Uncompromising and Occupant-Centered: Changing How We Engineer Buildings

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ABSTRACT

The way we design and build is changing: buildings are constructed to tighter tolerances, with controlled air infiltration, solar gains, daylight, heat losses, and even controlled internal loads. This load reduction is driven by the global need to reduce energy use, a driver that is so strong it can blind us to the fundamental reason we build buildings: to shelter their occupants.

Buildings must uncompromisingly both minimize energy use and optimize occupant comfort. For mechanical engineers, this means we can't just be heating and cooling experts, we need to become thermal comfort experts. Engineering is conservative, but conservative doesn't mean static. There are three aspects of our profession that must evolve: our system selections, our design tools, and our post-construction involvement.

- In low-load buildings, simple technologies, passive strategies, and personal comfort systems can replace standard mechanical systems while wasting less material, money and energy. With significantly less load to meet, we can rely on technology that could previously only assist a primary system.
- Just as cars aren't characterized solely by their top speed, mechanical engineers need more than a peak load calculation to understand and design buildings. We need design tools that enable collaborative design and help us understand our buildings as systems, not components.
- Post-construction involvement of mechanical engineers plays two critical roles: it ensures the design intent is realized in operation and it provides a feedback loop for future designs. The mechanical designer brings irreplaceable value to a building's operation.

We have designed three exemplary low-load buildings: the Bullitt Center, the Rocky Mountain Institute Innovation Center, and the Clarum Passive House. In this paper, we use the successes and failures of each project to demonstrate how we can evolve as mechanical engineers.

Introduction

This study looks at three buildings that share several traits – they are all: medium to small office buildings, (at least partly) owner occupied, owner-developed, targeted Net Zero Energy (as well as other goals), 100% electric, have operable windows and use radiant heating. Most importantly, these buildings were each designed specifically for minimal energy use and for thermal comfort. Design for thermal comfort can be contrasted to design for air temperature ranges, used as an uncertain proxy for thermal comfort. Occupant comfort has been termed "spatial alliethesia" by the Center for the Built Environment; using this terminology, mechanical engineers need to become alliesthesiologists – people that deliver thermal delight.

This paper analyzes energy use and thermal comfort data, in concert with the relevant design data to assess the effectiveness of the individual building systems and design approaches. Thermal comfort is defined in EN ISO 7730:2005 and ANSI/ASHRAE 55-2013 as the combined influence of four environmental factors: dry bulb air temperature, mean radiant temperature (MRT), humidity and air speed and two personal factors: clothing level and metabolic level. A common metric for thermal comfort is Predicted Mean Vote (PMV), which uses correlations to estimate the average of a group of occupant's individual comfort levels. Numerically, the ASHRAE Thermal Sensation Scale ranges from +3 (hot) to -3 (cold) and acceptable thermal comfort is considered ±0.5 which is within the neutral range.

Bullitt Center

Size: 51,000ft^2, 6 stories
Location: Seattle, WA
Climate: Cool Marine
Doors Opened: April 2013

The Bullitt Center was one of the first buildings to achieve the Living Building Challenge. Not a project for small gestures, the stated goal of the Bullitt Center is to "drive change in the marketplace faster and further by showing what's possible today" (Bullitt Center 2013). The developers, the Bullitt Foundation, occupy part of the building, lease out the remaining spaces, and use a MEETS financing structure to get a return on the energy efficiency measures.

The Bullitt Center design strategy was to reduce energy usage by minimizing reliance on mechanical systems. Significant effort was invested in making the mixed mode strategy functional – a task typically beleaguered by unpredictable occupant behavior and complex control requirements. The high performance curtain wall system is a key design feature for thermal comfort that also contributes to the low energy use. Low solar transmission glazing and exterior operable louvres reduce radiant temperature discomfort during warm, sunny conditions; while high insulating properties reduce radiant discomfort and potential convective drafts during cold outdoor conditions. Other design aspects that provide high thermal comfort are the operable windows and ceiling fans which allow for increased air movement, and the high thermal mass radiant active slab.

The high thermal mass slab has provided better thermal comfort during cooling hours than predicted in design, but has required some controls tuning. Initially controlled to continually adjust based on space temperature demand, it was found that the slab thermal mass overwhelmed other heating and cooling loads. For example, the night flush would cool the space down, but as soon as windows closed, the air temperature would quickly rise back up to the slab temperature. A revised control strategy keeps the slab at a more constant temperature that provides radiant temperatures for improved thermal comfort.

The Bullitt Center is the earliest design presented in this paper. The lessons learned from this building have directly improved the designs of successive buildings, particularly RMI.

Clarum Passive House

Size: 5,700 ft^2, 2 stories
Location: Palo Alto, CA
Climate: Mixed marine climate
Doors Opened: April 2014

The Clarum Passive House was one of the first Passive House office buildings on the West Coast. The owner, Clarum Homes, has been developing custom Passive House homes and educating clients on their benefits since the concept was introduced to the Bay Area. In looking for a new office, Clarum Homes implemented what they'd learnt developing homes and applied it to a major renovation.

The Passive House standard is founded on creating thermally comfortable spaces; the definition of Passive House is a building that achieves thermal comfort with minimal heating and cooling systems (Feist 2015). This uncompromising approach of thermal comfort plus energy efficiency is what distinguishes Passive House from other energy use standards.

The Clarum Passive House design focused on highly-insulating enclosure with reduced thermal bridging. This includes a fully insulated slab, wood framed walls with continuous insulation only penetrated by screws, and a 12" structural insulated panel (SIP) roof. Radiant heating and cooling ceiling panels, coupled with tempered ventilation air allows the HVAC system to address air temperature, radiant temperature, and humidity. The radiant heating and cooling ceiling panels are controlled based on operative temperature (a combination of air and mean radiant temperature), which is more effective at controlling radiant systems than air temperature alone.

The windows were initially designed with extensive exterior shading to control solar loads, but late-stage changes eliminated the exterior shading. Without the ability to redesign glazing types, sizes or locations, this has inevitably led to localized energy and thermal comfort issues. These have been worked through during operation with measures such as internal blinds and increased cooling system capacities. This design change highlighted to the project team the interdependence of building systems.

RMI Innovation Center

Size: 15,900ft^2, 2 stories
Location: Basalt, CO
Climate: Cool dry climate
Doors Opened: November 2015

The Rocky Mountain Institute Innovation Center strove to eliminate mechanical systems and redefine how we design for thermal comfort. RMI developed the Innovation Center to "demonstrate how deep green buildings are designed, contracted, constructed, and occupied" and to "propel the industry" (RMI Innovation Center 2016).

Rocky Mountain Institute held the design team to a high standard, not just in design quality, but in design approach. Indoor design conditions were specified using Predicted Mean Vote (PMV) rather than relying on traditional air temperature bands. This approach requires a design tool that can estimate PMV by calculating all four environmental factors (air temperature, mean radiant temperature, humidity, and air speed). Using a dynamic and integrated software tool, a custom analysis tested and optimized the proposed design.

In a drastic departure from traditional heating and cooling systems, the building relies on an electric resistance radiant floor for heating and has no compressor-based cooling. Personal comfort and occupant-controlled systems were heavily integrated into the building design. All office spaces have Hyperchairs, a personal comfort system originally developed by the Center for the Built Environment, which have embedded electric resistance heating and small fans in the seat back to provide a cooling effect. This type of system allows for a wider comfort range in the space because occupants are able to control their hyper-local conditions, meeting both requirements of thermal comfort and minimized energy use.

Before the RMI Innovation Center, these personal comfort systems were largely untested in-situ. After a few months of operation in winter, RMI has decided to increase the space set points. This decision represents their current approach to personal comfort systems – that they should be designed to "meet the final 10% dissatisfied" occupants. This comes from an understanding that ±0.5 PMV, which indicates acceptable thermal comfort, is designed to correlate to 10 percent of people dissatisfied (PPD). Therefore, their current approach is not that personal comfort systems should be used to get conditions within the ±0.5 PMV range, but ensure comfort for 100% of people.

Methods

For all buildings, the three environmental factors of **air temperature**, **mean radiant temperature** and **humidity** were measured, while the remaining factors were estimated. Except as noted, air speed of 15 fpm is used to approximate the relatively still air for all buildings, appropriate because none of the buildings rely on air-based conditioning systems. Clothing level was estimated at 0.8 Clo during summer months (May through October) and 1.0 Met during winter months (November through April). Metabolic rate was estimated at 1.1 throughout the year, correlating to an activity of typing.

Bullitt Center. The building management system does not track mean radiant temperature so standalone globe temperature loggers were used to measure air temperature, humidity and mean radiant temperature. Two loggers were placed on Level 3, near the south façade and the north façade. These were located roughly 2m from the façade and 0.8m above finished floor to estimate conditions for a typical occupant. Given the floor plans are relatively similar, the conditions on Level 3 are considered representative for the other floors. Energy use is tracked by a separate energy management system.

Clarum Passive House. The HVAC system measures air temperature, mean radiant temperature, and humidity levels for all zones. Energy use is tracked by a separate energy management system.

RMI Innovation Center. The building management system tracks air temperature for all zones, along with humidity and mean radiant temperature for select zones. Data is presented for those zones where all three variables are monitored. The building management system also tracks energy use data.

Operational thermal comfort data is plotted on a psychrometric charts generated using software based on the validated PMV model used by the Center for the Built Environment's Thermal Comfort Tool (Tyler 2013).

Results

Energy Usage Data

The energy use intensity and photovoltaic energy generation for the first fully occupied and operational year is presented in the table below for each building. The Bullitt Center was initially partially occupied so the reporting period starts two years after the building opened. The Clarum Passive House energy use excludes car charging, which represents an additional 8%

energy consumption. The RMI energy use and generation are extrapolated from the first three months of metered data. The data wasn't adjusted for seasonal variation and doesn't take into account ongoing commissioning and tuning.

Table 1: Energy use and generation

Building	Energy Use Intensity	Photovoltaic Energy Generation	Reporting Period
Bullitt Center	12.0 $kBtu/ft^2$	17.0 $kBtu/ft^2$	Apr 2015 – Mar 2016
Clarum Passive House	28.9 $kBtu/ft^2$	31.0 $kBtu/ft^2$	Jan 2015 – Dec 2015
RMI	17.0 $kBtu/ft^2$	26.0 $kBtu/ft^2$	Feb 15 – May 16[1]

[1] Extrapolated to estimate annual energy use and photovoltaic generation

All buildings are Net Zero Energy as they generate more energy than they use. These buildings have significantly minimized energy use, reducing demand on fossil fuels and on the utility energy grid.

Loads. The common design approach for all buildings was the minimization of heating and cooling loads. This approach is based on the idea that the most efficient equipment will always be the equipment you don't need. Similarly, it will always be easier to add photovoltaic capacity or upgrade equipment efficiency than to rotate, re-configure, or re-insulate a building. Table 2 below compares conventional loads to those of the three high performance buildings. For all loads except occupancy, the three buildings show significant reductions compared to conventional assumptions.

Table 2: Load comparison between conventional assumptions and high performance buildings.

		Units	Conventional Assumption[1]	Bullitt Center	Clarum Passive House	RMI Innovation Center
Heating Loads		$btu/(hr \cdot ft^2)$	25-40	15	3.3	10
Cooling Loads		$btu/(hr \cdot ft^2)$	30-40	23	3.5	N/A
Air Supply[2]		cfm/ft^2	1 – 1.5	0.19	0.23	0.1
Peak Internal Load	Occupancy	ft^2/person	80-150	150	250	Based on desk count
	Lighting	W/ft^2	1.5-3.0	0.4	0.5	0.55
	Plug Loads	W/ft^2	0.5-2.5	0.7	0.95	0.88

[1] Based on building average (not perimeter) values from HVAC: Equations, Data, and Rules of Thumb and US-based but not climate specific (Bell 2000)
[2] The term "air supply" indicates total air supply used to condition a space and may be a mix of recirculated and fresh air.

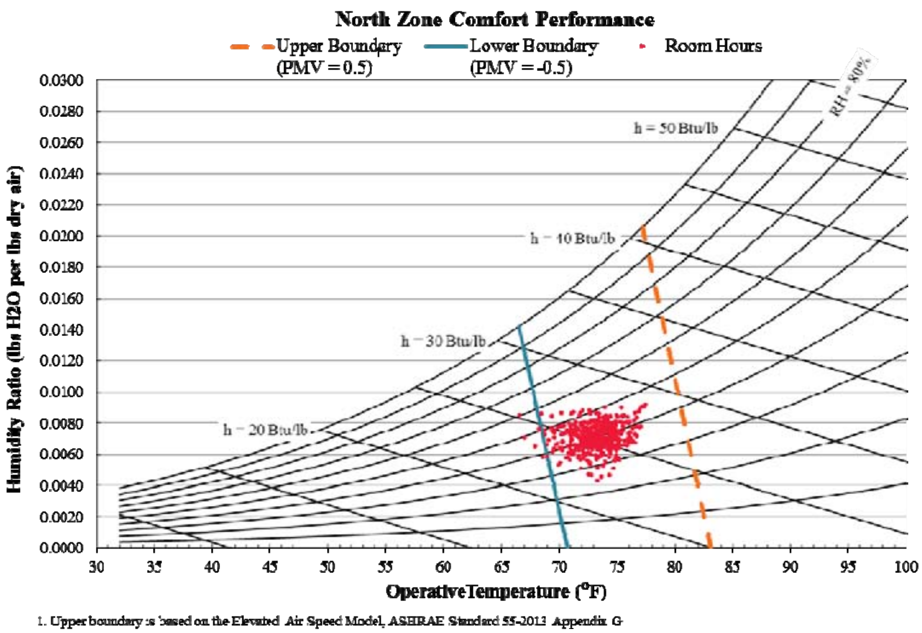
Reducing loads also helps achieve the goal of thermal comfort combined with minimized energy use. For example, an air-based conditioning system would need proportionally less air to meet a lower load, giving the designer the flexibility to reduce, modulate or re-direct air volumes or speeds to optimize thermal comfort – all while using less energy. Additionally, a building with low heating and cooling loads will typically have low radiant temperature asymmetry because often the gains that cause high loads, are the culprits of radiant temperature asymmetry. The common example of this is high performance glazing which insulates and regulates solar gains, keeping window surface temperatures close to the space temperature.

Thermal Comfort Data

Bullitt Center. The thermal comfort study of the Bullitt Center (Elley 2011) predicted comfort throughout the year predominantly due to the passive design strategies. The active cooling system (the active radiant slab) was demonstrated in this study to address the 50 hours per year that weren't addressed by the passive cooling systems. This analysis took into account air temperature and air speed, and factored in the thermal mass, but didn't use a multi-variable thermal comfort using a parameter such as PMV. In subsequent projects, similar analysis software has been used but thermal comfort metrics are discussed explicitly and used as a design tool to guide discussion and decisions.

The operational thermal comfort data is plotted on psychrometric charts in Figure 1. The upper and lower boundaries represent ±0.5 PMV based on the factors outlined previously, although the upper boundary was increased based on the ASHRAE 55-2013 Elevated Air Speed Model. Each point represents the average conditions in an hour during occupied hours. Where the points fall between the upper and lower boundaries, the space is considered statistically comfortable.

This data shows that the space predominantly remains within the thermal comfort bounds, although conditions are occasionally slightly cool. Conditions are tightly clustered, representing consistent and steady internal conditions. This is related to the high thermal mass slab, which helps regulate temperature and slows temperature change in the space.



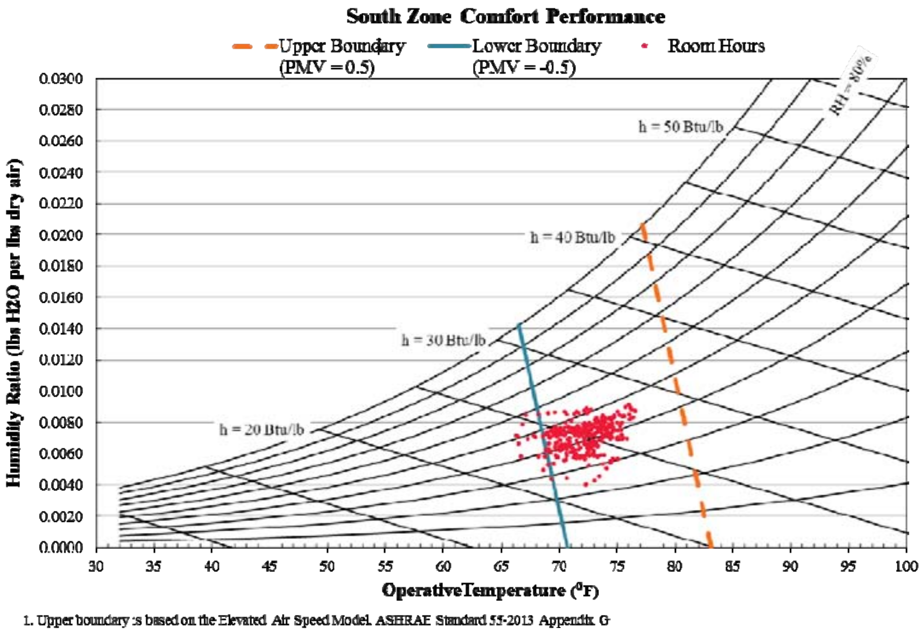


Figure 1: Operational thermal comfort conditions for a 3rd floor open plan north zone (top) and south zone (bottom).

Clarum Passive House. The psychrometric charts in Figure 2 show the number of hours at specific comfort conditions. The red box bounds the range of conditions that meet ±0.5 PMV. Monitored data for four spaces is shown, including a meeting space, an open office space, and two private offices with different orientations.

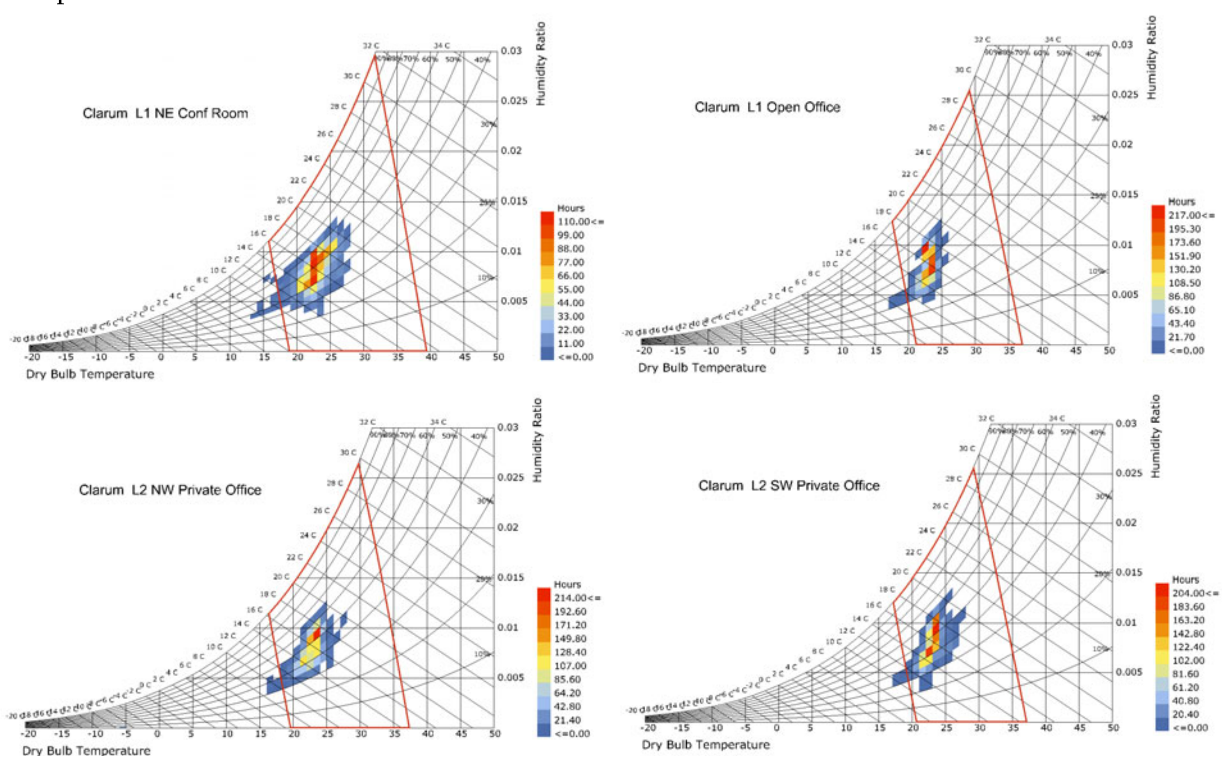


Figure 2: Clarum Passive House operational thermal comfort data

The meeting space has the least clustered or tight control of conditions, while the other spaces show similar patterns of comfort conditions. All spaces remain between 30-65% humidity with a couple hours at lower humidity. The dry bulb temperature remains between 21-24°C (70-75°F) most of the time, with some lower temperatures, particularly in the conference space.

The higher variation in the conference space and, to some degree, the private offices is related to the transient occupancy and loads, as well as the increased use of operable windows.

RMI Innovation Center. The RMI Innovation Center, which was designed most recently, used the most detailed thermal comfort design approach of the buildings presented in this paper. The design team used the PMV metric to define space requirements and they made decisions about how to heat or cool spaces based on the predicted hourly comfort conditions. An outcome of this design process was predicted hourly conditions plotted on psychrometric charts, which are shown below and can be directly compared to the operational monitored data.

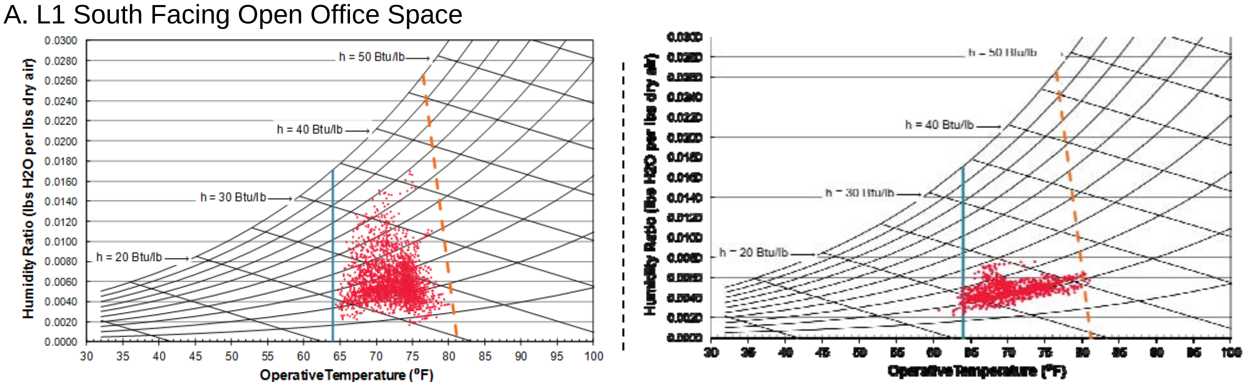
The figure below shows the design data on the left and the operational data on the right, for the same space and using the same comfort parameters. Rather than using the typical factors described earlier to generate the upper and lower bounds, the design parameters have been used. In general, this is 0.57 Clo and 1.2 Met in cooling conditions and 1.01 Clo and 1.0 Met in heating, with 19 fpm air speed. Where ceiling fans are used to increase air speed, the upper bound (i.e. in cooling) is defined using the ASHRAE 55-2013 Elevated Air Speed Model, as can be seen in charts C and D. For office space (A, C, D), Hyperchairs were factored into the lower boundary, although this assumption may change for future designs depending on the further operational outcomes. For the conference space (B), the upper bound was defined based on higher air speed (100 fpm) and higher metabolic rate (1.7 Met), correlating to active speaking activity.

The monitored conditions are similar to the design conditions and generally fall within the defined thermal comfort ranges, with the exception of the conference meeting space (B). The conference meeting space is a transiently occupied, event space although the current data does not clearly show whether the slightly cool conditions occur when the space is unoccupied. The remaining spaces, although they typically fall within the thermal comfort bounds, cluster more heavily towards the lower bound and occasionally conditions are slightly cool.

Design Thermal Comfort | Operational Thermal Comfort

Upper Boundary (PMV = 0.5) | Lower Boundary (PMV = -0.5) | Room Hours

A. L1 South Facing Open Office Space



B. L1 South Facing Conference/Meeting Space

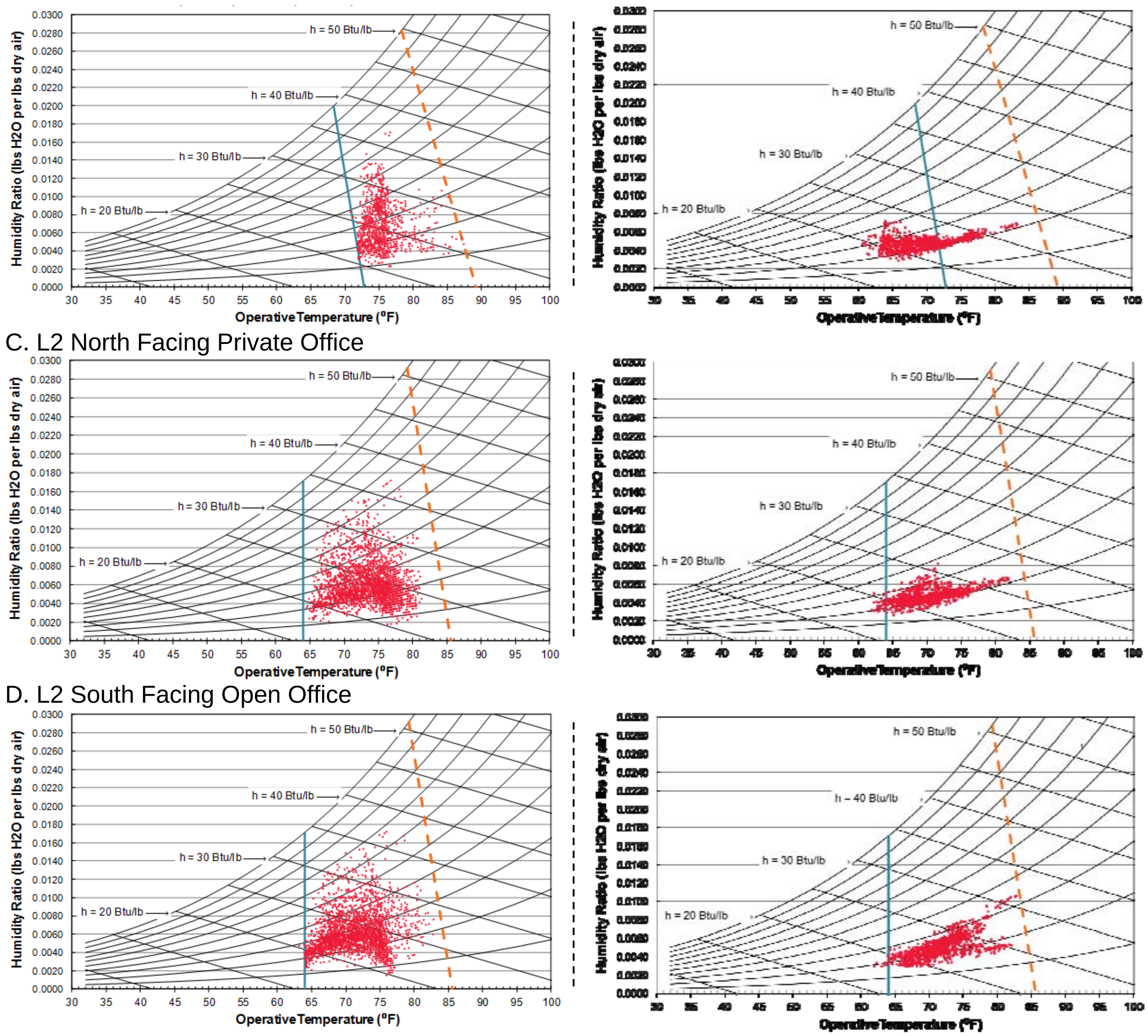


Figure 3: Design (left) and operational (right) hourly conditions during occupied hours for RMI Innovation Center

Discussion

The data for all buildings and spaces consistently shows that they are providing thermal comfort, although frequently closer the lower comfort bound and occasionally slightly cool. The notable exceptions are the RMI level 1 conference space, which is often cool and the Clarum Passive House level 1 meeting room, which has a wider spread of conditions.

The Bullitt Center pushed boundaries and as such, has been an amazing opportunity for design team (who have remained involved), the occupants (who participate actively in their building operation), and the public to learn about high performance designs. The building team has learnt how to operate their building to provide excellent comfort conditions. An example is the controls adjustment to account for the thermal mass of the slab, in response to occupant feedback and implemented collaboratively by the mechanical design engineers and facility management team. This control approach has fed forward into PAE's future designs for radiant and high thermal mass projects.

PAE's continued involvement, and the Bullitt Foundation's vested interest in the building's operation is due to several unique factors, including occupation of the building, a financial structure that allows the Bullitt Foundation to benefit from energy savings, and the individual organization's commitment to the project. Standard projects, what could be called "the 80%" project, may struggle more to get the same level of commitment in post-occupancy.

Given the large window spans in the Bullitt Center, noticeable radiant temperature asymmetry would have been expected with typical glazing and (lack of) shading. However, because of the high performance façade, this was not noticeable in the data. This an ideal application of customized analysis – where the project team wanted to push the limits of a component, while still attaining high standard of energy performance and thermal comfort.

The Clarum Passive House project provides high thermal comfort at a reasonably low energy use. What is unique about this building compared to the other two buildings is that it did not use any customized or advanced modeling during design. This demonstrates the effectiveness of using Passive House as a tool for thermal comfort, especially for buildings that don't have the budget, time, or expertise for customized analysis. Passive House, although far from a prescriptive, requires a rigorous reduction of loads for the express purpose of improving occupant comfort and minimizing energy.

The comfort of passive house buildings is purported anecdotally but few projects in the US have measured thermal comfort directly. For this project, the conscious effort on behalf all design and construction team members to reduce loads has led to an ultimately comfortable and low energy use building.

Through comparison between the RMI Innovation Center design and operational data, it is clear that we are able to predict operational conditions with reasonable accuracy. Each of the operational data charts was similar to the lower humidity and operative temperature conditions that would be expected for a winter monitoring period. This validates the design tools that were used as they evidently gave the designers a clear understanding of the how the passive and active components would interact.

In operation, RMI has addressed challenges with the perceived comfort from the Hyperchairs and has found that it, in general, the Hyperchairs shouldn't be used to reduce the lower thermal comfort bound. Instead, they should be used to address the 10% of people that are predicted to be uncomfortable within the range of ±0.5 PMV. Their ability to increase the upper thermal comfort bound has yet to be determined. The use of electric resistance heating in the RMI Innovation Center has allowed a significantly simpler HVAC system, without the high energy use typically associated with electric resistance, because of the low heat losses and utilization of passive heat gains.

Conclusion

A common theme amongst these projects is that it's hard to be first: innovation, by definition, means doing things that haven't been done before and everything new comes with unknowns. Each building has encountered unique challenges relating to thermal comfort and energy use, particularly during occupancy. The process of working through these challenges adds to the success of these buildings and what they are able to contribute to the industry.

The building design and construction industry has been slow to change and in some areas, productivity had decreased (World Economic Forum, 2016). With growing global environmental concerns, change is imperative. Mechanical engineers have a critical role to play in this transformation as they are centrally placed within the project team and can connect the sometimes disparate elements of energy use, occupant experience, and building operations.

Mechanical engineers won't transform into Alliethesiologists overnight, but here's what we can do now to move our industry forward:

- **Advocate for good envelope** design as a pre-condition to better comfort, smaller HVAC systems, and lower energy use.
- **Discuss thermal comfort** directly; educate yourself and your team to enable these discussions
- **Agree on thermal comfort** criteria and hold the design to that standard; don't consider two buildings that provide different levels of thermal comfort as equivalent
- **Start with a blank slate**, design passive strategies first, then determine what mechanical systems are required – but don't assume they will be required
- **Use design tools to understand** how the building will operate and how it will respond to its occupants and environment
  - Use a rigorous energy and comfort standard for buildings that are using proven approaches or that are constrained by time, budget or expertise
  - Use appropriate customized analysis for buildings that are pushing limits or trying something new
- **Stick with your buildings:**
  - **Start small –** collect whole building energy use and maintain relationships with owners
  - **Upskill –** acquire skills in troubleshooting, data collection, and retrocomissioning
  - **Encourage policies** and financial structures that get owners and developers incentives for ongoing building savings
  - **Aim to be involved** in every building for five years after completion

Limitations and Further Development

The following items are limitations of the current data and analysis. Their acquisition would further develop the current analysis:

- Occupant feedback surveys
- Radiant temperature sensor accuracy is known for the loggers placed in the Bullitt Center (±1.1°F) but was not available for the BMS-integrated sensors in the Clarum Passive House and RMI Innovation Center; this information would help inform the validity of the data
- Additional Bullitt Center thermal comfort monitoring data; the data presented does not cover a full year
- Additional RMI Innovation Center thermal comfort monitoring and energy use data; data from a full year of operation would provide an understanding of how the building operates in all seasons

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