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Upscaling participatory thermal sensing: Lessons from an interdisciplinary case study at University of California for improving campus efficiency and comfort

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ABSTRACT

Heating, Ventilation, and Air Conditioning (HVAC) is responsible for most of the energy consumed in many university buildings, which are still often uncomfortable for occupants. Previous research suggests crowdsourcing thermal comfort feedback from occupants, called participatory thermal sensing (PTS), and incorporating it into the HVAC control system can improve energy efficiency and comfort simultaneously. Most PTS research has focused on automated closed-loop systems whereby occupant feedback is automatically integrated into HVAC operations, but such systems are difficult to scale. PTS can also be implemented in a manual closed-loop system, whereby facilities management personnel analyze occupant feedback then make appropriate changes to HVAC operations. This approach may be easier to scale, but little is known regarding how to implement such a program. This paper describes lessons learned from a campus-wide manual closed-loop PTS program at University of California, Davis, after 23 months of implementation. We discuss the program in terms of three main goals: inspiring occupant participation, interpreting the data, and improving comfort and energy efficiency. Each goal requires a different set of skills and resources, which has resulted in an inter-sector and interdisciplinary project team comprised of facilities management staff and behavioral science and engineering researchers.

Heating, Ventilation, and Air Conditioning (HVAC) typically accounts for more than 40% of energy use in institutional buildings [1]. Conventional HVAC control strategies in large institutional buildings involve centralized control of temperature set points, which are standardized based on building functions. Occupants have restricted access to controls, which are often exclusively available to facilities management personnel. When occupants are not involved in the control loop, HVAC systems are necessarily reactive and based on assumptions regarding thermal comfort. This can lead to inadequate comfort and energy waste [28]. Furthermore, lack of perceived control of indoor thermal conditions is associated with lower occupant satisfaction [2].

University campuses frequently use "work order" systems to respond to issues identified by occupants, but this process is not widely used by students—the majority of building occupants. There can also be a lack of incentives for facilities management departments to save energy. Instead, there may be incentives to err on the side of over-conditioning to minimize complaints, which add to workload and are sometimes the basis of evaluations.

1. Participatory thermal sensing

Participatory thermal sensing (PTS) has been proposed as a strategy to improve energy efficiency and comfort by crowdsourcing thermal comfort feedback from occupants and incorporating it into HVAC management (e.g., [3]). The general strategy is to solicit thermal comfort "votes" (e.g., hot, cold) from building occupants and integrate that data into the HVAC management system. Most prior studies of PTS focused on university buildings ([3–10,23,11,16,24,14,12]), although a company called Comfy has commercialized PTS and produced reports and publications on their system (e.g., [13]).

The most common user interface in PTS programs has been a basic mobile application [3,14], although Song et al. [15] employed a more complex dashboard with a variety of features. The format for thermal comfort voting in past studies ranged from 3-point to 10-point scales, frequently using the ASHRAE Standard 55 7-point scale (e.g., [3]) or an adaptation of it (e.g., [7]). Most scales were labeled using words (e.g., "hot", "neutral", "cold"), although Purdon et al. used icons (snowflake,

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smiley face, or fire). Most scales made use of color; specifically, blues to indicate cold, reds to indicate hot, and greens or grayscales to indicate satisfaction or neutrality, respectively. Instead of rating one's thermal sensation (e.g., hot, cold), voting systems can also be framed as a command to the HVAC system (e.g., [5]); for example, in Comfy's interface users vote: "Warm my space" or "Cool my space".

Most PTS studies have focused on developing automated closed-loop control systems. For example, Erickson and Cerpa [3] employed a control algorithm based on a reconciliation of predicted mean vote (PMV), which is a modeled estimate of occupant comfort, and actual mean vote of occupants in real-time via their PTS program, Thermovote. Purdon et al. [14] used a "drift" strategy, whereby temperature set points slowly drifted toward ambient outdoor temperature unless occupants reported discomfort via the PTS program; their system also integrated occupancy data and optimized for offices with multiple users.

Past studies have demonstrated that automated closed-loop PTS systems can be leveraged to improve energy efficiency and occupant comfort. For example, Comfy's self-evaluations show significant savings and improvement in comfort, as well as high rates of occupant participation and satisfaction [13]. However, PTS programs at universities have often been based on simulations, not actual occupant behavior. A few field experiments are the exception ([3,4,5,16,12]), but these were relatively limited in terms of the testbed, participation, and/or duration of the experiment.

Balaji et al. [4] tested their system in one university building with 65 participants for ten days. Erickson and Cerpa [3] tested Thermovote for five months with 39 participants in a graduate student lab and administrative office space, together comprising seven HVAC zones within a single building. Ghahramani et al. [5] tested their system with 6 participants for 6 weeks. Lam et al. [16] deployed their system in three testbeds: a classroom with 87 students for 3 h; a room in an office building with 13 occupants for 10 days; and a conference room with 12 people for the duration of 4 meetings. Winkler et al. [12] tested their control system across 3 buildings with 61 people for 40 weeks. The relatively small and controlled testbed in these studies was reasonable given the difficult task of developing an automated closed-loop PTS system.

2. Present research

While past studies have demonstrated the technical potential of PTS for improving efficiency and comfort on university campuses, further research is needed to explore how PTS might be successfully scaled up and implemented in a longer term, campus-wide program. To begin, a manual closed-loop control system, whereby facilities management personnel analyze occupant feedback and respond by making appropriate changes to HVAC operations, is much more feasible in this context than an automated closed-loop system. Implementing a campus-wide automated closed-loop PTS system would take an extraordinary amount of time and resources due to the wide variety of campus spaces, uses, occupancy patterns, and diversity of HVAC equipment and systems. Therefore, the present research is concerned with how to successfully scale and sustain a manual closed-loop PTS program across a university campus.

The University of California, Davis, Energy Conservation Office (ECO), a branch of the Facilities Management Department, began the development of a manual closed-loop PTS program called Ther*MOO*stat to access more granular and instantaneous data regarding occupant comfort to inform their procedures and initiatives. The ultimate goals were to improve comfort and increase energy efficiency on campus. Prior to Ther*MOO*stat, UC Davis exclusively used a "work order" system to manage thermal comfort complaints.

For the Ther*MOO*stat project, ECO brought together skilled staff (energy analysts, designers, and software developers) and developed collaborations with academic researchers on campus in the fields of engineering and behavioral science. The diverse expertise, experience, resources, and skills of this inter-sector and interdisciplinary team converged to pursue the above goals. For example, a behavioral science perspective was brought to bear on the challenge of inspiring occupant participation in the program. The high level of involvement of Facilities Management was crucial for scaling PTS campus-wide, particularly for interpreting and responding to the PTS data; Facilities Management is responsible the operation and maintenance of campus buildings and has the resources to manage such a program. This project differs from other university PTS programs in that it was initiated by Facilities Management rather than academics. Finally, energy efficiency and control systems researchers were involved to test the possibility of automating the control loop and assess feasibility of integrating PTS with the Building Automation System (BAS).

Our guiding framework in this paper is that successfully scaling up a manual closed-loop PTS program to an entire university campus involves three general goals:

- **Inspire occupant participation:** *Recruit and sustain participation.*
- **Interpret the data:** *Develop actionable insights about campus comfort and efficiency*.
- **Improve campus conditions:** *Make changes to improve campus comfort and efficiency*.

This paper describes the Ther*MOO*stat program and lessons learned in terms of these three goals. Throughout the paper we highlight the role and value of interdisciplinarity in the development, implementation, and evaluation of a large-scale manual closed-loop PTS program.

3. Inspire occupant participation

An initial objective for any PTS program is recruiting participation. Moreover, unlike most previous university PTS studies, we aimed to sustain participation over a long period of time. These are particularly challenging tasks with a manual closed-loop control system where feedback does not automatically elicit an immediate or certain response in HVAC operations.

Usability of the PTS user interface and user experience are important factors that could influence occupant engagement, particularly in the context of a manual closed-loop control system. Past university PTS studies have not focused on these aspects. ECO staff designers and programmers collaborated with a behavioral science researcher to design Ther*MOO*stat to be engaging.

In this section, we first describe Ther*MOO*stat's design and engagement strategies. We then present Ther*MOO*stat participation rates (i.e., feedback submissions) over time, which speaks to the effectiveness of those design and engagement strategies. Finally, we report findings from a user survey to dig deeper into users' motivations and expectations.

3.1. Designing for engagement

Ther*MOO*stat was launched in late September, 2014, as a widget on the university web portal. The widget is accessible to all UC Davis students, faculty, and staff. User interaction with the widget consists of a simple user interface (UI) to prompt the user to enter their location and submit thermal feedback (Fig. 1).

Thermal feedback is solicited with a modified and abridged version of the ASHRAE scale; 5-point instead of 7-point, with more colloquial wording ('Hot', 'Warm', 'Perfect', 'Chilly', 'Cold' instead of the original 'Hot', 'Warm', 'Slightly Warm', 'Neutral', 'Slightly Cool', 'Cool', 'Cold') intending to appeal to student users. A cow (named Joules) is featured, and inspired the name Ther*MOO*stat. Cows are iconic to UC Davis, a hub for agricultural research. From a design perspective, strong, cohesive, and fun visual design is intended to make the app engaging and memorable. From a behavioral perspective, Joules the cow is an

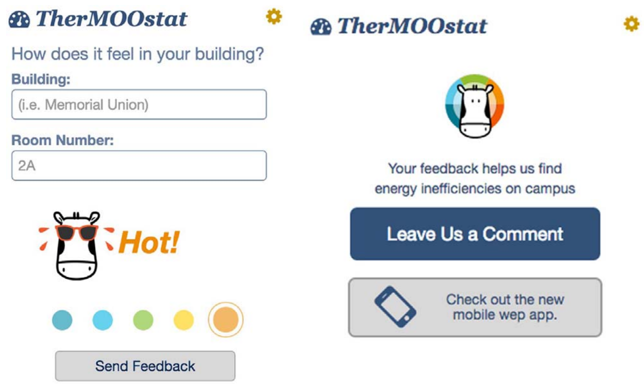

Fig. 1. Ther*MOO*stat widget UI.

empathetic gauge that users may connect with emotionally [17].

In a second phase, we developed a web app for use on mobile devices (Fig. 2) to enable easier access for staff who may not visit the university's web portal as frequently as students. The web app was designed to behave like a native mobile app (e.g., iOS or Android); users can save it to the desktop of their smartphone or tablet. It works on all operating systems and was developed to work with all browsers.

We added elements to the app aimed at rewarding and maintaining participation. After submitting feedback, participants are shown a pie chart with a breakdown of how others have voted in that building. We hoped this would provide social reinforcement for participation. We also added a more prominent disclaimer to the final screen, informing users that submitting feedback is not equivalent to submitting a work order; in the widget this disclaimer was accessible on the settings menu but not on any of the main screens. The purpose of these additions was to influence users' expectations and prevent frustration that might occur since there is typically no immediate or certain response to individual submissions (Facilities processing and response to the feedback is discussed in subsequent sections).

Unlike the widget on the myucdavis portal, the app requires promotion. It has been promoted at university events and around campus via giveaways (t-shirts, stickers, and coffee sleeves), as well as flyers and chalk drawings on classroom blackboards. Promotions typically feature Joules the cow and other consistent design features for coherence of message and memorability.

3.2. Participation rates

Ther*MOO*stat received 900 feedback submissions per month for the first two months of implementation. Subsequently, participation rates gradually declined and fell sharply in the summer, including May when school was still in session (Fig. 3). Participation increased after the introduction of the app. Digging deeper, we saw that the app increased engagement among staff (Fig. 4), who make up a significantly greater

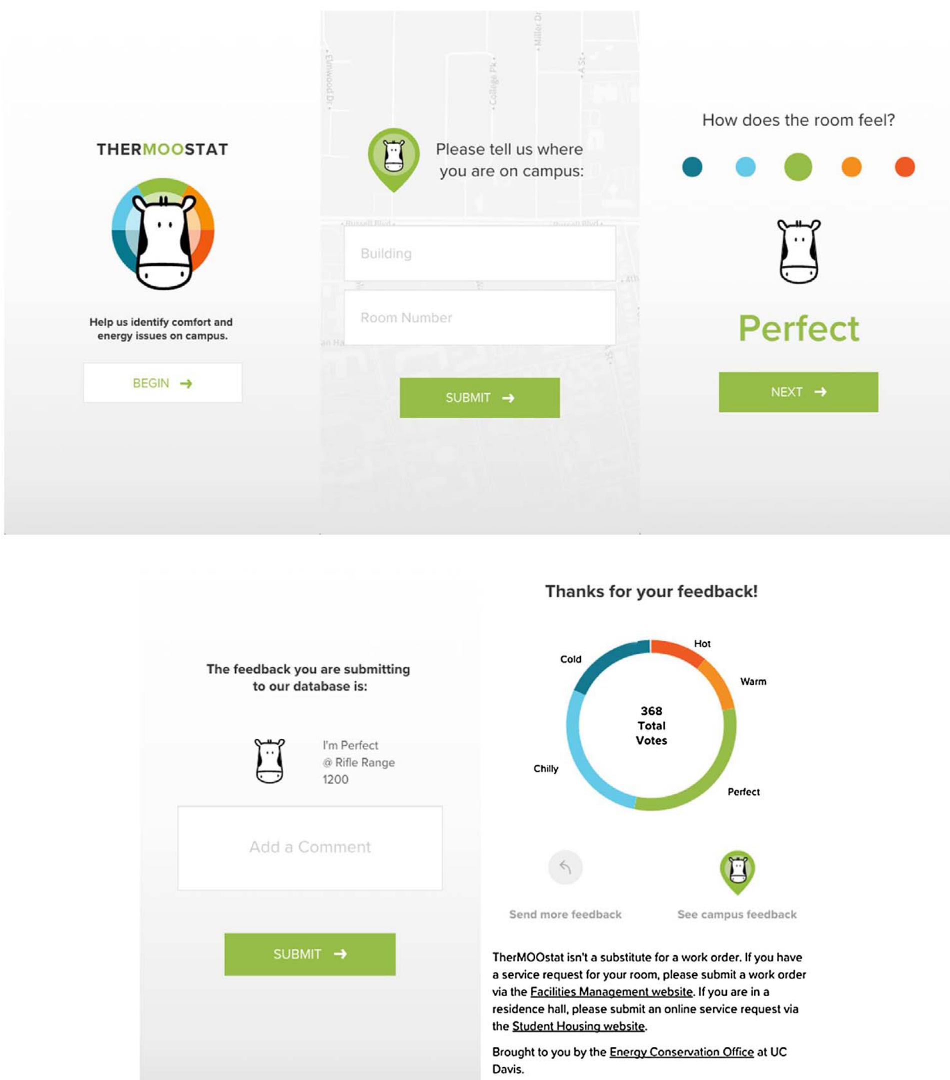

Fig. 2. Ther*MOO*stat App UI.

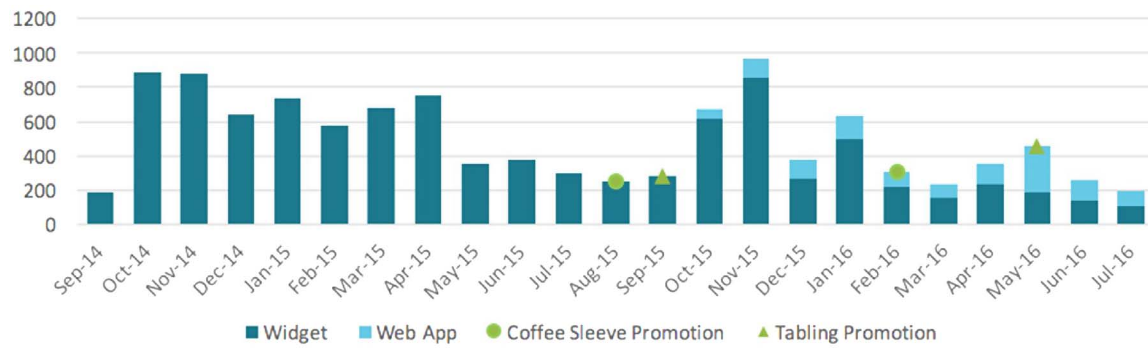

Fig. 3. Number of Ther*MOO*stat feedback submissions per month, marking promotional events.

proportion of its users; specifically, 42% of 2,269 app users were staff, compared to 4% of 10,275 widget users ($z = 52.6$, $p < .001$). What may appear to be a seasonal pattern in Figs. 3 and 4, with more feedback submissions occurring in the fall and fewer as the seasons progress, is less pronounced when controlling for student enrollment (Fig. 5); instead, an overall negative trend predominates. For further details on patterns of participation, including distributions of thermal feedback submissions, see Sanguinetti et al. [18].

3.3. User motivations survey

We surveyed Ther*MOO*stat users in order to better understand their motivations for participation, and implications for the sustainability of the program. Our survey included questions aimed specifically at capturing users' motivations for voting (*When do you use TherMOOstat?* and *What do you expect to happen when you use TherMOOstat? Please share with us you own reasons for using TherMOOstat*). We also asked participants to describe the objective purpose of Ther*MOO*stat in their own words, as this would have implications for their motivations for participating and expectations for the Facilities Department's response. Finally, we asked users how quickly they expected Facilities to respond to their feedback with changes in room temperature, and whether they would also appreciate certain kinds of communications in response to their feedback.

Participants were recruited via email and received a $5 Starbucks gift card for completing an online survey. We drew our survey sample from the population of Ther*MOO*stat users who voted between January 1 and June 30, 2016. We recruited everyone who voted more than twice during that period (oversampling to adequately represent more frequent users; Table 1), which was 150 users; 50 users who voted twice, randomly selected; and 50 users who voted once, randomly selected. Out of the 250 recruited, 157 users opened the email, 51 initiated the survey, and 46 completed it. The survey was programmed to end after 50 responses; we sent a link to one user upon request after the original link was closed.

The majority of Ther*MOO*stat users (89%) reported that they expected their space to become more comfortable as a result of submitting feedback (Fig. 6). It follows naturally that discomfort was by far the most frequently reported precursor for submitting feedback (Fig. 7). Open-ended responses revealed that when discomfort persists, frustration and attrition may result, e.g., "So far there has been ZERO response to my feedback"; "If the situation doesn't change I'll stop using the service per the adage about surveys; don't ask for opinions on things you aren't willing to fix."

Though comfort was by far the strongest motivation for users, energy savings, participation, perceived control, novelty, and entertainment were also featured in survey responses. For example, 50% of users expected that their participation would increase energy efficiency (Fig. 6) and open-ended responses highlighted efficiency as a motivational factor, e.g., "to avoid the overuse of AC and save energy in hopes that UCD will be an even more sustainable and green campus". Some users also appreciated the opportunity to participate in the system and gained a sense of perceived control, e.g., "I like the idea of having some influence on the thermal comfort of our building. It also feels very proactive instead of just sitting around complaining about being hot or cold". Finally, there was also some evidence that our design strategies were successful in provoking engagement (e.g., "The tile on myucdavis webpage looked cute"), including the finding that boredom prompted feedback submissions for 16% of users (Fig. 7).

When asked to describe the purpose of Ther*MOO*stat in their own words, most participants indicated that the data would be used to improve energy efficiency and/or comfort (e.g., "To reduce energy use and increase creature comfort"). When participants considered how these improvements to comfort and/or efficiency would be made, most implied a manual closed-loop system, whereby personnel would analyze the data then act on it (e.g., "To report uncomfortable temperatures throughout campus, with the hope that someone will be able to fix it"). However, a minority of responses indicated some participants might believe the system was automated (e.g., "A crowd sourced temperature control system"; Adjust temperatures based on real-time feedback").

Participants most frequently reported that they expected temperature changes 'within a week' of submitting feedback (43%), followed by 'within minutes' (20%), 'eventually, over a longer period of time'

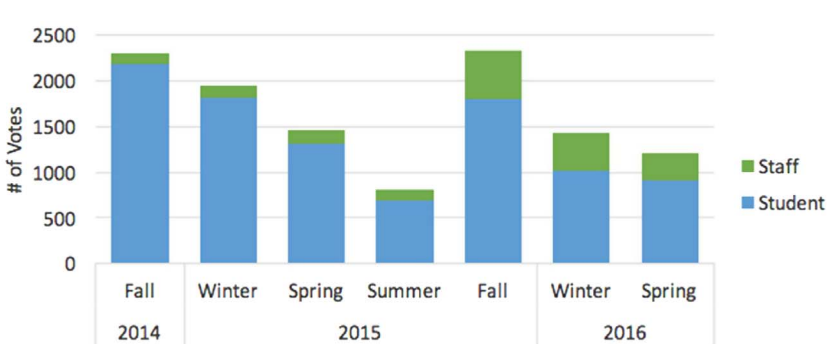

Fig. 4. Number of Ther*MOO*stat feedback submissions per month, students compared to staff.

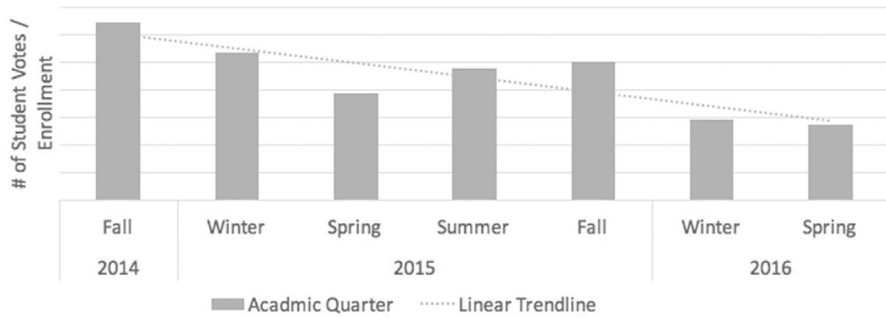

Fig. 5. Number of student feedback submissions per academic quarter, normalized for number of students on campus.

Table 1
User motivation survey sample compared to population.

		Survey sample	Population of users
User group	Student	71%	91%
	Staff	27%	7%
	Faculty	0%	2%
Voting frequency	1–2 times	20%	77%
	3–4 times	14%	16%
	5–9 times	30%	7%
	10+ times	36%	0%

(18%), 'within a month' (9%), and 'never' (2%). This expectation appears to be related to frequency of feedback submissions; i.e., users who submitted more feedback anticipated a longer timeframe for Facilities' response (Fig. 8). Most participants indicated they would appreciate communications from Facilities regarding when to expect changes in room temperature (94%), how the HVAC system is operating in their space (63%), and how Ther*MOO*stat has been used to improve comfort (63%) and energy efficiency (63%) across campus. There was less interest in receiving information on how to adapt to current room temperature (25%).

4. Interpret the data

TherMOOstat feedback is displayed in real-time on an in-house website for a team at the ECO office. This team consists of three members whose combined time is equivalent to one full-time employee. In this section, we describe ECO's method of processing Ther*MOO*stat data and the interpretations that have resulted, including how individual thermal feedback submissions can be interpreted and aggregated to identify energy and comfort issues at the room, building, and campus levels. We also describe how we have triangulated thermal feedback data with other data sources to better understand it.

4.1. Understanding the individual feedback submission

We review the website each morning and check every hour during the work day. The core data displayed on the in-house Ther*MOO*stat website includes a timestamp, a building name and room number, a comfort vote, and a user's comment (if filled out). Each incoming feedback submission is analyzed, with the exception of submissions without a building name, room number, or comfort vote.

We cross-reference the building and room number on a feedback submission with data in the Building Automation System (BAS), if the building has one. Most large buildings in campus have a BAS, provided by three main vendors. We have more control and visibility into buildings that have variable air volume (VAV) systems, occupancy sensors, and more heating, ventilation and air conditioning (HVAC) data points stored and trended through the BAS. Feedback submissions for buildings that are not visible through the BAS are considered low priority because it requires an HVAC technician to manually analyze the building in order to interpret the situation. The exception is if multiple votes are received from one room in the timeframe of one hour; in such cases the data are taken to a staff member in the HVAC shops of Facilities Management Department for investigation.

When cross-referencing a feedback submission with BAS data, we check room/zone level data as well as building HVAC system level data. In terms of room and zone level data, our first step is to check temperature set points. If the room temperature is within 2 °F of the set point, this is considered to be meeting campus heating and cooling standards (as set by the Energy Manager); however, we still look into other possible issues. Next, we check airflow into the room; draft is a common cause of a 'Chilly' or 'Cold' vote. When the room has a VAV system, we also check the valves and dampers serving the room; about twelve times we have found valves and dampers stuck in the open or closed position, leading to cold and hot experiences by our users, respectively.

At the building HVAC system level, we attempt to verify the appropriateness of the air handler discharge temperature, temperature of chilled and hot water systems, and pump, boiler, and fan coil unit operation, as applicable. We also check for overridden set points that are no longer appropriate.

Analyses of incoming feedback submissions via cross-referencing with BAS data have yielded two types of inferences. One is that set points need to be adjusted, which may include changing room temperature set points, changing airflow set points, or releasing overrides on set points. Another is that more in-depth changes to the BAS are required, in which case a work order is initiated and routed to HVAC technicians. A third conclusion is that no inference can be made,

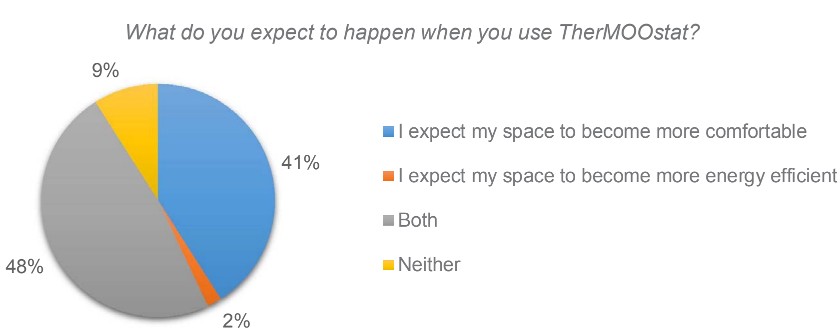

Fig. 6. Ther*MOO*stat user expectations regarding program purpose, to improve comfort, energy efficiency, both, or neither.

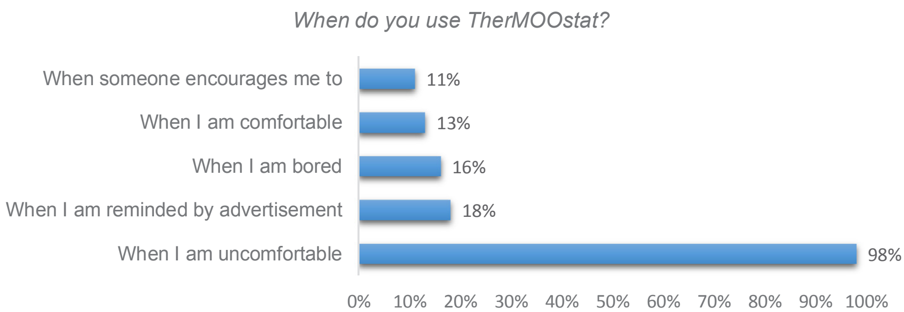

Fig. 7. Precursors of feedback submissions.

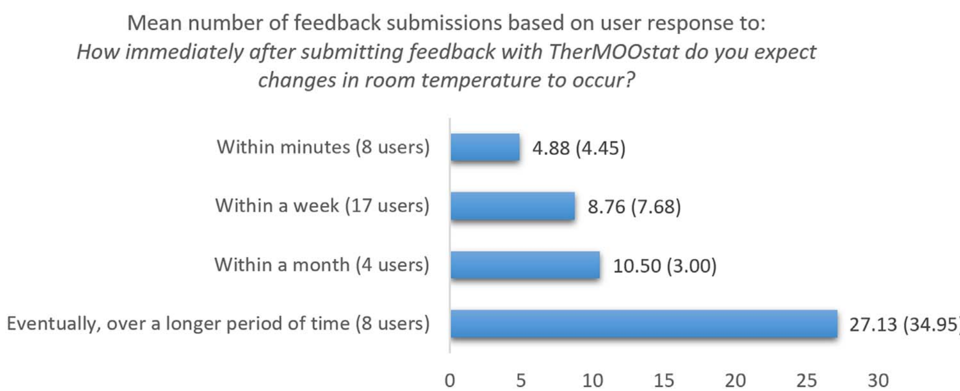

Fig. 8. User expectations for immediacy of Facilities' response in relation to mean number of feedback submissions (standard deviations in parentheses).

therefore further data are needed; in such cases the ECO team may look into who sent the feedback, initiate a site visit and/or interview with the occupant, or set up a data logger in the room.

4.2. Understanding aggregated feedback

The ECO team uses an online software called AirTable to identify broader trends, over time and across rooms within the same building (Fig. 9). Each row, or case, in the table represents a room. Columns include the types of feedback received (e.g., 'Hot', 'Cold', etc.), feedback trends (consistently cold or hot, variable, seasonal or unknown/to be determined), room temperature, set points and mechanical notes from the initial analyses of individual feedback submissions, and the actions taken in that room. Room-level cases are tracked over months of time and continuously watched for changes in feedback trends.

Using AirTable to track room-level feedback over time, the ECO team has been able to interpret cases as comfort issues, energy efficiency issues, or those with potential for both comfort and energy efficiency improvements. Cases where there is a large volume of feedback but the BAS is functioning properly are interpreted as the room being uncomfortable in its current BAS programming. Cases where the BAS set points have been overridden or scheduled in a way that leaves room to augment efficiency are interpreted as opportunities for improving energy efficiency. Classrooms and lecture halls are tracked most consistently on AirTable due to a relatively higher volume of feedback, making it easier to discern patterns. Ultimately, this makes them targets for projects to improve comfort and efficiency on campus.

To visualize thermal feedback at the campus-level, ECO developed a map-based website called Ther*MOO*map (Fig. 10). On Ther*MOO*map, feedback submissions are aggregated by building. A marker on each building displays the number of submissions for that building over the academic quarter (with the option to change the academic quarter viewed); this value is represented by the size of the marker and the value within it. The color of the marker represents the mode of

Feedback	Feedback Trend	Room T...	Mechanical Notes	Action
Cold	Consistent cold	Zone RT 10 A...	3/28 complained it was too hot - o...	Email response from, Resolved
Cold	Consistent cold	Limited visibility	73 has local controls	Email response from, Resolved
Cold	Consistent cold	RT 67.25, SP ...	5/18 raises heating set points in roo...	Email response from, Resolved
	Consistent cold	RT 2:00 PM: 8...	3/28 complained it was too hot - o...	Investigation from, Resolved
Cold	Consistent cold	Lab office, SP...	5/18 raises heating set points in roo...	Investigation from, Monitor for trend
Chilly	Consistent cold	RT 68, DAY H...	3/4 following up with 3/15 Follo...	Investigation from, Dormant
Cold	To be determined	RT 68, DAY H...	3/4 following up with 3/15 Follo...	Investigation from, Dormant
Chilly, Cold, Warr	Variable	RT staying ar...	3/4 following up with 3/15 Follo...	Investigation from, Dormant
Hot	Consistent cold	RT 74, ST 74	Chilled water doesn't turn on until OAT re...	Monitor for trend
Cold, Hot	Variable	RT 10:30 AM: ...	3/15 looking into AC-2 issue, unit is ...	Monitor for trend
Hot, Warm, Cold	Variable	RT @ 11 AM: ...	Shields should be communicating with Sie...	Monitor for trend
Cold, Warm, Chill	Consistent cold	RT 10:30 AM: ...	3/15 looking into AC-2 issue, unit is ...	Monitor for trend

Fig. 9. An example from Ther*MOO*stat AirTable used to track room-level feedback.

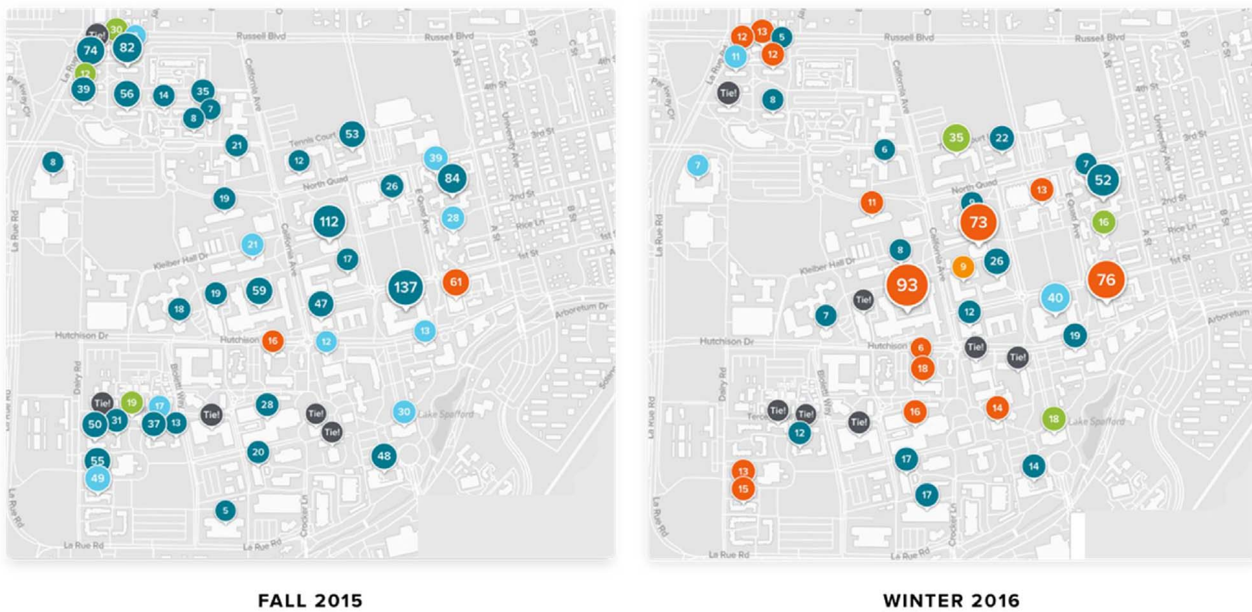

Fig. 10. Ther*MOO*map website, a map-based visualization of building-level modes of feedback submissions.

feedback submissions (‘Hot’, ‘Warm’, etc.). Bimodal distributions are indicated by gray markers, with the text “Tie!” intending to call users’ attention to the disagreement of comfort votes in the building. The team has used Ther*MOO*map and other means of graphic analysis to explore campus-level trends in feedback submissions.

Ther*MOO*map has revealed seasonal patterns in thermal comfort across campus (Fig. 10). Specifically, Ther*MOO*stat users submit primarily ‘Cold’ votes during the fall quarters and ‘Hot’ votes during the winter quarters. Fall quarter includes September through December, some warmer and some cooler months, so the implications are unclear. Comparing these data to average outside air temperature, we observed that a greater proportion of ‘Cold’/‘Chilly’ votes occurred during warmer quarters and a greater proportion of ‘Hot’/‘Warm’ votes occurred during cooler quarters (Fig. 11). These data suggest the campus is being overcooled during cooling season and overheated during heating season, highlighting an opportunity to leverage Ther*MOO*stat data to simultaneously improve comfort and energy efficiency in buildings on campus. Such applications of the data are the subject of our next section.

To better understand variations in feedback submissions within seasons, we explored the average daily distribution of feedback submissions during heating and cooling seasons (we used winter and summer quarters, respectively; Fig. 12). In summer, ‘Hot’/‘Warm’ submissions are relatively evenly distributed, and ‘Cold’/‘Chilly’ submissions peak in the afternoon when indoor/outdoor temperature contrast is greatest. In winter, ‘Cold’/‘Chilly’ submissions are more prevalent in the mornings and ‘Hot’/‘Warm’ submissions are more prevalent in the afternoons. Further research is needed to explore the causes of these patterns.

5. Improve campus conditions

Use of PTS data to improve comfort and efficiency is the most compelling criteria for a successful program. Ther*MOO*stat thermal feedback data have been leveraged for four different applications by the ECO team, Facilities Management more broadly, and academic researchers (Table 2). The following section presents case studies to illustrate each application.

5.1. Improve occupant comfort and/or energy efficiency

In Pritoni et al. [19,20], we presented a typology of responses to issues identified by ECO's interpretation of feedback submissions. Three types of solutions to improve comfort and/or efficiency are via an on-site equipment fix (e.g., changing set point on manual thermostat, adjusting ceiling vents, moving thermostats, fixes stuck valves, replace

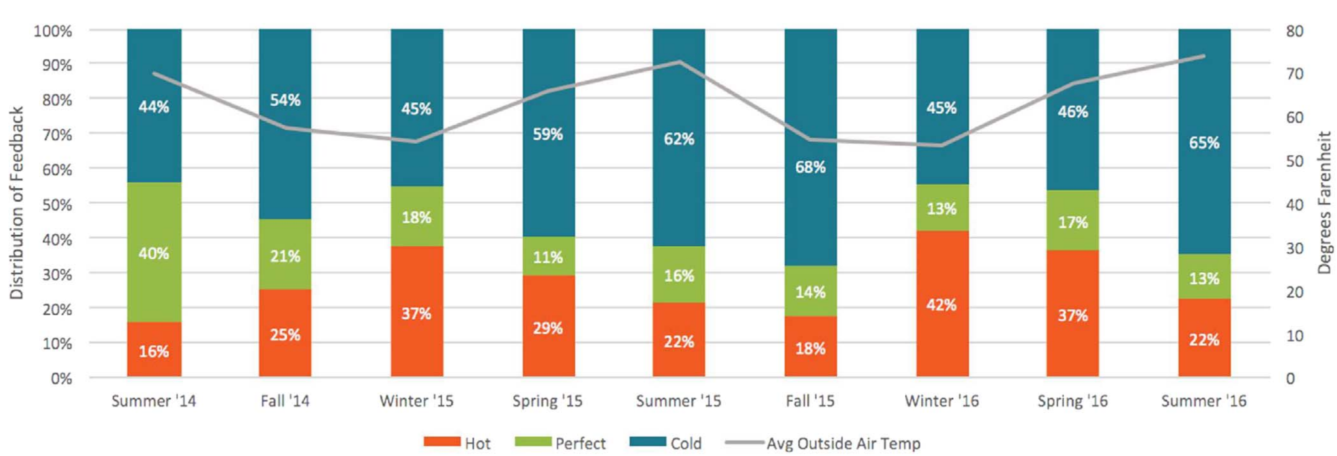

Fig. 11. Campus-wide distribution of feedback submissions; Hot represents the sum of ‘Hot’ and ‘Warm’ feedback, and Cold represents the sum of the ‘Cold’ and ‘Chilly’ feedback.

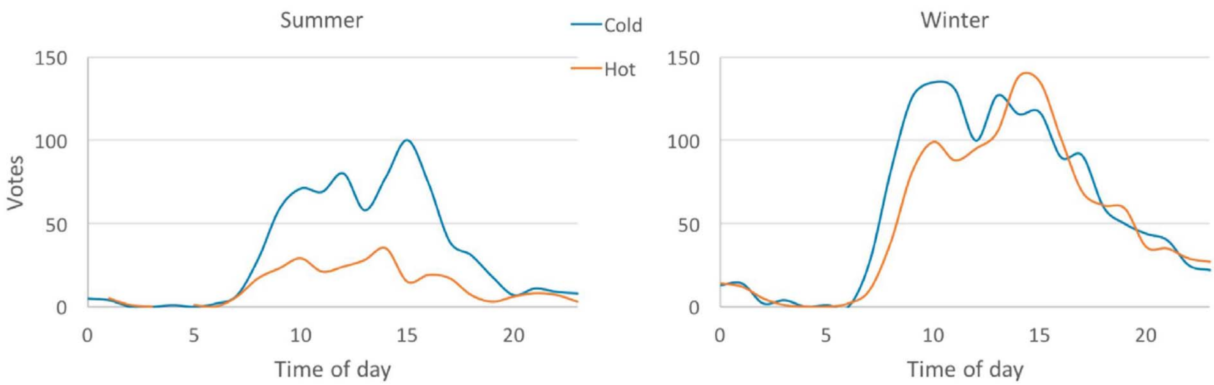

Fig. 12. Distribution of feedback submissions by time of day in Summer (cooling season) and Winter (heating season); hot represents 'Hot' and 'Warm' feedback; cold represents 'Cold' and 'Chilly' feedback.

equipment); modification of BAS programming via the BAS interface (e.g., changing set points, removing set point overrides, coordinating VAVs, optimizing BAS scheduling sequence); and educating or engaging users in energy conservation (e.g., explaining how HVAC system works and adaptation strategies).

An illustrative case study for a solution that involved an on-site physical fix was in response to conflicting feedback from adjacent rooms, one warm and the other cold. Upon site inspection, ECO found that the vent in the warm room was completely closed (vent positions are not visible in the BAS). This closed vent was increasing the airflow in multiple surrounding rooms. ECO manually adjusted the vents and received positive feedback from the occupants.

Building A is an illustrative case study for a solution that involved reprogramming the BAS. Building A, comprised mainly of classrooms, received 43 responses from 31 people over 79 days for Room 6, a large classroom (162 square meters) in the basement. Comments such as ""Ay caramba! I am so sweaty! My neighbors don't appreciate how stinky I am. Help me help them! Turn down da heat" caught ECO's attention. A site inspection followed by an analysis of the BAS revealed that the four variable-air-volume (VAV) boxes serving the room were reprogrammed incorrectly after being repaired just before the feedback submissions increased. Three of the four boxes were supplying insufficient airflow to the room, causing comfort issues. Fig. 13 shows the reduction of hot feedback in May, 2015, after reprogramming the BAS in late April.

An example of an educational solution was in response to consistent conflicting feedback from different users in the same zone. ECO explained the HVAC zone boundaries and discrepancy in experience of other occupants to each respective occupant who had been submitting feedback, as well as strategies for adapting to the temperature.

5.2. Prioritize energy retrofits

Facilities Management maintains a database of buildings that require energy retrofits, identified via work orders. Some of these buildings require major capital investment to improve performance, so it is important to prioritize buildings for long-term planning of retrofits. ECO has used Ther*MOO*stat data to help identify and prioritize buildings that need energy retrofits.

For example, Building B, a classroom building, is on a deferred maintenance list, among others determined to be low priority. There have been more feedback submissions for Building B than any other building to-date (1,037; the second highest volume is 830 submissions for a large library). ECO is using the consistent high volume of feedback in Building B to advocate that the retrofitting of Building B be accelerated. They are developing a report that includes the distribution of thermal feedback submissions, an analysis of the HVAC system, content of the work orders submitted, and a suggestion to improve visibility into the building with occupancy sensors.

5.3. Test automated control algorithms

Similar to previous studies of automated control PTS systems (e.g., [3,14]), an engineering research team developed and tested a new control system that could take actions on the HVAC directly based on Ther*MOO*stat votes. The vision was that the thermal feedback vote would be pre-processed by an automated system allowing direct change of set points, as well as notification to the ECO team of anomalous HVAC behavior. The system was prototyped in the ECO office, a small building (322 m^2), using smart thermostats and custom software running in the cloud (see [19] for the details of this experiment); preliminary results show savings up to 30% over the traditional control strategies.

5.4. Evaluate efficiency initiatives

Facilities Management has traditionally been cautious with respect to HVAC management as it relates to (assumptions about) occupant comfort, in the sense that they try to minimize change and err on the side of longer operating hours and liberal conditioning (colder in the summer and hotter in the winter). To increase efficiency, ECO is challenging this cautious approach. For example, another ECO team has begun working on active building commissioning, aiming at improving energy efficiency through optimization of building operation. The commissioning team has implemented several energy efficiency measures, including new temperature guidelines that regulate temperature boundaries toward more energy-saving standards. We have started using Ther*MOO*stat as an evaluative tool for these measures to assess impacts on comfort; in this way, Ther*MOO*stat is supporting more

Table 2
Applications of thermal feedback data.

Application	Method
Improve occupant comfort and/or energy efficiency	Reactive: listen to feedback then reprogram BAS, repair equipment, and/or educate occupants
Prioritize energy retrofits	Reactive: listen to feedback then prioritize building and occupant needs for future retrofit projects
Test automated control algorithms	Integrated: change HVAC operations automatically based on feedback
Evaluate efficiency initiatives	Proactive: change HVAC operations then monitor feedback to assess the impact on occupant comfort

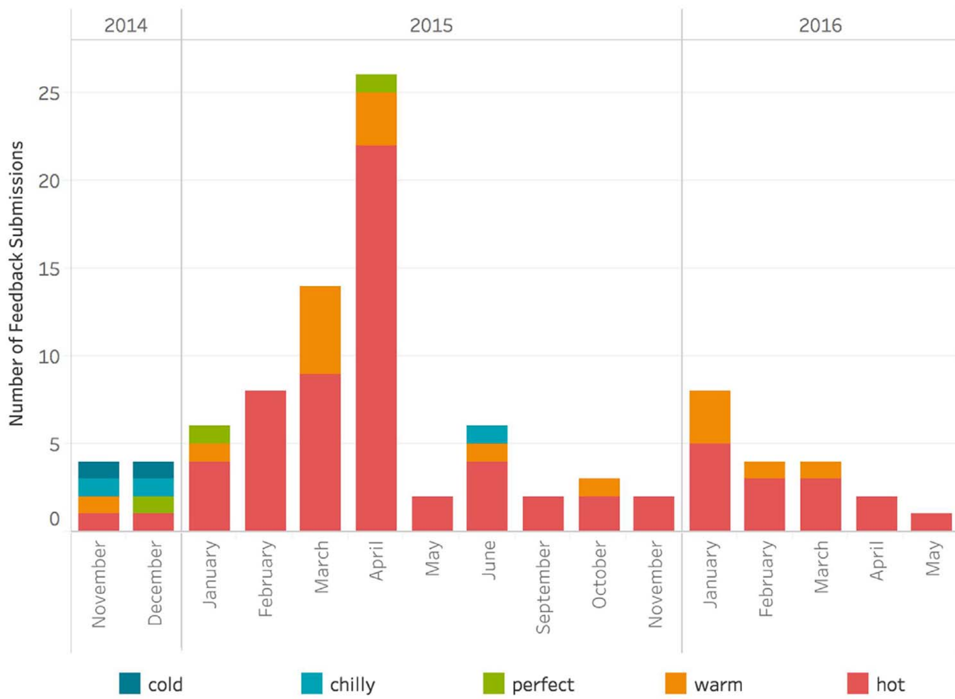

Fig. 13. Feedback in Building A, Room 6.

proactive efficiency initiatives.

The commissioning team has implemented lower cost energy-saving measures such as dual set point temperature controls and demand control ventilation in two laboratory buildings on campus. After these changes were implemented, the team encouraged building occupants to use Ther*MOO*stat. Feedback from those buildings was then monitored to determine the impact of the initiative on occupant comfort, and to pinpoint rooms that required further attention and engineering solutions.

Two rooms have been identified so far, both receiving consistent 'Cold' and 'Chilly' votes since the initiative. In one room, the team located a poorly placed thermostat that was leading to issues with the temperature readings and BAS control. In the second room, the team found disconnect between the room classification/programming in the BAS and the actual room use, i.e., the room was programmed to run as a laboratory when it was being used as a computer classroom for students. In both rooms the issues were addressed remotely through the BAS and the 'Cold' and 'Chilly' feedback has ceased. However, there have also been complaints made and addressed outside of Ther*MOO*stat in response to the active commissioning initiative; not all communications have been effectively filtered through Ther*MOO*stat.

6. Discussion

This case study affirms that it is possible to successfully scale a manual closed-loop PTS program across a university campus. Over 23 months, we have recruited sufficient participation to enable meaningful interpretations of the thermal comfort data, and those interpretations have spurred a variety of initiatives to improve comfort and energy efficiency on campus. However, when it comes to the sustainability of the program, in terms of maintaining occupant participation, the future is uncertain. We turn to a discussion of lessons learned and limitations concerning how to collect, interpret, and respond to PTS data in a long-term, campus-wide, manual closed-loop program.

6.1. How to inspire occupant participation

After nearly two years of implementing a campus-wide PTS program, we have learned several lessons about how to engage students and staff, and maintain engagement. We learned that different platforms can engage different stakeholders; there was little staff engagement in the program until we developed the web app. We learned that some students and staff will persist in providing feedback despite a lack of immediate or certain response. However, there are limits to their patience. Participants who understand that changes may take longer to occur submit more feedback, therefore it is important to be transparent, and effusive, about the timeframe for closing the loop between occupant feedback and Facilities' response.

Participation can be maintained over an extended period of time, with reasonable promotional efforts, at levels that enable meaningful interpretation and various uses of data, though more issues could be addressed if we had higher participation rates. We have experienced a negative trend in participation over time. We know some users have experienced frustration when they are not satisfied with Facilities' response (or lack thereof) and users' expectations for more immediate impacts are correlated with lower rates of participation. However, further research is needed to better understand declining participation. For example, our success in addressing comfort and efficiency issues may contribute to declining participation. A novelty effect could also help explain the increase in votes in fall quarters and subsequent decline; as more students are exposed to the program and try it out once or twice, there are fewer visits until a new group of students arrives in the fall. The biggest lesson we have learned here is that interdisciplinary collaboration between design professionals and behavioral scientists is crucial to understanding users and maximizing our ability to sustain occupant engagement and participation.

6.2. How to interpret the data

Ther*MOO*stat has yielded many insights about the campus that would have otherwise not been possible, from triaging incoming feedback submissions to be able to act quickly if necessary, to tracking trends in aggregated feedback over time that reveal opportunities for improving comfort and efficiency. In terms of interpreting the individual feedback submission, the team has learned that comments are extremely useful in providing context. In fact, we are considering further enhancements to produce similar kinds of contextual data, i.e., asking the user if they are currently in the room or submitting feedback from memory, giving users an option to say if they think the issue is chronic, and asking about their recent level of physical activity. Further research is needed for a more nuanced understanding of patterns in aggregate feedback, e.g., conflicting votes in the same room/zone and season.

Other datasets have been critical to the interpretation of Ther*MOO*stat feedback. In particular, data from the BAS is a keystone element in the program. This is also a limitation because the BAS is not available in all campus buildings, including some that house classrooms with high volumes of feedback. Furthermore, triaging Ther*MOO*stat submissions (associated with rooms) by cross-referencing them with BAS data (organized by HVAC zones) requires labor-intensive interpretation of drawings and BAS labels; matching them automatically is currently impossible. Finding a way of associating a feedback submission with its corresponding HVAC zone would significantly simplify ECO's procedures for interpreting Ther*MOO*stat data. The team also looks outside the BAS for other factors that may correlate with discomfort and/or inefficiency, such as building age, geographic orientation, access to a thermostat, daytime occupancy, and vent type and location. Working with the Facilities Management Department enables access to the BAS and other datasets.

6.3. How to improve campus conditions

ECO has been able to apply insights from PTS data to directly make improvements to occupant comfort and building energy efficiency. They have also discovered more creative and proactive applications, such as evaluating ambitious efficiency initiatives, and hopefully making those projects more prone to approval in future. However, complexities still need to be addressed in order to maximize the usefulness of a campus-wide manual closed-loop PTS program.

Future research is needed to establish quantitative evidence for energy savings resulting from applications of Ther*MOO*stat data; lack of such evidence is a limitation of this research. Evaluation of energy savings in this context is particularly challenging. In a large building with complex HVAC, isolating the energy savings in a single zone is difficult, especially when HVAC energy use is not sub-metered. Interaction between zones, thermal lags, and unmeasured effects (e.g., thermal loads due to occupancy) are difficult to quantify. On the other hand, detecting impact at the building level requires significant changes to the HVAC set points or hardware; the initiatives described in this research were not at that scale.

Uncertainty in savings contributes to the inertia and the resistance to change of Facilities Management. Quantifying energy savings is also important to determine if Ther*MOO*stat is an economical endeavor (i.e., worth one FTE of ECO personnel). However, other qualitative benefits should also be considered in such an assessment, such as giving students a voice and improving comfort and productivity.

Ther*MOO*stat generated 12,000 feedback submissions over 23 months, which may seem like a large sample. However, when split between over 100 buildings and exponentially more rooms, this sample was insufficient for certain applications. For example, automated closed-loop control systems, such as the one described in Pritoni et al. [19], require a continuous stream of data to work reliably. Designing a control algorithm that uses such sparse data as we have received is challenging. If feedback submissions are missing, the software is not able to distinguish whether it is because the building is unoccupied, people are comfortable, or people are not using the system. Automating controls in large buildings also requires consideration of security and reliability issues, which our team has not yet addressed.

Using PTS to support change management, e.g., in our active building commissioning initiative, is a work-in-progress. Major projects may need a more personal approach instead of or in addition to using Ther*MOO*stat as an evaluative tool, e.g., more front-loading; face-to-face communications between occupants, laboratory managers, and Facilities personnel; and/or more active involvement of occupants and managers in project goals and implementation.

7. Conclusion

In our experience, scaling up a manual feedback-control loop PTS program to an entire university campus is feasible, useful, and tentatively sustainable. The successes of Ther*MOO*stat are largely attributable to the interdisciplinary and inter-sector approach that leverages the ECO team's professional design and software development skills, Facilities Management's access to informational, political, and human resources required to implement the program on a large scale, and the engineering and behavioral expertise of academic research partners pushing forward the frontiers of innovation and knowledge. There is much be gained from programs like Ther*MOO*stat, in terms of both practical applications for improving comfort and efficiency as well as research applications for discovering better ways for managing HVAC in large institutional settings.

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