Human Factors and Thermal Comfort Considerations with Electrical Demand Response Program Implementation

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Abstract
Maintaining thermal comfort within an occupied building requires energy, thus optimized solution methods for balancing energy use with indoor environmental quality (adequate thermal comfort, lighting, etc.) are needed. Current building temperature control systems do not adequately take in account the adaptive capability of the occupants, but this concept can be used advantageously during implementation of demand response. Demand response programs can affect both the occupants' thermal comfort from temporary adjustments to space temperature settings. This paper describes ongoing research and field testing of methods to optimize building energy consumption for heating, ventilation and air conditioning applications accounting for human factors such as the thermal comfort by the occupants. Model predictive based controllers (MPC) could serve as powerful tools to optimize the operation of smart buildings and improve human comfort perceptions while helping to better integrate renewable energy systems with increased grid stability.

Keywords Human Factors, Thermal Comfort, Demand Response, Model Predictive Control

1.0 Introduction
The advent of a smart grid opens the potential for smart buildings to participate in load management and demand response programs in collaboration with the electrical utility or grid system operator. Demand response may be used for managing electrical loads during peak, high-demand periods or for optimized integration of intermittent renewable energy sources into the grid. Smart buildings and the smart grid may not be perceived as having a direct impact on the indoor environment of buildings, but the interaction of smart buildings with a smart grid in areas like demand response programs can affect both the occupants' thermal comfort as well as the building's energy consumption (and the corresponding environmental impacts). For example, maintaining thermal comfort within an occupied building requires energy, and therefore optimized solution methods for balancing energy use with indoor environmental quality (adequate thermal comfort, lighting, etc.) are needed. Current building temperature control systems do not adequately take into account the adaptive capability of the occupants, which can be used advantageously during implementation of demand response programs.

This paper describes ongoing research and field testing of methods to optimize building energy consumption for heating, ventilation and air conditioning applications, accounting for human factors such as the thermal comfort by the occupants. We also discuss our vision for how model predictive control techniques could be employed to optimize the operation of smart buildings and improve human comfort perceptions while helping to better integrate renewable energy systems with increased grid stability.

2.0 Occupant Thermal Comfort

Thermal comfort has different definitions from various points of view, but these are all generally associated with a thermal balance of the body (1). Thermal comfort has been defined as “The condition of mind which expresses satisfaction with the thermal environment” (2). Thermal comfort from this view point is extremely subjective, and it is hard to deal with in practical terms. An energetic definition for thermal comfort states that thermal comfort is reached when “heat flows to and from the human body are balanced and mean skin temperature and sweat rate are within the comfort range, which is only dependent on metabolism”. It could be clearly understood that mean skin temperature is a dominant factor in both later definitions (3). On the other hand, “Dissatisfaction may be caused by the body being too warm or cold as a whole, or by unwanted heating or cooling of a particular part of the body (local discomfort)” (4).

2.1 Adaptive versus Heat Balance Thermal Comfort Models

Approximately 50 years ago, Fanger proposed a heat balance model to enable predictions of the acceptability of a certain thermal environment for a group of people with different activity and clothing levels. The Predicted Mean Vote (PMV) index was developed to be a representative of the “mean thermal sensation vote for a large group of building occupants for any given combination of thermal environmental variables, activity and clothing levels” (5). The PMV can be affected by air temperature t_a, mean radiant temperature t_{mrt}, relative air velocity ʋ, air humidity P_a, metabolism or type of activity M, and clothing level I_{cl}, as shown in Equation 1 below.

$$PMV = f(t_a, t_{mrt}, v, P_a, M, I_{cl}) \quad (1)$$

There is an empirical relationship between the PMV index and the Predicted Percentage Dissatisfied (PPD). PPD represents a predicted percentage of building occupants that would be dissatisfied with the existing thermal environment. Many heating, ventilation and air-conditioning (HVAC) standards have been applying PMV-PPD globally in the built environment, with the thermal comfort zone typically is defined to fall between a PMV -0.5 and +0.5.

There are two main concepts which are thought to be misrepresented in Fanger’s model: (a) Thermal neutrality is not equal to the best thermal comfort since more people would prefer non-neutral condition for their thermal comfort; and (b) Not all people feel discomfort in very high and very low PMVs and a non-negligible number of people would prefer such a condition (6).

Dr. Thomas Bedford published a book in 1936 where he proposed an adaptive thermal comfort model (7). The model was the result of field studies in which occupants in their everyday environment were questioned about their thermal vote. People in these studies were subject to the regular natural variability of thermal conditions in the spaces, and researcher interference was minimized. He also measured environmental parameters such as temperature and subjects skin temperature on forehead, palm, and foot. Statistical analysis of these results led to the development of the adaptive thermal comfort model method (7,8). In field studies by Nicol and Humphreys (9), the temperature range that occupants describe as “comfortable” was shown to be wider than that of the heat balance approach. They related this discrepancy to the adaptive behavior of subjects as the result of a feedback loop between their comfort and behavior. Various studies have revealed that the optimum temperature of comfort strongly correlates with the mean temperature that people had recently experienced, and the predicted mean vote (PMV) is just weakly correlated with the indoor temperature (10). In summary, what the adaptive approach proposes is that thermal perception is an amalgam of environmental and personal factors, similar to Fanger's model, and other more complex factors such as "demographics, context, environmental interaction, and cognition as well as occupant's past thermal history". We are working to demonstrate in field studies that this concept can be employed to reduce peak energy demand.

2.2 Field (Real-world) versus Climate Chamber Based Studies

One potential problem is that much of the model basis we have for thermal comfort have depended on experiments done in a climate controlled chamber in an invariant thermal condition rather than in "real-world" operational conditions. However, what happens in the real world can be much different from that in controlled chamber. Our studies described herein are focused on the typical population that would be affected by the zone temperature changes that may be implemented as part of a demand response or overall energy efficiency measure, and we include a commentary on how our results compare to other published studies based on field or controlled chamber data.

3.0 Thermal Comfort Considerations on Demand Response

Temporarily adjusting HVAC system setpoints is a common method to save on energy consumption and peak demand, and these can apply to both the heating and cooling seasons. However, the degree of the setpoint changes can significantly impact the thermal comfort perception of the building occupants.

3.1 Demand Response in the Electrical Grid

Electrical energy differs from other types of energy (such as liquid fuels) in that the production and consumption occur essentially simultaneously. Power grids must be able to provide for the peak demand that occurs. That peak typically occurs during summer afternoons and early evenings during the cooling season. Demand response (DR) is a prevailing practice to increase power grids stability, minimizing the need for increased electricity production and transmission during peak demand periods, usually through load shedding. A smart grid enables buildings to respond to a DR signal as well as provide current operation data to grid operations. Smart buildings (and their associated controls and equipment) are capable of responding to demand response requests to manage peak demand. Some response measures may involve adjustments in HVAC operational setpoints (such as zone temperatures or supply air flow rates) or lighting, thus potentially altering an occupant's comfort perception.

Demand response, while potentially reducing peak demand, overall energy consumption, and utility costs for customers can affect the building occupants physically and psychologically; it might impair their comfort, productivity, mood or even health. However, in some cases this reduction in service results in a stable, if not even improved, comfort vote and could be considered an energy efficiency measure (11). An example of this potential for improvement with DR is for overcooled buildings that end up with an improved thermal comfort or PMV. Building overcooling during the summer to avoid humidity problems is a common issue with many buildings, at least in the United States (12). The detectability and acceptability of demand response and load shedding via HVAC system operation adjustments significantly depends on the rate of load shedding, overall magnitude of the changes, and their frequency. However, in most demand response practices stable ambient temperatures are reached usually in less than one hour after changing the zone control temperature.

3.2 Accounting for Thermal Comfort in Demand Response Programs

Adjusting the built environment temperature in accordance to the outside air temperature can reduce energy consumption for HVAC operation since the occupants have already adjusted to these ambient temperatures themselves. The consideration of the adverse effect of demand response on occupants' thermal comfort should be balanced with the large amount of energy that is consumed for conditioning purposes to keep ambient temperature uniform within a narrow range.

The temperature and operational settings for building HVAC systems influence strongly the energy consumption, but also can significantly impact the occupants thermal comfort perceptions. An early study by Berglund and Gonzales (13) concluded that a temperature ramp of 0.6° C/h from 23 to 27 °C would be acceptable for at least 80% of the occupants as long as the dew point temperature remained below 20° C. Newsham studied the effect of simultaneous light dimming and cooling load shedding on office workers and concluded that a steady increase in temperature up to 1.5 °C from the normal temperature over a 3 hour period (0.5° C/hr) is not detectable for office workers or if detectable, would be acceptable in the circumstances studied (14).

4.0 Case Study and Results to Date

We have discussed above why it is important to understand the thermal comfort perceptions of the local population with respect to demand response program implementation. The thermal comfort perception is also recognized as being a function of age, activity level, time of exposure, regional climatic and cultural considerations, etc. If HVAC system adjustments are to be made for demand response or overall energy conservation, then it is important to account for these factors with respect to the population of occupants in the buildings that are involved to determine how far adjustments can be made and the potential energy savings that might be achieved in practice. This section describes our work to do just that.

4.1 Thermal Comfort Survey Testing and Results

A number of studies have been done over the years concerning the thermal comfort perception of people as a function of various controlled parameters such as temperature, humidity, etc. Most of these studies have been conducted in controlled laboratory type situations, although some have done so in real-world settings. Since perceived thermal comfort and tolerance ranges vary according to the population involved, along with the indoor and outdoor conditions or seasons, we elected to conduct a field study that incorporates these factors. Specifically, our goal was to assess the thermal comfort perceptions of a representative sample of participants occupying buildings where DR and MPC are being developed. Initial results of our study are described in this section.

4.1.1 Methodology

Starting with the summer cooling season of 2014, we have been investigating the effect of increased setpoint temperature on energy use reductions and the thermal comfort perceptions of the building occupants during 'real-world' conditions at the University of Georgia. These tests simulated what could be done on campus during a Demand Response event, and involved surveying more than 1500 students, faculties and visitors about their thermal comfort perceptions during periods when zone temperatures had been adjusted. The primary focus of our studies in 2014 and 2015 was on measuring the energy savings potential when making temporary adjustments to the HVAC system settings (zone thermostat setpoint, etc.). During this initial testing, thermal comfort surveys similar to those done in 2016 were conducted to confirm for the university facility management that the level of changes done would be acceptable to the typical population that occupies these buildings. In 2016 testing was focused on measuring occupant thermal comfort response to various zone temperatures, with the intent on identifying a more optimal set of standards for temperature settings in our campus buildings.

The test subjects were mostly college age students chosen randomly among those passing through or sitting in hallways, classrooms, auditoriums, dining halls or dormitory rooms. Indoor and outdoor dry bulb temperature and relative humidity were measured during the testing period, and occasionally the corresponding CO_2 levels were also recorded. The 2016 thermal comfort testing also recorded each subject's age, gender, time of exposure, and type of clothing worn. Each subject was unaware that zone temperature adjustment testing was being done until they were surveyed.

The 2016 research shifted to a more intense survey of occupants in classroom zones where the temperature was preselected. Students were asked to complete verbal questionnaires, and each class were questioned two times with different room temperatures each time (in most cases). The subjects were asked to express their thermal sensation based on a seven-point scale specified for "point-in-time surveys" in ASHRAE Standard 55-2013 (2) as cold, cool, slightly cool, neutral, slightly warm, warm and hot (represented by actual thermal comfort vote scores of -3 through 3, respectively). Subjects were also questioned about their health status (if they felt healthy or sick) and if they had made any behavioural adjustment to improve their thermal condition perception (such as making changes in clothing level, changing position, having a cold or hot drink, etc.).

4.1.2 Thermal Comfort Perception Study Results

Data from the survey were analysed and comparisons made of the thermal comfort perception results to trends noted in previously published studies. The actual thermal comfort vote of students in 12 different classrooms were collected on two separate days and (for the most part) with different zone temperatures. This allows thermal comfort perception comparisons using essentially the same student populations for each paired test under different air temperature conditions. The number of students in each class section ranged from 18 up to 54. Testing was conducted during late September and early October of 2016 and the average difference in zone temperatures between the two test dates for a given classroom or class section was approximately 1.5° C. Zone air temperatures during the testing ranged from 21.5 to nearly 26° C. Figure 1 shows the corresponding test conditions for the 24 test periods (12 paired class tests) on a psychrometric chart. Note that all but a few of these tests conditions correspond with the assumed thermal comfort zone described by ASHRAE Standard 55-2013 for occupants with a clothing level of 1.0 CLO.

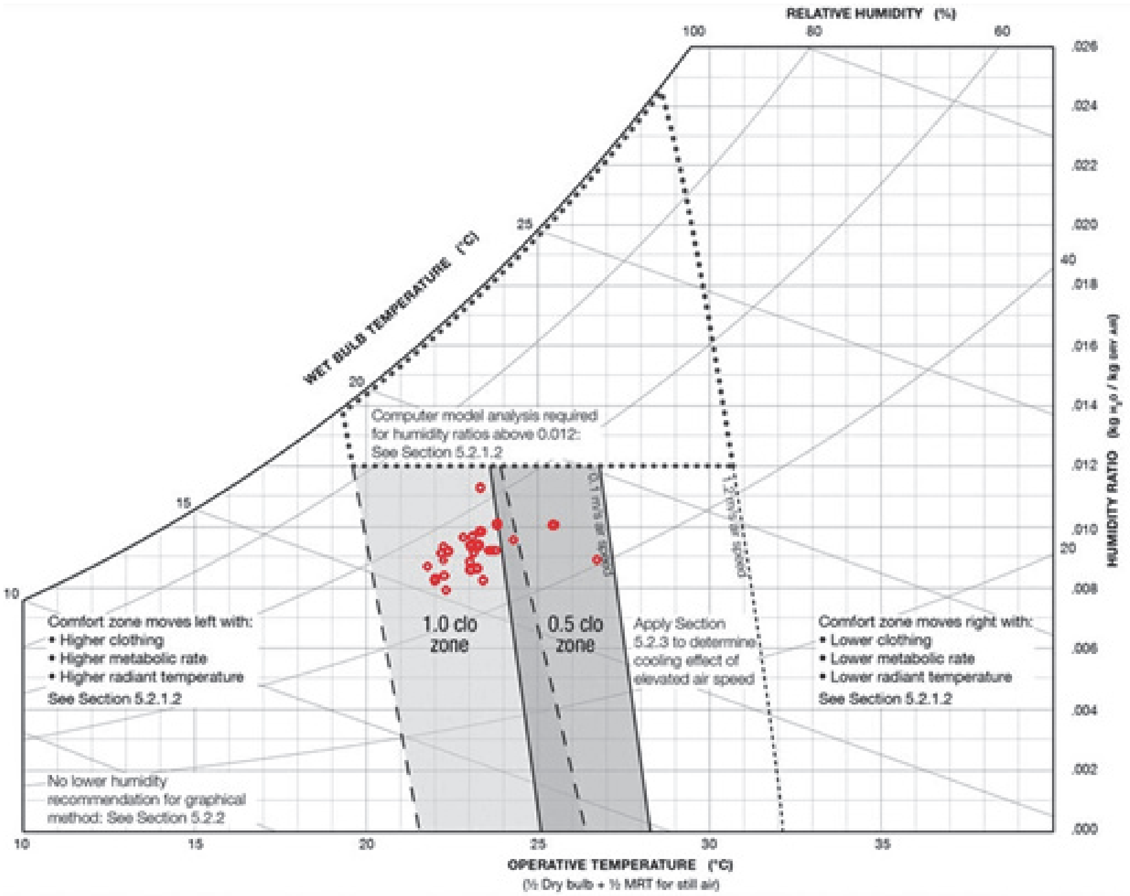


Figure 1 – Classroom zone temperature conditions for the 24 testing periods compared to ASHRAE Standard 55 comfort zones

Individual data for all students in a class were also averaged to obtain the Actual Mean Vote (AMV) for a given class section and date. Figure 2 shows these AMV values for the 12 pairs of tests run, with the same classroom and class sections pairings connected via a line. Based on the student survey responses, for most cases the clothing levels (as measured by the CLO factor) did not change considerably between the two test dates. The results show that when classrooms temperatures were increased the occupant's thermal comfort (expressed as average actual mean vote) tended to increase, but for most cases remained in the acceptable range (-0.5<AMV<0.5). These findings are in line with some other published field studies (15). Three of the class sections, however, did not follow this pattern and actually resulted in lower AMV values with warmer room air temperatures. These are connected with a dashed line (two of the classroom pairings were done at the same temperature and thus give some insight into the potential random deviation of this type of survey. We also not for example one of the class pairings resulted in a AMV value decrease from about -0.5 to -1.0 even though the room temperature was slightly warmer during the second test. This discrepancy might be associated with higher ambient temperature and humidity levels on those days that affect occupant's CLO and expectation, although other reasons may exist as well.

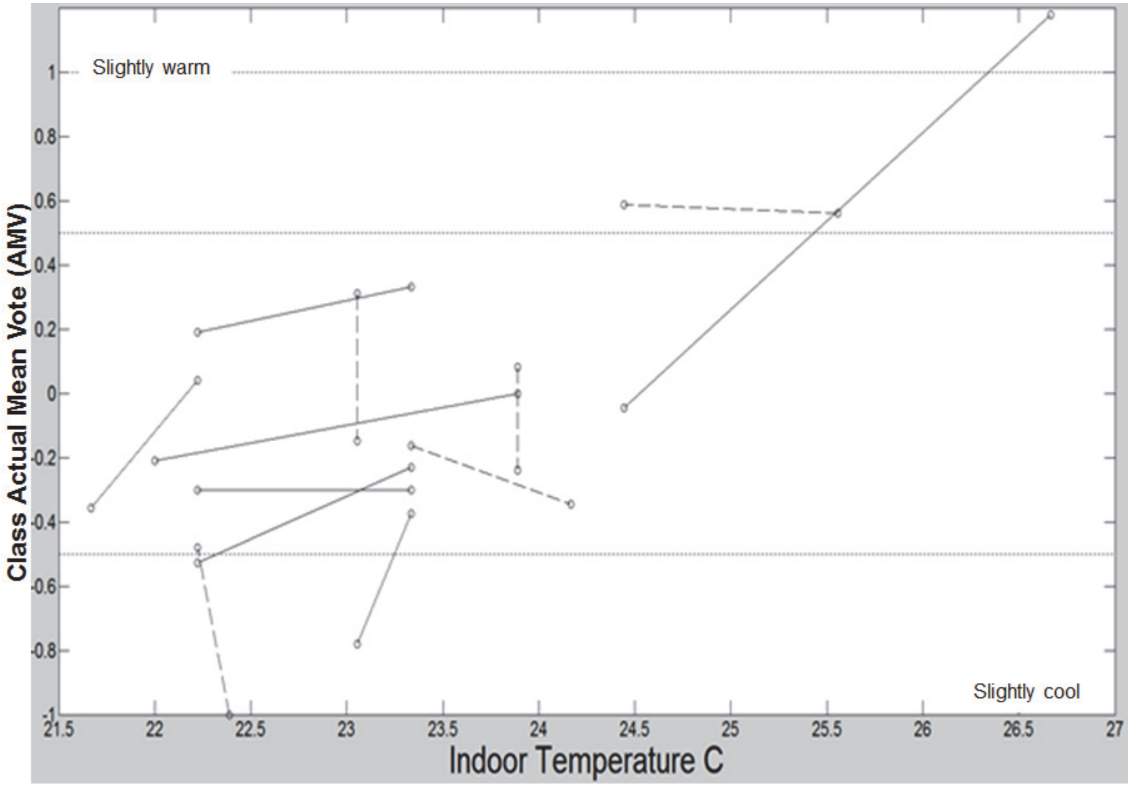


Figure 2 – Actual Mean Vote versus zone temperature

Figure 3 provides a more detailed breakdown of the frequency of responses for the thermal comfort votes during testing of the various classroom zone temperatures, with the frequency defined as the fraction of all respondents expressing that particular thermal vote. The main trend noted with this population of students is that as outside dry-bulb temperature increases, occupant's clothing insulation (CLO value) decreases but also that the Actual Mean Vote also slightly decreases. It is assumed from this that outdoor air temperature, by influencing occupants clothing level or by adjusting their expectations, impacts their thermal comfort sensation while indoors (although there is no clear and solid evidence of adjusted expectations in this particular survey). This finding is also compatible with previous studies (16-18).

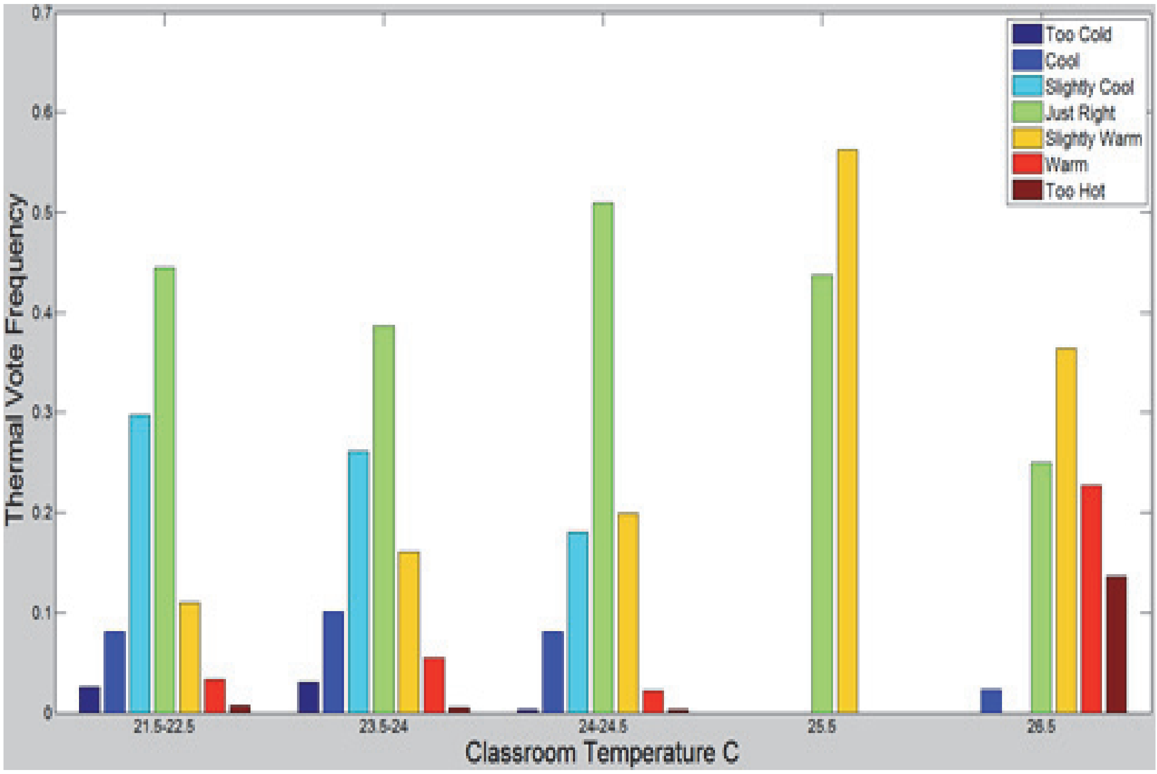


Figure 3 – Frequency of individual thermal comfort votes over the range of classroom zone temperatures tested

Some subjects, although they had not been questioned on this topic, mentioned their preference for what would be interpreted as a 'non-neutral temperature'. This in contrast with Fanger's PMV/PPD model that assumes neutral condition as the preferred comfort condition (19). This will be the subject of further investigations to investigate the differences between neutral temperature, comfort temperature, and also acceptable temperature that occupants (at least in this student population) can tolerate during demand response.

4.1.3 Application to Demand Response

Classrooms in the UGA campus buildings are usually set to operate at zone temperatures between 20 and 22° C. However, the results of our studies revealed that this temperature could be increased up to 26° C without significantly compromising occupant thermal comfort. Based on the energy demand studies described below in Section 4.2, we estimate that significant energy savings (at least 15%) could be achieved with increasing the zone temperatures by between 1.5 and 2° C. More than 16% of the occupants surveyed mentioned that they had included some sort of adaptive behaviour, and that is promising evidence for the potential to increase indoor temperatures even further without adversely compromising the occupant's comfort. Given the results of our thermal comfort studies in 2016, zone temperature increases even higher than that should be possible within the campus buildings. Therefore, this measure should also be considered by the university as an overall energy efficiency practice, rather than just a Demand Response measure.

4.2 Estimation of Energy Reductions with Simulated Demand Response

We have conducted several rounds of testing on the University of Georgia campus to determine or estimate the potential reduction in peak electrical demand when temporary changes were made to the HVAC system operation when operating in cooling mode. Such changes to the building HVAC operation include adjustments in the zone and supply air temperatures, and reducing the maximum supply air flow rate provided by the variable speed fans. Since most of the buildings on campus are cooled using chilled water from a district energy system, we have also tested the ability of this chilled water network to store 'coolth' by precooling the water during off-peak times and then letting the water temperatures rise a little above normal operation during peak periods.

Figure 4 provides a summary of one day of testing compared to a baseline reference on the following day. The maximum ambient air temperature and weather conditions for the two days were nearly identical. Peak energy demand and total energy consumption were reduced by over 11% each compared to the reference day.

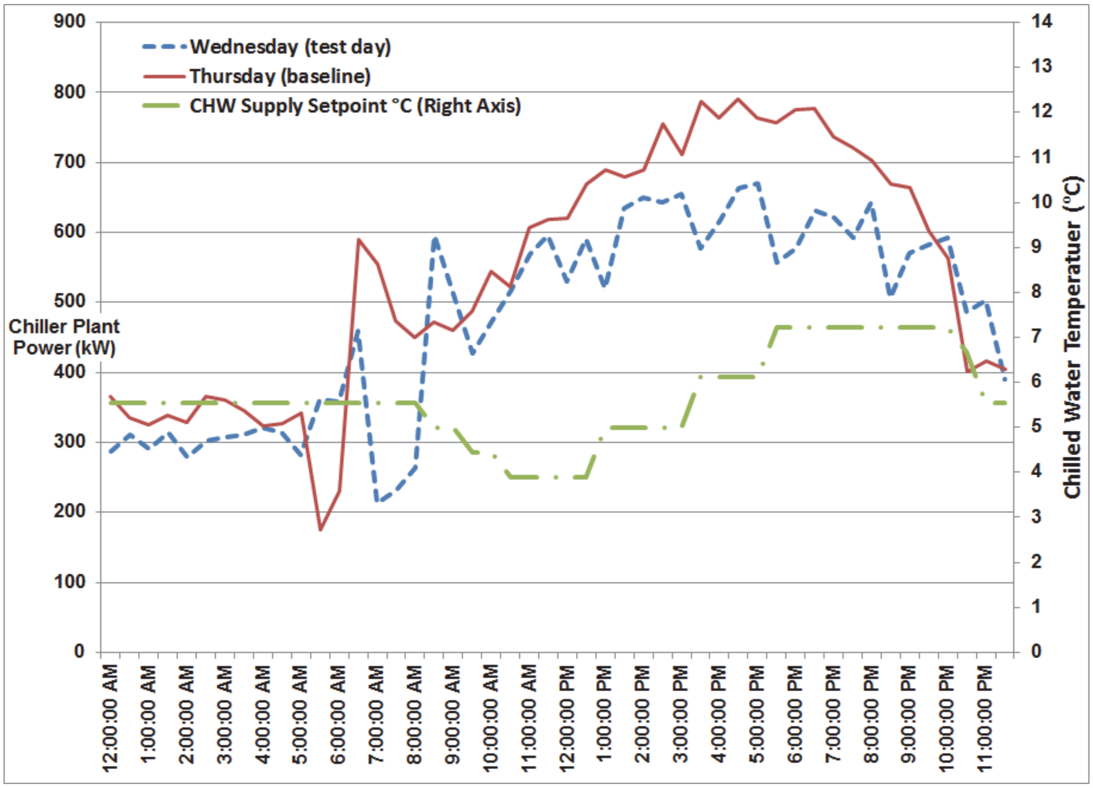


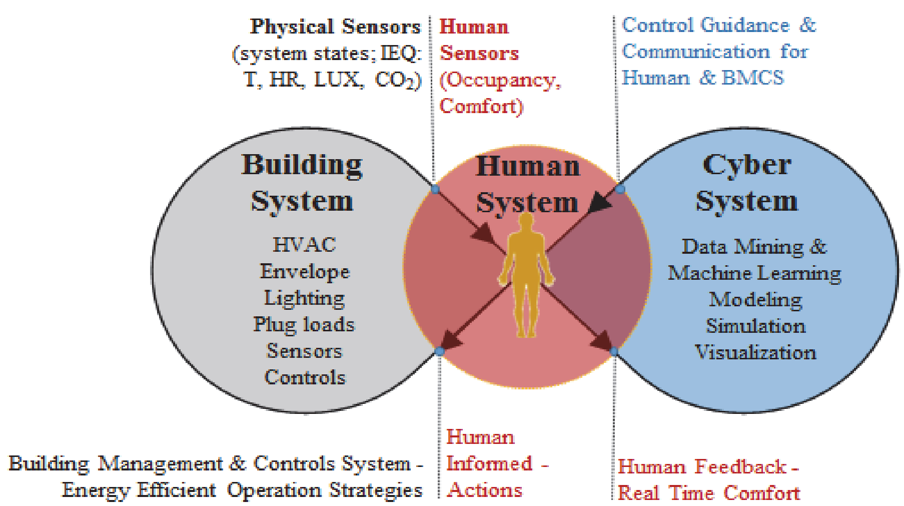
Figure 4 – Results from Simulated Demand Response Testing, August 2015

Thermal comfort surveys were also conducted during the test and baseline reference days, and the results indicated no significant changes in the percentage of people dissatisfied (PPD) from the overall mean votes collected with the calculated PPD being only 5.5% on the baseline day and 5.1% on the test day. This actually represents a slight improvement and is another indicator of the potential for overcooling. We are encouraged by these results, particularly in light that changes were only made on a portion (roughly 15%) of the systems connected to this chilled water network and the fact that the power requirement for this one chiller plant represents about 2% of the total campus load during peak demand periods.

5.0 Application of Model Predictive Control to Optimize Energy Consumption with Occupant Thermal Comfort

The use of MPC is a potentially powerful tool for building cooling systems and has shown potential to overcome the challenges where other control approaches have failed. The design of MPC has been a concept of interest for a number of years in industry and academia because of its ability to yield high performance control systems capable of operating without expert intervention for long periods of time (20). A wide variety of comparisons made recently show that an MPC approach outperforms most control techniques from different aspects such as energy and cost saving, peak load shifting, satisfying complicated operational constraints, improvement in efficiency and transient response (21-23). From the control point of the view, MPC could be one of the better candidates for supervisory control of building cooling systems. The application of MPC to minimize operational cost considering potentials of active and passive energy storage has been investigated during the past decade, for example in (24-25). Any MPC-based building control must be able to predict efficiently and accurately the change in energy consumption if a combination of demand response measures (such as changing set points in some or all of the zones, or supply air temperature and flow rate) are temporarily implemented to handle demand response requests.

One major development challenge that our work aims to address is the incorporation of human factors into the MPC scheme. Humans 'sensor' play a factor in the interaction of the building energy management and control systems with the developing cyber based controls (Figure 5). Peak demand response strategies often include making changes to the building zone temperature set points by temporarily raising them to decrease the overall cooling demand (and hence electrical energy consumption). The fear of causing too much of a temperature swing leading to thermal comfort complaints is one of the major barriers to maximizing the practical implementation of demand response measures by facility operational staff. A recent paper summarizes the technical, societal and human factors issues associated with connecting smart buildings into a smart grid (26).



Source: Lawrence Berkeley National Laboratory

Figure 5 – Integration of Building and Human Cyber Systems for Energy Management

We see MPC as a supplement to, not a replacement for, existing building energy management systems. We see MPC techniques as being most helpful when operations that are outside the 'normal' are desired, for example with participation in automated demand response events. The MPC 'system' will receive inputs from various information sources, such as: monitoring of the building(s) operation during the current day and recent history (say the past 24-48 hours); real-time energy prices or demand response signals; and weather. It also could potentially receive input about other systems such as renewable energy production at the campus or regional level and energy storage system capacity, if installed. MPC output will be the set of recommendations for how the individual buildings and their equipment should operate based on an optimization scheme that would minimize energy peak demand, overall energy consumption while minimizing any negative effects on occupant thermal comfort perceptions and other building operations. The recommendations would include the start and stop times when temporary HVAC set point changes would occur and the level of the changes implemented (which could be different for different zones based on predicted occupancy and the occupant population). The MPC output would also define other temporary system operation changes such as the chilled water supply temperature set point as outlined with the testing programs in the previous section. The optimization could also potentially include the predicted carbon footprint for that system operation. The MPC controller is not used to directly control equipment and systems in the building or set of buildings, but rather is an input to the building's energy management system control as illustrated in Figure 6.

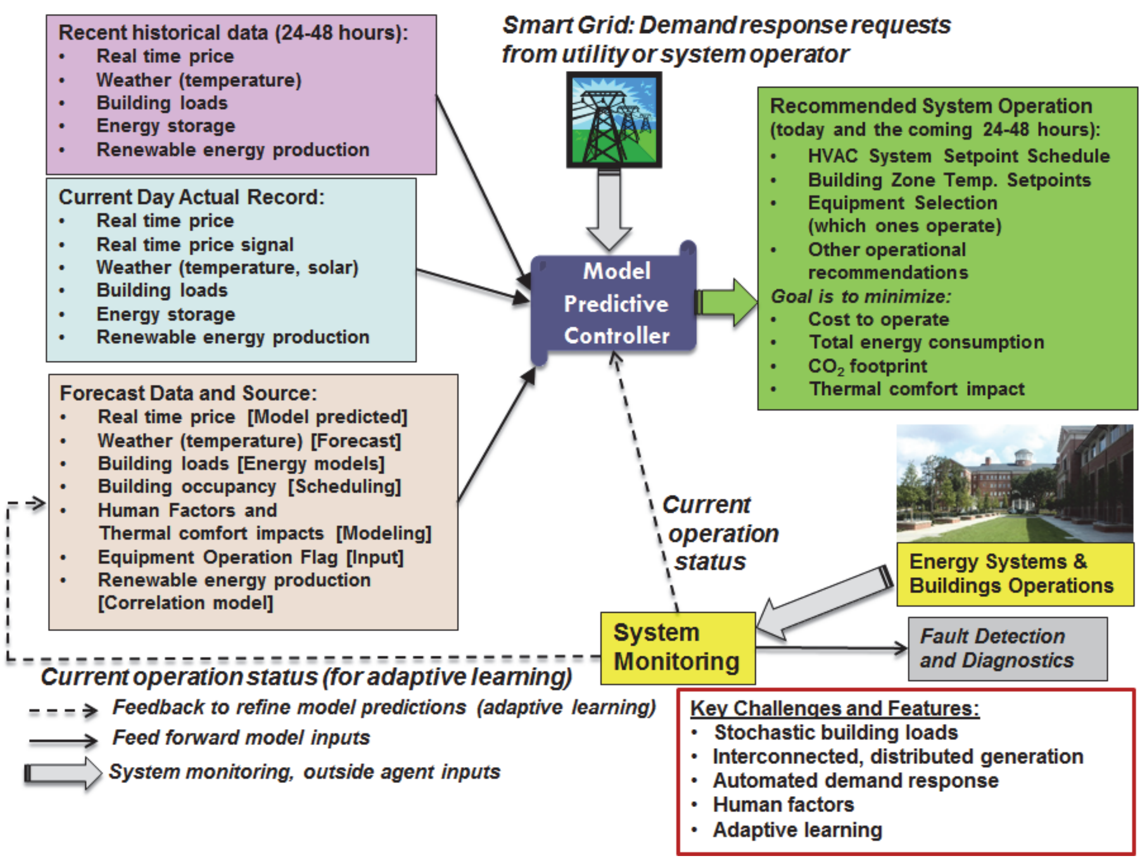


Figure 6 – Long-term Vision for Model Predictive Control Optimization

6.0 Summary and the Way Forward

Model Predictive Control can be used to fine tune how buildings are operated. Current operation of the facilities on our university campus tends toward overcooling in the summer. Based on our recent studies, there is a significant potential for reducing both peak demand total energy consumption when the HVAC control systems account for the thermal comfort adaptations of the building occupants.

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