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Occupant thermal feedback for improved efficiency in university buildings

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ABSTRACT

Heating, Ventilation, and Air Conditioning (HVAC) systems are responsible for more than half of the energy consumed in many buildings on university campuses in the US. Despite the significant amount of energy spent on HVAC operations, thermal comfort conditions in campus buildings are frequently poor. Faulty assumptions or a lack of data regarding occupant comfort can lead to energy waste from overheating or overcooling. Additionally, inadequate operational procedures and outdated technology make it difficult for occupant needs to inform temperature management. For example, campuses frequently use "work order" systems to manage temperature issues, but this process is slow and not widely used by students, i.e., the majority of building occupants. Previous research suggests that thermal comfort feedback from occupants can simultaneously drive energy efficiency and improve comfort in university buildings. However, these prior studies were limited to single buildings or zones inside buildings. This paper describes the campus-wide deployment of TherMOOstat, a software tool that solicits thermal feedback from students, and analyzes its impact on energy use and energy management procedures. Thermal feedback can be submitted any time from any building on central campus. Over 10,000 feedback submissions were received across one year, transforming occupants into meaningful sensors. The research team explored manual and automatic methods to link occupant thermal feedback to the energy management system, resulting in improved efficiency and comfort.

1. Introduction/background

1.1. Thermal conditioning in institutional buildings

In the US, Heating, Ventilation, and Air Conditioning (HVAC) operations account for more than 40% of total energy use in institutional buildings, and often exceeds 60% in laboratories [1]. Infrastructural solutions to optimize HVAC efficiency are available to new construction, but institutions, e.g., governmental and university campuses, often inhabit long-standing buildings. Innovative HVAC control strategies represent a solution to HVAC efficiency relevant to existing institutional buildings. While some of these control methods such as demand controlled ventilation and variable capacity control may require new hardware, other strategies like dynamic pressure resets and dynamic setpoint management can be deployed with changes limited to the software [2–4].

The conventional approach to HVAC management in large institutional buildings involves centralized control of temperature setpoints, whereby thermostats are accessible to a restricted number of occupants, or in some cases exclusively to facilities management personnel. In cases where occupants are out of the loop, control strategies typically involve standardized temperature settings based on building type and use, as well as assumptions about occupant thermal comfort. These HVAC control systems have limited ability to respond to occupant thermal preferences, thus providing inadequate level of thermal comfort, and using far more energy than needed [5].

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1.2. Thermal comfort

Thermal comfort is a complex phenomenon, defined by American Society of Heating, Refrigerating and Air-Conditioning Engineers [6] as "that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation". Despite its subjective nature, researchers have tried to model and quantify thermal comfort for practical applications, such as standardized thermostat settings. Fanger [7] developed a model to predict the mean thermal sensation of a group of people, i.e., Predicted Mean Vote (PMV), and the percentage dissatisfied with thermal conditions, i.e., Predicted Percentage Dissatisfied (PPD), based on six parameters: air temperature, radiant temperature, air speed, humidity, occupant clothing, and metabolic rate. This method still represents the core of established building standards that define acceptability of the indoor environment, such as ASHRAE [6] Standard 55 and the International Organization for Standardization [8,31,32] Standard 7730. However, research has since demonstrated a low correlation between thermal comfort and actual room temperature [18], suggesting there is no good substitute for direct occupant feedback to determine thermal comfort.

1.3. Participatory control through occupant feedback

In the past five years, a number of studies have developed innovative strategies to incorporate occupant feedback into HVAC management and control strategies for institutional buildings. Many of these studies focused on university buildings [9–12], and the majority imply or demonstrate improved efficiency and/or comfort as a result of including direct assessments of occupant thermal comfort in HVAC control strategies.

Some of these studies described open-loop systems, in which feedback was not directly incorporated into HVAC controls [13], but the majority developed closed-loop control systems. Erickson and Cerpa [11] employed a control algorithm based on a reconciliation of PMV (used as proxy for thermal comfort) and actual mean vote of occupants in real-time. Hang-yat Lam et al. [14,12] used a temperature-comfort correlation model to establish a relationship between the indoor and outdoor temperature and the comfort index of each individual occupant. They used this relationship to calculate setpoints and drive the HVAC system. Purdon et al. [15] rejected PMV entirely and used an algorithm that simply increased or decreased the temperature based directly on thermal comfort votes. They also used a "drift" strategy, whereby temperature setpoints slowly drift toward ambient outdoor temperature, unless occupants explicitly state lack of comfort. Gupta et al. [16] used a further simplified binary indication of comfort to estimate user comfort range and fed the information to an energy cost optimizer to change setpoints. Baker and Hoyt [9] used machine learning to estimate time-dependent occupant preferences and use them to widen temperature deadbands in the building management system [9].

The most common type of interface used for soliciting thermal comfort feedback from building occupants in these studies was a basic mobile application [11], although Song et al. [17] employed a more complex dashboard with a variety of features. The format for thermal comfort voting ranged from 3-point to 10-point scales, frequently using the ASHRAE Standard 55 7-point scale (e.g., [11]) or an adaptation of it (e.g., [18]). Most scales were labeled using words (e.g., "hot", "neutral", "cold"); Purdon et al. used icons (snowflake, smiley face, or fire). Most scales also made use of color, i.e., blues to indicate cold, reds to indicate hot, and greens or grayscales to indicate satisfaction or neutrality, respectively.

Estimated energy savings in these thermal comfort studies ranged from 5% [10] to 60% [15]. Thermal comfort and/or satisfaction (not always sufficiently distinguished from each other) were found to be improved (satisfaction; [11,14]), maintained (comfort; [12]), or negligibly reduced (comfort; [15]). With the exception of [9], the testbed for these experiments was typically limited to one or two university buildings, and often just a subset of rooms or zones within a single building. Most evaluations were based on simulations. The few field experiments ranged from 10 days [10] to 5 months [11] in duration.

This body of work has mostly focused on the software and hardware advances for participatory control systems, while little attention has been paid to the impact of this technology on the organization that adopts it. The facility management department is often in charge of maintenance and management of comfort-related complaints in a large campus. Outdated technology and inadequate operational procedures, such as traditional "work orders" can be roadblocks to the deployment of innovative analytical tools and control strategies in real-world scenarios. Facility technicians adopt very simple protocols to deal with comfort complaints and do not like to interact with complex black-box algorithms when troubleshooting an HVAC problem. Since most actors in the organization are risk averse, a large campus is unlikely to massively adopt these automatic closed-loop systems. Our literature review highlights the need to further explore strategies to successfully deploy these systems at scale.

Here we describe design, development, and preliminary evaluation of a participatory thermal feedback and control system at University of California, Davis. In developing this system, we were guided by the following overarching goals:

- Engage building occupants, especially students
- Collect information to support analysis of energy efficiency and comfort
- Integrate occupant feedback into building control systems
- Improve energy efficiency and comfort.

The system was designed in three phases: open-loop feedback, manual closed-loop control, and a prototype of an automatic closed-loop system. We discuss the role of different actors in the development and deployment of this tool and the lesson learned at each stage of the implementation. The aim of this article is to be a "blueprint" for other campuses wishing to adopt a similar approach to achieve thermal comfort and energy savings without compromising human requirements. We emphasize the high organizational value of involving occupants in providing direct thermal feedback and of training the technical personnel in examining the operation and performing diagnostics of the systems based on occupant needs. We also highlight the challenges of applying cutting-edge tools developed in academia to a real campus.

2. Method

To set the stage for our project, we first briefly describe the traditional HVAC management workflow at UC Davis. We then outline our methodology for redesigning the process through the integration of a participatory thermal feedback and control system.

2.1. Traditional campus HVAC management

There are roughly 1600 buildings associated with the UC Davis campus. Of these, 700 are on the main campus. The Facilities Management Department oversees the operation of all these buildings, including maintenance and custodial services, energy conservation, and the customer support center. A work order system organizes and tracks service requests. Work orders are typically submitted by staff and faculty; most students cannot submit a work order via the online system. In 2015, 32,200 work orders were submitted, 19% of which concerned mechanical and HVAC scheduling issues.

The work order system is intensive in terms of human resources. Each complaint must be addressed, which involves someone at the call center entering information into a ticket, someone checking the building automation system (BAS) to identify and/or correct problems remotely, and often someone physically inspecting the systems in the building. The BAS is a traditional automation system provided by a large controls company and maintained by internal resources; there are over 100 large buildings using the BAS and each building has thousands of active sensor points. Ten HVAC control technicians and one lead programmer are tasked with responding to all HVAC-related work orders (totaling 6118 in 2015). As a result, the system of identifying and addressing HVAC issues on campus has been highly reactive.

With limited resources and a focus on customer service, Facilities Management has, historically, placed less emphasis on achieving energy efficiency. For example, there is an unverified assumption that relatively high temperature setpoints in summer can trigger more complaints. Furthermore, the potential energy savings for more conservative setpoints is difficult to measure, therefore there is no direct incentive in implementing them. Thus, this conventional HVAC management, which we believe represents the operations of many institutional buildings, fails to optimize both energy efficiency and occupant comfort.

2.2. Design of a new workflow and software tool

Fig. 1 shows the traditional HVAC management workflow (in black) involving occupants, facilities analysts, and HVAC technicians. Occupants submit work orders using an online form or contacting the call center. The work orders are sent to an analyst who prioritizes them and assigns them to HVAC technicians. These technicians physically inspect the HVAC system in the building and either reprogram the BAS through manual overrides or fix the physical problem that generated the complaint (e.g., fix a stuck damper). Most analyst time is dedicated to reactive maintenance. To free resources that can be dedicated to preventive maintenance or energy efficiency projects UC Davis Energy Conservation Office (ECO; an office within Facilities Management) plans to redirect most thermal comfort work orders to a new participatory thermal feedback and control system, called TherMOOstat. The core of this system is composed of two applications: a cow-themed thermal feedback application (the cow is an iconic symbol of UC Davis) and an automated control application. The architecture of this tool is depicted in Fig. 2. The feedback front-end interface collects thermal comfort preferences across campus and sends them to the back-end. The back-end filters the results and sends aggregated comfort data and special requests requiring additional analysis to the analysts (in green in Figs. 1 and 2), thus involving HVAC technicians only when strictly necessary. The new automatic control application analyzes occupant votes and, if necessary, adjusts the BAS setpoints (in blue in Figs. 1 and 2). Ideally, this automatic response should take care of a large portion of user requests. The authors, in collaboration with ECO, developed this new tool in three iterative phases. The final design of the software applications is detailed in the results section.

In Phase 1, our team developed the front-end interface and the back-end database for the thermal feedback application (Fig. 2). After preliminary tests, TherMOOstat was released campus-wide. In this initial phase, we aimed to identify and prioritize comfort and efficiency issues based on analysis of occupant feedback.

In Phase 2, we focused on a few critical buildings and rooms identified in Phase 1. Adjustments to the BAS were performed manually to fix the problems identified. We also collected a list of frequent issues and studied the technical challenge of exchanging information with the existing BAS. As an example of this process, we describe how we changed the control sequence in one building and analyzed resulting energy savings.

In Phase 3, we prototyped a software system to automatically close the HVAC control loop, adjusting zone setpoints based on occupant feedback. Each application uses an Application Programming Interface (API) to exchange data between applications and databases. A prototype was field tested in a small building to debug the software and evaluate the outcome of alternative control strategies.

3. Results

3.1. Phase 1: open-loop feedback system

3.1.1. Software developed

ECO developed two user-facing platforms: a widget on the University student and staff portal and a mobile web application. The purpose of having two platforms was to increase ease of access and gain a wider audience, e.g., users who do not regularly use the campus portal can use the mobile app. The interfaces were iteratively tested with users and the final design is shown in Fig. 3. The goal was to create an engaging and simple interface. The front-end was programmed with ColdFusion Adobe package, JavaScript, and CSS, whereas the back-end was coded with a MEAN stack (MySQL database, Express, AngularJS, NodeJS).

User interaction is the same via the widget and mobile app. First, the user is prompted to enter their building name and room number (Fig. 3, Image 1). Thermal feedback is then solicited by asking, "How does it feel in your room?" Response options are Hot, Warm, Perfect, Chilly, or Cold (Fig. 3, Image 2). We chose an abridged version of the ASHRAE scale, omitting the 'Slightly Warm' and 'Slightly Cool' levels, similar to Jazizadeh et al. [18], and modified the wording to be more colloquial with the intention of appealing to the student user group (i.e., 'Perfect' instead of 'Neutral' and 'Chilly' instead of 'Cool'). Users are also given the opportunity to leave comments in an open-response format before they submit their feedback (Fig. 3, Image 3). At the end of the submission, a summary of all votes for the building is provided to the user. More information about behavioral principles used in the design of the interface can be found in [19].

We connected other applications to the database through APIs. For instance, we displayed aggregated comfort data on a campus map to show users how others on campus have voted (Fig. 4). We also used these APIs to download data for further analysis with external tools.

3.1.2. Participation

The TherMOOstat widget was released in September 2014, and the web app in October 2015. In 2015, the TherMOOstat widget received an average of 550 thermal comfort votes per month. The web app, while only active for four months, received an average of 168 thermal comfort votes per month. The widget and app collectively received just under 10,000 thermal comfort votes and over 500 comments in 2015.

TheMOOstat users include UC Davis students, staff, and faculty. There were about 4300 unique users of the TherMOOstat widget and app in 2015. Widget users consisted of 89% students, 7% staff, 0.5% faculty, and 3.5% unknown. The app users consisted of 40% students, 57% staff, and 3% faculty. Users submitted thermal feedback for 152 of the 498 buildings listed on the app/widget. The highest volume of feedback came from buildings with heavy student traffic, reflecting the high percentage of student users.

3.1.3. Data and analysis

Over a 16-month period, between September 2014 and December 2015, the distribution of the aggregate thermal feedback

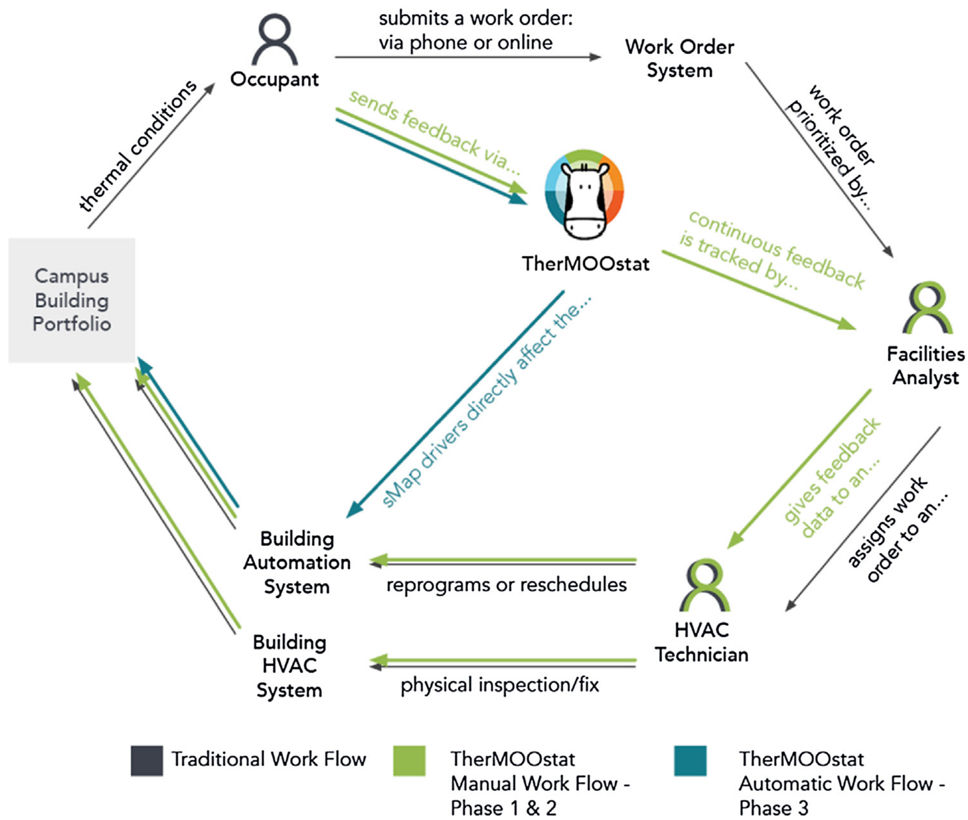

Fig. 1. Traditional and new workflow for HVAC management. The existing work-order system is depicted in black, the flow that was added via TherMOOstat in phase 1–2 is in green, and the automatic control tested in phase 3 is in blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

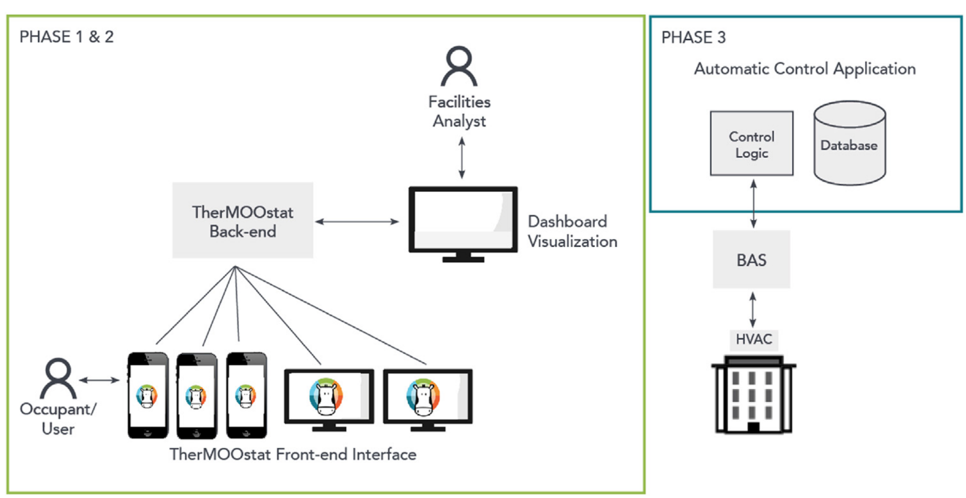

Fig. 2. Architecture of TherMOOstat. In green is the feedback application developed in phase 1–2, and in blue is the automatic control application developed in phase 3. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

was 17% Hot, 10% Warm, 18% Perfect, 21% Chilly and 34% Cold. Comments spanned a variety of topics: users asking for something to be fixed, describing what they had to wear to feel comfortable, mentioning energy waste, and asking questions about counter-intuitive HVAC practices (e.g., why the cooling is on when it is cold outside).

To create a picture of thermal comfort on campus, we aggregated thermal feedback data by building and room and analyzed time trends and corresponding sensor data in the BAS. Critical buildings and rooms were found and tracked over time. For example, the largest blue marker in Fig. 4 represents 828 TherMOOStat votes in Wellman Hall, a building comprised entirely of classroom space. In addition to the high volume of feedback, 50 comments came in from this building. Within three months of the release of TherMOOstat, Wellman Hall was identified as a hotspot for thermal comfort issues. ECO was already aware of a few mechanical HVAC problems that required expensive solutions, but thermal feedback from students in the classrooms was helpful for prioritizing issues in this building.

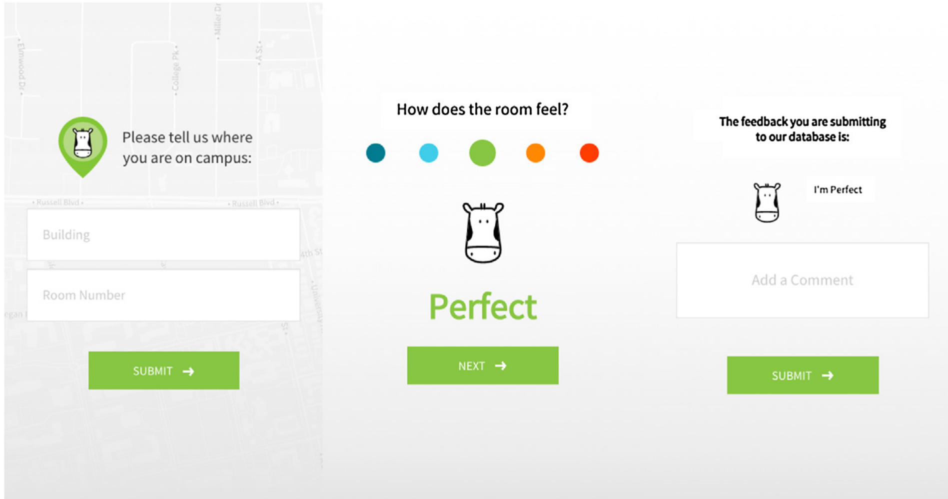

Fig. 3. TherMOOstat user interface.

Fig. 4. Over a year of TherMOOstat thermal feedback mapped on the UC Davis Campus Energy Education Dashboard. The value in the markers is the total number of comments for a building. The color of the marker is the most frequent vote (i.e., the mode): cold, chilly, perfect, warm, or hot.

3.2. Phase 2: manual closed-loop feedback system

3.2.1. Data and analysis

Using the comfort feedback to identify critical rooms, the energy analysts developed a procedure to analyze the corresponding zones on the BAS by looking at zone setpoints, airflows, discharge air temperatures and other BAS points in the air handling unit. TherMOOstat data was especially helpful in spotting problems in classrooms and other spaces occupied by students, who did not have access to the old work-order system. By focusing on rooms and buildings identified in Phase 1, we were able to discover 10 types of issues, listed in Table 1. Each case represents a single room, a group of adjacent rooms, or a larger open space. After addressing all issues we recognized three categories of problems: problems that required a mechanical or physical fix (case 1–3), problems that could be solved by changing BAS settings (case 5–8), and opportunities to engage users in energy efficiency by educating them about their building's HVAC system and strategies to adapt to indoor temperatures (case 9–10). The last group includes lack of understanding of local controls (e.g., thermostats) and campus temperature guidelines or disagreement between occupants of the same thermal zone.

Further, we evaluated the potential energy impact of the solutions implemented for case #8. This room is a 2664 ft^2 lecture hall with 296 seats. Thermal feedback collected over a twelve-month period showed prevalence of cold and chilly responses, which prompted us to look for opportunities to improve the control sequence. The room is conditioned by a dedicated air-handling unit utilizing chilled water and hot water from the campus central plant. We noticed a number of very conservative settings (as if the room were always occupied): since this classroom has a variable schedule every quarter, the single-speed fan was scheduled to be on 17 h per day (from 5 am to 10pm), including week-ends, and the room temperature setpoint was set to a consistent and year-long 72 °F. In addition, the outdoor air damper was fixed at 20%, recirculating most of the return air. We also noticed the presence of a CO_2 sensor, which was not utilized by the control algorithm.

To create a new control strategy, we rewrote the control code using the traditional BAS. We turned the fan on based on CO_2 levels, applied a dual temperature setpoint with a deadband, and regulated the outdoor damper to reduce on CO_2 concentration. The results reduced energy use and improved air quality.[1] Fig. 5 shows the heating energy, fan state and outdoor air temperature in a week with the traditional algorithm (in blue) and a week with the new control strategy (in red). Each vertical section represents a day, from Monday to Sunday. With the new strategy the fan turns on later, and does not run in the unoccupied days, using 46% less energy. During the weekdays, the new algorithm causes a higher heating peak later in the day, to compensate for lack of heating during the early morning, since the fan is off. The higher average heating values during the weekdays are partially caused by lower outdoor temperature (Thursday and Friday) and by larger portion of outdoor air taken in to improve air quality. Normalizing by weather conditions the new strategy led to 23% heating savings and 12% reduction of average CO_2 in the room. Most of the heating and fan savings were generated during the weekend. Fig. 5 (Heating Energy, in blue) clearly shows that heating an empty room (over the weekend) requires more energy than heating an occupied one, therefore it is particularly important to detect when the room is unoccupied. Notably, we implemented these changes remotely, without the site visit of an HVAC technician.

The concerns about potential occupant complaints for these energy-savings settings are now mitigated by the new thermal feedback system (students can now vote if they do not feel comfortable) and by measuring actual room occupancy with the CO_2 sensor. The same control strategy can now be extended to similar systems across campus. ECO has designated an engineering team to commission and optimize buildings; they use TherMOOstat data to target and prioritize buildings.

[1] This analysis was conducted using a methodology based on ASHRAE guideline 14 (and the International Performance Measurement and Verification Protocol®).

3.3. Phase 3: automatic closed-loop feedback system

3.3.1. Software developed

To demonstrate how TherMOOstat comfort votes can be integrated into the control logic of a building, without the intervention of ECO's energy analyst and lead HVAC programmer, we prototyped a closed-loop controller. The software is a Python-based control system that uses the Simple Measurement and Actuation Profile (sMAP) to connect to networked devices. sMAP is an open-source software developed at UC Berkeley that connects different information sources exposing a consistent and easy-to-use API. It stores the time-series and metadata collected into an efficient database and provides a way of reading and writing sensor and actuator points in real-time [20]. We built an additional control layer on top of sMAP to implement different control strategies. The software architecture (Fig. 6) is based on previous work on sMAP-based control systems [21–23]. The automated control application is displayed in the lower section of the figure. The thermal feedback application (Fig. 6, top) provides real-time information to the control logic, through a driver. A second driver connects the control logic to the thermostats. Each data stream is saved in sMAP time series database, represented on the lower right. The whole software stack is implemented in the cloud using Amazon Web Services. The control engine can easily switch between control strategies to iteratively improve and debug the system and test the best alternative algorithm. The code was implemented using Python scripts and uses open-source software packages.

As proof of concept we implemented and compared three control strategies:

1. Traditional schedule based on typical campus setpoints and hours.
2. Direct setpoint adjustment based on comfort feedback. The software collects comfort votes every 5 min and averages them (chilly: +2, cold: +1, perfect:0, warm:-1, hot:-2). The average score is added directly to the thermostat setpoint (in °F). The override lasts for 2 h, then the original scheduled setpoint (typical campus setting) is restored.
3. Drifting algorithm (similar to Purdon et al.). The algorithm takes into account occupant feedback as (2.) above, but if no feedback is provided for more than 2 h, it slowly adjusts the temperature setpoint towards outdoor temperature. The drift rate is set to 0.5 °F/hour. When users vote, the setpoint is adjusted accordingly and the timer is restarted. In addition, when occupancy is not detected, the algorithm converts to energy-saving settings, further lowering the setpoint. We also defined a minimum temperature setpoint (62 °F, ∼17 °C) during business hours.

3.3.2. Data and analysis

For simplicity, we tested the new software in a small office building conditioned by rooftop units (small packaged HVAC systems). This three-zone building has a simpler HVAC system than larger buildings and thus allowed faster implementation. Further, the building was previously managed using simple non-connected programmable thermostats, without the use of a BAS. We replaced the existing thermostats with new Wi-Fi thermostats and limited the control strategy to zone-level supervisory control, i.e., changing the heating and cooling setpoints and the thermostat mode. The experiment is valuable to UC Davis and can be implemented in

Table 1
Thermal Feedback, Issues Identified, and Solutions Implemented.

Case	Thermal Feedback	Issue Identified	Solution Implemented
1[a]	Chilly and cold feedback, with low temperatures confirmed by BAS	Manual setpoint on thermostat too low	Required physical inspection and fix via a site visit
2	Hot and warm feedback from adjacent offices	Low airflow, need to adjust ceiling vents	
3	In one month, 25 cold responses sent from one person	Reheat actuator for a hot water coil needed to be replaced	
4	Cold feedback, with multiple comments about AC running when it is cold outside	Stuck reheat valve	
5[a]	Trend of consistent cold feedback with several comments from users	Temperature setpoints were changed/overridden in a previous season and were no longer appropriate	Modified BAS program, via the BAS interface
6	Increasing number of hot feedback, with comments about stuffiness	Multiple VAVs serving one room. Lack of coordination between the VAVs caused low airflow	
7[a]	Chilly and cold feedback, and low temperatures confirmed by the BAS	Setpoints/deadband inappropriate for the room use or size	
8	Consistent cold and chilly feedback over several months	Opportunity to optimize the BAS scheduling sequence and use CO_2 sensors for occupancy data	
9	Disagreement among feedback from the same zone	Use a data logger for a second source of room temperature. Educational opportunity to explain the different HVAC zones of the building	Educational opportunities to engage users in energy conservation
10[a]	User asking for an increase or decrease in temperature in the comment box	Initial investigation in the BAS, followed by an educational email or site visit to explain energy saving opportunities and adapting to indoor temperatures	

[a] Indicates that the case had multiple occurrences within the 16 month time period.

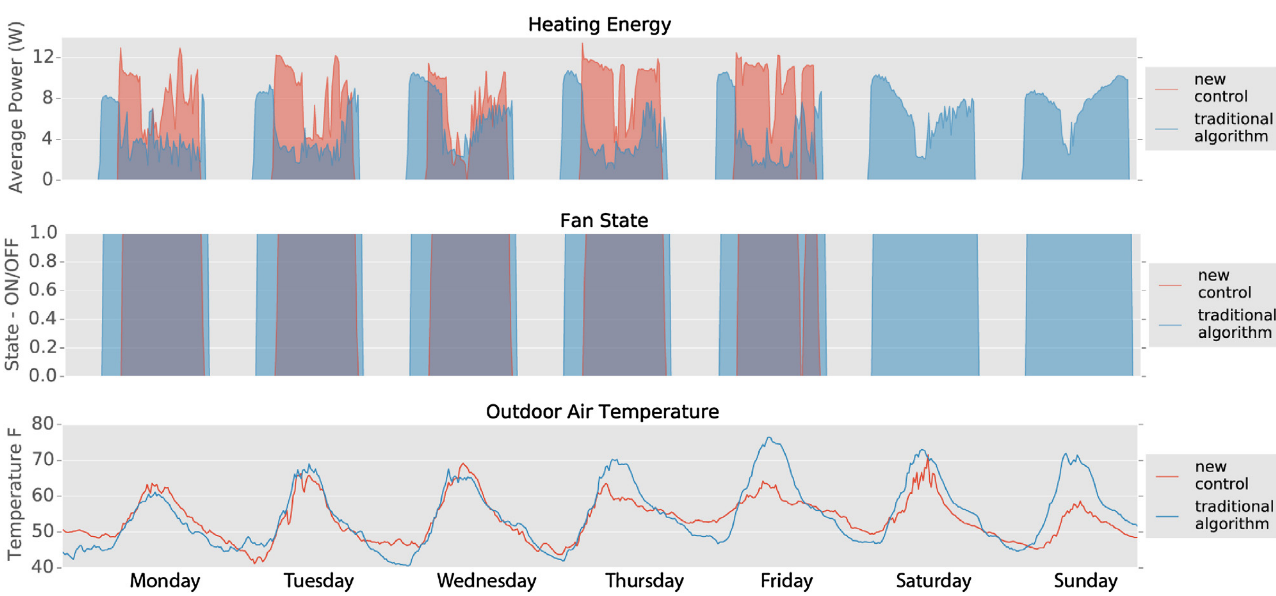

Fig. 5. Energy Analysis of Phase 2: Case # 8.

numerous other small buildings on campus that are currently not controlled by the BAS.

The experiment was conducted during January 2016, adopting the control strategies for an entire day and alternating them. Preliminary results are presented in Table 2. The third strategy saved more than 30% gas and 20% fan power over the traditional schedule, after weather normalization. Despite the savings, the comfort feedback showed very little difference between the three strategies.

4. Discussion

The overarching goals of our project were to (a) engage building occupants, especially students; (b) collect information to support analysis of energy efficiency and comfort; (c) integrate occupant feedback into building control systems; and (d) improve energy efficiency and comfort. We now consider the degree to which these objectives were met.

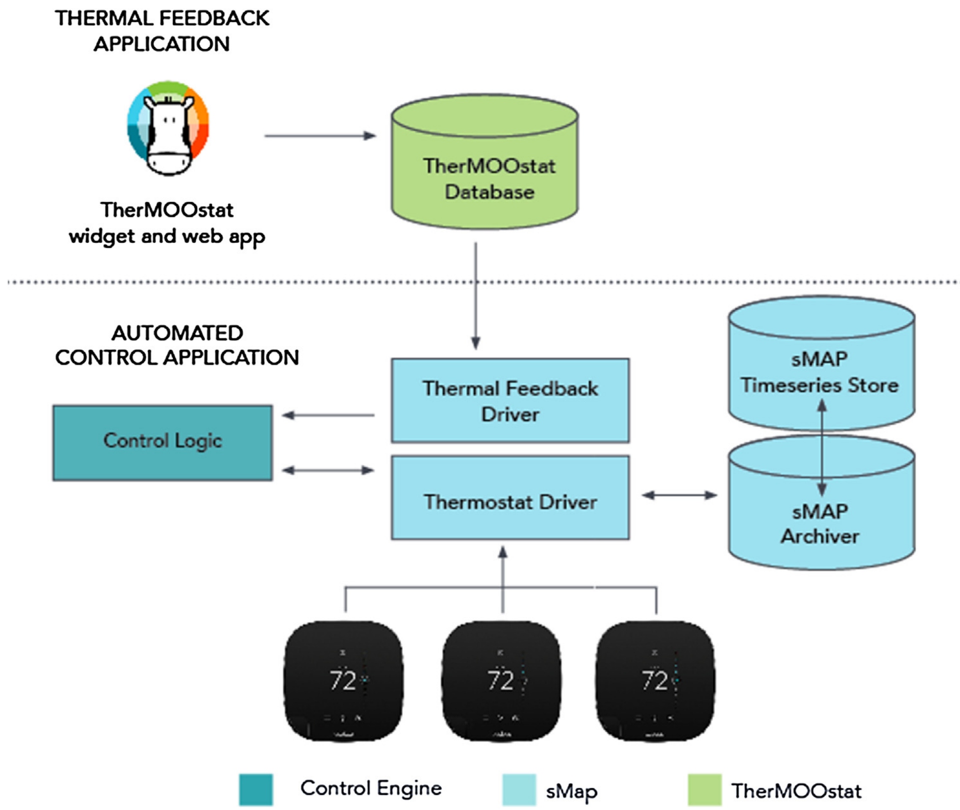

Fig. 6. Testbed Software Architecture.

Table 2
Energy Analysis of Phase 3: Closed-Loop Controller.

	Traditional Schedule	Direct Feedback	Feedback + Drifting + Occupancy
Daily Gas Use (Heating)	43.7 kBtu/day (46.1 MJ/day)	32.0 kBtu/day (33.1 MJ/day)	23.6 kBtu/day (24.9 MJ/day)
Daily Fan Use	16.7 kWh/day	14.9 kWh/day	11.9 kWh/day
Average Outdoor Temp	44.7 °F (7.1 °C)	46.4 °F (8.0 °C)	46.7 °F (8.0 °C)
Daily Comfort Votes	3 votes (average chilly)	3 votes (average chilly-cold)	2 votes (avg cold)

4.1. Engaging the community

TherMOOstat was successful in engaging building occupants, with more than 10,000 feedback submissions and 4000 unique users. A large proportion of the feedback came from students, whose input has been largely excluded with the traditional work order system. Staff and faculty were a smaller percentage of the users because the first interface was exclusively provided through a campus portal that is scarcely used by staff. The alternative TherMOOstat web app had higher usage from the non-student population, but there is still a need for more thermal comfort votes from staff and faculty, who typically occupy spaces other than classrooms, such as offices and laboratories. Future research should also explore the degree to which student participation in TherMOOstat and similar projects promotes energy awareness and engagement in other energy conservation projects on campus. Furthermore, projects like TherMOOstat could be leveraged to crowdsource information about occupants' willingness to adapt to more energy conservative HVAC operations.

4.2. Analyzing HVAC efficiency and thermal comfort

TherMOOstat data proved valuable in prioritizing building analysis and retrofits. In addition to comfort votes, thermal feedback with descriptive comments supported analysis and initiated conversation with building occupants (see also [19]). Despite the small sample size, we believe that the issues identified in Phase 2 (Table 1) are representative of HVAC problems that have an impact on comfort campus-wide. We also discovered that about half of these issues can be addressed remotely, by adjusting the BAS, giving some control to the users, and with communication strategies.

Several buildings for which we collected feedback do not have detailed BAS information or are not connected to the BAS. For these under-sensed buildings it was difficult to match feedback to room temperatures or energy data. Further, comfort issues are frequently related to air movement, which is not measured by the BAS inside the thermal zones. These sites require physical inspection and might need additional instrumentation for continuous monitoring.

4.3. Closing the loop

The third goal of this project was using feedback votes as an additional source of information to feed an automatic closed-loop system. We prototyped a simple system using Wi-Fi connected thermostats controlling rooftop units. The software developed allowed great flexibility in testing alternative control algorithms. Using simple Python scripts, we could control the devices from a virtual machine in the cloud and compare three strategies: a traditional constant setpoint schedule, a strategy that reacted to thermal comfort votes, and an energy-efficient strategy that reacted to votes, but also slowly drifted setpoints towards outdoor air temperature [15]. In a preliminary test, we showed that the third strategy can save 20–30% of the energy use without compromising comfort.

During the tests, we realized a limitation in adding exclusively thermal feedback to the control logic. Comfort votes are useful to avoid overheating or overcooling of a zone, but absence of votes corresponds to having a broken "human sensor". In fact, the system is unable to distinguish between "space comfortable", "space unoccupied" and "broken feedback loop" (i.e., occupants cannot vote or their votes are not received). To address the latter we actively encouraged feedback and ran a diagnostic on the system to make sure the system was receiving votes. In general, we believe that the thermal feedback should be always complemented with occupancy sensing to develop energy-saving strategies. The experiment also demonstrates that modern software-based control systems can be used to inexpensively and flexibly retrofit small commercial buildings.

For this preliminary test we used a building without BAS for several reasons. First, the campus is deploying an improved IT security infrastructure and the traditional BAS is undergoing hardware and software changes. Security is becoming a very important concern as more connected devices (such as Wi-Fi thermostats, mobile phones and wireless sensors) come online and connect to the campus IT network [24]. The threat of a security breach needs to be addressed, because it may jeopardize the deployment of any new wireless technologies. Further, we wanted to develop a modular and universal controller that could be scaled up to the entire campus without significant customization for each building. However, we found that BAS control sequences frequently involve complicated code that is customized for a specific set of sensors and actuators, and thus varies by zone and building. It proved difficult to find a general way of interacting with these sequences without developing additional building-specific code. Even mapping BAS zones and sensors to TherMOOstat rooms was not trivial. As pointed out by previous research [25–27], BAS sensor names do not contain enough information to describe the HVAC and zone configuration. We had to use mechanical drawings and BAS visual interfaces to map BAS zones and sensors to TherMOOstat rooms in our analysis (Phase 1 and 2). We need to automate these procedures to be able to deploy comfort-driven control applications in the whole campus. How to deploy scalable and portable applications (i.e., "write once, run everywhere") in buildings is an active area of research [22,28,29], but no universal solution has yet emerged.

4.4. Improving efficiency and comfort

The two examples of retrofits presented in Phase 2 and 3 resulted in significant energy savings. However, when we implemented other small retrofits, we found challenges in the estimation of the energy impact. This exercise was particularly difficult when the retrofit affected a portion of a building that was not submetered. The goal of the project was using existing BAS sensors to measure the savings, to allow to scale up the same methodology to the entire campus. Unfortunately, we discovered that buildings are frequently instrumented with the minimum number of sensors required to close the HVAC control loops. HVAC energy analysis, instead, requires much more data. In many cases, we had difficulties in estimating a reliable energy baseline to compare the post-retrofit energy with. Since a portion of the HVAC energy use is dependent on occupancy (e.g. it takes less energy to heat a room full of people), we needed to have accurate occupancy estimation. Unluckily, most of the rooms lack occupancy sensors and occupancy in university campuses is highly variable. This problem lead to high uncertainty on the baseline, and thus also on the savings. This comes as no surprise, as this issue is described in ASHRAE guideline 14 [30]. However, this uncertainty discourages energy conserving practices, since the impact of such procedures is hard to measure. ECO is developing standardized analysis and benchmarking procedures to partly overcome this problem.

To measure whether there was change in occupant comfort, we compared TherMOOstat feedback before and after the issue was addressed. In most of the cases we saw a decrease in hot or cold (uncomfortable) feedback, but rarely recorded an increase in perfect (comfortable) feedback. In some of the most critical cases, we contacted the occupant directly to make sure the issues were resolved. [19] analyzes in detail occupant comfort, participation and feedback during our project.

5. Conclusion and recommendations

Many institutional buildings and traditional HVAC control systems lack technology that can optimize operations for comfort and energy, and commercially available control systems do not allow for sufficient input from building occupants. This paper presents the design, development, and preliminary evaluation of a participatory thermal feedback and control system at University of California, Davis. The tool was developed in three phases. During the first phase we created the user interfaces and back-end to collect comfort data used to identify comfort issues at campus level. In the second phase we focused on a few buildings considered critical. For these subset we categorized problems and implemented solutions, such as reprogramming the BAS. In the third phase we developed and tested a software system to automatically close the HVAC control loop, i.e., adjusting the control system based on occupant feedback.

The project was successful in attracting interest and participation of the campus community, gathering more than 10,000 comfort votes in a year. Most of the people felt cold or chilly in buildings, regardless of the season. The granular information collected was useful to identify common issues and prioritize campus initiatives aimed at improving comfort and energy efficiency. While the results with the prototype of closed-loop HVAC control system are encouraging, future work is needed to address the connection with the main campus BAS and to test larger-scale deployments. Automation of data mapping and development of "portable" control code that can run on multiple buildings without significant customization remain the hardest challenges. Research should also address IT security, as this is likely to become the most important feature of future information and control systems. This work revealed problems and challenges common to many university campuses and other large institutions, and constitutes a necessary first step for our university and other campuses to tackle the research questions that are still unanswered.

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