chair heating and cooling effect. However, live telemetry from digital PCS chairs can provide visibility into comfort needs/desire across different building spaces in real time. This information could be linked to HVAC control to improve comfort satisfaction and energy use.

2.2. Development of Personal Comfort Models Using Occupant Behavior with PCS Chairs

Another dedicated report was written to present some additional analysis made possible by the rich dataset collected from the Internet-connected PCS chairs. This full report is contained in Appendix 2.2. Developing Personal Comfort Models Using Occupant Behavior with PCS Chairs.

A new Personal Comfort Model (PCM) was developed to address some of the limitations of existing thermal comfort models used by the industry. To account for thermal comfort in building design and operation, the standards currently use models designed to predict the average comfort of a large population. There are two main models: Predicted Mean Vote (PMV) and the adaptive model for naturally ventilated buildings (ANSI/ASHRAE 2016). These models, however, do not address individual differences in comfort needs/desires, even though it is well known that there can be significant differences in thermal comfort preferences between individuals.

To address these issues, a new modeling approach, PCM is proposed.

- PCM uses the individual as a learning objective instead of aggregate population.
- PCM uses direct feedback from individuals along with physical measurements of local conditions to characterize person-specific comfort needs/desires.
- PCM takes a data-driven approach to allow flexible testing of different explanatory variables and machine learning algorithms.

Our findings show that PCM consistently outperforms conventional (PMV and adaptive) models across all tested subjects and algorithms with the overall prediction accuracy of 74%.

2.3. Occupant Voting-based Temperature Control for SMC

Occupant voting-based control was installed in the SMC office building in February 2016. At the time of installation, the existing heating and cooling setpoints in the building were 70 and 74°F, respectively, representing the baseline float range for zone setpoints. This is a wider baseline float range than is often encountered, possibly already capturing some of the energy use reduction observed with the voting-based control. From these baseline conditions, beginning at the end of July 2016 the project implemented a progressive expansion in four steps of the float range, reaching 69-76°F at the end of August 2016. During the study period, the occupant participation rate was 41% (166 out of a total of 400 invited occupants), which is within the typical range according to the vendor. 72% of all voting requests were to "cool my space," while 22% were to "warm my space." The others requested no change.

The pattern of voting requests by different users varied quite widely, even within the same VAV zone and under similar zone air temperatures. This result is consistent with known differences in thermal preferences between individuals, and was also demonstrated with the use pattern of the PCS chairs in section 2.1.

There were no noticeable changes in occupants' voting and discomfort complaints due to the expansion of the setpoint float range. Since deployment of the PCS chairs (although, to a smaller number of users) coincided with the expansion of the float range, feedback from the PCS field study suggest that the PCS chairs played a role in maintaining the high degree of occupant satisfaction—by providing individual control for cases where challenging physical characteristics of the space or conflicting comfort preferences did not allow consensus set points to be established for the same zone.

Full details of this voting-based control analysis are contained in Appendix 2.3. Occupant Voting-based Temperature Control for SMC.

2.4. Measurement and Verification of Changes in Energy Consumption at SMC

We evaluated the effect that expanding the default zone heating and cooling setpoints using voting-based control had on whole building HVAC energy consumption in the San Mateo County office building. Overall, we conclude that the overall change in energy consumption is within the 'noise' of variation of how this building operates. The results do not conclusively show whether the intervention saved energy or not. However, based on a past study on the prediction accuracy of Measurement & Verification methods in a large set of buildings, it is likely that if savings are present, they are less than 10% of HVAC energy consumption in this building. This is lower than expected based on prior modeling work performed at CBE and the General Services Administration. In addition, they are lower than those found in field studies in which we expanded zone setpoints, though these studies inferred savings at the zone, not the air handling unit level.

These results might be explained by differences between this and typical deployments noted in section 2.0.4, including an already relatively wide float range baseline. Another potential explanation is that this building operates with current best practice controls (dual max control logic and reduced zone minimum airflows) and the other studies were not representative of this more efficient VAV building. It is likely that the savings potential of expanding setpoints would be lower in this type of system.

It could be that expanding setpoints using voting-based control may not always save energy, as the relatively few zones that drive HVAC consumption in the building are the zones in which occupants are most likely to vote. A more robust assessment of energy performance of voting-based control when used to implement a change in the default zone setpoints would preferably include a study of multiple buildings, across a range of climates, with a longer baseline period and intervention data for each building. However, the above observation highlights an interesting opportunity. We can identify these relatively few zones that disproportionately drive HVAC consumption. We can even potentially rank them in terms of effect. We can then intervene with personal comfort systems and expand heating and cooling setpoints in these select zones, starting from the ones that drive HVAC consumption the most. This will likely have a larger energy savings, with a lower initial cost, than other approaches.

Full details of this M&V analysis of energy consumption at SMC due to zone setpoint expansion using voting-based control is contained in Appendix 2.4. Measurement and Verification of Changes in Energy Consumption at SMC.

CHAPTER 3:
Demonstration #2 – Sutardja Dai Hall, UC Berkeley

In this Chapter we present our findings from Task 3.1, Demonstration #2. The field testing conducted earlier in the project of optimized VAV control strategies in Sutardja Dai Hall on the UC Berkeley campus proved to be very productive. Our research team benefitted from accessibility of building controls, engagement of a progressive and accommodating Facility Director, knowledge of the building systems, and proximity of the campus site. For these reasons, we decided to extend this work and selected Sutardja Dai Hall (SDH) for a second demonstration field study site. Occupant voting-based temperature control (Comfy) was installed in SDH for the duration of our field study.

These earlier field tests in SDH served as the Project's developmental, or Stage 1, testing, during which we implemented and evaluated the innovative technologies in the Project: personal comfort systems (PCS), optimized VAV control strategies, and integrated information technology solutions. The lessons learned from this developmental testing informed our field study protocols that we refined and applied in our subsequent full demonstration field studies. Appendix 3.0.1. Developmental Field Study Report and Demonstration Field Study Plan presents two major results for the Project: (1) Developmental Field Study Report presents the results of the earlier Stage 1 testing in SDH; and (2) Demonstration Field Study Plan describes criteria for selecting demonstration buildings and control zones for field measurements, required measurements, BMS trend data, and additional sMAP enabled data collection, detailed testing protocols for deploying and testing the PCS chairs, Comfy^{tm}, and advanced VAV controls, requirements for occupant response data collection via survey or smartphone apps, and proposed schedule and sequencing of the field demonstration studies.

3.0.1 Building description

Sutardja Dai Hall (SDH) is located on the northeast corner of the UC Berkeley campus. This 7-floor, 141,000-ft^2 was designed by SmithGroupJJR and was completed in 2010 (Figure 3.1). One wing of the building includes private and open plan office space housing groups including the Center for Information Technology Research in the Interest of Society (CITRIS), a few classrooms, light laboratories, café, auditorium, and data center. The other wing is a nanofabrication laboratory for the Electronic Engineering and Computer Science (EECS) department.

Figure 3.1. Sutardja Dai Hall, UC Berkeley campus

The office wing has a single duct, Variable Air Volume (VAV) air handling unit with hot water reheat. A Siemens Apogee Building Management System (BMS) provides direct digital control (DDC) to the zone level. The building has two 600 ton Trane chillers, controlled through the BMS. The absorption chiller was designed to use steam from April through October when steam on the UC Berkeley campus is not in high demand for heating. A centrifugal compressor chiller was designed to be used from November through March.

3.0.2 Demonstration timeline

Table 3.1 presents the timeline for our demonstration field study in SDH. Abbreviations are defined in the legend below the table.

Table 3.1. Demonstration timeline: Sutardja Dai Hall, UC Berkeley campus

	2014 Oct-Dec	2015 Jan-Mar	2015 Apr-Jun	2015 Jul- Sep	2015 Oct-Dec	2016 Jan-Mar	2016 Apr-Jun	2016 Jul-Sep	2016 Oct-Dec	Future
Measurement	DAT	DAT Live C	DAT Live C	DAT Live C	DAT Live C	DAT Live C	DAT Live C	DAT Live C	DAT Live C	
Control Architecture	sMAP	sMAP	sMAP	sMAP	sMAP	sMAP	sMAP	sMAP	sMAP Direct	
Advanced Control Strategies	SAT	SAT SAP	SAT SAP	SAT SAP TAV	SAT SAP TAV	SAT SAP TAV	SAT SAP TAV v2	SAT LC SAP TAV v2	SAT LC SAP TAV v2	
Occupant-Based HVAC Control	Voting Blast J 2014>	Voting Blast	Voting Blast	Voting Blast	Voting Blast	Voting Blast	Voting Blast	Voting Blast	Voting Blast	
Personal Comfort Systems				C Chrs (Aug)	C Chrs					
Interactions Observed	Con Op	Con Op	Con Op	Con Op	Con Op	Con Op	Con Op	Con Op	Con Op	
Integration Issues				F Stable						
Integration Solutions					Z Mgmt	Z Mgmt	Z Mgmt	Z Mgmt	Z Mgmt	

Legend

Measurement

DAT—Discharge Air Temperature Sensors

Live C— Live energy consumption and cost estimates for each air handler

Controls Architecture

sMAP—sMAP and pybacnet

Advanced Control Strategies

SAT—Fault-Tolerant Supply Air Temperature

SAT LC—Fault-Tolerant Supply-Air Temperature based on Live Cost Optimization

SAP—Fault-Tolerant Supply Air Pressure

TAV— Time-Averaged Ventilation

TAV v2—Time-Averaged Ventilation improved

Occupant-Based HVAC Control by Comfy™

Voting—Preference expressed for warmer or cooler temperatures, dead band adjusted per votes

Blast—Instant “blast” of heating or cooling upon request (available once every 10 minutes)

Personal Comfort Systems

Chairs— Low-energy heated and cooled chairs without communication capability

C Chrs—Low energy heated and cooled chairs with communication capability

Interactions Observed

Con Op—Concurrent operations of occupant-based HVAC controls and VAV control strategies

Integration issues

F Stable—Fan Stability

Integration Solutions

Z Mgmt—Zone Management

3.0.3 Measurement

Prior to the initiation of field testing the project supported upgrade of building controls with discharge air temperature sensors. The project also implemented live energy consumption and cost calculations for the air handler.

3.0.4 Occupant-Based HVAC Control

Commercially available occupant-based HVAC control software (Comfy™) was installed in SDH in January 2014, operating through the duration of the field tests. This technology is cloud-based software that operates at the zone level— enabling occupant requests for heating and cooling, responding to requests with a "blast" of immediate heating or cooling, aggregating requests as votes, and using machine learning to establish space temperature settings and a dead band within limits of a float range.

Marketing information for the technology includes assertions about improving both occupant satisfaction and energy performance. However, the compact reached with customers increasingly focuses only on thermal comfort, with no guarantees for or accounting of energy use reductions. Please see Chapter 2 for more details on this technology in the context of demonstration field study #1. Please see Chapter 6 for more information in the context of commercialization.

An analysis of operation of the occupant-based HVAC control in SDH is presented in Section 3.3. Information about interaction with low-energy communicating PCS heated and cooled chairs is presented in Chapter 2 along with discussion of the energy impacts of the technology, and potential performance synergy with advanced VAV control strategies. Occupant-based HVAC control also operated alongside advanced VAV control strategies in SDH, but the assessment of integration is limited to the observation that these technologies can be compatible with minimal integration.

3.0.5 Advanced VAV Control Strategies

Already understood to be essential for obtaining the best performance from VAV systems in traditional applications, effective VAV control strategies are now becoming recognized as important for maximizing the benefits of occupant-based approaches deployed in VAV buildings.

Minimum air flow set points for VAV terminals are often well above minimum airflow requirements leading to a risk of over-cooling building spaces and unnecessary use of energy. Simulations indicate that the best currently deployed supply-air temperature reset strategies often do not find the optimum energy cost point. Time-averaged ventilation and live cost-based control are approaches which can address these issues. These innovative technologies are described in detail below in Section 3.1 in the context of implementation of one of the Project demonstrations.

VAV control strategies were implemented in the following sequence:

1. Fault-Tolerant Supply Air Temperature Control
2. Fault-Tolerant Supply Air Pressure Control
3. Time-Averaged Ventilation (v1)
4. Time Averaged Ventilation (v2)
5. Fault-Tolerant Supply Air Temperature Reset Based on Live Cost Optimization

Time-averaged ventilation control implementation and evaluation is described in Section 3.1.1 Control implementation and evaluation of fault-tolerant supply air temperature based on live cost optimization is described in Section 3.1.2. Both of these advanced technologies showed great promise, achieving substantial energy savings in field tests, Commercialization of these technologies is discussed in Chapter 6.

3.0.6 Personal Comfort Systems

Development of communicating versions of low-energy PCS heated and cooled chairs for field testing in SDH is described in Section 3.2, along with results of the field study.

3.0.7 Integration

Concurrent operation of occupant-based HVAC control and advanced VAV control strategies was implemented throughout the demonstration field test in SDH. Concurrent deployment of PCS chairs was implemented for several months in late 2015.

The SDH field tests served to demonstrate the basic compatibility of the technologies operating concurrently, but could not explore interactive effects. The SMC demonstration field tests were complementary, providing insights into potential synergies of the technologies, but without actual concurrent implementation of the advanced VAV control technologies (Please see Chapter 2).

One technical hurdle was addressed in the SDH demonstration field test when fan instability was encountered during early implementation of the first version of time-averaged ventilation control. Integrating zone control at the building level resolved this issue (please see Section 3.1.1 for details).

3.0.8 Enabling Information Technology

Innovative open-source software has recently become available that can provide flexibility in collecting data and implementing control (Peffer et al. 2016). A copy of this paper is contained in Appendix 3.0.2. Writing Controls Sequences for Buildings. The simple Monitoring and Actuation Profile (sMAP) was deployed as a part of Project demonstrations in three distinct modes—all facilitating technology integration: 1) implementing advanced control algorithms using an sMAP-BACnet™ driver called the pybacnet[10] package to interface with the building management system (BMS), 2) as part of the underlying technology for the commercially available occupant voting-based temperature control product, and 3) facilitating data collection for PCS chairs.

The third mode is illustrative of the popularity of the technology as a research or measurement and verification tool. (More details of this specific application are available in Appendix 2.1) The second mode illustrates the utility as well as the substantial level of product development and support required for a successful commercial application. The first mode is a pre-commercial deployment illustrating the potential to provide a nimble alternative to a direct BMS implementation.

The advanced control algorithms can be implemented either with sMAP technology or directly with a BMS. Commercialization of the former is still pending a business entity emerging to develop and service products. The relative ease of the latter depends on the characteristics of the BMS. More contemporary BMS with increased operability and storage capability are more nimble in integrating new applications.

sMAP technology may end-up being more important for older buildings applications where the BMS is less nimble. This technology development at UC Berkeley is itself evolving with the emergence of more sophisticated iterations—using a different archiver in the eXtensible Building Operating System or XBOS (Fiero et al. 2015), replacing powerdb with the high performance Berkeley Tree Database or BTrDB (Andersen et al. 2016a), and providing drivers with distributed authentication and authorization through BOSSWAVE[11]. Zhao et al. (2016) provide a further description of how sMAP and XBOS were applied in the field study in Sutardja Dai Hall.

3.1 Advanced VAV Control Strategies

The research team implemented several advanced variable-air-volume (VAV) control strategies in SDH using the open source sMAP architecture and the pybacnet package, without having to interface with the proprietary building management system software (in this case, a Siemens Apogee system). This in itself is novel, as it implies that this can be done in a scalable way

[10] https://github.com/BuildingRobotics/pybacnet

[11] https://github.com/immesys/bw2/wiki/BOSSWAVE-overview

within buildings, regardless of the BMS vendor and at low cost compared to a traditional controls retrofit. In this section, we present the control development and implementation, and the energy savings based on field measurements in SDH for two strategies: (1) time-averaged ventilation (TAV) and (2) cost-based supply air temperature reset. We also present a summary of all advanced VAV control strategies considered during this project.

3.1.1 Time-Averaged Ventilation (TAV)

For most building systems, VAV box flow minima are higher than the ventilation minimum required by current code (Title 24 and ASHRAE 62.1). This means that the majority of VAV boxes in buildings are supplying ventilation air at unnecessarily high rates, which wastes energy both at the air handling unit which must condition and move that air, and by cooling the zone down to the heating set-point. This is one of the main reasons why spaces in many office buildings are typically too cold, often during summer periods. To resolve this issue, we developed a Time-Averaged Ventilation (TAV) strategy that can be applied to each zone in the building. It cycles the airflow from 0% (i.e., a fully closed damper) to a higher value, defined by the larger of either 30% of the design maximum airflow or the maximum airflow required to avoid stratification at the design heating condition. Time averaging is allowed by ASHRAE Standard 62.1-2013 and by Title 24 2013. When considering the average flow over a period, TAV controls to the ventilation minimum for each space as opposed to the controllable minimum (typically much higher), leading to significant energy savings.

A separate technical paper was prepared describing the field investigation of TAV in Sutardja Dai Hall. The paper has been submitted and accepted for publication in *Energy and Buildings* (Kaam et al. 2017). Key highlights of the paper are as follows:

- We developed a control sequence that alternates each zone VAV damper between open and closed.
- We tested it in a Variable Air Volume system building with single-max control logic and high minimum flow rates.
- Hourly average airflow accurately met the required ventilation rates in each zone.
- Results of the intervention study showed a reduction in fan (15%), reheat (41%), and chilled water (23%) energy.

The paper is contained in Appendix 3.1.1. Time-Averaged Ventilation for Optimized Control of Variable-Air-Volume Systems.

3.1.2 Cost-based supply air temperature reset

In early VAV system implementations, building operators used constant values for duct static pressure (DSP) and supply air temperature (SAT) setpoints. These constant setpoint strategies were improved to become linear resets that increase static pressure and decrease supply temperature with respect to increasing outside air temperature. More recently, with the advent of Direct Digital Control with feedback from every zone in the building, demand based reset approaches are used where DSP and SAT setpoints vary based on the requirements of the most demanding (''critical') zone, often using 'trim and respond' logic. The current best practice in operation in many VAV buildings today is a demand based reset that constrains the range of possible SAT setpoints based on the outside air temperature.

However, there is an additional consideration in the case of SAT reset, the potential to supply lower temperature air while still meeting comfort conditions in the zones in the building. Reducing SAT reduces fan energy by reducing the airflow required by any zones that are currently in cooling mode. This will also increase cooling energy at the AHU if it is not in economizer mode, and increase reheat use for those zones that are at or near the zone heating temperature setpoint. Thus, the optimum SAT setpoint depends on the status of the airside economizer, and the relative cost of fan energy, cooling energy, and zone reheat energy at that particular moment.

We developed a new supply air temperature control reset strategy for multi-zone variable air volume systems. The strategy is intended to be simple enough to implement within existing building management systems. At 5-minute intervals, the strategy estimates the cost of fan, heating and cooling energy at three different supply air temperatures, and chooses the lowest cost as the setpoint. We implemented this strategy in Sutardja Dai Hall and compared the energy costs to the industry best practice control strategy in a randomized (daily) controlled trial over a 6-month period. We showed that the new control strategy reduced total HVAC energy costs by approximately 29%, when normalized to the typical annual climate data for this location and operating only during typical office hours. These findings indicate that the current industry best practice control strategy does not find the optimal energy cost point under many conditions. This new control strategy is a valuable opportunity to reduce energy costs, at relatively little initial expense, while avoiding more complex approaches such as model predictive control (that the industry has been hesitant to adopt).

A separate technical paper was prepared describing the field investigation of cost based SAT reset in Sutardja Dai Hall. The paper is contained in Appendix 3.1.2. Evaluation of a Cost-Responsive Supply Air Temperature Reset Strategy in an Office Building. The paper also describes the new control strategy in language common to the industry (see sequence of operations included as supplemental material in the appendix) so that readers may easily specify and implement this immediately, in new construction or controls retrofit projects.

3.1.3 Summary of Innovative VAV Control Strategies

During the early stages of the project, the research team developed a detailed summary of the key VAV control sequences and other considerations that could be candidates for testing and demonstration during the project. These included: (1) reducing VAV box minimum airflows, (2) adjustment of space temperature setpoint, (3) supply air temperature and duct static pressure reset, (4) limiting adverse impact of rogue zones, and (5) occupancy-based control of ventilation and temperature reset. Many of these strategies were studied extensively, as described in Sections 3.1.1 and 3.1.2. This summary is contained in Appendix 3.1.3. Innovative VAV Control Strategies.

3.2 Occupants and Comfort

We conducted developmental testing of the newly developed (version 1) digital PCS chairs in Sutardja Dai Hall. The purpose of this field study was to test the performance and reliability of the new digital PCS chairs and to evaluate our field study protocols in preparation for the major demonstration field study at the San Mateo County office building (see Chapter 2). The first step in this process was to develop a new controller for the PCS chair that provided the capabilities to collect and store data (e.g., cooling or heating intensity, temperature, relative humidity and occupancy status) and communicate wirelessly with the internet to enable real-time access to and use of the data.

To test the chairs and our field study protocol, we recruited fifteen office workers on the 3rd floor of SDH to use a digital PCS chair between August and October 2015. The participants had one week of an adjustment period with the digital PCS chairs and then were invited to take 'post-chair' right-now surveys three times a day, at 10:00 am, 1:30 pm, and 3:30 pm. Overall, the results showed that introducing the PCS chairs improved thermal acceptability for all temperature conditions.

A separate report was written describing the details of the PCS field study in SDH. It is contained in Appendix 3.2.1. PCS Chair Telemetry and Occupant Survey Protocol.

Several lessons were learned from the field study, as listed below

<u>PCS Chairs:</u>

- Control interface design: Human subject testing revealed that the phone application may not be the most intuitive way to control PCS chairs. Users prefer a physical UI dedicated for the chair control. Based on this learning, we designed the next version of the digital controller (version 2) to have a physical UI that utilized the rheostat in the UI, similar to the one in the analog version, with added components including LED lights to indicate control intensity. We deployed the digital PCS chair v.2 with a physical UI at the demonstration study at SMC.
- Chair battery indication: It is necessary to monitor the power supply and inform the users when the battery needs to be recharged. This functionality was not supported in the current version of the digital controller hardware. The digital PCS chair v.2 measures battery voltage and indicate battery status via an LED light on the physical UI.
- Chair and UI connection: The Bluetooth connection between the chair and the phone frequently failed. This prevented the occupants from being able to use the chair. In the version 2 chair design, we have upgraded the Bluetooth hardware significantly, and have also removed the dependency on Bluetooth by physically connecting the UI interface with the digital controller.
- Location of chair temperature sensor: The heat generated by the carrier board affects readings from the temperature sensor because the sensor is in the same enclosure. In the version 2 chair design, we adopted a modular design approach and install temperature

and humidity sensors on a separate circuit board so that they can be located away from heat sources.
- Chair troubleshooting and maintenance: During the field study, we learned that the chairs required frequent software updates and hardware maintenances. As such, it is important to allocate appropriate budget and personnel to provide both on-site and off-site technical support during the PCS chair deployment.

Survey methods:

- Streamline survey questions: We decided to remove questions related to air quality from the right-now surveys so we can focus more on thermal comfort. We added new questions specifically for the PCS chair users to better understand what drives the chair usage and how it affects comfort.
- Survey platform: Qualtrics provides a flexible platform to create new survey questions. We decided to use Qualtrics for the demonstration study at SMC.

Energy savings:

- Integrated control strategies: There are various ways to integrate the chairs into HVAC control, which we have not yet tested in this field study as the focus was heavily on the chair testing and design iterations. Zone controls can be linked to occupancy, temperature, and heating/cooling usage data from the chair. UC Berkeley Electrical Engineering and Computer Science (EECS) researchers have demonstrated the feasibility of integrated control strategies through laboratory experiments. Please refer to Andersen et al. (2016b) for details. A copy of this paper is contained in Appendix 3.2.2. Well-Connected Microzones for Increased Building Efficiency and Occupant Comfort.

3.3. Occupant-Responsive HVAC Control: Analysis at SDH

Occupant voting-based temperature control (Comfy^tm^) was installed in the Sutardja Dai Hall (SDH) in January 2014. We analyzed votes during the period from October 2015 – October 2016. Due to the variable student occupancy in the building, it is difficult to estimate the percentage of occupants who voted. However, from the collected data we know that during that one-year period, there were 111 users in the building and 3,068 votes were made. Of this total, 58.4% of all requests were to "warm my space," while 37.6% were to "cool my space." The others requested no change. In comparison to the pattern of use at SMC (section 2.3), we see that SDH tends to operate at a cooler temperature, resulting in more requests to be warmer.

The pattern of requests by different users varied quite widely, even within the same VAV zone and under similar zone air temperatures. This result is consistent with known differences in thermal preferences between individuals.

Overall, the largest number of requests were to "warm my space." This pattern was seen during all four seasons of the year where the highest number of warming requests occur in the morning when people arrive at their workstation. These requests tend to diminish during the remainder of the day as the zone temperatures warm up. It is interesting to note that some users predominately request to be warmer, while others mostly request to be cooler. But there are still about 25% of the users who requested a balance between heating and cooling.

Full details of this analysis are contained in Appendix 3.3. Occupant Voting-based Temperature Control for SDH.

3.4. References

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CHAPTER 4:
Demonstration #3 – Integral Group Office Building, San Jose, CA

The original scope of work called for the performance of two demonstration field studies: (1) One involving the integration of project innovations in an existing building with a conventional VAV overhead air distribution system. As described in chapters 2 and 3 of this final report, the research team decided to conduct demonstration field studies in two buildings with conventional VAV overhead systems due to the valuable results we were able to obtain from both the San Mateo County office building in Redwood City and Sutardja Dai Hall on the UC Berkeley campus. (2) One involving the integration of project innovations into a new building with advanced low-energy space conditioning systems, including radiant heating and cooling, and others such as displacement ventilation, underfloor air distribution, or natural ventilation/mixed-mode. For this second building type, we selected the Integral Group office building in San Jose, which features a radiant floor slab system as its primary space conditioning system.

The CBE research team had previously conducted a field study in the Integral Group office building as part of a CEC PIER-sponsored research project, "Personal Comfort and Radiant Slab Systems" (Bauman et al. 2015). In this earlier field study, we deployed the analog version of the heated and cooled chairs, footwarmers, and desktop fans to test the comfort and energy implications of these personal comfort system (PCS) devices. The field measurements were conducted during the winter months from October 2014 – February 2015. For the demonstration field study to support the current project, we extended the field measurements into the summer of 2015, with occupant voting-based temperature control deployed as another occupant-responsive control technology. In the Demonstration Report #3 below, for completeness we include the previous winter season results, as well as the new results and lessons learned from the summer of 2015.

4.0.1 Selection of Integral Group office building

The Integral Group office was selected as one of the demonstration sites to meet the requirement of the scope of work to study a building with an advanced low-energy space conditioning system, such as the radiant floor slab system installed in the building. In addition, the research team felt that there are potential synergies between PCS and a thermally massive radiant floor slab. Concrete radiant slab systems tend to be quite slow in their ability to respond to quick control changes. On the other hand, their thermal inertia allows them to have an advantage over conventional air distribution systems by reducing peak cooling loads and shifting thermal loads to nighttime and off-peak hours when cooling can be performed more energy efficiently and utility costs are reduced. In contrast, PCS can respond nearly instantly to user's individual thermal preferences. Therefore, PCS can complement the radiant floor slab system. One of the major objectives of this field study was to evaluate the performance of PCS in a building with radiant slabs. Through field testing, we measured the impact of PCS on occupant comfort and building energy when heating and cooling set-points are expanded in the radiant zones.

4.0.2 Demonstration timeline

Table 4.1 presents the timeline for our demonstration field study in the Integral Group office building. Abbreviations are defined in the legend below the table.

Table 4.1. Demonstration timeline: Integral Group Office Building

Period	2014 Oct-Dec	2015 Jan-Mar	2015 Apr-Jun	2015 Jul- Sep	2015 Oct-Dec	2016 Jan-Mar	2016 Apr-Jun	2016 Jul-Sep	2016 Oct-Dec	Future
Right-now Surveys	yes	yes		yes						
M&V			Trndr	Trndr H Temp	Trndr H Temp					
Control Architecture										
Advanced Controls										
Occupant-Based HVAC Control						Voting				Voting? Blast w Fan?
Personal Comfort Systems	Chairs	Chairs	Chairs	Chairs D Fans						
Interactions Observed										
Integration Issues										
Integration Solutions										

Legend

Surveys
M&V

Trndr—Data Acquisition Software by Comfy™
H Temp—Hobo ™ temperature loggers

Controls Architecture
Advanced Controls Strategies

SAT—Fault-Tolerant Supply Air Temperature
SAT LC—Fault-Tolerant Supply-Air Temperature based on live cost optimization
SAP—Fault-Tolerant Supply Air Pressure

Occupant-Based HVAC Control by Comfy™

Install—Technology Installed
Voting—Preference expressed for warmer/cooler temperatures, control dead band adjusted per votes
Blast w Fan—Concept is "blast" of heating or cooling upon request (available once every 10 minutes), future actuates ceiling fan for cooling in the context of radiant cooling

Personal Comfort Systems

Chairs— Low-energy heated and cooled chairs without communication capability
C Chrs—Low energy heated and cooled chairs with communication capability
D Fans—Desk fans

Interactions Observed

DB Expansion—Default dead bands expanded from SMC 70-74°F to 69-76°F

Integration issues
Integration Solutions

4.0.3 Building description

The Integral Group office building located in San Jose, California, was formerly a two-story, windowless, massive concrete tilt-up type structure of 7,200 ft^2 used as a bank branch office. In 2005 the building was purchased by lighting engineer David Kaneda with the aim of renovating it to the highest LEED rating of Platinum, as an office for his firm, Integrated Design Associates (IDeAs). Kaneda engaged Scott Shell of EHDD Architects in San Francisco to help design the facility, and Shell convinced him to go beyond LEED Platinum and to construct a building with zero net energy use.

The building was completed and occupied in 2007, and employs skylights, low-e and electrochromic windows for natural lighting, radiant heating and cooling using slab-embedded tubing driven by a ground-source heat pump, ultra-efficient electric lighting with advanced controls, carefully selected computers and office equipment, and about 30kW of rooftop photovoltaic panels. The building was certified as zero-net energy in 2012. Figures 4.1 and 4.2 show pictures of the building exterior and interior.

Figure 4.1. Integral Group office building exterior

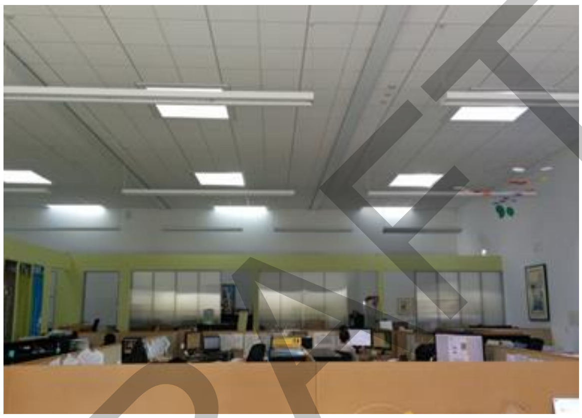

Figure 4.2. Integral Group office building interior

4.0.4 Approach

The field study in the Integral Group office building required a different approach. Since the building uses a radiant floor slab system for both heating and cooling, we could not investigate any advanced VAV control strategies in this building. Instead, we focused on the combination of PCS and occupant voting-based temperature control (Comfy^{tm}). We took advantage of the heated and cooled PCS chairs that had been deployed back in October 2014 as part of a previous CEC PIER-funded project. However, these earlier analog versions of the chairs did not have wireless communication capabilities. Due to limited resources, we needed to save our available Internet-connected PCS chairs for use in our other two demonstration field studies. In addition to the PCS chairs, we also gave footwarmers, and desktop fans to some of the occupants in the Integral Group office. All 24 occupants received a PCS chair and participated in the field study. Figure 4.3 shows a chair user at the Integral Group office building.

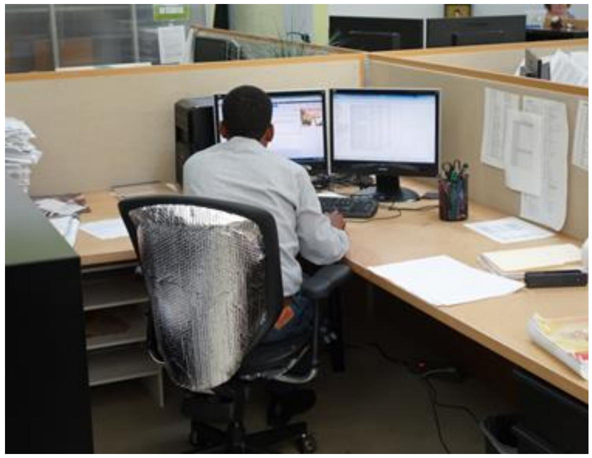

Figure 4.3. A chair user at Integral Group office

4.0.5 Data collection

We measured both globe temperature and air temperature to quantify the effects of mean radiant temperature in the studied zones. The cooled and heated radiant slab can cause stratification; hence we also measured the distribution of temperatures in the study area. We monitored energy use, HVAC system performance, and indoor environmental conditions. Table 4.2 shows the measurement parameters and devices used for recording indoor environmental conditions.

Table

Table 4.2. Measurements and devices

Physical parameters	Devices	Accuracy	Point
Room T, RH/outdoor	OnSet Hobo U12-013	Temperature: ± 0.35°C RH: ±2.5%	Eight points in the building
Globe temperature	OnSet TMC1-HD external temperature sensor	±0.25°C	Seven points
Floor Surface temperature			Two points
Stratification			One point

We measured globe temperature at seven different locations within the open plan workspace and private offices. We recorded floor temperatures at two different locations. Room temperature stratification was also measured in two different locations, at 0.1 m, 0.3 m, 0.6 m, 1.1 m, and 1.7 m heights above the floor, and at 0.1 m below the ceiling height. We placed a Hobo data logger in the building's courtyard to measure outdoor temperature. A nearby weather station provided independent weather data for comparison. Figure 4.4 shows the three zones covered in this study as well as the location of the sensors. Zone 1 is the open-plan office (blue area), Zone 2 is the conference room (green area), and Zone 3 is the private offices (pink area).

Figure 4.4. Measurement devices and locations at Integral Group office

4.0.6 HVAC data collection

We downloaded the building's HVAC trend data via remote access to the building's BMS server. The trends include zone temperature at each thermostat, slab temperature, heating/cooling water temperature from the heat pump, water valve positions, and outdoor air temperature.

4.0.7 Power data

We reviewed the trend data from the building's heat pump, solar panel electrical energy generation, as well as whole building electricity bills. HVAC energy use is calculated by adding the energy generated from solar panels and subtracting plug loads and lighting energy from the total energy bill. Figure 4.5 shows Figure of the building's electric power system.

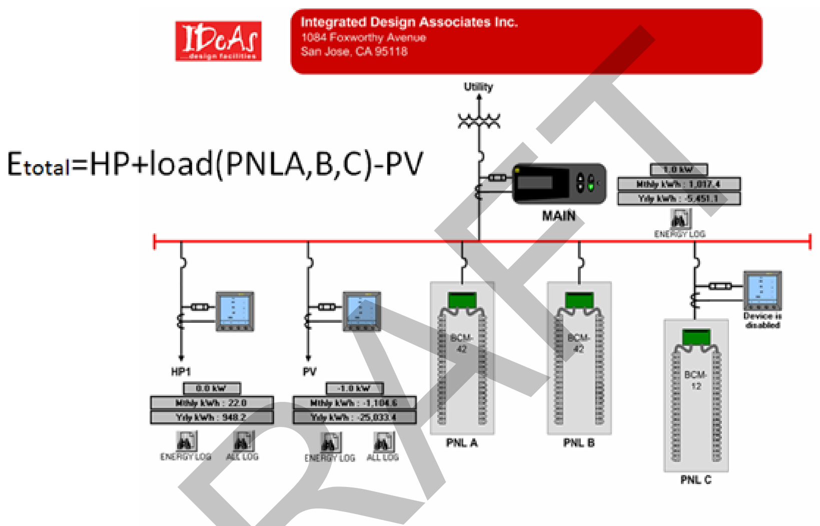

Figure 4.5. Schematic diagram of electric power system

4.0.8 Occupant surveys

We evaluated the impact of PCS on occupant comfort in winter and summer by conducting right-now surveys. We surveyed occupants three times per day with the same set of questions, shown in Figure 4.6**Error! Reference source not found.**.

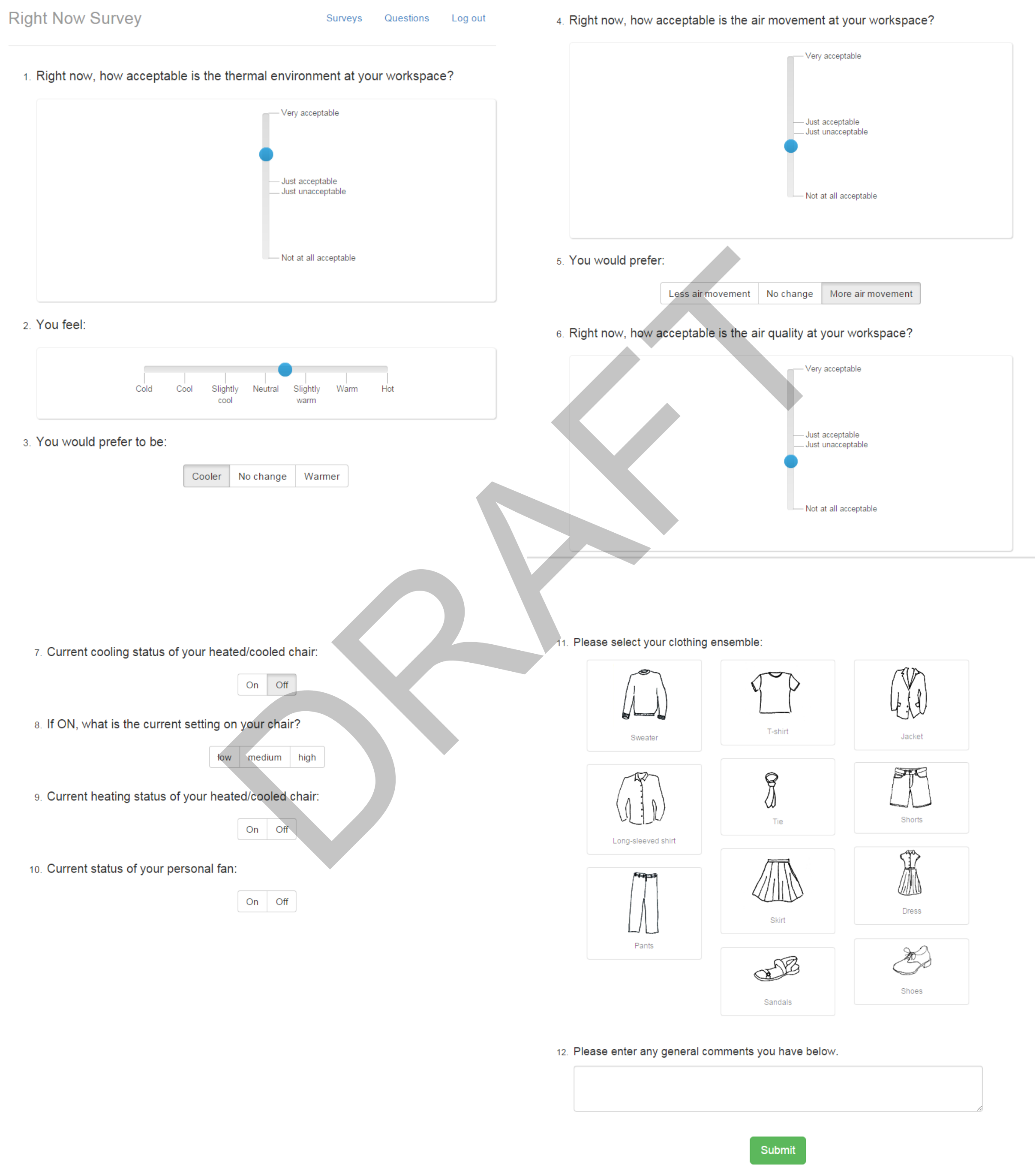

Figure 4.6. Online right now survey

4.0.9 Field study timeline

Tables 4.3 and 4.4 show the timeline for the winter and summer studies. The team established the baseline case in the course of the previous project (Bauman et al 2015) by conducting right-now surveys before deploying PCS devices. This took place between October 16 and October 22, 2014 during the swing season of San Jose, CA. The pre-existing set-point range in the building was 71°C - 75°C.

We deployed heated and cooled chairs on October 23, 2014. After an adjustment period, post-chair right-now surveys took place from November 3, 2014 to February 1, 2015 to capture the winter conditions. On February 2, 2015, we distributed footwarmers to the participants to provide additional comfort during the winter testing. Another set of right-now surveys took place between February 2 and February 20, 2015. During the winter study period, we applied two changes to the heating set-point to evaluate the effectiveness of PCS at cooler temperatures. Table 4.3 shows the sequence of heating set-point changes. At the end of the winter study, we raised the heating set-point back to 71˚F. Occupants were blinded from the set-point changes during the field testing periods. These results from the previous project are reported in Bauman et al 2015.

We paused the surveys during the spring season and resumed in June 2015, as part of the current project, to capture the summer conditions. The summer study took place between June 15 and September 5, 2015. Occupants had both chairs and desktop fans. We increased the cooling set-point twice during the summer study period. Table 4.4 shows the sequence of cooling set-point changes. At the end of the summer study, we restored the cooling set-point back to 75˚F.

Table 4.3. Winter survey schedule (Bauman et al. 2015)

Year	Date	Setpoint (ºF)	PCS	Phase	Notes
2014	Oct 16-22	71-75	none	Base	
2014	Nov 3-19	71-75	Chair	T1	Chair delivered on Oct. 23
2014	Dec 15-17	69.5-76.5	Chair	T2-F	Floor heating failed
2015	Jan 12-16	71-75	Chair	T3	SP changed back
2015	Jan 20-Feb 1	69.5-76.5	Chair	T4	SP 1.5°F expanded
2015	Feb 2-10	69.5-76.5	Chair + footwarmer	T5	Footwarmer delivered on Feb.2
2015	Feb 11 - 20	67-78	Chair + footwarmer	T6	SP 3°F expanded

Table 4.4. Summer survey schedule

Year	Date	Set-point (ºF)	PCS	Phase	Notes
2015	Jun 15- Jul 15	71-75	Chair + Fan	T7	Original SP
2015	Jul 27- Aug 15	69-77	Chair + Fan	T8	SP 2°F expanded
2015	Aug 15 – Aug 30	67-79	Chair + Fan	T9	SP 4°F expanded

4.0.10 Preliminary results from testing to date

Figure 4.7**Error! Reference source not found.** shows the distribution of air temperatures over all study periods. The temperatures only represent the times when surveys were submitted. During the winter study, air temperature ranged from 70˚F to 78°F (mean=73°F) before the temperature set-point changes. There was a three-day period (Phase T2-F in Table 4.3) when the radiant system accidently failed, causing a significant temperature drop (73˚F to 66°F) as shown in Figure 4.7. Integral Group repaired the system and restored the set-points back to the original. We continued our field testing in January 2015 and applied a heating set-point change from 71˚F to 69.5˚F and then to 67˚F. However, these adjustments did not have much impact on the actual room temperature due to high internal thermal loads.

In summer, during the current project, air temperature ranged from 72˚F to 80°F (mean = 76°F) with the original cooling set-point of 75˚F. Increasing the cooling set-point by 2°F effectively increased the mean room temperature to 77°F. An additional increase of 2°F (77˚F to 79˚F) further drove the mean room temperature to 78°F. °F) with the original cooling set-point of 75˚F. Increasing the cooling set-point by 2°F effectively increased the mean room temperature to 77°F. An additional increase of 2°F (77˚F to 79˚F) further drove the mean room temperature to 78°F. °F) with the original cooling set-point of 75˚F. Increasing the cooling set-point by 2°F effectively increased the mean room temperature to 77°F. An additional increase of 2°F (77˚F to 79˚F) further drove the mean room temperature to 78°F.

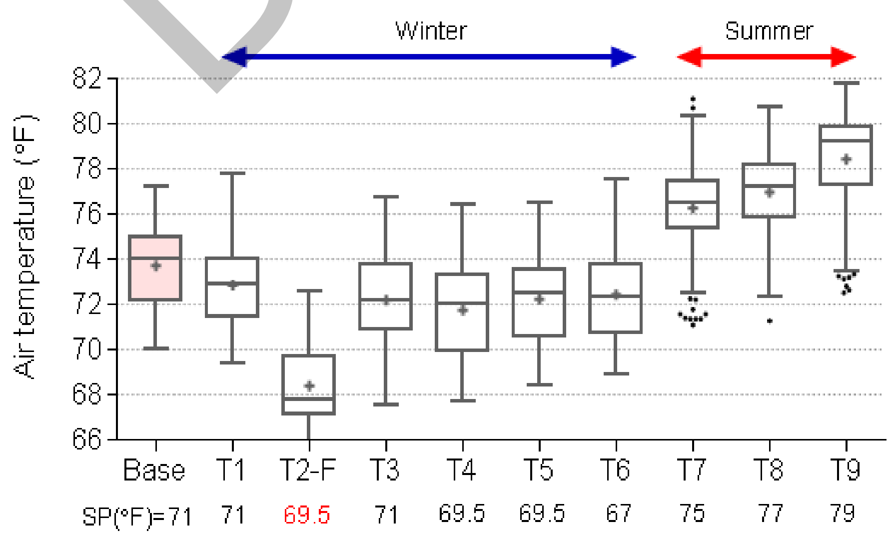

Figure 4.7. Room temperatures of all test phases

Figure 4.8 shows thermal acceptability votes and percent satisfaction rates of all test phases. Overall, the PCS chair was able to maintain thermal comfort with expanded temperature set-points. In all test periods except for the period of system failure, the average thermal acceptability with PCS was 82%, exceeding the baseline acceptability of 71%.

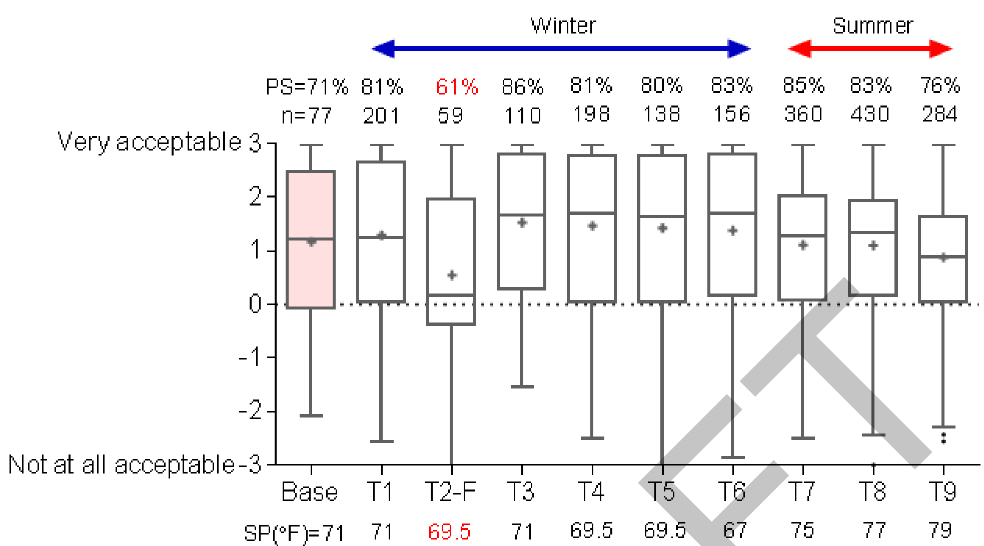

Figure 4.8. Thermal acceptability votes for all test phases

Figure 4.9 shows thermal sensation votes for both test phases. In winter, the votes were mostly within the range of "slightly cool" and "neutral" except for the period of system failure. We did not observe significant differences across different testing phases in winter. In summer, thermal sensation votes were mostly in the range of "neutral" to "slightly warm" except for the T9 phase. During T9, half of the survey responses were beyond "slightly warm", indicating that the PCS devices alone were not sufficient enough to keep the overall sensation at neutral.

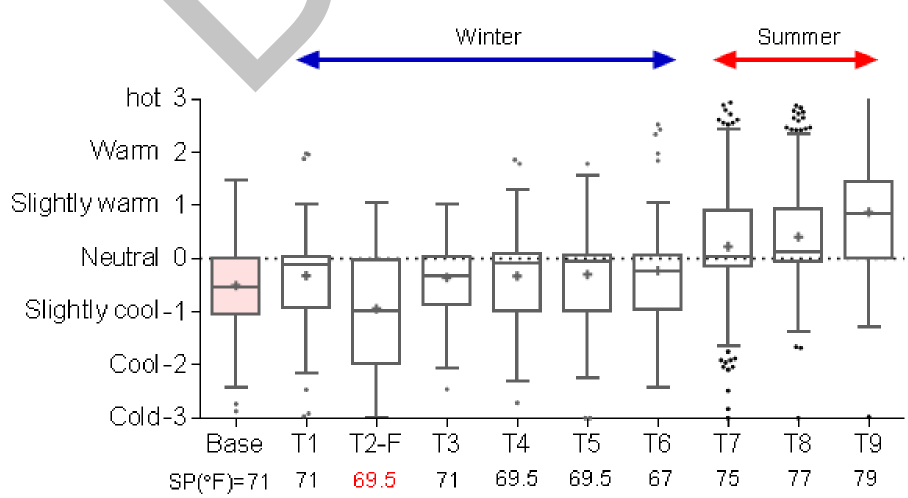

Figure 4.9. Thermal sensation votes of all test phases

Figure 4.10 shows the PCS chair usage over both study periods. The results clearly demonstrate how the occupants switch their preference from using primarily heating during the winter to using cooling during the summer. It is interesting to note that the average percentage of chair users (heating during winter or cooling during summer) is no higher than 30-40%.

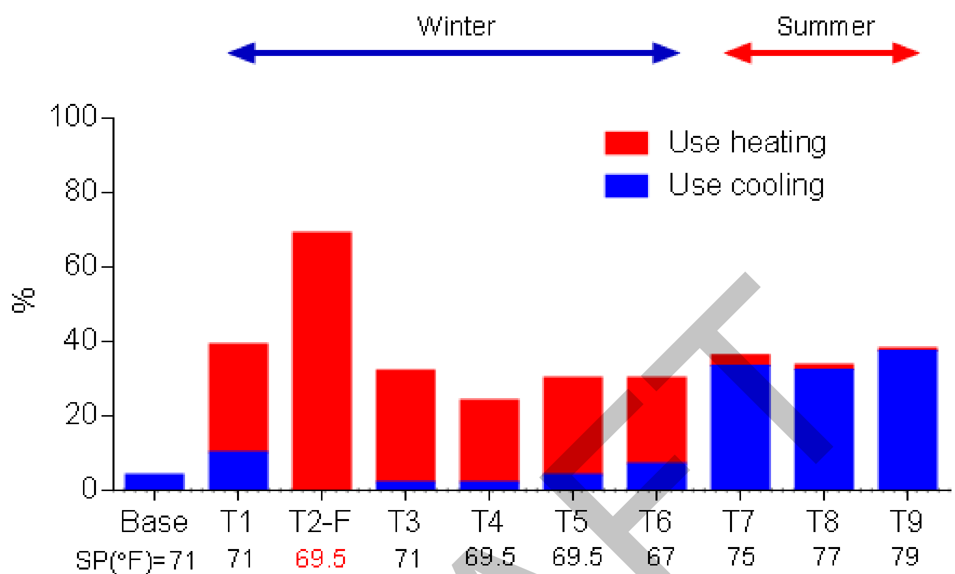

Figure 4.10. PCS usage in different phases

4.0.11 Occupant-responsive building controls

Occupant voting-based temperature control was installed in December 2015 by Comfy™, a recently founded technology startup. This technology is a software service that allows occupants to vote whether they are too hot, too cold, or neutral using a web interface. The underlying software uses sMAP and interfaces with the building management system to generate an immediate cold or hot response from the building's HVAC system (known as "blast mode"). It also learns voting patterns over time and modifies the zone temperature setpoints accordingly. Since the Integral Group office uses a radiant floor slab system, we requested that the normal blast mode not be installed. Instead, the proposed implementation was to make a change in the zone setpoint once per day based on the occupant responses received during the previous 24 hours. This recommendation was in accordance with operating guidelines for thermally massive radiant systems that avoid making any requests for quick changes in control.

During March 2016 as the weather started to warm up we observed some higher zone temperatures and increased complaints from some of the occupants. It was during this period that we determined that the occupant based-voting was not working in the way planned—still operating in the same blast mode as in a standard VAV reheat system. This quick response control was inappropriate for the radiant slab system in the building. Comfy™ did not have the software resources available to implement our originally proposed control algorithm and so this ended our investigation of integration with occupant voting-based temperature controls in the Integral Group office.

4.0.12 Summary and lessons learned

The demonstration field study in the Integral Group office in San Jose was undertaken to test how many of the innovative technologies developed in this project would integrate with a building that used an advanced HVAC system (in this case, radiant slab heating and cooling) instead of a more conventional VAV reheat air distribution system. Our major findings and lessons learned are summarized below.

- The quick-responding PCS heated and cooled chairs, along with other PCS devices (desktop fans and footwarmers), were able to provide improved thermal acceptability compared to the baseline acceptability (pre-PCS) of 71%. This improvement occurred for all testing periods during which the room temperature setpoints were expanded to cover the range of 67°F to 79°F. The only period when thermal acceptability fell below the baseline rate was when the building's heating system inadvertently failed and temperatures dropped to uncomfortable conditions.
- The advantage of PCS is in its ability to provide fast-responding conditioning to occupants when they desire it. The research team believes this capability is particularly well-suited for buildings involving low-energy radiant slab systems. Thermally massive radiant systems are unable to make quick changes in response to load or control changes. The PCS chairs can address these situations to satisfy an occupant's personal preferences, for example: cool mornings upon first arrival, when returning from a lunchtime activity or workout (increased metabolic rate), and warm conditions in the late afternoon.
- Measured HVAC energy savings in the building due to widening of the temperature setpoints were modest because the building is already extremely energy efficient. The main benefits were in terms of comfort, as described above.
- The installation of Comfy in the Integral Group office proved that this occupant-responsive control technology does not work with a radiant slab system when implemented in the "blast mode" control approach. Although we were not able to test other control approaches for Comfy in the building, we believe that there may be potential for the two alternative control strategies described below.
    - 24-hour setpoint adjustment – As described above, our original plan was to collect occupant Comfy votes during each day and use them to make any adjustments to the zone temperature setpoint for the following day. This adjustment would only be made once per day, so this approach would not provide the occupants with any kind of immediate response to their requests for more cooling or heating.
    - Use of Comfy to control ceiling fan – Integral Group was planning to install one large diameter Big Ass Fan in the main open office area on the ground floor. Although we were not able to complete this activity during the project due to delays beyond our control, the research team believes that this could be a good approach for integrating Comfy with a radiant slab system. By connecting the fan controls to the building management system and Comfy, it should be possible to use Comfy votes for more "cooling" to activate (or increase) the ceiling fan in the office. This would provide a quick response during the times when radiant slabs cannot satisfy

occupants' immediate or changing comfort needs. In addition, this large diameter fan will affect several occupants, and so the same challenges exist as in a VAV system, where multiple users with different comfort requirements are located in the same thermal zone, controlled by one setpoint. Comfy has the potential to find the consensus setpoint in these cases.

4.0.13 References

Bauman, Fred; Hui Zhang; Ed Arens; Paul Raftery; Caroline Karmann; Jingjuan (Dove) Feng; Yongchao Zhai; Stefano Schiavon; Darryl Dickerhoff; Xiang Zhou. Center for the Built Environment, University of California, Berkeley. 2015. Advanced Integrated Systems Technology Development: Personal Comfort and Radiant Slab Systems. California Energy Commission. Publication number: CEC-500-2016-068.
http://www.energy.ca.gov/2016publications/CEC-500-2016-068/index.html

CHAPTER 5:
Energy and Comfort Simulations

This section describes several activities that were undertaken using energy simulations to help provide comparisons and predict effectiveness, energy savings and comfort potential of the various combinations of strategies proposed in this research. An accompanying report presents full details of this work and is contained in Appendix 5.1. Energy and Comfort Simulations. A companion document is also included in Appendix 5.2. EnergyPlus Modeling Specifications.

5.1 Implement Clothing Insulation Model in EnergyPlus

Previously, EnergyPlus did not have the capability to realistically model the dynamic behavior of people regarding clothing worn throughout the year. During this project, modifications were made to the EnergyPlus release source code to model this behavior directly based on the dynamic clothing insulation model developed by Schiavon and Lee 2013. EnergyPlus users can now simply select this model from a drop-down list. Similarly, EnergyPlus now also models the ASHRAE Standard 55 (ASHRAE 2013) comfort criteria directly, by simply selecting the applicable model from a dropdown list, whether it is the method based on the predicted mean vote or the method based on the adaptive model by de Dear and Brager (1998).

5.2 Energy Comparison Parametric Studies

The Project updated simulation of energy use reduction with expanded zone air temperature setpoints, as might be achieved through use of Personal Comfort Systems (PCS) and/or occupant voting-based temperature control. Using parametric EnergyPlus models, the research team refined similar investigations from previous studies (Fernandez et al 2012, Hoyt et al 2012) by using building type models and parameters appropriate to the current context. The results of this simulation study are reported by Hoyt et al. (2015). A copy of the final publication is attached as Appendix 5.3. Extending Air Temperature Setpoints. The study also assessed energy savings potential from reducing zone minimum airflows to the required ventilation minimum airflow, as enabled by time-averaged ventilation (Section 3.1.1).

Key findings from the simulation study are as follows. Without reducing satisfaction levels, by increasing the cooling setpoint of 22.2°C (72°F) to 25°C (77°F), an average of 29% of cooling energy and 27% total HVAC energy savings are achieved. Reducing the heating setpoint of 21.1°C (70°F) to 20°C (68°F) saves an average of 34% of terminal heating energy.

These findings are supported by empirical studies from another project (Arens et al 2012). The empirical investigation conducted in one of the demonstrations for this project was inconclusive (Section 2.4). This demonstration included an already wide baseline range of 70-74°F, as well as active occupant vote-based temperature control with implementation conditions that may have confounded energy use reduction (Sections 2.0.4, 2.3, 2.4).

5.2.1 CBE Energy Setpoint Savings Calculator

As part of the above work, we also developed a web-based tool to aid in visualizing this data to designers, owners, occupants, and operators of buildings. The tool can be found here: http://comfort.cbe.berkeley.edu/energycalc/.

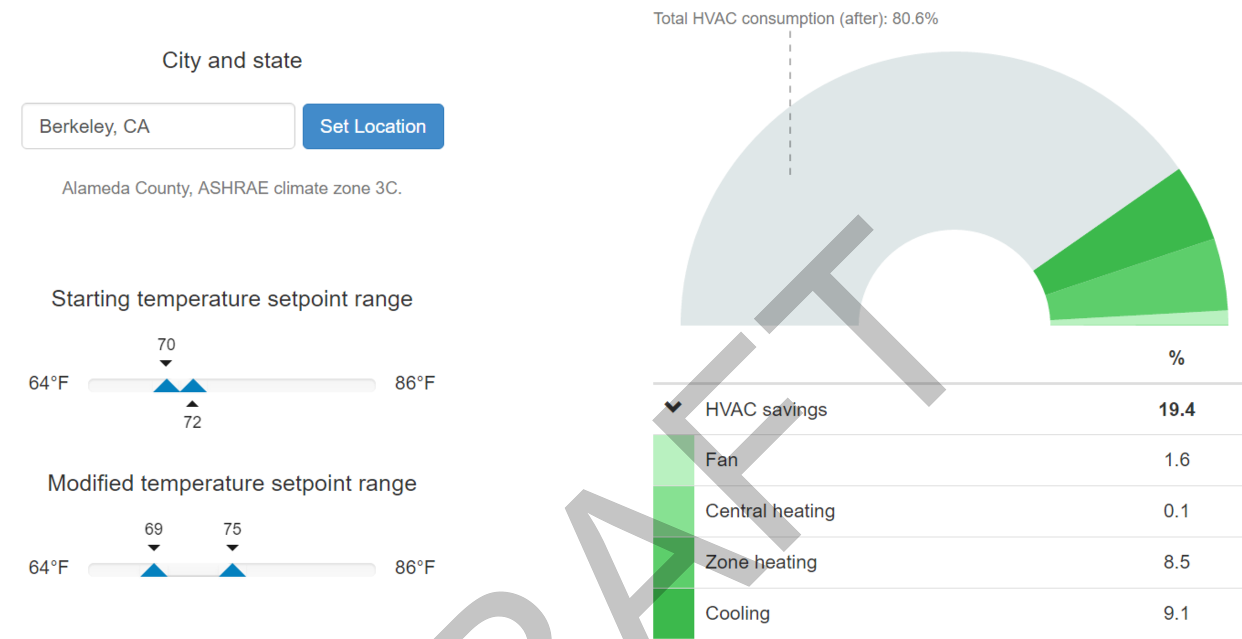

Figure 5.1. Screenshot of web tool to estimate energy savings from expanding setpoints based on zip code.

5.3 Simulation of Advanced Supply Air Temperature Reset Strategies

A new simulation tool was developed to model advanced supply air temperature (SAT) reset strategies that cannot currently be modeled in other commercial building simulation tools. Several SAT reset strategies were evaluated, including existing strategies, a newly developed approach, and the theoretical optimum control. Parametric simulations were performed to evaluate the impact of key building and HVAC factors on the various SAT reset strategies.

The goal of this simulation effort is to provide a method to:

- Evaluate the performance of the current best practice control sequences.
- Evaluate the novel cost-based optimization approach that was implemented in the Sutardja Dai Hall field site as part of this study (section 3.1.2).
- Compare the performance of the various SAT reset strategies to determine how closely they approach the theoretical optimum.

The SAT control strategies that were evaluated include:

1. Warmest: maximum SAT reset that still meets loads, this is similar to the typical strategy modeled in building simulation tools, though the eQUEST implementation also limits zone airflow.
2. Current ASHRAE Guideline 36 (ASHRAE 2016) best practice: maximum reset with outside air temperature limits between 60 and 70 °F.
3. Current ASHRAE Guideline 36 (G36) best practice: maximum reset with outside air temperature limits between 50 and 80 °F.
4. Fixed Setpoint: fixed setpoint of 55 °F with no reset.
5. Cost-Based reset: new approach that seeks to minimize energy cost by evaluating energy estimates in real time.
6. Theoretical Optimum: reset that provides the lowest possible energy cost as a reference to gauge the performance of the other methods.

The results of the simulation study show that relative performance of existing SAT reset control strategies is heavily dependent on a number of building and HVAC system factors, with these strategies using 3-15% more whole building energy cost than theoretical optimum control. Surprisingly, the control strategy described in ASHRAE Guideline 36 as the current industry best practice does not consistently provide lower energy costs compared to fixed SAT control. An adjustment to the default settings in the G36 strategy to have wider temperature limits improved its performance in each case and on average improves whole building savings by 1.8% over the current G36 limits. There is potential to use a simulation tool to customize G36 type limits to each application. However, the novel Cost-Based reset approach outperformed all of the other control strategies, achieving 5.6% whole building energy savings over the current G36 approach, and consistently approached the theoretical optimum performance. A key advantage of the Cost-Based reset approach over G36 is the ability to optimize for a wide variety of factors without any customization or tuning at individual building sites. See section 3.1.2 for field testing results of the cost-based SAT reset strategy.

5.4 References

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Schiavon, Stefano, and Kwang Ho Lee. 2013. "Dynamic Predictive Clothing Insulation Models Based on Outdoor Air and Indoor Operative Temperatures." *Building and Environment* 59: 250–60. http://dx.doi.org/10.1016/j.buildenv.2012.08.024

CHAPTER 6: Demonstration, Deployment, and Commercialization

During the early stages of the Project, the research team conducted developmental, or Stage 1, testing, during which we implemented and evaluated the innovative technologies in the Project: personal comfort systems (PCS), optimized VAV control strategies, and integrated information technology solutions. The lessons learned from this developmental testing informed our field study protocols that we refined and applied in our subsequent full demonstration field studies. Appendix 3.0.1. Developmental Field Study Report and Demonstration Field Study Plan presents these two deliverables, the results of the early developmental testing and the field study plan for the upcoming demonstrations.

6.1 HVAC Control Based on Occupant Requests

Cloud-based software is commercially available to enable sophisticated HVAC temperature control at the zone level—enabling building occupant requests for heating and cooling, responding to requests with immediate heating or cooling, aggregating requests as votes, and using machine learning to establish space temperature settings including dead bands. Space temperatures are typically allowed to float to establish wide dead bands based on occupant preference.

This control strategy may have the side effect of energy savings, especially in scenarios with low space utilization, low occupancy, or a baseline with an unnecessarily small dead band between zone heating and cooling set points. However, the primary intent is to maximize occupant satisfaction by finding the widest range of space temperatures bounded by occupant preferences. This strategy is informed by customer experience indicating that occupants prefer a diversity of ambient temperatures roughly correlated with outdoor temperatures—specifically disliking a tight uniform year-round dead band, over cooling in summer, or over heating in winter.

6.1.1 Occupant interaction with the service is through a web page or smart device app

The product described here and deployed in the project demonstrations is Comfy™. No similar products have been identified[12].

This product is marketed as a subscription service to increase personal thermal comfort of commercial building occupants. Marketing targets high-level executives concerned with multiple aspects of employee wellbeing. Though energy use reduction is asserted in marketing materials, no guarantees are made and no accounting of energy use is provided as a part of the service. Customer service and fulfillment is focused on occupant satisfaction around thermal comfort and interaction with the product.

[12] Other known apps enabling occupant control are limited to simple direct set point adjustments.

Product integration with the HVAC system is limited to zone temperature controls, avoiding interaction with other aspects of HVAC control (e.g., supply air temperature control at air handlers). This is part of a conscious strategy to limit interactions with other aspects of HVAC control and with facilities manager's strategies to save energy.

This strategy is evident in a recent evolution of the product to eliminate the management console for the building manager. This move educes the likelihood of multiple efforts to resolve hot and cold calls. Even more responsibility is created for product customer service—to resolve any issues that result from difficulty fulfilling occupant heating or cooling requests, or from otherwise controlling ambient temperatures. This is seen as advantageous over the complexity of interacting with facilities managers and energy management strategies. An online tool is anticipated allowing building managers to see, but not intervene with product activity.

This business model has been successful in meeting the vendor's goals for sales growth. Planning for additional growth is managing the effort-intensive customer service function by simplifying support—to focus on interaction with occupants around temperature control at the zone level while limiting interaction with facilities managers and energy management strategies.

This vendor has observed the market for software-based energy management services, noting two important things: 1) there is intensive effort involved in validating energy savings claims to fulfill explicit energy management assertions, and 2) this is a highly competitive market with as many business failures as successes among these vendors. This vendor is able to successfully market, generate revenue, and grow at the desired rate with the comfort-only offering. It sees no reason to add expenses, tackle more challenging scaling issues, or incur more business risk by explicitly including energy performance.

6.1.2 Other Vendors

It is possible that other vendors will enter the market with products offering similar HVAC control—based on immediate system response, longer term control based on an aggregate of occupant requests, and immediate relaxing of dead bands in the absence of requests. Perhaps these vendors will provide products explicitly integrated with direct energy management strategies. These products might have an advantage over the comfort-only products with clients that have especially strong energy management goals and/or facilities managers taking a strong leadership role.

6.1.3 Factors Enabling Commercialization

There may be potential for this technology to enable energy savings, even without a direct emphasis on energy in marketing of customer fulfillment.

6.1.4 No Direct Engagement with Energy Efficiency Standards

The vendor's avoidance of explicit energy savings claims precludes interaction with standards as a commercialization accelerator.

6.1.5 Building Labeling

Building labeling systems targeting environmental stewardship (e.g., LEED™) are increasingly incorporating credit for direct occupant control of thermal comfort conditions (e.g., space temperature or operable windows) or monitoring of thermal comfort conditions.

Products employing HVAC temperature control based on occupant request can often gain credit for occupant control and/or monitoring. Commercialization might be accelerated for HVAC control based on occupant requests by advancing credit for occupant control and/or monitoring—in a way that takes advantages of the synergies between comfort and energy efficiency.

6.1.6 Building Leasing

Standard building leases often specify tight temperature control requirements. These requirements are not necessarily consistent with comfort science or the advantages of HVAC control based on occupant requests. Building leases that reference accepted comfort standards (e.g., ASHRAE Standard 55) or explicitly allow occupant voting with learning algorithms might accelerate commercialization of HVAC control based on occupant requests.

6.1.7 Building Controls

Deployment of the product is facilitated by a high degree of BACnet-based interoperability for the building automation system, as well as sophisticated cyber security protocols that both enable and protect cloud-based communication.

6.1.8 Interaction with Advanced HVAC Controls

Few interactions or conflicts were observed between HVAC control based on occupant requests and advanced HVAC controls demonstrated by this project. This might be expected given the vendor intent to decouple as much as possible the occupant based temperature control at the zone from energy management strategies for other HVAC controls.

Observations during the demonstration field test indicate integration with advanced VAV controls may have a synergistic effect on energy use reduction.[13] Please see Chapter 2 for details.

Observations of the technologies deployed alongside each other suggest the following steps for potential technology integration:

- The occupant-based controls interface could notify the user when their cooling request will determine the optimal set point for the whole building. i.e., when their request will require a lower supply air temperature set point at the air handling unit.

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[13] Energy savings from occupant-based HVAC control was not observable outside experimental uncertainty in the demonstration field test. This may have been due to a relatively efficient baseline condition and/or issues with VAV controls.

- The occupant-based controls interface could notify the user when their heating/cooling request may be due to a fault in the HVAC system. i.e., when the zone is not capable of controlling to the set point at the time the user votes.

This integration, coupling the technology with energy management efforts for the centralized parts of the HVAC system, is possibly counter to the current business model of the vendor. The vendor is avoiding such coupling. As such it may be unlikely to be implemented.

6.1.9 Interaction with Personal Comfort Systems

There are two most likely modes of deployment of personal comfort systems (PCS e.g., low energy heated and cooled chairs) with HVAC control based on occupant requests:

1. Deployment of PCS for all occupants in a zone.
2. Deployment of PCS for a small number of occupants not satisfied with the performance of the HVAC controls based on occupant requests.

The vendor is interested in the potential of the second mode—to increase occupant satisfaction from already high percentages to be all-inclusive. This enhances the value of the simple comfort-only product offering. Given the strong growth rate of this product offering, even a small number of PCS per building could represent a major market. The vendor considers sophisticated communications capability to be a key enabling feature for PCS, including the ability to obtain additional indirect information on preferences from occupant operation of the PCS.

Anecdotal results from the demonstration field study support the idea of deployment of PCS for a small number of occupants who cannot be satisfied by consensus set points. Limited availability of PCS chairs precluded exploration of the mode deploying to all occupants in a zone. Please see Chapter 2 for more details.

6.2 Advanced VAV Control Strategies

Two advanced variable air-volume (VAV) control strategies were developed and demonstrated by this project:

- Time-Averaged Ventilation
- Live Cost-Based Optimization of Supply Air Temperature

6.2.1 Time-Averaged Ventilation

Implementation of time-averaged ventilation by this project builds on and leverages previous understanding of the challenges that lack of turndown capability for VAV boxes pose for of optimizing ventilation rates. Codes and standards (e.g., California Title 24 and ASHRAE Standard 62) already recognize the practicality of averaging periods of closed dampers providing near zero ventilation with periods of open dampers to provide required ventilation rates.

This project has created algorithms that actively produce pulse width modulation of dampers to explicitly control ventilation rates. The project has demonstrated programming of these algorithms using an open source software package (sMAP and pybacnet) and the existing building automation system controller and network infrastructure. Confidence developed though this project has led to implementation by project team member Taylor Engineering in another San Mateo County building and at least one other application in California.

6.2.1.1 Codes and Standards

No codes or standards changes are needed to allow implementation of TAV technology. Changes in codes and standards can encourage implementation, accelerating commercialization of TAV technology. Performance assessment in standards or new construction incentive programs need to recognize the ability of the technology to control tightly to the minimum ventilation rate and allow the full energy performance advantage to be captured. These potential changes are discussed in more detail in Chapter 7. With these potential changes the full imperative to increase energy efficiency from the standards will be in effect for TAV technology.

6.2.1.2 Technology Transfer

Per Section 3.1.1 a paper describing TAV implementation has been published by this project (Kaam et al. 2017). The TAV approach has also been incorporated in ASHRAE Guideline 36 (anticipated to be published later in 2017)—which will provide broad distribution and encourage widespread application. Professional meeting presentations are also planned to disseminate results.

6.2.1.3 Potential Additional Commercialization Steps

Additional activities that could further accelerate commercialization include a scaled pilot, possibly as a part of an emerging technology program, or a targeted incentive program.

6.2.1.4 Alternative Approaches

Other new technology can and should compete with TAV to optimize ventilation rates. VAV boxes with inherently greater turndown ability, possibly with new anemometer technology, or tighter design could compete with or complement TAV. Because of these alternatives, TAV technology is likely to find greater applications in retrofit than in new construction where controllers are more likely to be more accurate down to very low flows.

6.2.1.5 Interaction with Occupant-Based Control Technology

This project implemented TAV technology in parallel HVAC control based on occupant requests (i.e., Comfy ™) including the "blast" capability providing immediate heating or cooling (and increased ventilation). It was relatively straightforward to restore TAV operation after a "burst" episode. So there is no inherent incompatibility of the technologies. However, the current deployment of TAV does not capture the extra ventilation provided in the "burst" episode and so performance may be slightly impinged.

6.2.2 Live Cost-Based Optimization of Control Parameters

This project field tested a new air temperature reset algorithm based on estimating the dynamic cost of chilled water, reheat, and fan power, and then selecting the SAT that yields the minimum cost, subject to comfort constraints. The implementation is designed around the specific configuration of the demonstration site. Prior to commercialization efforts more development and field test activities are needed in buildings with variations in equipment.

The complexity of the algorithms implies substantial product development efforts. It is not yet clear if this will occur through open source software that vendors can adapt to their product offerings or through product-specific software development by individual vendors.

Two eventual technology transfer venues are inclusion in:

- ASHRAE Standard Guideline 36—High Performance Sequences of Operation for HVAC Control Systems. This is likely to be included in the first version, to be published later in 2017.
- Future versions of advanced VAV design guides.

6.3 Personal Comfort Systems

This project continued demonstrations of personal comfort systems (PCS), primarily the low energy heated and cooled chair, often alongside other technologies. Results are consistent with significant potential for energy savings as well as improved occupant comfort.

Results illustrate the importance of the user interface and communications capabilities for low energy heated and cooled chairs. Commercialization efforts will benefit from feeding this information into ongoing product improvement efforts.

There is a marketing opportunity for PCS in conjunction with sophisticated HVAC control based on occupant requests (Please see Section 6.1). Vendors of the control technologies may seek to increase the occupant satisfaction percentage even more, approaching 100% with PCS. This is envisioned as a deployment of PCS limited to a small residual percentage of dissatisfied occupants, as opposed to a universal deployment of PCS.

Other aspects of commercialization are being addressed in proprietary discussions with licensee(s) of the low energy heated and cooled chair technology. Specifics are proprietary.

Other parts of this report detail some additional activities supporting commercialization:

- Method of test for PCS devices (Chapter 1)
- Modeling specifications accounting for PCS devices (Appendix 5.2)
- Proposed changes to codes and standards (e.g., ASHRAE Standard 55) considering PCS devices (Chapter 7)

6.4 Enabling Information Technology

Innovative open-source software can enable the development and integration of the occupant-based HVAC technology explored by this Project. The field research on the PCS chairs was supported by the simple Measurement and Actuation Protocol (sMAP), with similar data management capability likely playing into and deployment integrated with other HVAC technology. sMAP is an underlying technology for the commercially available occupant voting-based temperature control product. sMAP provides a means to deploy advanced VAV control algorithms that offered advantages over direct implementation through a BMS.

This technology is itself evolving with UC Berkeley Electrical Engineering and Computer Science Department researchers creating a different archiver in the eXtensible Building Operating System or XBOS (Fiero et al. 2015), replacing powerdb with the high performance Berkeley Tree Database or BTrDB (Andersen et al. 2016), and providing drivers with distributed authentication and authorization through BOSSWAVE[14].

sMAP/XBOS provides utility by providing a consistent interface to link data from various sources to flexible and extensible control code, enabling interoperability (Peffer et al 2016). sMAP/XBOS provides simple uniform abstractions of sensors and controls that can make it easier to apply advanced techniques, especially in buildings with older direct digital control BMS.

Addressing portability between buildings and establishing viable business models are among the remaining milestones on the path to commercialization for this enabling technology. More progress is needed in automating metadata acquisition to map the structure and relationships for legacy BMS points serving a range of HVAC configurations. The use of the technology by the occupant vote-based temperature control vendor illustrates the extensive level of effort required to develop and service a robust product. Business models to fund this must be linked to value-added for building operations.

6.5 References

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[14] https://github.com/immesys/bw2/wiki/BOSSWAVE-overview

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CHAPTER 7:
Standards and Codes

The purpose of Task 4: Standards and Codes is to facilitate a discussion of the project's potential to influence the future development of efficiency standards for buildings and appliances. A technology must have a record of accomplishment in the market before being considered as a basis for code development. The product must demonstrate adequate and consistent energy savings, be readily available in the market, and be non-proprietary in nature in order to be considered for a code revision.

In this chapter we identify code change potential for Personal Comfort Systems and Variable Air Volume System Controls. Further, this report identifies the potential for code changes at both the state energy code level (Title 24 Building Energy Efficiency Standards, Title 20 Appliance Efficiency Standards), as well as national energy and comfort standards (ASHRAE Standards 90.1, 189.1 and 55).

Table 7.1 provides a snapshot of the code potential analysis conducted. Full details on each of the code opportunities are provided in Appendix 7.1. Standards and Codes. Below, we present a summary.

7.1 Title 24 Code Change Options

In this section, we describe the potential code changes possible within California's Title 24 building energy efficiency standards based on results of this project. There are generally three types of code changes feasible for Title 24 – prescriptive requirements, performance specifications and modeling rules for the performance approach.

Title 24 code change cycle is a three- to four-year process and the CEC's priorities for the 2019 Title 24 code is to focus on residential building energy efficiency and renewables in order to achieve the stated goal of Zero Net Energy for residential buildings by 2020. As such, there are limited opportunities to affect changes to commercial buildings in 2019. With that in mind, this section outlines code change ideas that we feel are necessary but the implementation of these code change ideas may not be done within the time period of this project. For example, the recommended changes may need to be considered for the 2022/2023 Title 24 and beyond. Where feasible, we make recommendations for code changes now (2019) versus where the changes may need more time due to lack of industry consensus, experience or cost-effectiveness.

7.1.1 ACM rules for modeling PCS

Allow different temperature setpoints when equivalent comfort is demonstrated through the use of PCS devices, compared to traditional setpoints used by building codes and operators. The energy modeling rules for Title 24 can be developed based on further work on the Corrective Power index explained in Section 2.2 as well as MOT being developed for ceiling fans under the proposed ASHRAE Standard 216. Note that this change cannot be proposed to Title 24 till the underlying work on ASHRAE Std. 216 and MOT for PCS is completed.

Table 7.1: Summary of Potential Code Changes

Measure Category	**Title 24 Potential Changes**	**Title 20 Potential Changes**	**ASHRAE 90.1/189.1 Potential Changes**	**ASHRAE 55 Potential Changes**
Personal Comfort Systems	ACM rules for modeling PCS Compliance Option for Occupant Feedback Systems	Minimum Efficiency for Personal Heater Performance Metrics for PCS		Comfort Assessment Methods for PCS Comfort Classes Based on PCS Compliance Option for Occupant Feedback Systems
Variable Air Volume System Controls	Time Averaged Ventilation Prescribed Supply Air Temperature Reset Require Controls that Prevent Zone Fighting Require Zone Discharge Air Temperature Sensors		Time Averaged Ventilation Prescribed Supply Air Temperature Reset Require Controls that Prevent Zone Fighting Require Zone Discharge Air Temperature Sensors	

7.1.2 Compliance Option for Occupant Feedback Systems

Develop a compliance option for occupant feedback systems that allows different temperature setpoints when equivalent comfort is demonstrated through the use of Occupant Feedback Systems, compared to traditional setpoints used by building codes and operators. At this stage, the study results show that energy savings are minimal at best for the particular strategy evaluated and more work is needed to evaluate savings potential over a larger range of buildings and occupant feedback systems before a code change can be proposed.

7.1.3 Time-Averaged Ventilation

With the development and validation of an effective control sequence to implement time-averaged ventilation (TAV), the prescriptive requirements in Title 24 could be revised to eliminate the 20 percent airflow criterion when in deadband and to prescriptively require the use of TAV when the required ventilation is less than 20 percent of the peak airflow. The definitions of the reference/baseline building system for the performance modeling approach in Title 24 could also be revised accordingly. The study results are robust enough to support a code change initiative for the 2022 Title 24 updates.

7.1.4 Prescribed Supply Air Temperature Reset

The prescriptive code sections that require supply air temperature reset in Title 24 and Standard 90.1 could be revised to require reset based on zone feedback for systems with DDC to the zone. Note that this is a fairly simple change that represents best practice and we are suggesting this change to fill an apparent weakness in the current code language. Thus, we feel this code change has the potential to be adopted for 2019 (schedule permitting) or 2022 Title 24 updates.

7.1.5 Require Controls that Prevent Zone Fighting

Zones that share an airspace coul be programmed to not operate in competing modes (heating & cooling) at the same time. Examples include: multiple thermostats in one room, large spaces served by multiple zones with separate thermostats, etc. This proposed requirement can be implemented in most programmable digital control systems, although the process is manual and can be time consuming. While the code change is easy, there needs to be more work done to identify best practices to implement the proposed requirements.

7.1.6 Require Zone Discharge Air Temperature Sensors

This measure would improve upon the requirements for zone discharge air temperature sensors for VAV reheat zones. The proposed code change adds clarifications to the existing Title 24 requirements. A discharge air temperature sensor is required to meet the current Title 24 requirements for controlling heating discharge air, but the code language is not clear and is occasionally mis-interpreted.

7.2 Title 20 Code Change Options

Title 20 is a continuous improvement process as opposed to Title 24 which is updated on a set schedule of 3-4 years. However, the CEC still has a rigorous process of selecting measures and stages/groups Title 20 measures based on overall code priorities. Title 20 requirements include mandatory performance thresholds (e.g. minimum lumens/watt for lighting), test standards and performance specifications. Unlike Title 24, where a builder/designer has options to not include measures that are prescriptively required and use the performance method to trade-off measures, Title 20 requirements set the floor for what equipment can be legally sold in the state. As such, there is a high bar for changing Title 20 requirements and extensive industry and stakeholder participation is necessary to ensure that Title 20 rules are just and help the overall state.

7.2.1 Minimum Efficiency for Personal Heater

This project developed a personal heater thermal manikin based method of test and implemented one test procedure. However, at this stage, a change in Title 20 cannot be proposed because, before implementation, the developed method of test should be compared with alternative methods for measuring the Heating Effect. Based on the study results to date, the efficiency levels may need to be set based on the mode of heat transfer (conductive, convective, radiative).

7.2.2 Performance Metrics for PCS

Based on results of this project as well as related studies being conducted by CBE, a performance index called 'corrective power' (CP) has been proposed. CP is defined as difference between two ambient temperatures at which equal thermal sensation is achieved - one with no PCS (the reference condition), and one with PCS in use. CP represents the degree to which a PCS system may "correct" the ambient temperature toward thermal neutrality. At this time, the CP concept has been established but further work is necessary to established methods of test to calculate and verify CP of various PCS devices. Current work is based on literature review and needs to be expanded to field verifications based on various methods before a MOT is developed for PCS devices that can be used for Title 20 performance metrics for PCS.

7.3 ASHRAE Standards 90.1/189.1 Change Options

Similar to Title 24, the ASHRAE Standard 90.1 code updates are on a three-year cycle for full publication. However, unlike Title 24, where there is a set rule-making period for each full update of the standard, 90.1 works on a continuous maintenance model where addendum are proposed, discussed, modified and approved through an exhaustive committee process within ASHRAE and a public review and comment on the proposed requirements. ASHRAE 90.1 sets the minimum requirements for energy efficiency of most buildings except low-rise residential buildings and has been the benchmark for commercial building energy codes in the US.

ASHRAE Standard 189.1 is also on a three-year cycle as is Standard 90.1, as well as using the continuous improvement model. Standard 189.1 provides total building sustainability guidance for designing, building, and operating high-performance green buildings. From site location to energy use to recycling, this standard sets the foundation for green buildings by addressing site sustainability, water use efficiency, energy efficiency, indoor environmental quality (IEQ), and the building's impact on the atmosphere, materials and resources. Standard 189.1 is a compliance option of the International Green Construction Code™ (IgCC).

The proposed code changes for 90.1 and 189.1 are similar in nature to those proposed for Title 24. For the sake of brevity of this report, we do not repeat those requirements within this sub-section but refer the reader to Table 7.1 for a summary and Appendix 7.1 for details.

7.4 ASHRAE Standard 55 Change Options

7.4.1 About Standard 55

Standard 55 is in a continuous improvement process much like 90.1 and 189.1 where proposed standards changes are considered as addendum to the existing standards. Standard 55 applies to both design and operation of buildings through separate sections of the Standard.

7.4.2 Recent Updates to Standard 55 Relevant to PCS

Many personal comfort systems rely on using elevated airspeed for achieving intended cooling. In addition, mixing via ceiling fans or ducted mechanical systems inadvertently affect comfort under heating conditions. These approaches to building environmental controls required new attention to how air movement was addressed in Standard 55. During the course of this project, the following work was done on Standard 55 provisions for air movement: raising the still air zone threshold to 0.2 m/s, and eliminating the upper airspeed limit when the airspeed is under group/individual control. As part of these changes CBE prepared new text and comfort zone graphics. CBE coordinated with comfort researchers in Germany, UK, and Australia to fix bugs and annotate the SET model which underlies the determination of comfort under the four environmental parameters affecting thermal comfort. The ASHRAE Std. 55 version of the computer code is now the standard. This international work was done via CBE's concurrent involvement in IEA Annex 69. ASHRAE Publications will release an ASHRAE version of the CBE Thermal Comfort Tool to be the official calculation tool for Standard 55. The Thermal Comfort Tool operates with the newly-standard version of the SET model.

A User's Guide has been prepared for Std. 55 by TRC with CBE as a participant. Within the User's Guide, the role of air movement on comfort is addressed for the full range of operative temperatures and humidity using the ASHRAE/CBE Thermal Comfort Tool. The User's Guide was published by ASHRAE in 2016.

Finally, window shades are also PCS options, since solar gains are localized and window shades are typically under occupant control. The design and operation of window shades required provisions in the Standard. CBE developed in this period a new normative addendum in Standard 55 for accounting for shortwave (solar) radiation effects on occupants. The new normative procedure is embodied in the SolarCal model, which is now incorporated in the CBE Thermal Comfort Tool, and will soon also be part of the ASHRAE official tool. The addendum was formally adopted by ASHRAE in November 2016.

7.4.3 Proposed Changes

7.4.3.1 Comfort Assessment Methods for PCS

Update Standard 55 requirements and assessment methods to explicitly address PCS in their ability to provide occupant thermal comfort at conditions that may be different than those of the ambient environment due to user adaptation and localized comfort provided by PCS. Work on this proposed change depends on and building on work being done on International Energy Agency EBC Annex 69 "Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings."

7.4.3.2 Comfort Classes Based on PCS

This change proposes a new approach to evaluating the potential of occupants to regulate environmental conditions to attain thermal comfort in buildings based on the level of personal occupant controls available to the occupants. In principle, a building with higher level of personal control will get a higher classification designation.

During the 2017 Winter meeting of the ASHRAE SSPC 55 (the cognizant committee in charge of ASHRAE Standard 55), there was a proposed addendum proposed by committee members (including members of this study team). More discussions will follow and there is likely to be a vote ready proposal within six months.

7.4.3.3 Compliance Option for Occupant Feedback Systems

For ASHRAE standard 55, develop modeling rules for addressing occupant feedback systems that cannot be currently modeled. As with the Title 24 code change potential, more work is needed to evaluate savings potential over a larger range of buildings and occupant feedback systems before a code change can be proposed.

GLOSSARY

Term	Definition
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BMS	Building management system
C	Degrees Celsius
CBE	Center for the Built Environment
CITRIS	Center for Information Technology Research in the Interest of Society
CP	Corrective power
DDC	Direct digital control
DSP	Dust static pressure
EECS	UC Berkeley Department of Electronic Engineering and Computer Science
F	Degrees Farenheit
G36	ASHRAE Guideline 36
GSA	U.S. General Services Administration
HE	Heating effect
HVAC	Heating, ventilating, and air-conditioning
IDeAs	Integrated Design Associates
IEQ	Indoor environmental quality
IgCC	International Green Construction Code
LEED	U.S. Green Building Council's Leadership in Energy and Environmental Design
NSF	National Science Foundation
PCS	Personal comfort systems
PHE	Personal heater efficiency

PIER	California Energy Commission Public Interest Energy Research
PMV	Predicted mean vote
RD&D	Research, development, and demostration
RTU	Rooftop units
SAT	Supply air temperature
SDH	Sutardja Dai Hall, on the UC Berkeley campus
sMAP	Simple monitoring and actuation profile
SMC	San Mateo County
TAV	Time-averaged ventilation
UCB	University of California, Berkeley
UI	User interface
VAV	Variable air volume

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