OPTIMIZING OCCUPANTS' ADAPTIVE THERMAL COMFORT WITH ENERGY COST/CONSUMPTION IN AIR-CONDITIONED BUILDINGS: A FIELD STUDY ON UGA CAMPUS

by

SAMA AGHNIAEY

(Under the Direction of Thomas M. Lawrence)

ABSTRACT

Buildings are a significant contributor to global warming where almost 20% of total energy consumption worldwide is dedicated to buildings' heating, ventilating, and air-conditioning (HVAC) systems. Demand response (DR) could substantially reduce energy consumption and the associated environmental impacts especially during peak-electricity-demand hours. HVAC systems have a great potential to participate in DR programs. However, since HVAC systems' operation significantly contributes to building occupants' health and well-being, it is essential to find a tradeoff between energy consumption by HVAC systems and occupants' thermal comfort in buildings.

Unfortunately, DR measures, if are not accompanied by proper thermal comfort and IEQ measures, could cause serious health issues including reduced performance and sick building syndrome. To avoid this, multiple researchers tried to optimize buildings' energy consumption/cost with occupants' thermal comfort. Conventionally, buildings' HVAC systems are controlled through keeping zone temperatures in a desired range. However, this control strategy could result in excessive energy consumption while not necessarily satisfying most of building occupants due to the lack of scaling occupants' thermal preferences and their adaptive behavior. Others proposed the use of PMV/PPD indices or ASHRAE Standard 55 graphical comfort zone to ensure occupants' thermal comfort while optimizing building energy consumption. However, based on the literature, these static thermal comfort indices do not guarantee occupants' thermal comfort. On the other hand, optimizing energy consumption or energy cost only either underestimates the impact of real time price (RTP) for electricity on users' consumption behavior, or misrepresents the real amount of energy consumption required by necessary services in buildings.

Current research proposes a weighted-sum, genetic algorithm (GA) method to optimize occupants' mean thermal preferences with energy consumption on the university of Georgia's (UGA) campus, where weights are a function of RTP. Initially, an extensive field study is conducted on UGA campus to model the occupant's thermal sensation and preferences in real-world conditions. Building energy consumption for space cooling is simulated using eQuest software. Different DR strategies versus RTP are benchmarked. The results show that this optimization method is a promising tool in maximizing occupants' thermal comfort while minimizing building energy consumption during DR events on UGA campus.

INDEX WORDS: Demand Response, Thermal Comfort Optimization, Occupants' Thermal Preferences, Building Energy Consumption, Building Energy Cost

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DEDICATION

Dedicated to my aunt, Farank, who did not live long enough to witness this fabulous moment of success. Who I am grateful to for her ceaseless love, care, and heartful support to make me a better person.

Dedicated to my mother, Farah Ziba, who I would not be who I am without her relentless support and her selfless endeavors, enabling me to fulfil my lifelong dreams.

To my dad who taught me the lesson of perseverance and determination.

Dedicated to my sister, Shima, my second mom and my second heart, whom without I would not be my complete self.

To my brother, Nima, who never stopped supporting me and loving me, who was there for me whenever I wished for.

To my second brother Taghi who completed us and brought the ultimate joy and happiness to our family.

Dedicated to my sweetheart, Youna, who taught me how to love unconditionally from the depth of my heart. Whose existence, smiles, smell, words, and everlasting love empowered me from beyond the oceans and mountains that stood between us, every single moment of my life.

And, dedicated to Dr. Thomas M. Lawrence for four years of mentorship and company, for putting his trust on me four years back, and to whom I will be grateful to throughout my entire carrier.

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CHAPTER 1

A LITERATURE REVIEW CONCERNING BUILDING OCCUPANTS' THERMAL COMFORT

In the US, Europe, and most developing countries, buildings are responsible for about 40% of total energy consumption, with roughly half of this energy being dedicated to heating, ventilating, and air-conditioning (HVAC) systems, installed to provide thermal comfort for building occupants (Hoyt et al. 2005, Osterman et al. 2015). One study stated that more than 62% of buildings' energy use is dedicated to comfortable indoor conditions (Nghana and Tariku 2016). Thermal comfort has different definitions from various points of view, but these are all generally associated with a thermal balance of the body (Hoyt et al. 2005). One definition states thermal comfort as "the condition of mind which expresses satisfaction with the thermal environment" (ASHRAE Standard 55-2017). Thermal comfort from this viewpoint is very subjective, and it is hard to deal with in practical terms. A thermo-physiological definition relates thermal comfort to "the firing of the thermal receptors in skin and in hypothalamus" (Höppe 2010). In this sense, thermal comfort is a minimal rate of signals from these receptors. There is also an energetic definition for thermal comfort stating that thermal comfort is reached when "heat flows to and from the human body are balanced and the mean skin temperature and sweat rate are within the comfort range, which is only dependent on metabolism" (Fanger 1970, Höppe 2010). It could be clearly understood that mean skin temperature is a dominant factor in the physiological based thermal comfort model approach (Yang et al. 2014). On the other hand, another definition states that "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)" (Hensen 1990). While cold discomfort mostly relates to steady-state skin temperatures, warmth discomfort is mainly associated with skin wettedness (Djongyang et al. 2010).

There are two most well-known thermal comfort models that are being practiced worldwide; the heat balance model or the PPD/PMV model and the adaptive approach. ASHRAE Standard-55 (2017), EN ISO 7730 (ISO 7730:2005), and EN 15251(EN 15251:2007) among thermal comfort standards that recommend using these models. This section presents a brief review of these models, their merits and drawbacks, and their main area of application.

1.1. Heat Balance Model or Rational Approach

In the 1960's, Fanger proposed the heat balance model (also known as the PMV/PPD model) to enable HVAC engineers to predict the acceptability of a given thermal environment for a large group of building occupants. Fanger's model was generally developed based on college-age students exposed to steady-state thermal conditions for three hours in climate-controlled chambers, wearing specified clothing and performing specified activities. The comfort equation, or heat balance model, is associated with thermal neutrality that occurs when "the heat generated through metabolism equals that dissipated to the environment through various mechanisms, mean skin temperature and sweat rate staying within certain limits, and no local thermal discomfort exists" (Fanger 1970, Van Hoof 2008). Then he expanded the experiments and proposed the Predicted Mean Vote (PMV) index to be a representative of a "mean thermal sensation vote for a large group of building occupants for any given combination of thermal environmental variables, activity and clothing levels”. This index incorporates ASHRAE’s seven points scale ranging from −3 for cold to +3 for hot as shown in Table 1.1.

Table 1.1 Thermal sensation vote versus PMV values (ASHRAE Standard 55-2017)

Thermal Sensation Vote	PMV Values
Hot	+3
Warm	+2
Slightly Warm	+1
Neutral	0
Slightly Cool	-1
Cool	-2
Cold	-3

The PMV equation (Equation 1.1) is a function of the air temperature (T_a), mean radiant temperature (T_{mrt}), relative air velocity (v), water vapor partial pressure (P_a) or relative humidity, metabolism rate or type of activity (MET), and clothing insulation level (I_{cl} or CLO) (Van Hoof 2008, Olesen and Parsons 2002)

$$PMV = f(T_a, T_{mrt}, v, P_a, MET, I_{cl}) \tag{1.1}$$

This analytical method is based on the heat balance of the body as presented in Appendix 1 and is only valid for metabolic rates between 1.0 and 2.0 MET and clothing level less than 1.5 CLO. Each MET equals 58.2 W/m^2 and is “the rate of transformation of chemical energy into heat and mechanical work by metabolic work of an individual, and per unit of skin surface area” as described in ASHRAE Standard 55 (2007). Metabolic rate for different activities could be found in Table 5.2.1.2, ANSI/ASHRAE Standard 55-2017. One CLO equals to 0.155 m^2. °C/W (0.88 ft^2·h·°F/Btu) and is defined as “the thermal insulation provided by garments and clothing ensembles" by ASHRAE Standard 55. CLO values for different clothing levels are presented in Table 5.2.2.2.A and B in ANSI/ASHRAE Standard 55-2017.

Mean radiant temperature is defined as the uniform temperature of an imaginary black enclosure in which the human body exchanges the same amount of heat through radiation as in the actual non-uniform enclosure (Atmaca 2007). Since most building materials have high emittance, they could be considered as black objects. Therefore, when there is a small temperature difference between surfaces, such as in buildings, T_{op} is calculated using Equation 1.2:

$$T_{mrt}{}^4 = F_{p-1}T_1{}^4 + F_{p-2}T_2{}^4 + \cdots + F_{p-n}T_n{}^4 \tag{1.2}$$

Where "F_{p-n}" is the angle factor between human body and surface "n". T_n is the temperature of surface "n".

Alternatively, the mean radiant temperature is calculated using a heat stress meter or a black globe thermometer. Globe temperature or black globe temperature (T_g) is the temperature inside a black globe (almost 15 centimeters in diameter). The mean radiant temperature can be calculated using the black globe temperature through Equation 1.3. In this equation ν_a is the air velocity in the room (m/s), T_a is the room air temperature (°C), D is the diameter of the black globe (m), and ε is the emissivity of the black surface that equals 1.0 for a black object (ISO 7726:1998).

$$T_{mrt} = \left[(T_g + 273)^4 + \frac{1.1\times10^8\,\nu_a{}^{0.6}}{\varepsilon.D^{0.4}}(T_g - T_a)\right]^{1/4} \quad (°C) \tag{1.3}$$

There is an empirical relationship between the PMV index and the Predicted Percentage Dissatisfied (PPD) shown in Equation 1.4 and Figure 1.1. PPD represents a predicted percentage of building occupants that would be dissatisfied with the existing thermal environment. The subjective nature of thermal comfort causes the PPD index never to reach zero; even a PMV of zero causes the PPD value in Equation 1.4 to equal 5% (Figure 1.1). Many HVAC standards globally have been applying PMV-PPD in the built environment, for example in Europe with EN ISO 7730 (2005), EN 15251 (2007), and ASHRAE Standard 55 (ANSI/ASHRAE Standard 55-2017) in the US. Fanger assumed that all occupants voting for PMV higher than +1 or lower than -1 are dissatisfied with the thermal environment. As shown in Table 1.2, in ASHRAE Standard 55, the thermal comfort zone is defined to fall between a PMV of -0.5 and +0.5 with the corresponding PPD value of 10% or less where it is believed that 80% of occupants would be satisfied with such an environment (10% dissatisfaction is allocated to local thermal discomfort), using the analytical method or PMV/PPD equations. Figure 1.2 also shows the ASHRAE comfort zone for two different types of clothing level (0.5 and 1.0 CLO) using graphical method (Fanger 1970).

$$PPD = 100 - 95\exp(-0.03353\, PMV^4 - 0.2179\, PMV^2) \tag{1.4}$$

Table 1.2 The acceptable thermal environment for general comfort (ANSI/ASHRAE Standard 55-2017)

PPD	**PMV Range**
< 10%	-0.5 < PMV < 0.5

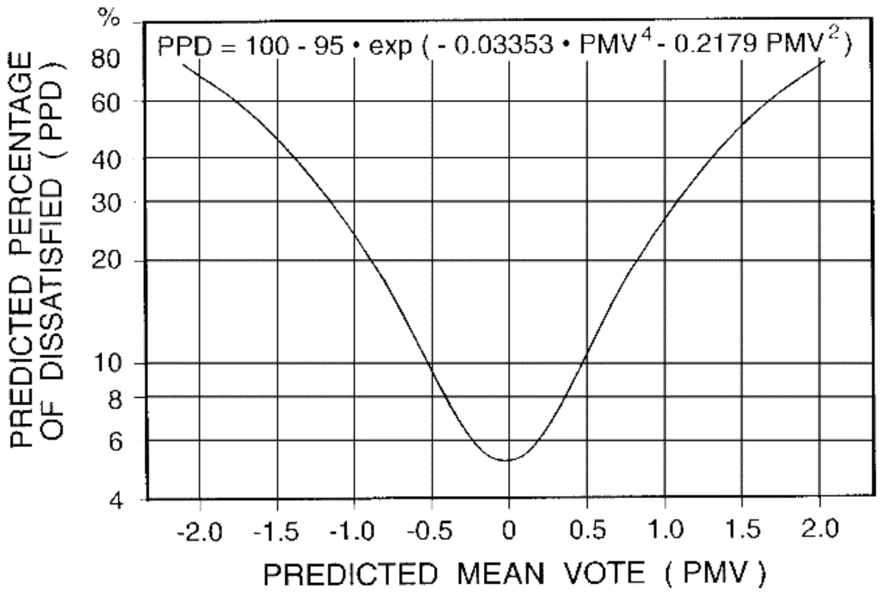


Figure 1.1 The predicted percentage of dissatisfaction (PPD) as a function of the predicted mean vote (PMV), (ANSI/ASHRAE Standard 55-2017)

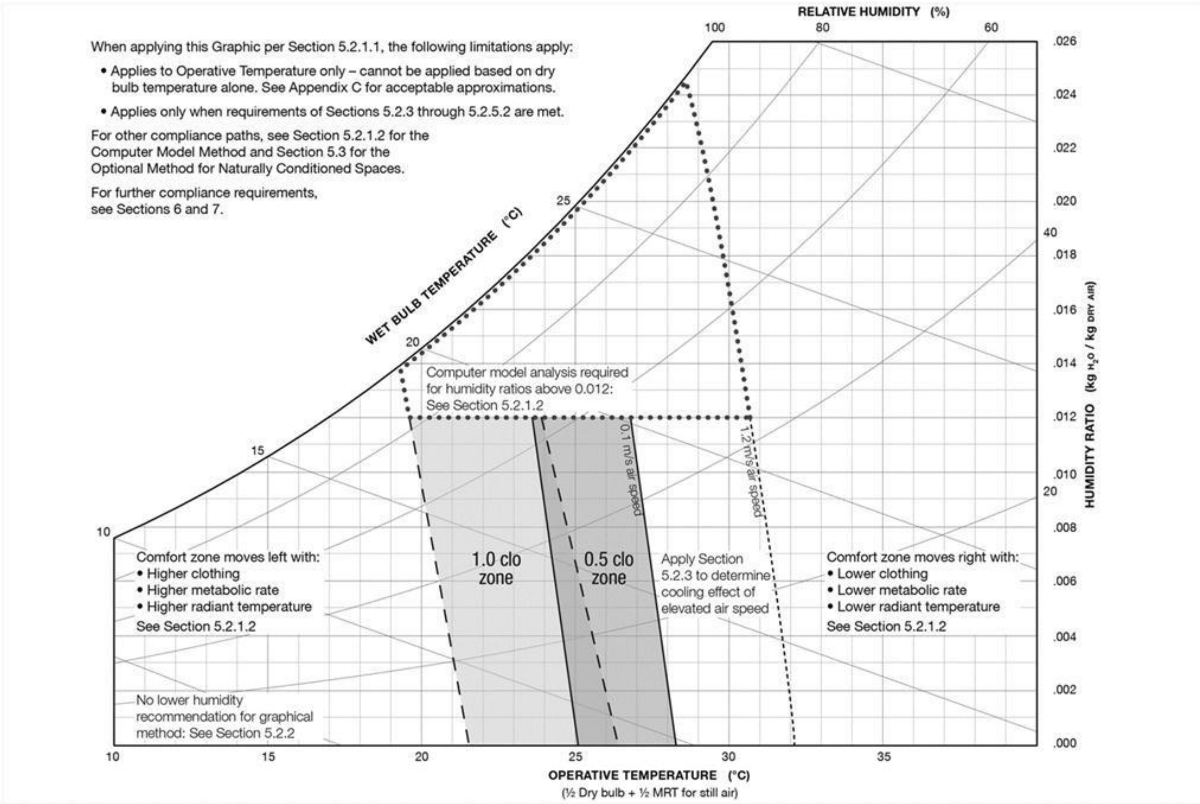


Figure 1.2 Acceptable range of the operative temperature and relative humidity for indoor spaces as specified in ANSI/ASHRAE Standard 55-2017

The thermal comfort range according to ISO/FDIS Standard 7730:2005 is specified as shown in Table 1.3:

Table 1.3 Recommended categories for acceptable thermal environmental conditions (ISO 7730:2005)

Category	**Thermal State of the Body as a Whole**		**Local Discomfort**			
	PPD%	**PMV**	**DR%**	**PD%**		
				Vertical air temperature difference	**Caused by warm or cool floor**	**Radiant asymmetry**
A	< 6	-0.2 < PMV < 0.2	< 10	< 3	< 10	< 5
B	< 10	-0.5 < PMV< 0.5	< 20	< 5	< 10	< 5
C	< 15	-0.7 < PMV< 0.7	< 30	< 10	< 15	< 10

Where DR% is the draft rate which is the “unwanted local cooling of the body caused by air movement” and depends of the room air velocity and air temperature, and occupants’ clothing insulation and activity level. PD% is the percentage of dissatisfaction caused by local discomfort or thermal asymmetry in indoor spaces.

According to EN Standard 15251:2007, the thermal comfort range in air-conditioned buildings is divided into four categories as shown in Table 1.4:

Table 1.4 Recommended categories for design of mechanical heated and cooled buildings (EN 15251:2007)

Category	**Thermal State of the Body as a Whole**	
	PPD%	PMV
I	< 6	-0.2 < PMV < 0.2
II	< 10	-0.5 < PMV < 0.5
III	< 15	-0.7 < PMV < 0.7
IV	> 15	PMV < -0.7, PMV > 0.7

1.1.1. The Heat Balance Model- Advantages and Disadvantages

Although the heat balance model has being applied to assess occupants’ thermal comfort for several decades, there are some drawbacks to this model that is encouraging researchers and design engineers to improve this model or search for possible alternatives. One potential problem is that Fanger conducted experiments in climate controlled chambers with invariant thermal conditions, rather than in the “real-world” operational conditions, implementing an experimental research design known as the preferred temperature method. Real-world operating conditions would be expected to be potentially different from that in a controlled chamber due to the interactions between the building structure, HVAC system, ambient conditions, and occupants. Therefore, people may experience non-uniform temperatures, transient thermal environment, local discomfort, and ramp or drift in the room thermal conditions (Hensen 1990).

Some other potential concerns related to Fanger's model development include: (a) the Hawthorne effect - which is the alteration of behavior by the subjects of a study due to their awareness of being observed (McCarney et al. 2007); (b) not taking into account the effect of human expectations; and (c) considering the human subjects as passive objects who are only the recipients of the thermal environment and do not actively interact with that (Hensen 1990, Fountain et al. 1996).

Fanger's model was generally based on testing college-age students in steady-state conditions for buildings in a moderate climate zone (Van Hoof 2008). However, later, he tested subjects from various climatic experience like winter swimmers, long-term inhabitant of the tropics, etc., and found approximately the same temperature preferences (De Dear et al. 1998). He stated that the PMV-PPD model should be used with care for PMVs outside the range of -2 and +2. He predicted a significant error for the PMV model especially in the hot side of the seven-point scale for thermal sensation. However, Humphreys and Nicol (2002) stated that PMV is only valid between -0.5 and +0.5 or neutral conditions, and the bias grows larger as it goes away from the neutral conditions.

The PMV model does not account for different building types with different services, and variations in human activities, age, race, gender, geographic location, and cultures (Van Hoof 2008). These limitations have illustrated a need of an approach that could be applicable to a broader range of climate zones, building types, occupancy lengths of time, and demographic groups of people. Van Hoof highlights this by stating that in order for Fanger's model to be applied as a reliable prediction tool, it needs to account for a broader group of occupants rather than college students and office workers, various ambient conditions and naturally ventilated spaces, and also to better specify the input parameters such as CLO and MET. For example, Fanger's model has not considered how the thermal environment influences an occupant's behavior and productivity, although through incorporating the clothing insulation level (I_{cl}) into the PMV/PPD equation his model does account for clothing adjustment that follows the ambient climate pattern. This could partially represent the occupants' behavioral adaptation or adjusted expectations as a result of seasonal or diurnal variations (Van Hoof 2008). The interactions between other transient environmental parameters that can affect occupants' thermal comfort perception such as odor, indoor air quality (IAQ), lighting, and noise is also missing in this model (Van Hoof 2008, Alm et al. 1999, De Dear 2004). The PMV model was developed based upon the steady-state thermal conditions and it does not account for a person just passing through or temporarily occupying a space, such as entering into a lobby area from the outside. One should note that it usually takes almost 15 minutes for an individual thermal sensation or comfort vote to be approximated as a steady-state vote. In other words, occupants' thermal perception might continuously change during the first 15 minutes upon entering a new thermal environment (Goto et al. 2000).

Many researchers have tried to validate or reject the PMV model through field studies or climate chamber experiments. Some of them have found a different numerical relationship between PMV and PPD than Fanger's model (Yoon et al. 1999, Mayer 2002, Arau´ jo and Arau´ jo 1999, de Paula Xavier and R. Lamberts). Some of them found larger inter-variation and intra-variations than Fanger proposed (Fountain et al. 1996). In other words, differences are greater than one scale (based on the seven-point scale for thermal sensation) between individuals where they are exposed to the same environment (inter-individual variance). The way people perceive their surrounding thermal environment can also vary in order of almost one scale from day to day in the same environment (intra-individual variance). The ASHRAE seven-point scale corresponds to a range of approximately 3° C (5-6° F), representing the full comfort zone in either winter or summer (ASHRAE Standard 55-2017, Fountain et al. 1996). Others have proposed that people usually feel warmer than would be predicted by the PMV model with PMVs between slightly cool and cool (-1 to -2), (Parsons 2002, Ning et al 2016).

The results from some field experiments raise doubts about the validity of Fanger's model in real environments, based on the discrepancies they found between the PMV values and the values for occupants' actual mean vote (AMV) (Parsons 2002, Ning et al. 2016, Doherty and Arens 1988, Kähkönen 1991). Fanger's model is more accurate in higher operative temperatures (26-30° C) and also for individuals at rest (Doherty and Arens 1988). Some researchers concluded that there is an asymmetric relationship between the actual thermal sensation votes and the desired thermal sensation (or thermal dissatisfaction), as opposed to the symmetric relationship between the PMV and PPD indices depicted in in Figure 1.1. They proposed that it is common for occupants to prefer a non-neutral thermal condition and this thermal preference varies asymmetrically around the neutral thermal sensation (PMV equal to zero). This asymmetry in several cases follows the ambient temperatures' seasonal variations (Fountain et al. 1996, Humphreys and Hancock 2007, Peeters et al. 2009).

In summary, there are two major concepts that are thought to be misrepresented by Fanger's model (Van Hoof 2008, Humphreys and Hancock 2007): (1) thermal neutrality is not equal to the comfort conditions since not all people would prefer a neutral thermal condition as a comfortable environment; and (2) not all occupants would feel thermal discomfort in a thermal environment with very high and very low PMV values and a non-negligible number of people would actually prefer such a thermal environment. There have been numerous efforts to improve and adjust the PMV model to improve its accuracy and broaden its validity range through different methods. These methods include incorporating the expectancy and adaptation factors (Fanger and Toftum 2002), replacing the operative temperature with the effective temperature (Gagge et al. 1986), and reducing bias against the contributing factors in PMV/PPD equations (Humphreys and Nicol 2002). Some researchers also tried to modify the associated heat transfer equation (Holmer 2004) or linearize the PMV calculations (Sherman 85). However, none of these modifications has yet reached a widespread application as the heat balance model. The heat balance model is dependent on how precisely the input variables are introduced into heat balance equation and the accuracy could vary in predicting occupants' clothing level and metabolic rate. Even in an office building with a specified dress code, input parameters are not always straightforward to calculate and the PMV/PPD valued could not be precisely calculated for all occupants.

One study investigating passengers and staffs' thermal comfort in an airport terminal in the UK revealed that the passengers' neutral and preferred temperatures were lower than that for the staff. They realized that passengers showed a wider acceptable indoor temperature range (almost 2° C wider) and more adaptive capabilities compared to the staff. This discrepancy was associated with the temporary or transient versus the longer-term exposure to the same thermal environment in the airport (Kotopouleas and Nikolopoulou 2016).

In spite of all the potential shortcomings observed in Fanger's model, this model still has a wide application in predicting occupants' thermal sensation in buildings. Many guidelines, standards, and building codes around the world are developed based upon this model. The PMV/PPD indices are also promising tools in a digitalized world because of their capacity to be integrated with sensors and other communication and information technologies, enabling the real-time control of buildings occupants' thermal comfort (Van Hoof 2008, Kumar and Sud 2010).

1.2. The Adaptive Approach

Adaptation has been described as "gradual diminution of organism's response to the repeated environmental stimulations and subsumes all processes which building occupants undergo in order to improve the 'fit' of the indoor climate to their personal or collective requirements" (Brager and De Dear 1998). In 1936, Dr. Thomas Bedford published a book proposing an adaptive thermal comfort model (Bedford 1936). The model was the result of numerous field studies in which occupants in their everyday environment were questioned about their thermal sensation and comfort. 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 the environmental parameters such as the air temperature and subjects skin temperature on forehead, palm, and foot. The statistical analysis of these results led to the development of the adaptive thermal comfort model, as reported by Barger and de Dear (Brager and De Dear 1998). Following Dr. Bedford's publication in 1936, researchers started to conduct similar field studies around the world.

Considering the subjectivity of thermal comfort and the complexity of interactions between occupants, buildings, and the thermal environment (Djongyang et al. 2010), it is important to accurately define and predict thermal comfort. This is needed not only because it contributes to a good indoor environmental quality, but thermal comfort can also have an influence on the occupant's health (physical and mental) and productivity. How thermal comfort is perceived also influences building energy consumption through adjustments that may be made in the HVAC controls and settings. Thus, the occupant's thermal perception influences the overall sustainability of a building. It is also human nature for people to adapt to their changing environment. This adaptation is the basis for an adaptive thermal comfort model (Nicol and Humphreys 2002).

The adaptive approach has been developed from field studies of people in their everyday environment and ordinary life. In contrast to laboratory experiments, field study is more closely relevant to people's normal living conditions (Nicole and Humphreys 2007). Unlike the heat balance model, the adaptive approach does not rely on observation of occupants' clothing insulation and assumed metabolic rate to establish the comfort temperature. However, it is a behavioral approach that accounts for the occupants' active engagement with the thermal environment and the building to make themselves comfortable through adjusting their clothing level, posture, etc. or the environment (Nicol and Humphrey 2007). The adaptive principal is expressed by Nicol and Humphreys (2002) as: "if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort". This definition emphasizes that people in their thermal environment are not the passive recipients of that environment. Indeed, occupants are agents that actively interact with their environment and try to adjust to the surrounding transient environment via multiple feedback loops (Brager and De Dear 1998, Nicol and Humphreys 2002, Bedford 1936). The adaptive model assumes that "thermal sensation, satisfaction, and acceptability are all influenced by the match between one's expectations about the indoor climate in a particular context, and what actually exists." (Brager and De Dear 2001). Although the heat balance model partially reflects some degree of behavioral adaptation through adjusting their clothing level, it fails to account for psychological adaptation, that is "the changes in the occupant's expectations and satisfaction as a result of their thermal experiences or their interactions with the environment” (Brager and De Dear 2001).

1.2.1. Concerns with Basing on Field Studies

The adaptive approach was developed based on field studies (Nicol and Humphreys 2002, Humphreys and Nicol 2000), however, some issues were noted with field studies that led to the heat balance model still being widely applied in industry standards such as ASHRAE Standard 55 and ISO 7730. For example, in field studies it is hard to measure or control the environmental parameters such as the air temperature because of its variability. It may also be difficult to generalize the result of one field study to another, even with similar thermal conditions. On the other hand, the rational approach presumes that the responses of subjects in steady-state conditions in climate control chambers could be generalized to a real situational environment. Field studies conducted by Nicol and Humphreys (2002) showed that the temperature range that occupants describe as “comfortable” can be wider than that of the rational approach. They related this discrepancy to the adaptive behavior of subjects as the result of a feedback loop between their comfort and behavior.

1.2.2. Factors Affecting Occupants’ Thermal Comfort with the Adaptive Approach

Rather than the four environmental factors recognized by the heat balance model (air dry-bulb temperature, relative humidity, air speed, and mean radiant temperature) and the two human factors (metabolic rate and clothing insulation level), there are a number of other environmental, societal, and human factors affecting occupants’ thermal perception in a given indoor environment.

The adaptive model is relatively successful in reflecting these additional factors and their impact on occupants' thermal sensation, as outlined in this section.

1.2.2.a. Naturally versus Mechanically Conditioned and Ventilated Buildings

In a naturally ventilated building, the best thermal comfort depends on the climate context. For example, in comparison to a mechanically conditioned and ventilated (called air-conditioned in this study) building, a warmer thermal environment would generally be expected and preferred in naturally ventilated buildings, by the occupants in a relatively warm climate (De Dear et al. 1998). In a colder climate zone, however, a cooler thermal environment would be expected. In other words, for people who live or work in naturally ventilated buildings with operable windows, there is an extended range of thermal preference and thermal tolerance that relates to the prevailing ambient conditions. In one study, the comfort temperature for naturally ventilated buildings was recorded to be 3° C higher than in mechanically cooled buildings in Japanese schools during the cooling seasons (Kwok and Chen 2003). In naturally ventilated and conditioned buildings, there is a linear relationship between outdoor air temperature and the neutral or comfort temperature (Figure 1.3).

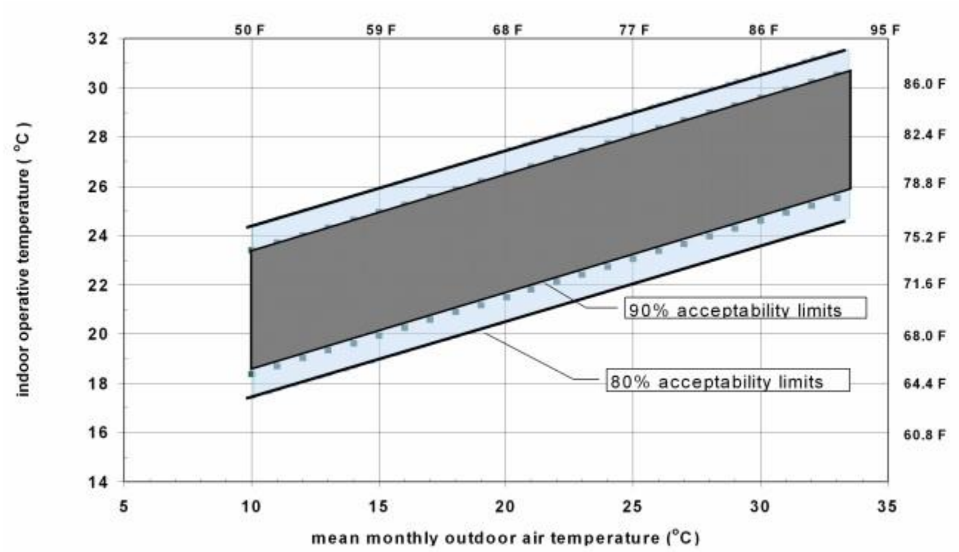


Figure 1.3 Acceptable operative temperature ranges for naturally conditioned spaces specified in ANSI/ASHRAE Standard 55 (2017)

Figure 1.3 depicts the acceptable operative temperature range for naturally ventilated spaces, associated with the adaptive approach, specified in ANSI/ASHRAE Standard 55. However, for a mechanically heated or cooled building, this relationship is much more complex and in air-conditioned buildings, the outside air temperature has a small impact on occupants' thermal comfort (Brager and De Dear 1998, Manu et al 2016). The comfort range in air-conditioned buildings could be as narrow as 2° C or more depending on the opportunities that the building provides for the occupants to adapt to their thermal environment and the extent of control they have over the environment. It should be also noticed that some buildings are naturally ventilated during some times of the year and mechanically conditioned and ventilated when ambient conditions are not favorable (mixed-mode buildings). De dear and Brager (1998) have stated that the higher thermal acceptability range in naturally ventilated buildings, compared to the air-conditioned buildings, is presumably associated with the occupants' lower expectations and their higher physical and behavioral adaptive capabilities as well as the higher air movement in naturally ventilated buildings.

1.2.2.b. Ambient and the Prevailing Indoor Air Conditions

In naturally ventilated, and even in air-conditioned buildings, the occupants' clothing insulation level and the expected comfortable temperature can follow the ambient weather patterns (Nicol and Humphreys 2007). Adjusting the indoor air temperature in a built environment in accordance to the outside air temperature can reduce energy consumption for thermal conditioning since the occupants have already adjusted (mentally and physically) to the ambient temperatures. For example, one study suggested that an indoor set point temperature that changes with the running mean of outdoor temperature does not necessarily result in thermal discomfort among building occupants, compared to a constant set point temperature, and may result in a significant building energy saving (McCartney and Nicol 2002).

The occupants' thermal comfort vote is related to the current and prior climate patterns (indoor and ambient) that people are exposed to. Their thermal adaptation is influenced by both outdoor climate and indoor thermal history, and the climatic adaptation is more dominant in transition seasons (Ning et al. 2016, Luo et al. 2016). Thermal comfort in residential buildings also shows a strong dependency on the outdoor ambient conditions (Peeters et al. 2009). Studies have revealed that the optimum temperature of comfort strongly correlates with the mean indoor temperature that people have recently experienced, while the predicted mean vote (PMV) is just weakly correlated with the indoor temperature history (Nicol and Humphreys 2002). Figures 1.4 and 1.5 depict the correlation of comfort temperature and mean thermal sensation votes with the prevailing mean indoor temperature based on their studies. This research has also proposed that the range of neutral temperature is too wide to be specified through the PMV equation (Equation 1.1).

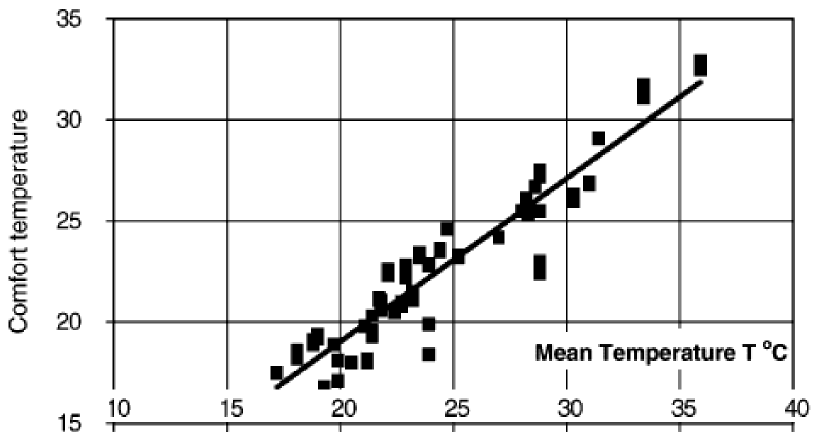


Figure 1.4 The variation of the comfort or neutral temperature with the prevailing mean indoor temperature (from surveys throughout the world), (Nicol and Humphreys 2002)

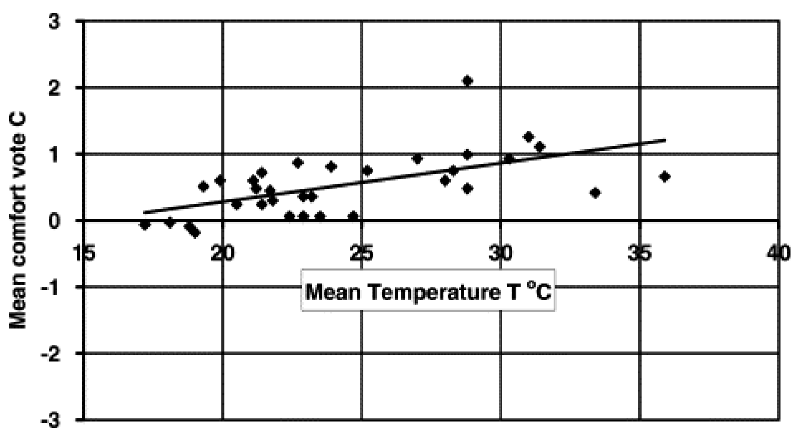


Figure 1.5 The variation of mean thermal sensation votes based on the ASHRAE seven-point scale with the prevailing mean indoor temperature, each point is the mean value from the comfort survey (Nicol and Humphreys 2002)

According to the EN standard 15251, thermal comfort range in naturally ventilated buildings is categorized into three different classes, i.e. I, II, and III as depicted in Figure 1.6. The vertical axis or Θ_{rm} shows the running average of outdoor air temperature and Θ_0 represents the indoor operative temperature. This comfort range is only valid for office buildings, dwellings and similar building types used mainly for human occupancy. Occupants are mostly involved with sedentary activities in these buildings and there is an easy access to operable windows. They are also allowed to freely adjust their clothing according to the indoor and/or outdoor environmental conditions (EN 15251:2007).

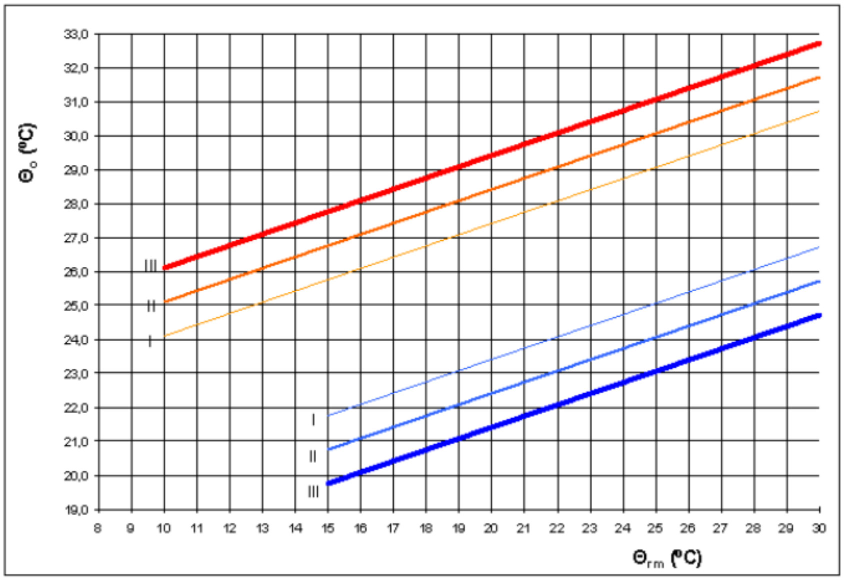


Figure 1.6 Design values for the indoor operative temperature for buildings without mechanical cooling systems as a function of the exponentially-weighted running mean of the outdoor temperature (EN 15251:2007)

1.2.2.c. Clothing Insulation

Outside ambient conditions (like temperature and relative humidity) also have an instrumental effect on the type and amount of clothing people wear, as well as their thermal comfort expectations (Nicol et al. 1999). The occupants' choice of clothing is influenced by their culture, climate context, type of activity, and building policies. Whenever occupants are given freedom to choose their clothing type and level, they are more likely to adapt to a non-optimal thermal environment and experience a better thermal comfort (Haneda et al. 2009). Some studies showed that having a restricted dress code could cause a thermal discomfort equivalent to a 4° C deviation from an optimum comfort temperature (Nicol and Humphreys 1973, Humphreys 1972). When temperature changes occur, a clothing level adjustment could be a temporary solution but it may not return the thermal comfort perception back to the previous condition and any clothing adjustment would generally be expected to lag behind the temperature change.

1.2.2.d. Control Options

Having control over a thermal environment would help adaptation to occur, and a surprisingly wide range of indoor temperatures could be acceptable through increasing the adaptive opportunities in buildings (Nicol and Humphreys 2007). Field studies revealed that when occupants have some level of control over their surrounding thermal environment, they show a higher tolerance regarding the variation from an optimum thermal condition (Leaman and Bordass 1999). Therefore, giving people more authority to control their indoor environment will contribute to both improved thermal comfort and possibly lower energy consumption (Lakeridou 2012). Nicol and Humphreys (2002) explain that comfort is not just the result of the effect of the environment on occupants, but also the result of their interaction with the environment. They add that as occupants are given more opportunities to adapt to the changing environment, they are less likely to experience thermal discomfort. The freedom or restrictions on the occupants' ability to control the thermal environment are related to the predominant culture in each specific building as well as regional societal expectations.

Control options are so influential in creating comfort that Nicole and Humphreys (1973) suggested that if occupants were given the opportunity to change their clothing level to avoid discomfort or to use other means of adaptation, it might be possible to estimate the comfort zone by analyzing the rate of clothing changes level alone or the number of open windows (Humphreys 1974). Paciuk (1989) concluded that a balance should be found between increasing personal satisfaction and increasing occupants' expectations in a workplace when control options are given to employees; giving the occupants more control over the thermal environment could have both negative and positive effect on occupants' thermal satisfaction. Nicol and Humphreys (2002) state that adaptive behaviors to reduce discomfort is a mixture of two major behaviors by occupants: changing the environment to meet their thermal comfort (opening/clothing a window, lowering blinds, etc.), or adjusting their behavior or thermal requirements to accord with the condition (adjusting clothing and moving through the building).

1.2.2.e. Space Type: Transitional versus Indoor Space

Transitional or transition spaces are areas between the outdoor and indoor environment bounded by a building envelope such as entrance lobby. The architecture and thermal environment in transition areas are under considerable influence of the outdoor conditions. These areas are effective in reducing occupant's thermal shocks when entering or exiting a building and in minimizing the heat gain or loss with the core areas of buildings (Chun et al. 2004). People in these places are typically walking, standing, or sitting (but different from sedentary behavior in offices). The dynamic characteristic of thermal environments in transition areas and the wide range of metabolic rates (MET) make it practically impossible to predict occupants' thermal sensation in transitional spaces using PMV/PPD indices (Chun et al. 2004). For example, the previously mentioned study conducted in an airport terminal in the UK showed significant differences between passengers' and staff's preferred or neutral temperature values (Kotopouleas and Nikolopoulou 2016). Airport staff preferred higher indoor temperatures compared to passengers and their acceptable temperature range was also narrower than that for passengers. The staff had limited adaptive capacity resulting from a rigid dress code and having no control over their thermal environment. Combining this with the longer time of exposure to the thermal environment and higher expectations from their workplace were listed as the sources of the discrepancy compared to passengers. One should also notice that it takes almost 15 minutes for occupants, upon their entrance to the building, to perceive their thermal environment as a steady-state condition (Kotopouleas and Nikolopoulou 2016, Humphreys and Nicol 2006).

1.2.2.f. Occupant Behavior

Human factors related to occupant behavior (OB) and expectations is a fundamental factor influencing buildings' energy consumption almost as much as the innovative energy efficiency technologies (Janda 2011). Failing to comprehensively understand OB in buildings and lacking an accurate quantified model of OB is a major contributor to the gap between the predicted and actual energy consumption, and the predicted and actual thermal comfort. These behaviors can have consequences for the building energy performance and indoor environmental quality (IEQ) since any adaptive changes in the building, such as opening a window, could change the overall IEQ and HVAC electric load. The OB in a building is so important that a wasteful behavior in an office building, like leaving lights or other equipment on when not in use, could result in as much or more energy consumption during non-working hours compared to the working hours (Masoso and Grobler 2010).

Integrating data- and model-driven OB with building technologies is one key to design and operation of low energy buildings (Hong et al. 2016). Modeling occupant behavior is a critical tool in capturing occupants' diverse and stochastic behavior and understanding the impact of OB on the buildings' energy consumption (D'Oca 2016). Occupant behavior has been represented by deterministic variables, like homogeneous occupancy schedule, and incorporated into the building energy performance simulation programs for almost 30 years. However, the deterministic approach due to its static-periodicity and its weakness in representing the variant OB results in a gap between the predicted and actual building energy performance (Hong et al. 2016). In order to better quantify occupants' consumption behavior, data regarding occupant-building interactions should be gathered through physical (sensors) or non-physical sensing methods (such as a survey). These data include occupancy pattern, occupants' interactions with the building envelope (like opening a window), and their interactions with the HVAC control system in the building. Although OB has some complicated, stochastic, and interdisciplinary characteristics, it could be predicted through understanding the correlation between driving stimuli and observed behavior and developing a stochastic model. The pattern of individual behavior can also be implemented in the building energy performance simulation through statistical analysis, data mining, and machine learning techniques, using big data streams (Hong et al. 2016).

1.2.2.g. Occupant's Economic Status

Economic status also can influence a person's thermal perception. People from a lower social-economic status are more tolerant to deviation from the optimum condition as they instinctively take advantage of some adaptive capabilities. People in more affluent status, however, may elect to just use energy to adjust their thermal environment. Indraganti and Rao (2010) found that the summertime neutral temperature is around 2° C higher for subjects from lower economic class in India. In residential settings, ownership does also affect occupants' adaptive behavior

(Brager and De Dear 1998, Indraganti and Rao 2010). For example, a homeowner may show a better adaptive behavior compared to the tenants.

1.2.2.h. Gender Differences

Some researchers have reported considerable gender related differences in thermal perceptions and thermal comfort preferences (Hwang et al. 2006), stating that women are more sensitive to their thermal environment and they typically prefer higher temperatures than men (Karjalainen 2012, Parsons 2002, Schellen et al. 2010). Others claimed that there is no substantial difference between thermal comfort perception and preferences based on gender (Olesen 2017). Fanger believed that women's lower overall metabolic rate, compared to men, could compensate for their lower skin temperature and evaporative heat loss (Fanger and Langkilde 1975), and thus believed that there is no notable difference between human thermal perceptions based on their genders. He related women's more complaint rate and their preference for warmer thermal environment to their lighter dress or clothing level.

Another researcher stated that current thermal standards were based on empirical models developed in 1960's (Kingma and Lichtenbelt 2015). In these models, the metabolic rate was quantified based on an average male and women's metabolic rate was underestimated by up to 35%. Hwang et al. (2006) found that female students had a narrower neutral temperature range and they would more readily adjust their clothing level with the indoor temperature. Karjalainen (2007) proposed that as women tend to be more critical of their surrounding thermal environment, they are most suitable subjects as test samples and if women are thermally satisfied with an environment, men's satisfaction will be more likely and achievable. Lan et al. (2008) correlating women's sensitivity to their lower skin temperature added that although women's comfort temperature is higher than that for men, they have the same neutral comfortable temperature as men.

1.2.2.i. Other Factors

Thermal comfort sensation (vote) in a building is influenced by a myriad of issues, such as: the local societal culture; the occupants' attitude and expectations about the thermal environment in the building; the general buildings' design, context, and occupancy type; and the overall indoor environmental quality related to areas other than thermal comfort (noise, odor, daylighting, ergonomics etc.), (De Dear and Brager 1998, Nicol and Humphreys 2002) It also depends on the rate of changes of the comfort temperature (seasonal, synoptic, or immediate) and its extent as people interact with their variant environment. Frontczak and Wargocki's (2011) investigation into the impact of different factors on human comfort resulted in the new concepts: people's relationship with their colleagues and their superiors, their level of education, and the time pressure they are exposed to would affect their thermal satisfaction. Psychological atmosphere at work and job stress would also influence occupants' perception of the air quality.

1.3. Summary

In summary, there are two major approaches to predict thermal sensation or comfort for a large group of building occupants. One is the heat balance model that was developed based upon the experiments conducted in climate control chambers in steady-state environmental conditions. This model only considers the impact of six environmental and personal factors in occupants' thermal comfort and could be applicable in different buildings with similar HVAC services and occupancy type specified for the model.

The other approach is the adaptive approach that is developed based on field studies in buildings and includes the impact of a variety of physical, psychological, demographic, cultural and societal factors on occupants' thermal comfort. What the adaptive approach proposes is that thermal perception is an amalgam of environmental and personal factors, like Fanger's model, but must include allowance for other more complicated factors. This approach encourages designers of HVAC systems to consider individuals as active agents that go through a set of adaptation including behavioral, psychological, and physiological adaptations (not relevant to the built environment) in a feedback loop. This could result in a reduced global energy consumption and corresponding greenhouse gas emissions, thus improving buildings' overall sustainability.

CHAPTER 2

A REVIEW ON THE IMPACT OF DEMAND RESPONSE ON BUILDING OCCUPANTS' THERMAL COMFORT

This section provides a breif introduction into the demand respond (DR), and its merits and potential drawbacks. A review of the literature concerning occupant thermal comfort, specially as it relates to the potential zone temperature modification that may be considered as a part of DR measure, is also presented in this section.

2.1. Demand Response

Mechanically conditioned buildings are significant contributors to overall global energy consumption and the corresponding impact on electricity demand and greenhouse gas emissions. Buildings' heating, ventilating, and air conditioning (HVAC) systems are responsible for roughly 20% of total energy consumption in developed countries and many developing economies as well (Hoyt et al. 2005, Osterman et al. 2015). Providing occupant thermal comfort alongside a supply of fresh air, maintaining their health and well-being, is the main purpose of HVAC system operation in buildings. This results in the consumption of a considerable amount of energy and money expenditures in buildings. Therefore, in an effort to more effectively manage energy consumption and peak energy demand, it is important to appropriately define thermal comfort and its relation with indoor temperature and other influential factors, such as relative humidity, air speed, radiant temperature, time of exposure at a given temperature, etc. Ultimately, we would like to achieve an optimized balance between thermal comfort and energy consumption.

Electrical energy production differs from other types of energy (such as liquid fuels) in that the production and consumption occur essentially simultaneously. This feature critically affects power grids' reliability, especially during peak demand hours when demand for electricity is maximum. During peak cooling demand hours that typically occur in summer afternoons and early evenings, the demand for electricity by commercial buildings and the industrial sector is high. As a result, during these hours there is a risk of generation and transmission capacity shortages in power grids, leading to potential grid reliability issues. To increase grid reliability and to address power capacity shortages, buildings could be integrated with a smart grid that enable them to participate in demand-side management programs. Participation in demand-side management programs will help to reduce peak electricity demand, total energy consumption, and consumers' utility cost (Lawrence et al. 2016). Participation in DR programs or temporary HVAC systems adjustment is a primary demand-side management approach (Parry et al. 2007).

DR is defined as "a set of time-dependent program activities and tariffs that seek to reduce electricity use or shift usage to another time period. DR provides control systems that encourage load shedding or load shifting during times when the electric grid is near its capacity or electricity prices are high" (Motegi 2007). Smart buildings and their associated control systems and equipment are capable of responding to DR requests from the utility or system operators to manage peak demand. The benefits to building operations are a minimized demand charge or minimizing total utility cost based on the real-time prices for electricity, or taking advantage of other financial incentives that might be offered. Some response measures may involve adjustments in HVAC operational setpoints (such as zone temperatures or supply airflow temperatures and flow rates) or lighting, thus opening up potential occupant comfort perception problems. When done right, a smart building can also provide a preferred or at least adequate indoor environmental quality (IEQ) for the building occupants. In this context, the important areas of IEQ affected include temperature, humidity, ventilation rates, and lighting levels (Lawrence et al. 2016).

Demand Response programs are becoming increasingly important globally as a powerful tool to manage peak demand and increase electrical power network reliability and sustainability. However, the potential for zone temperature changes used in DR to adversely impact occupants, even temporarily, points to a need for research to study and identify the impact of these measures on building occupants. The focus of these studies should be on the occupant thermal comfort, health, and overall productivity. It is essential to identify an optimum trade-off between energy consumption and the building occupants' thermal comfort before extensively applying DR strategies in buildings (Motegi et al. 2007). The measure of the overall performance of a building depends heavily on the occupant thermal perception. Considering the subjective nature of thermal comfort and the complexity of interactions between occupants, buildings, and the surrounding environment, it is important to accurately understand, define, and predict thermal comfort (Djongyang et al. 2010).

Demand response, while potentially reducing peak demand, overall energy consumption, and utility costs for customers can affect the building occupants physically and psychologically. The overall impact on occupants may include thermal comfort, productivity, mood, and their health. A decreased thermal comfort can adversely affect a person's self-estimated performance and their perceived air quality (Zhang et al. 2011). However, since perceived air quality and self-estimated performance are strongly correlated with the perceived thermal comfort rather than the ambient air temperature (Zhang et al. 2011), increasing building's set point temperature during DR does not necessarily impair the air quality perception or productivity of occupants as long as their thermal comfort is maintained. In some cases HVAC system adjutments can result in an improved comfort vote and thus this could be considered a long-term energy efficiency measure (Motegi et al. 2007). An example of this is implementing DR measures or increased cooling temperature set point in overcooled building that would result is an improved thermal comfort for many occupants. Building overcooling during the summer is a common problem in many buildings across the United States (Derrible and Reeder 2015, Mendell and Mirer 2009) and it is often the result of poor latent control, oversized HVAC systems, or a desire to ensure that indoor humidity problems do not occur.

Based on a large body of evidence in various research studies, it is apparent that in many cases the current operating cooling temperature setpoints in buildings are typically lower than necessary (Derrible and Reeder 2015, Parry et al. 2007). One study of a typical office building in Zurich shows that a 2 to 4° C (3-7° F) increase in zone setpoint temperature would result in a reduced annual cooling energy consumption by a factor of three, while another study predicted energy reductions by a factor of two to three if thermostat set point increases from 23 to 27 °C (73.4 to 80.6 °F) were implemented for night-time in Hong Kong apartment bedrooms (Mets and Davidson 2010). Admittedly, these two situations are on the optimistic side for percentage saving since there is generally a limited need for cooling in Zurich or nighttime cooling in Hong Kong. However, the effect of this increased set point temperature on building occupants has not been extensively studied and no survey paper focusing on the effects of temporary HVAC zone temperature adjustment during demand response events on people occupying the built environment has been published.

Figure 2.1 depicts the energy saving potential of widening cooling and heating thermostat set point temperatures for four different cities in the United States based on the building energy simulation modeling conducted by Hoyt et al. (2005). They investigated the potential for energy savings of an expanded thermostat set point temperature in office buildings. They concluded that when increasing the cooling set point temperature from 24 to 25º C, a cooling energy saving of 7-15% could be achieved depending on the buildings' operational features and the associated climate zone. The energy saving potential in that study was also reported to reach 35-45% if the set point temperature was extended from 24 to 28º C, however, the effect on occupants' thermal comfort at these temperatures was not reported.

Increased zone temperature set points with DR measures may increase energy used for reheating if not done in coordination with other control system changes. If the supply air temperature also correspondingly increases, there is a potential for an increased humidity level. Higher moisture levels could result in mold and mildew problems and bad odors. Increased humidity associated with higher temperatures may also affect indoor air quality (IAQ) through release of sorbed pollutants in building materials. While this is a valid concern, particularly in humid climates, with careful monitoring and control this issue can be avoided while still implementing HVAC system adjustments associated with DR measures (Aghniaey and Lawrence 2017). Additional studies also exist that similarly investigate the energy saving potential from adjusting cooling or heating temperature set point during DR events. However, DR cannot be successfully implemented in the real-world conditions if there is no balance between energy saving and occupant thermal comfort. The consideration of the adverse impact on occupants' thermal comfort should be balanced with the amount of energy consumption that is avoided to keep indoor temperatures uniform within a narrow range.

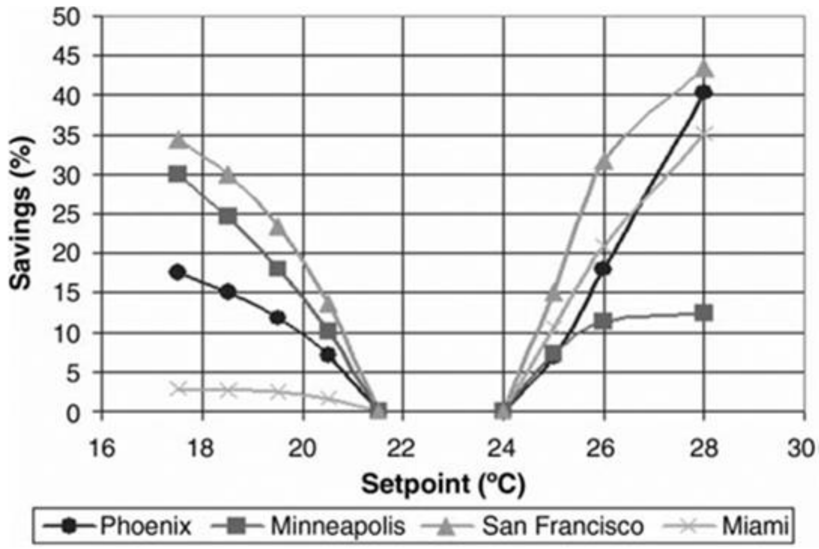


Figure 2.1 Percent energy savings for widened air temperature set points in office buildings from different U.S. climate zones (Hoyt et al. 2005)

2.2. Potential Impacts of Zone Temperature Adjustments with DR on the Building Occupants; Literature Review

Although DR measures can reduce peak demand, overall energy consumption, and utility costs, they can also affect the building occupants physically and psychologically. The overall potential impacts on occupants include thermal discomfort, decreased productivity, mood swings, and even their overall health. A decreased thermal comfort can adversely affect people's self-estimated performance and their perceived air quality (Zhang et al. 2011). Those authors also discussed that the perceived air quality and self-estimated performance are strongly correlated with thermal comfort perception rather than the indoor air temperature. Increasing the zone set point temperature during a DR event does not necessarily impair the air quality perception or productivity of occupants if they can maintain their thermal comfort elsewise, such as through personalized conditioning systems, ceiling fans, etc. In some cases, HVAC system adjustment can result in an improved thermal comfort, and thus these could be considered for a long-term energy efficiency measure (Motegi et al. 2007). An example of this is implementing DR measures in overcooled buildings that could result in an improved thermal comfort for many occupants. Building overcooling during the summer is a common problem in many buildings across the United States (Aghniaey and Lawrence 2017, Derrible and Reeder 2015, Mendell and Mirer 2009, among others), and it usually happens either to avoid increased thermal discomfort complain rates or often as the result of the oversized HVAC systems with poor latent control. Although there are many published studies investigating the energy saving potential for DR, the number of studies addressing the impact of DR on building occupants is limited. In this section, we review how thermal comfort considerations can, or should be, involved in DR measures to minimize the adverse impacts on building occupants.

The adaptive principle for thermal comfort assumes that adaptive characteristics can make it possible for occupants to adjust to the resulting changing indoor thermal environment if DR measures were implemented. However, it is important to identify the acceptable or allowable ranges for reduced HVAC services in order to minimize the adverse impacts on occupants and maximize the energy saving potential from DR. This section reviews studies conducted about the impact of increased cooling set point temperatures and the rate of changes of those temperatures on building occupants during DR.

2.3. Experimental Studies of Increased Cooling Set point Temperature Impact on Building Occupants

Several studies have shown that occupants are able to accept a much wider temperature range in real-world practices compared to a controlled laboratory setting. It has also been reported that a uniform or neutral temperature does not necessarily translate to thermal comfort or optimum comfort conditions. Table 2.1 summarizes some of the more relevant experimental studies investigating the impact of increased cooling temperature set point on occupants in commercial (non-residential) air-conditioned buildings.

Table 2.1 Summary of studies on the impact of increased cooling temperature set point on occupants' thermal comfort in commercial, air-conditioned buildings

Author	Study/ Building Type	Location/ Climate	Results
Gagge et al., 1967	Climate Controlled Chamber	Connecticut USA Moderate Climate	Thermal discomfort rapidly increases when increasing indoor temperature up to 28° C compared to temperatures above 28° C. However, thermal sensation vote evenly increases around both sides of the neutral thermal conditions when changing a warmer or cooler thermal environment to neutral. A hysteresis effect is more striking when changing the thermal environment from cold to neutral than changing it from warm or hot to neutral. Body temperature that stimulates physiological and behavioral thermoregulatory follows occupant thermal sensation and discomfort. Behavioral adaptation provides a long-term thermoregulation while physiological responses provide a short-term solution.
Jaakkola and Heinonen 1989	Field Study MM Office Buildings	Helsinki, Finland, Humid Continental	The sick building syndrome (SBS) and sensation of dryness are linearly correlated to room temperature as the most important indoor air parameter, adversely affecting occupants for temperatures above 22° C. There was an excess of SBS symptoms, both when the thermal environment perceived as too cold and too warm. A higher percentage of workers were thermally satisfied for temperature values below 22° C.
Humphreys and Nicole 1998	Field Studies	Various Locations	There is a correlation between neutral or comfort temperature and the mean indoor temperature that occupants had been recently exposed to. The occupant's preferred comfort temperature closely followed the prevailing mean indoor temperature, suggesting that occupants could feel comfortable in

			a wider range of thermal conditions, especially when there are sufficient options to adapt to that environment.
Kwok et al. 1998	Field Study AC/NV Classrooms	Hawaii USA Tropical	Rather than occupants voting for ±1 and 0, a significant number of subjects voting for ±2 and ±3 based on ASHRAE seven-point scale for thermal sensation, still found the thermal environment as acceptable. The neutral effective temperature for occupants in AC buildings was 27.4° C while the preferred temperature was 4° C lower than that.
Kwok and Chun 2003	Field Study AC/NV Classrooms	Japan Subtropical Climate	The comfort temperature for naturally ventilated buildings was reported to be 3° C higher than that for air-conditioned buildings during the cooling season. These results imply how human adaptive nature could help them widen their thermal acceptability range. Students felt slightly cool when temperatures were held as specified in the ASHRAE comfort zone, and the temperature for an occupant's neutral thermal sensation differed from their preferred thermal state as observed in AC classrooms.
Hoyt et al. 2005 Arens 2010 Humphreys and Hancock 2007	Theoretical and Field Studies	Various Locations	A uniform or neutral temperature and/or keeping operative temperature indoors in a narrow range does not necessarily translate to thermal comfort. Occupants can accept wider temperature ranges than what is normally practiced in buildings.
Hwang 2006	Field Study AC/NV Campus Classrooms	Taiwan, Subtropical Climate	Studied thermal acceptability, neutrality, and thermal preferences in classrooms in hot and humid climate: Although 86% of physical measurements fell outside the ASHRAE comfort zone, more than 80% of students felt thermal satisfaction in their thermal environment. In Taiwan, occupants are acclimatized to hot and humid climate and could accept higher indoor temperatures. Neutral temperature differs from ideal comfort temperature.
Nicole and Humphreys 2007	Field Study AC/NV Office Buildings	Europe France, Greece, Portugal, Sweden and the UK	Tried to determine the maximum comfortable temperature with and without mechanical heating and cooling: The level of thermal discomfort is a function of the normal indoor temperature in that space and the occupant's current preferred temperature. They realized that for temperature changes of ± 2 ºC from the optimal comfort temperature, thermal discomfort would increase considerably.
Cool Biz Campaign Tan et al. 2008, Xu et al. 2008	Field Study AC Office Buildings	Japan, Temperate Climate	Temperature values in office building were set at 28º C and employees were encouraged to dress lightly; short sleeves with no tie and jacket. It is believed that removing the tie and jacket would decrease body temperature up to 2º C, enabling occupants to adjust to 28º C

			The campaign resulted in some public behavioral changes towards reducing energy consumption, provoking the private sector to incorporate similar procedures. The energy saving potential of this practice was emphasized over its adverse effects on the occupants and their work performance.
Davies et al. 2008	Field Study AC Office Buildings	UK, Temperate Maritime Climate	For indoor temperatures between 24 and 26° C the indoor environment was considered acceptable. The PPD for air velocity of 0.1 ms^{-1}, metabolic rate of 1 MET, and clothing insulation of 1 CLO was more than 20%, however, for CLO levels equal or less than 0.5, the PPD was reported to be less than 20%.
Zhang et al., 2008	Climate Controlled Chamber	Beijing, China, Temperate and Continental Monsoon	Thermal sensation, acceptability, and comfort were closely correlated under uniform thermal conditions. Under non-uniform thermal environment, thermal acceptability and comfort were correlated. The range of thermal acceptability ran between PMV values of 0 and 1.5 (between slightly warm and warm) and subject were either comfortable or slightly uncomfortable in this range. While the overall thermal sensation remained the same, the thermal unacceptability and vote for uncomfortable environment was higher under non-uniform thermal conditions.
Van Hoof 2008	Review Paper	Various Locations	Because of differences in occupants' thermal preferences, thermal neutrality does not necessarily reflect the optimum comfort conditions while very high or very low PMV values do not necessarily cause thermal discomfort.
Cool Biz Campaign Haneda et al. 2009	Field Study AC Office Buildings	Japan, Temperate Climate	During the Cool Biz campaign, sometimes zone temperature exceeded 30º C and more than 70% of occupants were dissatisfied with their thermal environment. Variability within the indoor environment from the designated 'set point temperature' was reported. This new thermal environment resulted in more fatigue among the occupants and adversely affected their self-estimated performance.
Xu et al. 2010	Field Study Office Building AC	CA, San Bernardino, Hot/Dry Summers	Any increase in cooling temperature set point above 77º F (25º C) would result in a more than 20% dissatisfaction rate. The normal set point temperature for that office is 74º F (23.3º C).
The British Council for Offices Mui et al. 2010	Theoretical studies AC Office Buildings	UK, Temperate Maritime Climate	Suggested that all air-conditioned offices raise their set point temperature (typically at 22 ± 2º C) by 2º C. This decision was the result of theoretical studies based on the adaptive model, which suggested that PPD value for an office building operating at 26º C with air speed equal to 0.1 m/s and a CLO equal to 0.5 or less would be less than 10%. There were no supportive field studies to verify these results.
Erickson and Cerpa 2010	Theoretical Study		Developed an occupancy-based demand response algorithm to maximize energy consumption and cost savings while

	AC		maintaining occupant thermal comfort within the comfort zone, using the heat balance model.
Zhang et al. 2011	Field Study/ Controlled Chamber AC/NV/MM	Different Locations (Australia, Canada)	Investigated the acceptable temperature range in AC buildings: By increasing the indoor air temperature, the perceived indoor air quality and self-estimated rating of occupant performance do not necessarily decrease if occupant thermal comfort is maintained through ceiling fans, radiant cooling or heating system, or other personal conditioning systems. Thermal acceptability decreases to less than 80% for operative temperatures more than 26° C.
Roussac et al. 2011	Field Study AC Office Buildings	Australia Different Cities, Humid Subtropical	Studied occupant comfort and building energy use for two strategies; static control strategy or increasing set point temperature 1° C higher than normal and, adjusting indoor temperature according to the ambient temperature. Due to the increased complaint rate, occupants were adversely affected but possibly due to lower ventilation rate. Daily HVAC energy consumption was predicted to be reduced by 6% for the static and 6.3% percent for the dynamic control strategy.
Yun et al. 2012	Field Study AC Open Office Buildings	Korea Seoul, Subtropical Climate	Occupants feel comfortable even at 28° C depending on the prevailing mean temperature outdoors. The normal operating temperature in this building is 26° C.
Lakeridou et al. 2012, Lakeridou 2017	Field Study AC Office Buildings	UK, Temperate Maritime Climate	Investigated the potential for increasing minimum cooling set point temperature: Although increasing the set point temperature from 22-23 to 24° C made occupants warmer, it did not significantly affect their self-reported thermal comfort. Increasing indoor temperature in open-plan office area to 24° C did not substantially increase thermal discomfort. The actual percentage dissatisfied (APD) level for this temperature was near maximum within the acceptability range, implying that 24° C might be the maximum cooling set point temperature for this office environment. The APD level was higher than the theoretical PPD from Fanger's heat balance model, suggesting that local discomfort or other factors should be incorporated when choosing a cooling set point temperature for DR measures or as a "new normal".
Lakeridou et al. 2014	Field Study AC Office Buildings	UK, Temperate Maritime Climate	Studied the potential for introducing a minimum summer set point (SSP) temperature by UK government in office buildings: Summer set point (SSP) temperature was lower than 24° C for more than 60% of buildings. Occupants in public organizations generally preferred a mandatory SSP ≥ 24° C while those in private organizations preferred a SSP ≤ 24° C. Recommended SSP was generally preferred over mandatory SSP.

Manu et.al 2016	Field Study AC/NV/ MM, AC in Summer Office Buildings	India, Cities in Different Climate Zones	The adaptive model was valid for both NV and AC mode in mixed mode buildings. Fanger's heat balance model was over-predicting thermal sensation in the warmer side of the seven-point sensation scale, represented by actual thermal comfort vote scores of -3 through 3, respectively. There was a unit change in thermal comfort sensation vote for every 4° C change in indoor temperature in AC buildings.
Korkas et al. 2016	Theoretical Study AC		Developed a novel optimization method that could integrate renewable energy sources with building HVAC systems. The method could reduce energy cost during demand response events while maintaining occupant thermal comfort within ASHRAE comfort zone (PMV between - 0.5 and 0.5).
Zhang et al. 2017	Theoretical Study AC		Optimized direct load control (DLC) strategy for air conditioning to achieve optimum thermal comfort and cognitive performance: In densely populated commercial buildings, adequate thermal comfort and cognitive performance could still be achieved during demand response events. In this study, demand response was implemented through a DLC algorithm that has an off-cycle fraction of less than 50% where the building occupants were adapted to the cooler than neutral thermal environment in the buildings. The neutral temperature was calculated based on ASHRAE seven-point scale for thermal sensation.
Kampelis et al. 2017	Field Study AC University Campus	Crete, Greece Mediterranean	Developed a daily discomfort score to evaluate the impact of adjusting HVAC operation on building occupants' thermal comfort during DR measures. The cost saving assessment from DR measures would not lead to practical results if not followed by an evaluation of the impact on building occupants' thermal comfort. To exploit the maximum potential of DR and to achieve the expected energy and cost saving, an elaborate HVAC system control strategy is required to make sure that occupants' thermal comfort is not deteriorated.
Aghniaey and Lawrence 2018	Field Study AC Campus Classrooms	Athens, GA, USA, Subtropical	By temporarily increasing the classrooms cooling set point temperature from the typical 21-22º C (70-71º F) up to 25º C (77º F), the occupant's AMV values did tend to increase but for most cases the class averages remained in an acceptable thermal comfort range (-0.5 < AMV < +0.5). None of the respondents who perceived the thermal environment as slightly cool, neutral, and slightly warm considered the environment as being thermally unacceptable while 75% of occupants voting for cool and 62% of those voting for warm still considered their thermal environment as acceptable.

Note: In this Table, AC = air conditioned; NV = naturally ventilated; MM = mixed-mode ventilated and conditioned

The results of one study by De Dear and White (2008) concerning thermal comfort and DR is worth further discussion. In this study, the authors analyzed the effect of DR on residential building occupants' thermal comfort associated with Critical Peak Pricing and Direct Load Control strategies. They emphasized that, based on the adaptive thermal comfort model, “there is no absolute reference point or acceptable range on comfort continuum”; a repeated exposure of occupants to an increased indoor temperature would eventually increase their tolerance of those temperatures, as they get accustomed to the wider temperature swings that existed for prior generations before mechanical cooling systems.

2.4. The Importance of the Rate of Temperature Change

How building occupants accept DR and load shedding via HVAC system operation adjustments significantly depends on the rate of the load shedding, overall magnitude of the changes, and their frequency (Hensen 1990, Berglund and Gonzalez 1978). However, in most DR practices stable ambient temperatures are usually reached in no more than one hour after changing the zone control set point temperature. Table 2.2 reviews the impact of rate of changes in increased cooling set point temperature (drift or temperature ramp) on building occupants in commercial, air-conditioned buildings. Temperature drift is defined as monotonic, steady changes in temperature with time that is characterized by a starting value, amplitude, and the rate of changes (Hensen 1990).

Table 2.2 The impact of temperature drift or ramp rate on building occupants thermal comfort

Author	Study Type	Location	Results
Sprague and McNall 1970	Climate Controlled Chamber	Manhattan, KS, USA	Investigated the impact of a fluctuating dry bulb temperature on sedentary subjects: Fluctuations in standard temperature would not result in thermal comfort complaints if the peak-to-peak amount of temperature change were kept below that shown in Equation 2.1: $\Delta T^2 (CPH) < 15$ (2.1) Where CPH = cycles per hour or cycle frequency and T is the zone dry bulb temperature ºF. If ΔT=2º F (1.1º C) and CPH=3.75 cycles/hours or less, the fluctuation would be acceptable.

Wyon et al., 1971 (cited in Newsham et al. 2006)	Climate Controlled Chamber	Norway	Examined quick cyclic temperature ramp, starting from 25° C at the rate of 0.5° C/min. Occupants were able to change the ramp direction when they felt "Too Hot" or "Too Cold". Large and rapid temperature ramps were undetectable by occupants since skin temperature would lag behind rapid ramps. Larger ramps were more detectable to resting subject than working occupants.
Berglund and Gonzalez 1977	Climate Controlled Chamber	New Haven, CT, USA	A slow ramp of 0.5º C/h around thermal neutral temperature is not detectable by occupants and even a 2º C deviation from the neutral temperature would not cause more than 20% thermal dissatisfaction among occupants if done slow enough.
Berglund and Gonzalez 1978	Climate Controlled Chamber	New Haven, CT, USA	Investigated the effect of temperature drift on buildings occupant's thermal comfort perceptions; studied an 8½ hour ramp for 24 sedentary subjects (half men and half women) with CLO around 0.5: A temperature ramp of 0.6º C/h from 23 to 27º C (73 to 81º F) would be acceptable for at least 80% of the occupants, and increasing humidity would not cause a significant difference as long as the dew point temperature remained below 20º C (68º F).
Hensen 1990	Review Paper	Various Locations	Studied the acceptability of periodic variations and ramp in indoor temperature. If the operative temperature changes as slow as 0.6 K/h during the daytime and in an upward direction, it would be acceptable if that temperature drift does not extend beyond the comfort zone by more than 0.6 K and for longer than one hour.
Newsham et al. 2006	Climate Controlled Chamber	Ottawa, Canada	Studied the effect of simultaneous light dimming and cooling load shedding on office workers. A steady increase in temperature up to 1.5º C from the normal temperature over a 3-hour period (0.5º C/h) is not detectable by the office workers, or if detectable would be considered acceptable in the circumstances studied.
Kolarik et al. 2009,	Climate Controlled Chamber	Lyngby, Denmark	Longer exposure to temperature drift (even moderate ramps such as ±0.6 K/h for 3-4 hours) will eventually result in sick building syndromes and decreased task performance among occupants. There was no significant difference in AMV values between occupants with and without dress code freedom.
Zhang et al. 2016	Field Study	Sydney, Australia	Studied the impact of temperature cycling during DLC programs on occupants' thermal comfort: Thermal sensitivity has a positive relationship with the rate of temperature changes. For temperature variations less than 3 or 4° C compared to the prevailing operative temperature (22-24° C), there was no significant changes in occupants' thermal sensitivity. Above this threshold, thermal sensitivity increased significantly. Although all DLC conditions exceeded the ASHRAE limit for temperature ramp rate or drift, at least half of the conditions were acceptable for majority of the subjects.

The findings from Sprague and McNall (1970) agreed with the ASHRAE accepted temperature threshold for the rate of temperature changes, although the ASHRAE Standard took a more conservative approach, since it allowed for a lower maximum temperature amplitude. Figure 2.3 depicts the limit of temperature variation rate listed in ASHRAE Standard 55 (1970) compared to the findings from Sprague and McNall. As that Figure suggests, a temperature fluctuation up to 2.8º C (5º F) is feasible; i.e. for ΔT equal to 5º F, the maximum cycles per hour (CPH) must be approximately 1.5. The results clearly suggest that a higher temperature fluctuation is possible compared to the ASHRAE limit that was in place at the time when this study was published (ASHRAE Standard 55-1970). Later, in 2013, ASHRAE released new guidance about the limits on temperature drifts and ramps that was in a general agreement with findings from the Sprague and McNall study, allowing even for a higher temperature amplitude over a longer period of time (ASHRAE 2013). This newer guidance is summarized in Table 2.3, and these values have been retained in the latest version of this Standard that was released in 2017.

Table 2.3 Limits of temperature drifts and ramps as listed in ASHRAE Standard 55-2017

Limit of temperature drifts and ramps					
Time period, h	0.25	0.5	1	2	4
Maximum operative temperature changes allowed, ºC (ºF)	1.1 (2.0)	1.7 (3.0)	2.2 (4.0)	2.8 (5.0)	3.3 (6.0)

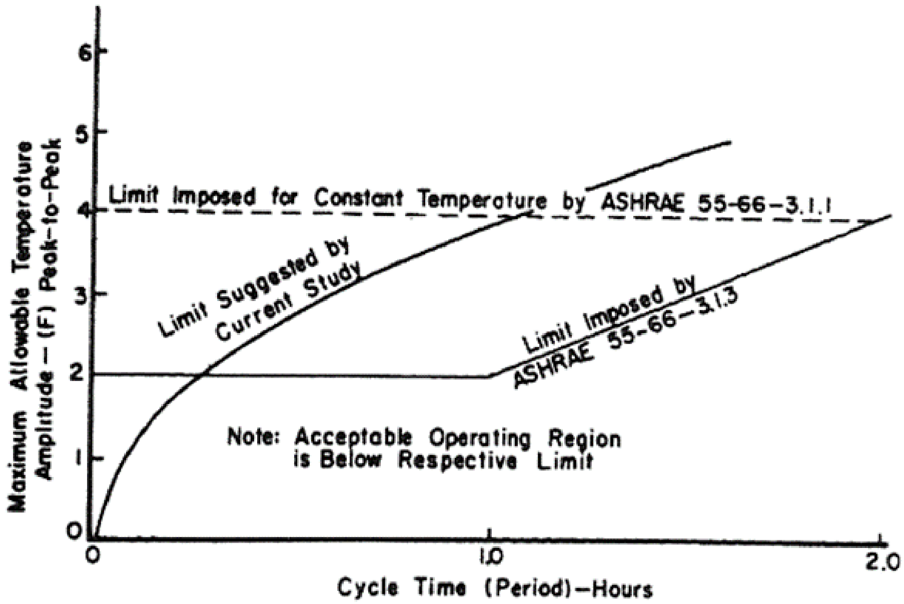


Figure 2.2 Suggested maximum temperature amplitude for thermal comfort vs. cycle time for triangular wave temperature variations (Sprague and McNall 1970)

2.5. Technologies to reduce the impact of DR on building occupants

The subjective characteristics of thermal comfort makes it impossible to satisfy all occupants in a thermal environment. The PMV/PPD diagram in Figure 1.1 suggests that it is impossible to provide the best thermal comfort for all occupants, no matter how much energy is consumed and in the best situations, the PPD value would still equal 5% (PMV=0), (ASHRAE Standard 55-2017, Van Hoof 2008). Personalized conditioning systems (PCS) are promising tools in improving occupant's thermal satisfaction especially during DR events, since they make it possible for buildings to operate with a higher or lower set point temperature, during cooling and heating seasons respectively, while improving occupant's thermal comfort and satisfaction; a practice that is expected to result in reduced HVAC energy consumption (Vesely` and Zeiler 2014).

Numerous studies have shown that using PCSs has the potential to increase occupant's individual thermal satisfaction, widen HVAC systems operating temperature range, and to decrease energy consumption for space cooling in buildings (Vesely` and Zeiler 2014). Therefore, applying Personal Environmental Control (PEC), (Hoyt et al. 2005) or PCS (Pan et al. 2005) could enable facility managers to provide the same comfort condition and even improve occupant's thermal comfort, particularly through targeting specific parts of their bodies, while consuming far less energy. Energy conservation is possible through reducing central HVAC systems operation time or reducing their heating/cooling load (Hoyt et al. 2005, Sun and Jasper 2015). Studies have shown that using PEC devices contributes to thermal satisfaction in zone temperature ranging from 18 to 30° C (64 to 86° F) with almost 40% annual energy saving while maintaining occupants' thermal comfort (Hoyt et al. 2005, Vesely` and Zeiler 2014, Jiang and Yao 2016).

Zhao et al. (2015) extensively studied individual preferences for thermal comfort and developed an online dashboard to collect thermal comfort votes. In one paper, he argues that individual thermal preferences and clothing choices differ significantly from person to person in the same thermal environment, however, the individual's personal preference does not vary significantly over time. Results from his field studies in an office building, involving 15 people during a three-month period, emphasize on the benefits of individualized thermal comfort control system in order to satisfy office workers in their microclimates. He also argues that the online dashboard could be linked to the real-time control systems in the future that could serve as a feedback to the HVAC control systems, enabling them to correct the thermal environments for the occupant's benefit (Zhao et al. 2015).

Some researchers have proposed the use of wearable individualized thermal comfort devices. Gao et al. (2012) describes a wearable vest with Phase Change Material (PCM) that provides a local cooling effect on subjects. The PCM vest improves the whole body thermal sensation, and is particularly recommended for elderly people and people with chronic diseases as well as those who are less involved in physical activities with high sweating rates. The vest is believed to have the potential to reduce the overall building energy consumption and to mitigate the adverse health impacts of heat waves, resulting from climate change, on building occupants. Other forms of PCM are available to increase the building mass, without leaving a significant effect on building construction techniques, and to reverse the heat flow direction (Nghana and Tariku 2016). Lightweight buildings in particular are prone to frequent indoor air temperature fluctuations, causing reduced occupant's thermal comfort and increased energy consumption. PCMs are capable of reducing almost 1.4° C (2.5° F) indoor air temperature fluctuations and 2.7° C (1.5° F) wall temperature fluctuations. Through reducing operating and radiant temperature fluctuations, PCMs decrease energy consumption (by up to 57% in winter) and tend to improve thermal comfort especially in winter (Nghana and Tariku 2016).

PCMs can also be applied as thermal energy storage tools to reduce HVAC energy consumption (Osterman et al. 2015) and as a tool to reduce peak temperature and prevent indoor overheating during demand response events in summer (Kotopouleas and Nikolopoulou 2016). Many other studies have shown that other individualized thermal comfort devices would also decrease building energy consumption while improving or maintaining occupants' thermal satisfaction (Vesely` and Zeiler 2014, Sun and Jasper 2015, Newsham 1997). Among those are personal heating/cooling garments, wearables or personal fans, heated/cooled chairs or desks

(Pasut et al. 2015), heated floors, wearable convective cooling systems that increase convective and evaporative heat loss (Sun and Jasper 2015), radiant lamps or pads, and partition- type fan-coil units (Pan et al. 2005). One study revealed that more than 90% of conditioned chair user subjects (a total of 23 persons) were comfortable at temperatures between 18 to 29° C (64 to 84° F) while more than 50% building energy saving was achieved (Wyon 1972). Other researchers (Pasut et al. 2015) using PCS also reported a maintained thermal comfort between the indoor temperatures of 18 and 30° C (64 and 86° F). Thermal comfort can be maintained at indoor temperature values up to 4 or 5° C (10° F) higher (during cooling season) or lower (during heating season) than typical industry design temperatures (such as listed in ASHRAE Standard 55-2017) when PCSs exist. Some researchers claim that a potential overall HVAC energy reduction of up to 60% can be achieved using PCSs while maintaining occupant's thermal comfort (Vesely` and Zeiler 2014, Schiavon 2010).

2.6. Summary and Conclusions

In this chapter, the literature about demand response as related to the HVAC systems adjustments and the corresponding potential impacts on building occupants' thermal comfort was reviewed. Demand response is a valuable tool in reducing or postponing the peak electricity demand in summer afternoons, improving power grids' reliability and decreasing user's utility bill. However, if it is not implemented properly, it could adversely affect building occupants' thermal comfort, productivity, and health (physical or psychological). Nevertheless, several studies have reported an improved occupant thermal comfort during DR events.

The impact of DR on building occupants substantially depends on the overall deviation of indoor temperature from the optimal conditions and the frequency and length of these variations. Based on the literature, a 3 or 4° C deviation from the typical comfort conditions during DR events could be acceptable by building occupants, if they are given sufficient adaptive options to adjust to the thermal environment and to reduce their thermal discomfort. A cyclic temperature variation of around 0.5° C per hour was acceptable for the most part of the literature, if the overall temperature fluctuations do not exceed a certain threshold. Personalized conditioning systems were also identified as valuable tools in improving individual thermal comfort while minimizing building energy consumption for air conditioning through extending HVAC temperature set point range.

CHAPTER 3

RESULTS FROM FIELD STUDIES CONCERNING OCCUPANTS' THERMAL COMFORT DURING SIMULATED DEMAND RESPONSE EVENTS

An extensive evaluation of the potential for Demand Response (DR) implementation was started in the summer of 2014 on the University of Georgia's campus (UGA), located in Athens, Georgia, USA. A key part of this program has been investigating the effect of simulated DR events through HVAC system set point temperature adjustments on buildings occupants' thermal comfort in public spaces of the campus. All tests were conducted in real-world operating conditions and the associated potential energy savings were estimated. This campus is located in a humid, subtropical climate region with hot and humid summers. The average high temperature is 32° C in summer (July) and the average annual precipitation is 118 cm. The annual average high and low temperatures are 23 and 17° C, respectively (U.S. Climate Data).

The study was initialized with a set of experiments in 2014, (Aghniaey et al. 2018) and focused on documenting the potential energy savings if DR measures were employed. The ultimate goal was identifying the settings that optimize energy consumption and energy cost savings combined with thermal comfort implications. The tests studied the energy saving potential for a coordinated set of adjustments in the chilled water, air supply, and zone temperature values. Part of the tests also focused on the building occupants' thermal sensation votes based on a three-point scale for various zone temperature set points. Earlier results were reported in Aghniaey et al.

(2018) as well as Aghniaey and Lawrence (2017, 2018a, and 2018b). Results from this part of the study are reported in section 1 of this chapter.

Later in 2015, field studies including extensive thermal comfort surveys started across the UGA campus that continued until October 2017. The main purpose of field studies was to evaluate the impact of implementing zone temperature adjustments (such as what might be implemented during demand response events) on the building occupants' thermal comfort in their everyday environment and in real-world conditions. Field studies were conducted with minimum interference of the research team. This way the Hawthorne effect, that is "the phenomenon of altered behavior or performance resulting from awareness of being a part of an experimental study" (Campbell et al. 1995) can be minimized.

The simulated demand response events were implemented through increasing cooling temperature set point in public spaces of the building (campus classrooms in this study) that are occupied for only between one and two hours by each individual occupant. The initial results of this study focus on analyzing the data collected in 2015 and 2016 to identify the distribution of occupants' thermal sensation, preference, and acceptability votes versus environmental and personal variables such as the indoor or outdoor air temperature, clothing insulation, and gender differences. Later analysis including the entire data set collected from 2015 through 2017 primarily focused on the variation of the occupants' actual mean thermal sensation votes (AMV), and mean thermal preference and acceptability votes with room operative temperature and comparing the AMV index with the PPD/PMV indices (comparing the adaptive thermal comfort model with the heat balance model). Methodology and results from these parts of the study are reported in section 2 of this chapter.

This should be noted that temporarily occupied spaces in this study are different from spaces studied by Yu et al. (2015, 2016, and 2017) that were mostly bookstores, banks, and supermarkets and were occupied for less than 40 minutes (transient thermal conditions). The public spaces in this study refer to the campus classrooms were a group of people occupy the spaces for around 60 to 90 minutes on average. Since the rooms' thermal environment in this study were steady during the experiments and responses were collected after occupants being present in the room for at least 15 minutes, the thermal environments were not considered as transient conditions (Goto et al. 2002). Public spaces, such as campus classrooms, especially in the lack of personalized conditioning systems, are particularly important since there are limited adaptive and control options for occupants to change the thermal environment to their benefits or to adjust themselves to larger temperature deviations. The type of occupants' activity and its importance in public spaces necessitates a careful evaluation of occupant thermal comfort in those spaces.

Survey questionnaires in 2017 included both continuous and categorical scales for thermal sensation. Previous questionnaires only included the categorical thermal sensation scale according to ASHRAE Standard 55-2017. AMV values from both categorical and continuous scales were compared and contrasted and the assumption of equidistance in ASHRAE seven-point scale for thermal sensation was investigated accordingly. Results from this part of the study are reported in Section 3 of this chapter.

3.1. Energy Saving Potential Concerned with Demand Response Measures

The HVAC testing conducted in 2014 (Aghniaey et al. 2018) included a series of step changes in the district energy system chilled water supply temperature. The tests were designed to take advantage of the inherent thermal energy storage with the chilled water distribution system to help supplement the cooling capacity of this network during peak demand periods. Thermostat set point temperatures in approximately 20% of the zones in two of the ten buildings connected to this loop were increased by 1.7° C (3° F) from the normal operating temperature of approximately 21° C (70° F) during the working hours (8 AM to 5 PM). Not all zones could be changed since each has to involve manual override of the Building Automation System (BAS). Air temperature, relative humidity, and occupant's thermal sensation were recorded.

During all survey sessions in this study, the survey subjects were not notified that they would be surveyed or that the zone temperature had been changed. The surveyed occupants were selected randomly in their everyday environment, doing their normal practices and were questioned if they felt too hot, too cold, or just right. Individual thermal sensation votes based on a three-point scale (Too Cold, Neutral, Too Hot) and the AMV values by room or classroom from these responses were compiled along with HVAC system energy consumption. These were calculated for both a baseline day (no temperature change) and the demand response test day. Since survey subject in this part of the study would be verbally questioned about their thermal sensation votes (as opposed to answering printed questionnaires) using a three-point scale added to the convenience of both surveyors and respondents.

Figure 3.1 depicts the chiller power requirement for the test day compared to a baseline day. The baseline was the next day that had nearly identical ambient weather conditions. Also shown in Figure 3.1 is the chilled water supply temperature schedule followed on the test day. The normal system operation is to maintain a constant supply temperature of 5.6° C (42° F), but for this test it was initially adjusted downward by 1.7° C before the test period and allowed to slowly rise to 1.7° C above the normal set point during the afternoon simulated demand response test.

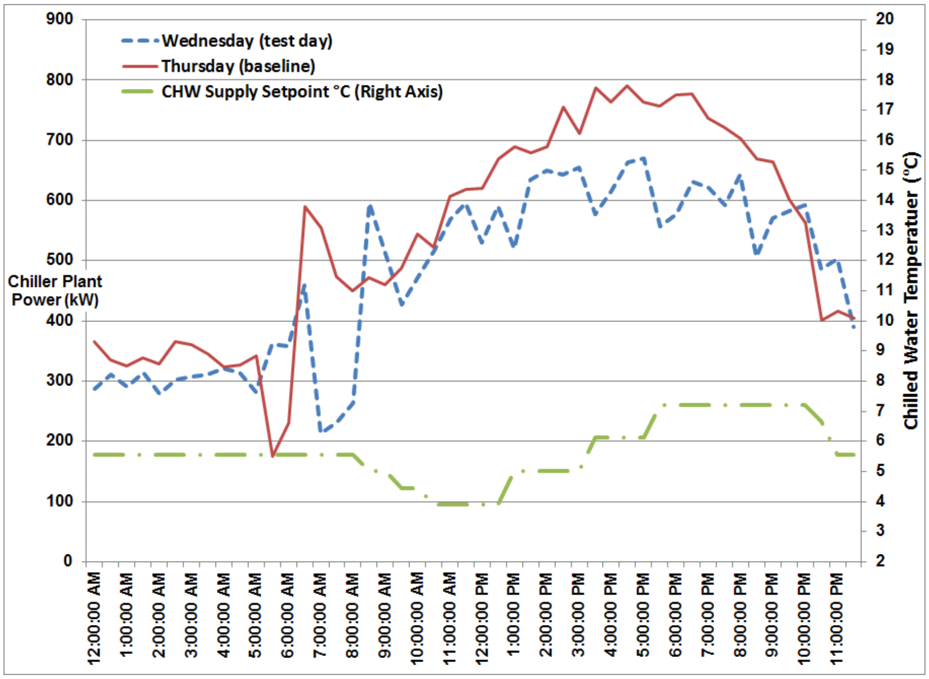


Figure 3.1 Total district energy chiller plant power consumption for the test day vs. a baseline

A reduction of approximately 11% in both peak demand and total energy consumption for the test day (measured in MW and MWh, respectively) was observed. Correspondingly, there was no statistically significant difference in the overall thermal sensation responses, measured as AMV, between the test and baseline days. The AMV value was indeed slightly closer to neutral for the test day.

3.2. Thermal comfort evaluation in campus classrooms during room temperature adjustments corresponding to demand response

This section concerns with the methodology that outlines the measurement and data collection methods and the characteristics of the surveyed building and occupants during the second phase of the study. Survey results are analyzed using the individual and class average thermal perception votes (statistics) and using meta-analysis techniques that averages the mean subjective responses over certain categories (meta- analysis). These two analysis methods are discussed separately in sections 3.2.3 and 3.2.4. The summary and conclusion is discussed at the end of the section.

3.2.1. Methodology

The second phase of the study that mainly focused on the impact of cooling temperature set point adjustments on building occupants during DR events started in summer 2015. Most of data for the thermal comfort research was collected in Correll Hall classrooms on the main campus of the University of Georgia. Correll Hall is a fully digitalized, five-story building that was opened in 2015. The building is fully air-conditioned and all classrooms are equipped with occupancy sensors. For classrooms facing south or north, they have semi-opaque adjustable roller blind shading for the fixed (non-operable) windows. For one of the classrooms in this study there is no exterior windows in the room, although it can get some daylight from windows in an adjacent room through the glass doors. Figure 3.2 (a-c) shows the Correll Hall building’s exterior view, a typical classroom, and the one classroom with indirect daylighting, respectively.

During this study, thermal comfort surveys were conducted in classrooms during simulated DR events whereby HVAC system operation was temporarily adjusted through increasing room cooling temperature set points. The HVAC temperature set point was preselected and adjusted remotely in one step and at least one hour prior to the beginning of the class sections.

(a)

(b)

(c)

Figure 3.2 (a) Correll Hall building exterior, (b) a typical classroom in Correll Hall, and (c) the classroom with indirect daylighting (UGA Terry College of Business, 2015)

The classrooms' temperature set points were not changed during the class sections, which lasted between 60 or 90 minutes long. The maximum observed variation in rooms' dry bulb temperature during the class sections was reported to be ± 0.5° C. The students were not informed of the temperature set point adjustments and that the study was taking place until they were asked to answer the survey questions at the end of the class sections. The room temperature was returned to the normal operating conditions after the end of each section.

It should be noted that since the environmental conditions in the classrooms remained steady during the class sections and since occupants were questioned at least 15 minutes after occupying the classroom (and generally between one and two hours), this should not be considered a transient thermal environment. The temperature for other areas in the building outside the tested classrooms, such as other classrooms, offices, and common areas, did not change during the testing periods of this study and remained around 22° C. Thus, students were temporarily exposed to the increased cooling temperature set points by entering the classrooms and being there for a short-term period of roughly one hour.

A total of 1336 survey responses were collected from students in 46 different course meeting sections and in 11 different classrooms. The number of students in the various class sections ranged from 18 to 54 persons. All surveys were conducted during cooling season periods of late spring, summer, and early fall of 2015, 2016 and 2017. Room operative temperature values during the testing ranged from 21° to nearly 27° C. Environmental data, such as dry bulb temperature, relative humidity, mean radiant temperatures, and CO_2 levels were recorded. The mean radiant temperature represents the combined effect of solar and other thermal radiations, air temperature, and air velocity on an exposed surface (like the human body) and is shown in Equations 1.2 and 1.3. The study subjects reported their subjective evaluations of the thermal environment along with demographic and other relevant information.

3.2.1.a. Environmental Measurements

The room dry bulb temperature (T_{db}) and relative humidity (RH) were measured in one-minute intervals during the class sections using temperature/RH loggers installed in representative locations. Other room environmental parameters were recorded while the thermal comfort survey was being conducted. A portable CO_2 meter and a globe temperature meter (heat stress meter) were utilized to measure CO_2 level and mean radiant temperature while subjects were answering survey questionnaires. Mean radiant temperature was also measured at the beginning of the course sections. All measured parameters were spatially averaged (arithmetic average) to represent a single parameter corresponding to the thermal environment in the classroom and student composition. Room air movement (air speed) was not changed from the normal operating conditions and measured velocities never exceeded 0.1 m/s. Relative humidity levels did not deviate significantly and were all within 50±10%. The dry bulb temperature remained nearly constant, with less than ± 0.5° C variation during each class section. CO_2 levels remained between 700 and 1300 ppm for all test periods. Table 3.1 shows the measured environmental parameters, measuring frequencies, and the location of each measurement above the floor. Table 3.2 shows the measurement accuracies for all devices used during this study. Real-time data related to the supply air temperature and relative humidity, as well as outside air temperature and relative humidity were also recorded via the campus data monitoring system.

Table 3.1 Measured environmental parameters, data recording frequencies, and measurement locations

Measured Parameter	Frequency	Location above Floor
Dry Bulb Temperature	Once per minute	0.6 – 1.1 meters
Relative Humidity	Once per minute	0.6 – 1.1 meters

Mean Radiant Temperature	Once at the beginning and once at the end of the section	0.6 meters
Carbon Dioxide (CO_2)	Once at the end of the section	1.1 meters

Table 3.2 The accuracy for measurement devices

Measured Parameter	**Measurement Device**	**Measurement Accuracy**
Dry Bulb Temperature	Temperature/RH% Meter	± 0.21° C @ 0 to 50° C
Relative Humidity	Temperature/RH% Meter	± 3.5% @ 15 to 45° C
Mean Radiant Temperature	Heat Stress Meter	0.6° C @ 0 to 50° C
Carbon Dioxide (CO_2)	Indoor Air Quality Sensor	± 50 ppm ± 5% of reading (0 ~ 2000ppm)

3.2.1.b. Subjective Measurements

The survey questionnaire initially used for the second phase of testing in this research study in 2016 evaluated only one dimension of thermal comfort, i.e., occupants' thermal sensation. Questions about occupants' thermal preferences and thermal acceptability were later added to the questionnaire and 496 survey responses were collected using the expanded version of the survey questionnaire. The questionnaire complied with the standard protocols, such as those outlined in Brager and De Dear (2001), and included evaluations based on the ASHRAE seven-point scale for thermal sensation, a garment check-list (for estimation of the overall clothing insulation level to obtain occupants' CLO values) and demographic information. All field surveys were administered at the same time as the indoor environmental measurements were being recorded. Students in the test classrooms were asked to express their thermal sensation votes based on the seven-point scale specified for "point-in-time surveys" in ASHRAE Standard 55 (2017). Students were also requested to express their thermal preferences based on a five-point scale that asked if they would prefer "Much Cooler", "Slightly Cooler", "No Change Required", "Slightly Warmer", or "Much Warmer" than the current setting (Humphreys and Nicol 2004, McCartney and Nicol 2002) and if they consider the current thermal environment to be acceptable or unacceptable. They were also asked to fill out some demographic information (age and gender), if they felt healthy or sick at that moment, their length of exposure to the thermal environment in the room, and information regarding their clothing type and level. Finally, they were requested to answer if they had involved in any behavioral adjustment to change the thermal condition to their benefit, such as making changes in their clothing level, changing position in the classroom, having a cold or hot drink, etc.

The general metabolic rate for the subjects in classrooms based on observations of their activity level was recorded and was assumed to be equal to 1.2 MET for survey subjects that were generally seated occupants in schools (ISO:7730). One MET equals to 58.2 W/m^2 and is the energy produced per unit area of skin surface for a person seated at rest (ASHRAE 2017). Test subjects were unaware that the room temperature adjustments had been done. Depending on the choice of the course instructors, survey questionnaires were available in either hard copies or online survey questionnaires that were emailed to the students at the end of the sections and responses were collected within five minutes.

3.2.2. Results and Discussion; Statistics

The results of this research revealed important information about how building occupants perceive and accept the thermal environment, and what they prefer to be the optimal thermal conditions with respect to variations in the room operative temperature. Figure 3.3 shows the actual mean vote values for the 15 pairs of tests runs conducted in 2016, with each pairing being the same classroom and class section for different test dates and conditions. These test pairs are connected via a line in this figure. For most cases the clothing levels (as measured by the CLO factor according to ASHRAE Standard 55) did not change significantly (more than ± 0.1 CLO) between the two tests dates and remained between 0.35 and 0.45 CLO for most cases. The relative humidity and air velocity remained approximately the same at around 50% and under 0.1 m/s for all survey sessions.

Survey points presented by black squares were conducted in early spring where people may not have adapted to the seasonal variations in a transitional season, and this might help explain the more extreme AMV values for these two sets of survey test pairings. The results show that when temperature values in classrooms were increased up to 25º C (77º F) the occupant's AMV tended to increase, but for most cases the AMV values remained in the ASHRAE standard 55 (2007) acceptable range ($-0.5 < AM\ V < 0.5$). For some class sessions, the occupant's thermal comfort improved with the increased temperature set point compared to the normal temperature set point in the room. These findings are in line with similar studies (Zhang et al. 2011).

A few of the class sections, however, did not follow this pattern, and these are connected with a dashed line in Figure 3.3. For example, we noted that one of the class pairings resulted in an average AMV value decrease from about -0.5 to -1.0 even though the room temperature was slightly warmer during the second test day. This discrepancy might be associated with the much different ambient temperature and humidity levels between test days that may have affected occupant CLO values and their thermal expectation, although other reasons could exist such as just random variation in response patterns. As would be expected, there were some outliers in the data, for example someone voting for the thermal environment as being too hot or too cold while the class average was for just right, slightly cool, or slightly warm.

We also noticed that people who reported themselves as being unhealthy at the time of survey did not generally perceive their thermal environment different from an average healthy subject in this testing. However, the number of people describing themselves as feeling unhealthy in this limited field study was not large enough to draw a conclusion.

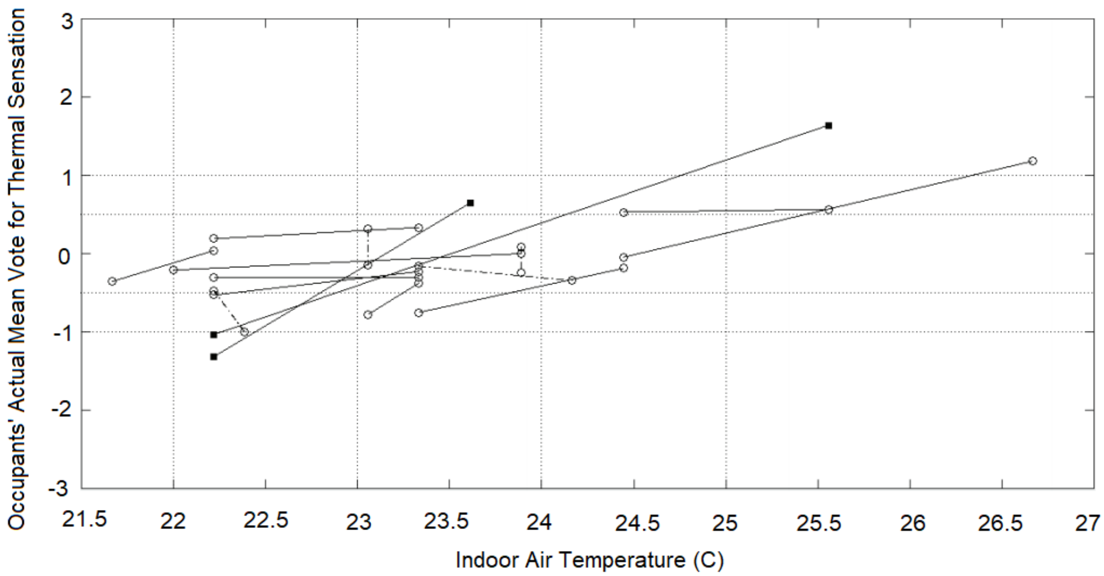


Figure 3.3 Occupants' Actual Mean Vote (AMV) vs. the indoor air temperature values in classrooms on UGA campus

Figure 3.4 provides a more detailed breakdown of the distribution of AMV responses, showing the frequency of thermal sensation votes from nearly 450 individual students in the classroom test pairings. The main observation here is that the respondents seemed to be most satisfied when classroom temperatures were in the 24-25.5º C (75-76º F) range, with very few people perceiving the environment as too cold or too hot. Another observation is that when the temperature is increased to more than 25º C (77º F), to create a warmer than neutral thermal environment, the number of occupants voting on the warmer side of the scale significantly increased. However, for temperature values less than 24º C (75º F) in a cooler than neutral thermal environment, the thermal comfort votes were still more evenly distributed between the cooler and warmer sides of the seven-point scale. This could indicate that occupants on this campus have a higher tolerance to a cooler thermal environment than neutral versus a warmer thermal environment or simply that the AMV values are asymmetrically distributed around the neutral conditions.

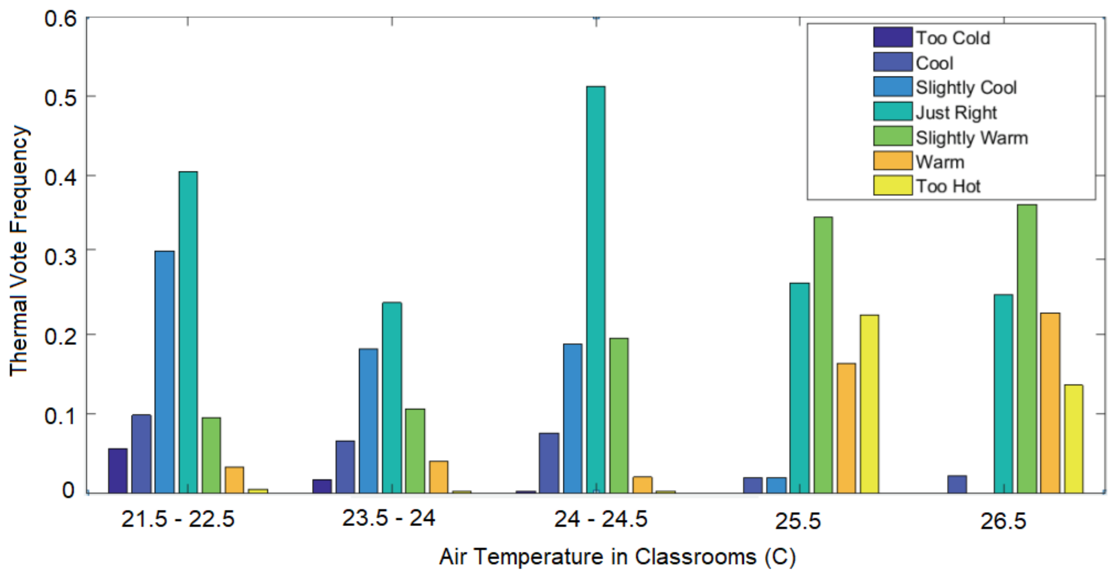


Figure 3.4 Frequency of individual thermal comfort votes vs. indoor air temperature values in classrooms

Figures 3.5.a and 3.5.b plot the AMV values for each class section as a function of the outdoor and the indoor air temperature, respectively. The trend of increasing class AMV values with increasing zone temperature would be expected (Figure 3.5.b), while the results shown in Figure 3.5.a indicate a small decrease in AMV with increasing outdoor ambient temperature variations. The outdoor air temperature influences the occupant's choice of clothing level (average CLO values slightly decreases with the warmer outdoor ambient temperatures). It is also possible that the respondents' thermal expectations were different with warmer ambient temperatures, although there is no conclusive evidence of adjusted expectations from this study.

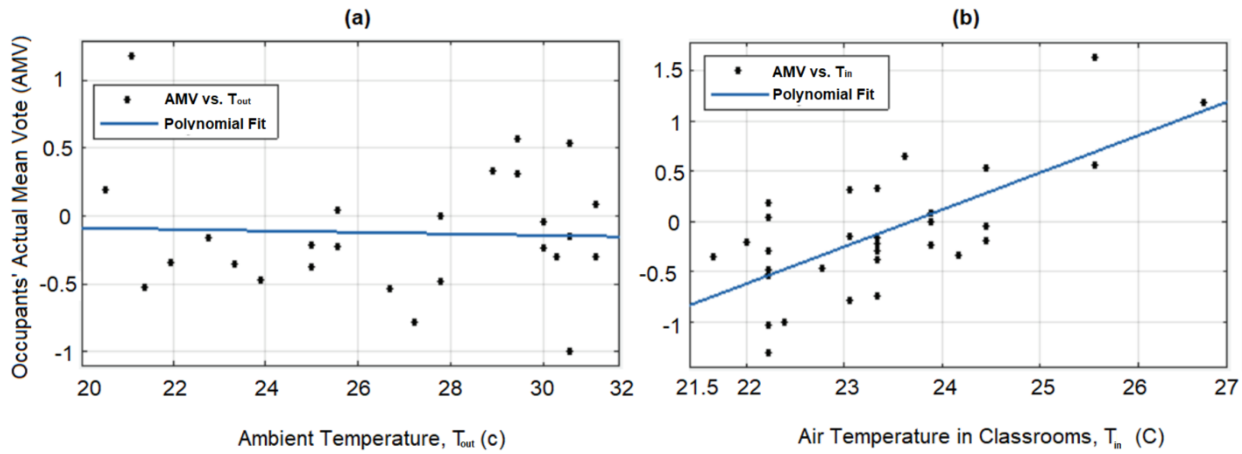


Figure 3.5 The variations of the AMV values for each class session vs. (a) outdoor ambient air temperature (T_{out}) and (b) mean indoor air temperature (T_{in}) in ºC

The results of this study also revealed that people have various definitions of thermal acceptability in a thermal environment. None of the respondents who perceived their thermal environment as slightly cool through slightly warm considered the environment as being thermally unacceptable, as shown in Figure 3.6.a. In addition, 75% of occupants voting for cool and 62% of those voting for warm still considered their thermal environment to be acceptable, while only 8% voting for too hot perceived their environment as thermally acceptable. Among subjects who reported their thermal acceptability votes in these tests, no one has voted for being too cold, thus information for this category is missing.

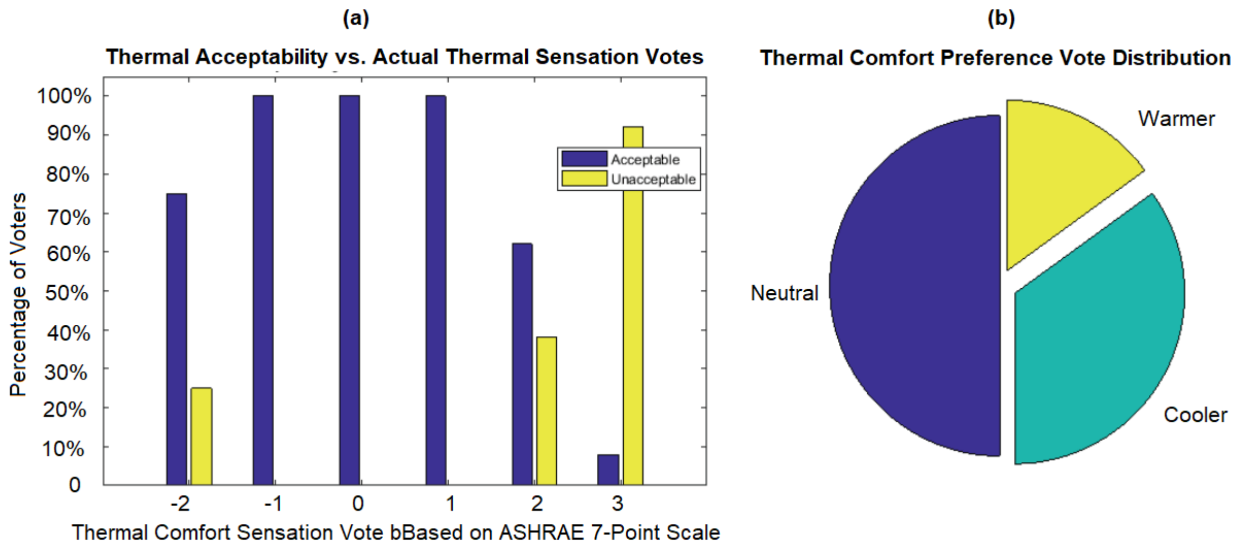


Figure 3.6 (a) Thermal acceptability compared to thermal sensation votes based on the ASHREA seven-point scale (b) the overall summary of subjects' thermal comfort preference votes

Figure 3.6.b indicates that roughly 50% of the survey subjects preferred a non-neutral thermal environment (either warmer or cooler), contrasting a basic assumption for Fanger's PMV/PPD model that considers thermal neutrality as equivalent to thermal comfort. Twenty-nine percent of the survey subjects either perceived their thermal environment as cool, slightly cool or warm but preferred no changes to be made to the air temperature, or they voted for just right based on the ASHREA seven-point scale for thermal sensation but still preferring a cooler or warmer thermal environment.

Figure 3.7.a depicts that women in this study (shown in the solid red line) generally feel cooler than men for the same indoor thermal environment, even while their clothing insulation (CLO) was marginally higher than men as shown in Figure 3.7.b. This finding is in contrast with Fanger's assumption that associates women's preference for a warmer thermal environment to their lower clothing insulation level (Van Hoof 2008).

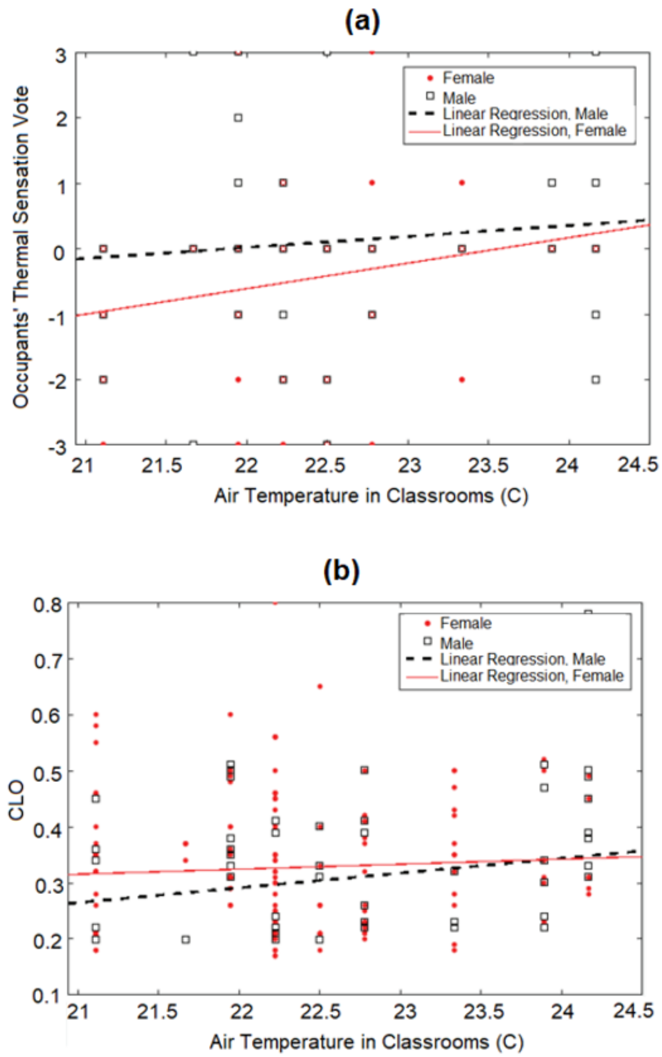


Figure 3.7 The comparison of men and women's (a) thermal sensation votes and (b) clothing insulation (CLO) versus indoor air temperature (° C)

In response to the question asking occupants about their adaptive behavior, 23% of the occupants reported being involved in some sort of adaptive behavior to make themselves comfortable, with almost all of these involving adjusting their clothing level. A very limited number of occupants (four people) reported attempts to make other changes beyond their clothing level, such as trying to adjust the thermostat's temperature set point (the room thermostats allow for ±2º C temperature adjustment), having a cold or hot drink, or by changing their locations in the room.

3.2.3. Results and Discussion; Meta-Analysis

Final data analysis using meta-analysis techniques revealed more information about occupants' mean thermal sensation, thermal preference, and thermal acceptability votes. Figure 3.8-3.10 depict the results from meta-analysis reflecting occupants' mean votes in 46 different class sections. Figure 3.8 plots occupants mean thermal sensation votes for each class section versus the room operative temperature. Figures 3.9 and 3.10 plot mean thermal preference votes and mean thermal acceptability percentages versus the room operative temperature for each class section. Mean thermal sensation vote is expressed as AMV, with all AMV values hereafter being based on the ASHRAE seven-point scale and as a function of the room operative temperature. Thermal preference votes are evaluated based on a five-point scale. The respective scores range from -2 for "Much Cooler" up to +2 for "Much Warmer". Thermal comfort acceptability percentage is expressed as the percentage of occupants who deem the thermal environment as acceptable based on a dualistic scale (Acceptable or Unacceptable).

We examined nineteen different potential model options for predicting occupants' subjective thermal comfort responses with respect to the room operative temperature, such as linear regression or a support vector machine. Based on the resulting coefficient of determination values (R^2), P-Values, and values for root mean square error (or RMSE as defined in Appendix C), quadratic regression models were chosen as the best fit. The quadratic regression equations for occupants AMV and thermal preference votes, and their thermal acceptability percentage with respect to the room operative temperature (T_{op}), and the corresponding R^2 values are shown on each graph. The coefficient of determination or R-Squared (R^2) is a statistical representative of how close the actual data are to the fitted line or to the predicted values and varies between 0 and 1. In other words, R^2 measures the proportion of the variation in a dependent variable (Y) explained by the independent variables (X_i) for a linear regression model. The closer R^2 values are to one, the more reliable and strong the model is. APPENDIX C presents R^2 in details.

The room operative temperature combines the effect of room dry bulb temperature (T_{db}), mean radiant temperature (T_{mr}), and air speed; this is the temperature that people sense in an indoor environment. Since the air movement in each classroom was fairly negligible (< 0.1 m/s), the room operative temperature was calculated as shown in Equation 1 (Nicol and Humphreys 2010, CIBSE 2006).

$$T_{op} = (T_{db} + T_{mr})/2 \qquad (3.1)$$

Figure 3.8 shows that with increasing the operative temperature in classrooms, the AMV values tended to increase. However, they generally remained within the ASHRAE comfort zone of between -0.5 to +0.5 when the room temperatures were within 22º and 25° C (although there were some individual AMVs outside the -0.5 to +0.5 range). When operative temperatures were below roughly 25º C, thermal acceptability was always above 80% (Figure 3.10), and occupants would generally prefer no significant temperature changes to be made (or only preferred a slightly lower or slightly higher temperatures), as shown in Figure 3.9. For operative temperatures beyond 25 ° C, the AMV values exceeded 0.5 (Figure 3.8) and thermal acceptability dropped to less than 80%. Accordingly, Figure 3.9 depicts that the average preference vote was for a cooler or a much cooler thermal environment, as expressed by the average preference votes dropping to below -0.5, when the operative temperature was roughly above 25° C (or 24.8° C). For operative temperature values greater than 26° C, the AMV values were above 1.0.

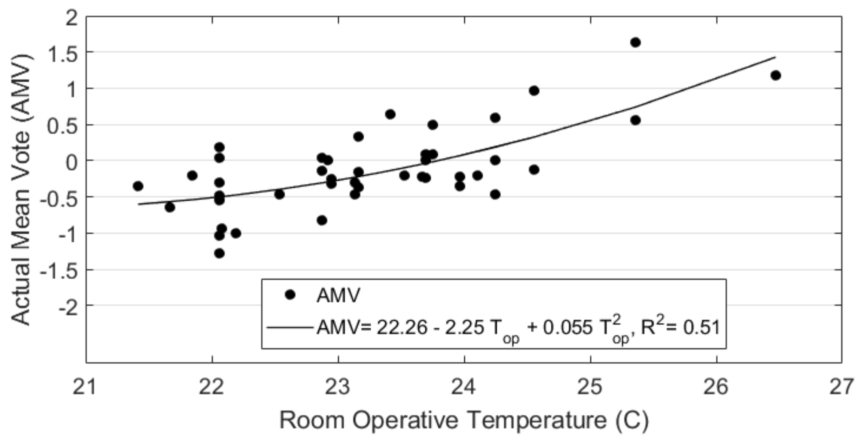


Figure 3.8 Occupants' mean thermal sensation votes or AMVs vs. room operative temperature (°C). P-value equals 0.001.

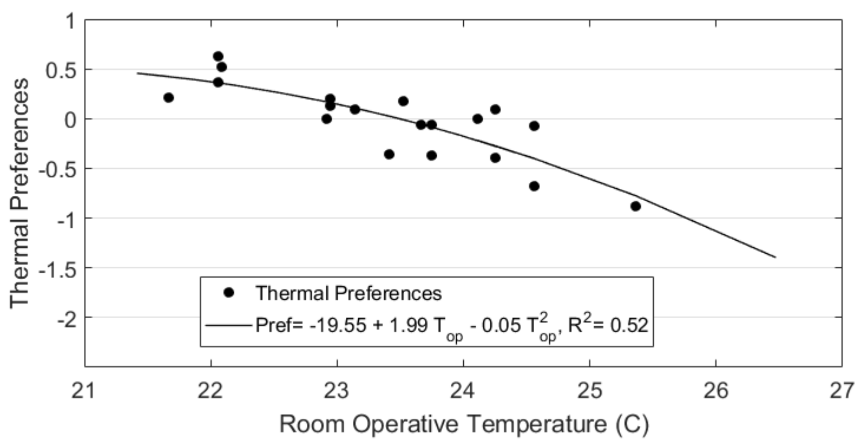


Figure 3.9 Mean thermal comfort preference votes vs. the room operative temperature (°C). P-value equals 0.001.

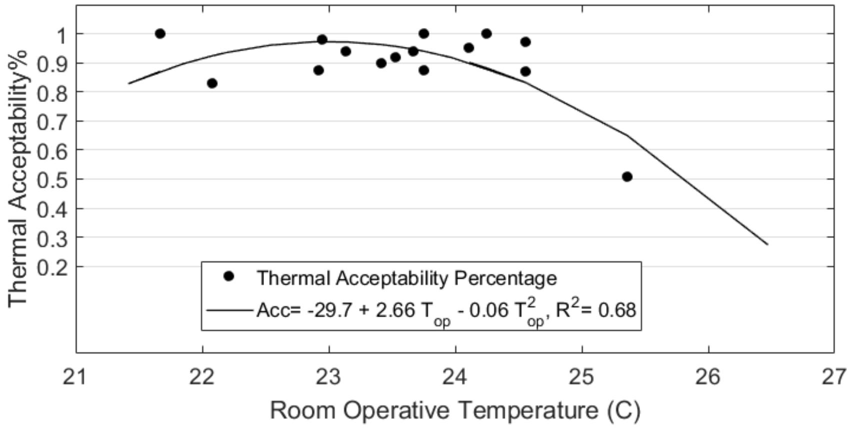


Figure 3.10 Thermal comfort acceptability percentage vs. the room operative temperature (°C). P-value equals 0.0005.

The indoor relative humidity during all testing ranged between 40% and 60% with an average value of 52%. Thus, relative humidity remained within the comfort zone described by ASHRAE Standard 55 (2017) for all tests conducted. The corresponding outside air temperature and humidity level varied between 20 and 33° C and from 30% to 100%, respectively, during the testing program.

Figure 3.11 shows the distribution of occupants' individual thermal sensation votes in different classrooms versus the room operative temperatures. The distribution of votes did not change considerably as room temperature increased from 21 to 24° C. By increasing the room temperature up to the 24.5° C group, the median remained the same (zero) while the ranges for occupants' thermal sensation vote shifted to the warmer side of the scale by one level. For the temperature range of between 21 and 24° C, 75% of occupants perceived their thermal environment as between slightly cool and slightly warm. For operative temperatures beyond 25° C, at least half of the occupants felt warm or hot and would be considered not comfortable according to the ASHRAE Standard 55. The standard deviation and number of surveyed subjects for each temperature category are indicated in the horizontal axis labels. The number of surveyed subjects is the highest within the temperature range of 22 and 25° C. A limited the numbers of room surveys were conducted outside this range at the request of the campus facility operations team to avoid potential thermal comfort complaints.

In Figure 3.11, the red lines in the middle show the second quartile or the median. Bottom and top boxes show the range of the first and second quartiles, and second and third quartiles, respectively. The whiskers or dashed lines extend from the minimum value to the first quartile and from the third quartile to the maximum value within each category. Red points indicate extreme thermal sensation votes that are three median absolute deviation away from the median. Since extreme votes are intrinsic to any thermal comfort related datasets, due mostly to the subjectivity of thermal comfort and its psychological roots, these votes are not treated as outliers in this study. STDEV and # show the standard deviation and the sample size within each category, respectively.

Figure 3.12 shows the arithmetic average of AMVs, thermal acceptability, the percentage of people who were involved in some sort of adaptive measures, and the average CLO levels for all class sections versus the room operative temperatures. "N/A" or not available indicates insufficient data to make a comparison at that temperature range. In this figure, all individual responses from various classrooms are divided into six different categories (21.5, 22.5, 23.5, etc.) based on the operative temperatures in classrooms and using meta-analysis technique. Occupants' adaptation is expressed as the percentage of people who were involved in some sort of adaptive behavior to minimize thermal discomfort during these class sections, such as changing their clothing type or level. For simplicity, the word "average" may not be repeated later in this study.

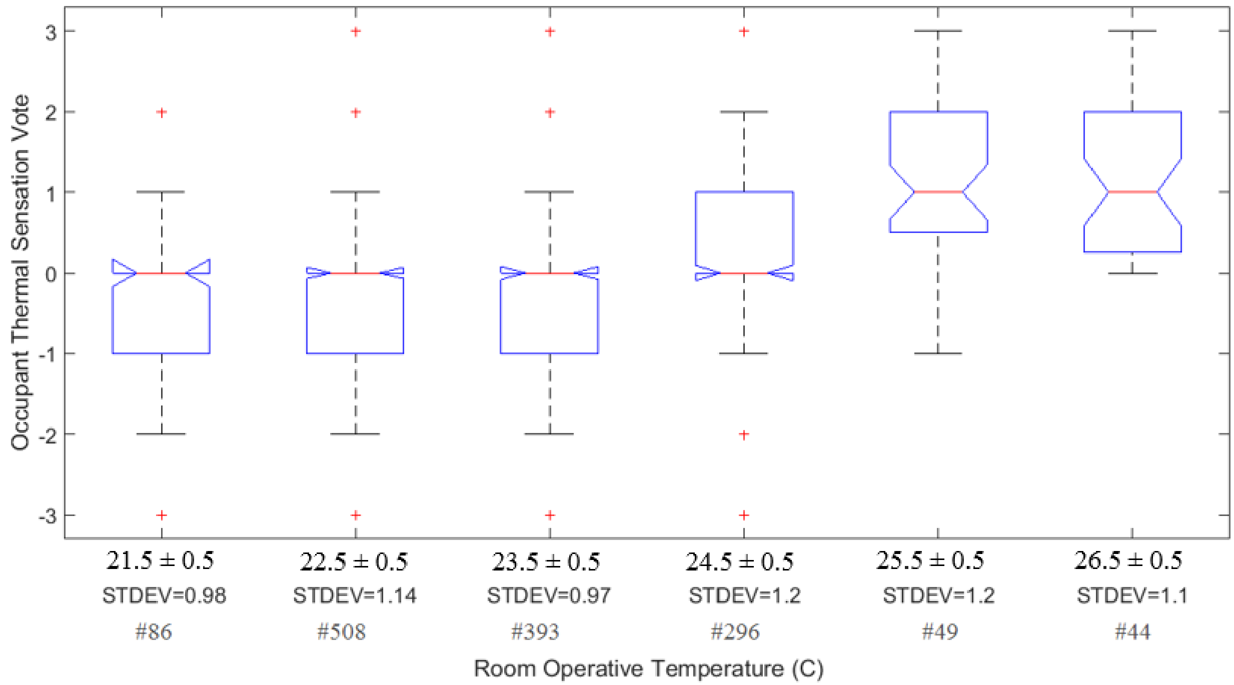


Figure 3.11 The distribution of occupants' thermal sensation votes for different classrooms vs. the room operative temperature (°C)

In this study, students were all seating on lightweight, mesh office chairs with a corresponding added CLO value essentially equal to zero. As shown in Figure 3.12, the average AMV values increased from - 0.4 at 21.5° C to approximately 1.2 when the room operative temperature was around 26.5° C. An unexpected decrease in the overall average AMV values is evident when the operative temperature increases from 21.5° C to the 22.5° C group. This might be explained by sudden decrease in average outdoor air temperature on some of the test days in the second group, compared to other test days during the survey. This could have psychologically affected occupants and changed their expectations (alternatively, this just could be attributed to random variabilities).

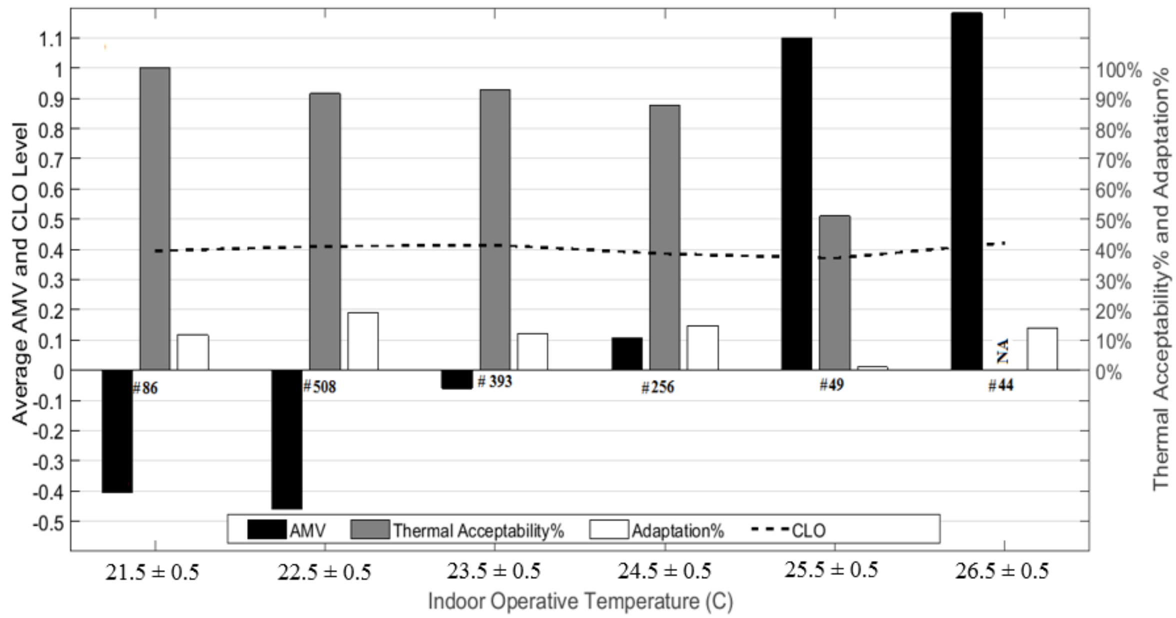


Figure 3.12 The average values of occupants' AMVs, the thermal acceptability percentage, and CLO values (left axis), and the adaptation percentage (right axis) vs. the room operative temperature (°C)

The average AMV values remained in the ASHRAE comfort range of between -0.5 and +0.5 (based on the seven-point scale for thermal sensation) for temperature values between 21 and 25° C, and the thermal acceptability was above 80%. For temperature values greater than 25° C, the average AMV values increased to more than 1.0 and the corresponding thermal acceptability level of occupants fell to less than 50%. A dramatic increase in occupants' AMV values (almost one point on this scale) and the corresponding decrease in thermal acceptability percentage for temperatures above 25° C might be explained by the shift in occupants' thermal sensation votes towards the warmer side of the scale, as shown in Figure 3.11. When considering tests runs at above 25° C, a substantial increase in the number of extreme votes (+3) was noted alongside the fact that none of the occupants voted for "Cold" or -3. There was also a lower number of surveyed subjects for temperatures above 25° C. All these factors are potential causes for the significant increase in the AMVs. Comparing the smooth increasing trend in Figure 3.11 with critical changes happening in Figure 3.12 makes it clear that how substantially the extreme votes affect the overall AMVs. However, removing these votes from the dataset would significantly decrease the robustness of the thermal comfort model and its accuracy. There was no statistically significant difference between thermal sensation of healthy and unhealthy subjects, based on their self-reported health status.

The average percentage of building occupants doing some sort of adaptive behavior (Adaptation) remained nearly consistent throughout the indoor temperatures tested and was less than 20% for all operative temperatures (and less than 30% when considering any individual course section). This was expected since there are only limited adaptive options in these classrooms for occupants to adjust themselves to various thermal environments. The only options available is by changing their clothing type or level, having a cold or hot drink, taking a break in common areas, or changing their position in the room. Changing the seat location in the room is barely helpful in minimizing occupants' thermal discomfort since there is a nearly uniform thermal environment in these classrooms, partially attributable to lack of ceiling fans and the windows being inoperable and covered with semi-opaque grey blinds (and one room has no exterior windows at all). More than 95% of those who were involved in some sort of adaptive behavior did so through changing their clothing level. It is expected that if more adaptive options were available, such as personal conditioning systems, ceiling fans, or controllable air conditioning systems, the use of adaptive behavior by the occupants would have been greater.

Thermal comfort is a subjective issue and it substantially depends on various cultural, social, and psychological factors. Inter-individual and intra-individual differences in occupants' thermal sensation and preferences can result in different AMV values from the same group of people and under the same environmental conditions on two different tests days (Aghniaey and Lawrence 2018b). Considering that this study was conducted in real-world conditions and not in climate-controlled chambers, the results are expected to reflect the impact of the non-physical factors mentioned above. Therefore, a wider variation in occupants' thermal sensation, preference, and acceptability votes would be expected to exist in this study compared to the experiments conducted in climate control chambers. With that in mind, a focus of this study is on finding the general trend in occupants' thermal sensation versus temporarily increased the room operative temperature and for this particular population demographic, with the results shown in Figures 3.8-3.12.

An ANOVA test (Analysis of Variance test) was conducted to identify if there was a significant relationship between occupants' AMV values and the room operative temperatures. The results showed a significance level, or P-value, of 0.002 in this study. A P-value < 0.05 indicates that the probability that the general trend in AMVs versus temperature shown in Figure 3.11 to be random is less than 5% and rejects the null hypothesis. Therefore, even with unequal sample sizes for different categories, a conclusive comparison can be made that the AMV values of various temperature ranges in Figure 3.11 are statistically different. Thus, we can safely make general conclusions from these results.

Figure 3.13 compares the average AMV and PMV values versus the room operative temperatures. Figure 3.13 shows the Actual Percentage of People Dissatisfied with the thermal environment (APD), PPD, and the Calculated Percentage of Dissatisfied occupants (CPD), respectively, versus room operative temperatures. PMV and PPD values are calculated using the thermal comfort tool developed by the Center for the Built Environment (CBE). This tool uses the measured environmental parameters (room operative temperatures, relative humidity, and air speed), and the two subjective parameters, i.e., CLO and MET as input parameters. CPD is calculated using Fanger's PPD/PMV equation shown in Equation 3.2 (PPD/PMV equations are shown in Figure 1.1 and Appendix A). In the study, CPD values were estimated as a function of the AMVs from the surveys, as opposed to PPD using PMVs. This index is introduced to clarify if the proposed relationship between the percentage of dissatisfied occupants and their thermal sensation vote is applicable in real world conditions studied.

$$CPD = 100\exp(0.03353\,AMV^4 - 0.2179\,AMV^2) \tag{3.2}$$

Figure 3.13 reveals that occupants' AMV values are generally higher than the corresponding PMV values. In other words, occupants in this study perceive their surrounding thermal environment warmer than that predicted by the heat balance model, by an average value of 0.57 or approximately half a scale unit.

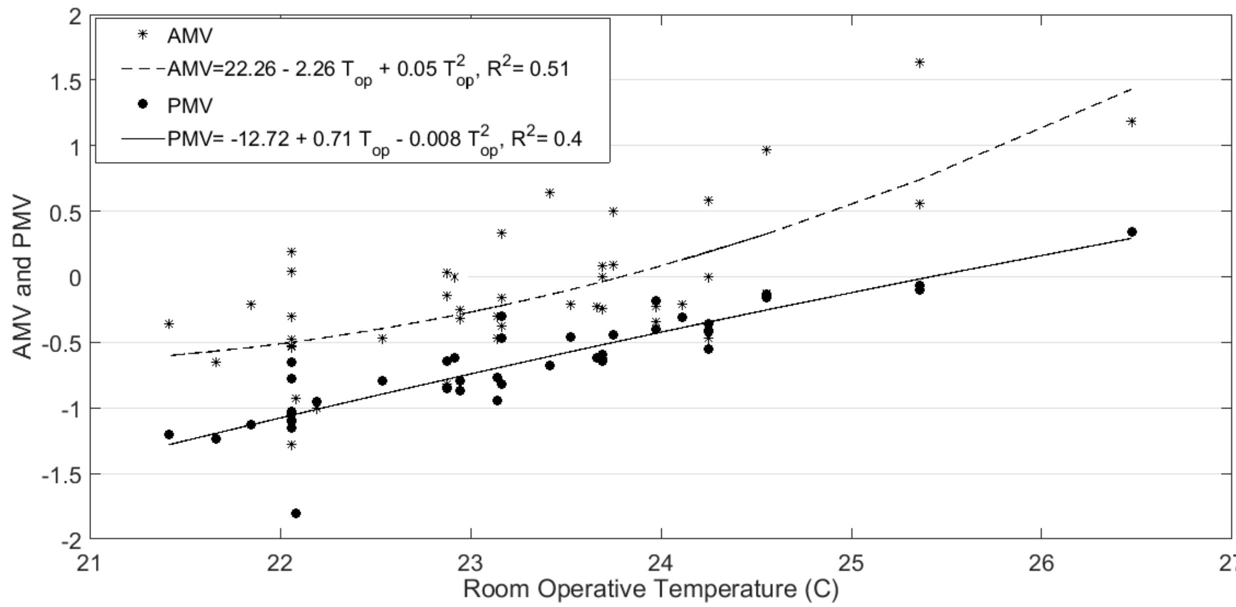


Figure 3.13 The AMV and PMV values versus the room operative temperatures (°C)

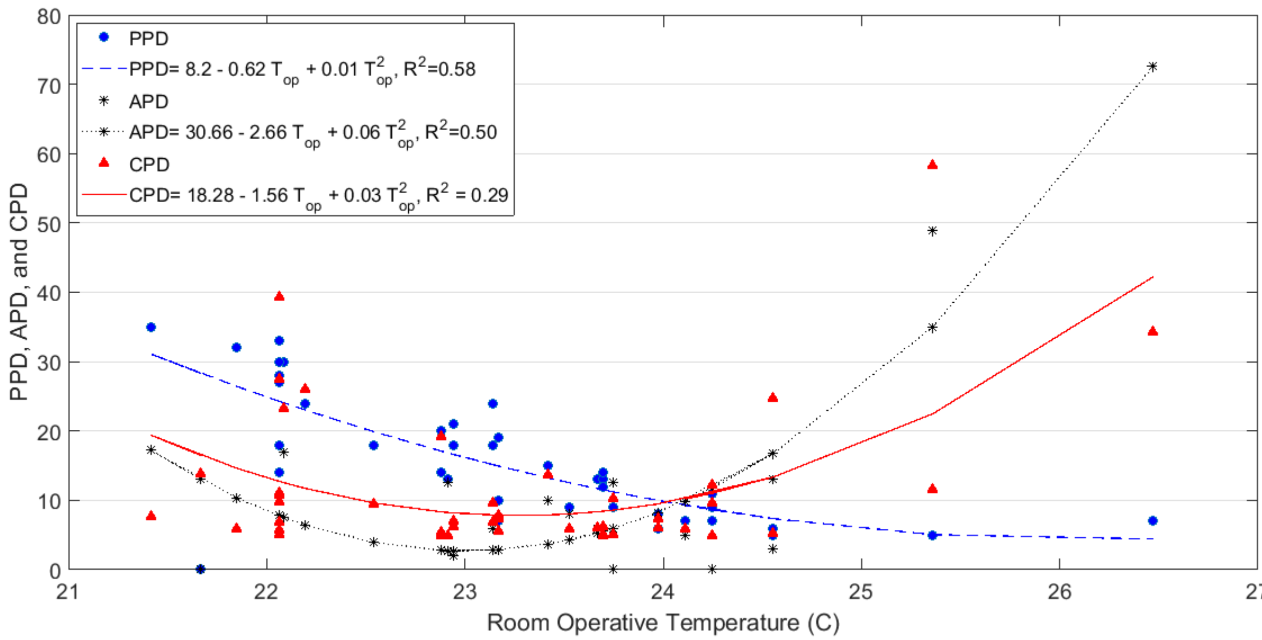


Figure 3.14 The PPD, CPD, and APD values versus room operative temperatures (°C)

Figure 3.14 shows that the average percentage of people dissatisfied with their surrounding thermal environment (expressed as APD values) is lower than predicted by heat balance model (PPD) for operative temperatures less than 24° C. At 24° C the two parameters are equal, while they tend to diverge as room temperatures increase to more than 24° C. The actual percentage of dissatisfied occupants continues to increase and goes beyond 20% for operative temperatures beyond about 24.5° C. The predicted values, however, decrease to around 5% at 26° C (the minimum possible value for PPD) and would be expected to increase for temperatures higher than 26° C. The minimum APD occurs at 23° C. Based on the results shown in Figure 3.13, it can be concluded that within the tested temperature range (21-27° C) and for occupants who were exposed to the tested rooms' temperature for between 60 and 90 minutes, the heat balance model over-predicts thermal dissatisfaction for lower operative temperatures (below 24° C). The heat balance model also under-predicts dissatisfaction for those occupants who were temporarily exposed to indoor temperatures above 24° C.

The calculated percentage of dissatisfied occupants or CPD (computed as a function of AMV using Equation 3.2), is relatively close to the actual values or APDs from these survey results at cooler environments (T_{op} < 24° C). However, at room operative temperatures above 24° C, the calculated values tend to be higher than the actual values, with an average estimation error of 6% and a maximum deviation of 39% within the tested temperature range. It could be concluded from these results that Fanger's PPD-PMV equation does not accurately predicts the percentage of dissatisfied occupants based on their thermal sensation votes, at least when the average AMVs are greater than zero and for short-term exposure to the room temperature.

A final comparison was made based on the occupants' gender. Figure 3.15 and 3.16 compare the occupants' average AMV values for men and women, based on the ASHRAE seven-point scale, and their thermal preference votes based on a five-point scale, both with respect to the room operative temperature. The figures also show the CLO values for men and women. The CLO values were calculated using the self-reported levels for occupant clothing following ASHRAE Standard 55 (ASHRAE Standard 2017). We realized that the AMV values for women were generally lower than that for men at the same thermal environment. Women also preferred a warmer thermal environment compared to men. We realized that women in this study on average did not wear a lighter CLO level than men, which is in contrast with Fanger's assumption that women feel cooler partially because of their lighter level of clothing compared to men (Van Hoof 2008). The reasons behind this are unclear, and may have to do with women's generally lower metabolic rate or skin temperature. Regional and cultural differences and variations in normal dress could be a reason as well. These results are compatible with the results derived from Figure 3.7 that analyzed the AMV values for each indivudual class session (versus the overall average AMV values for each indoor temperature range or meta-analysis).

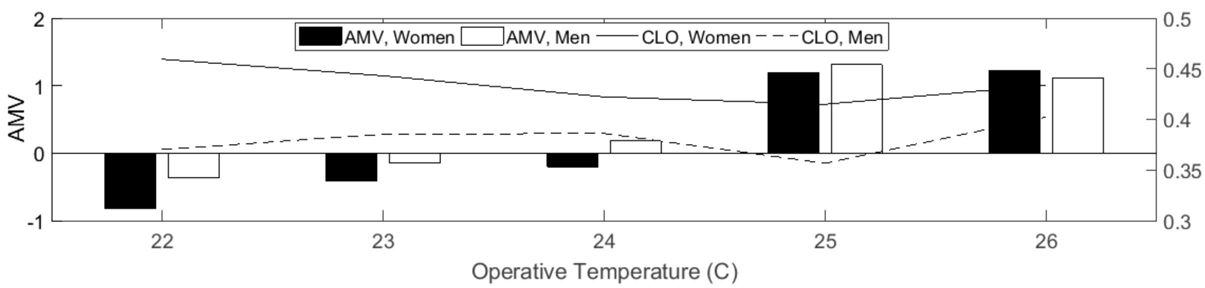


Figure 3.15 A comparison between men and women's AMVs (left axis) and their CLO values (right axis) vs. the indoor operative temperatures (°C)

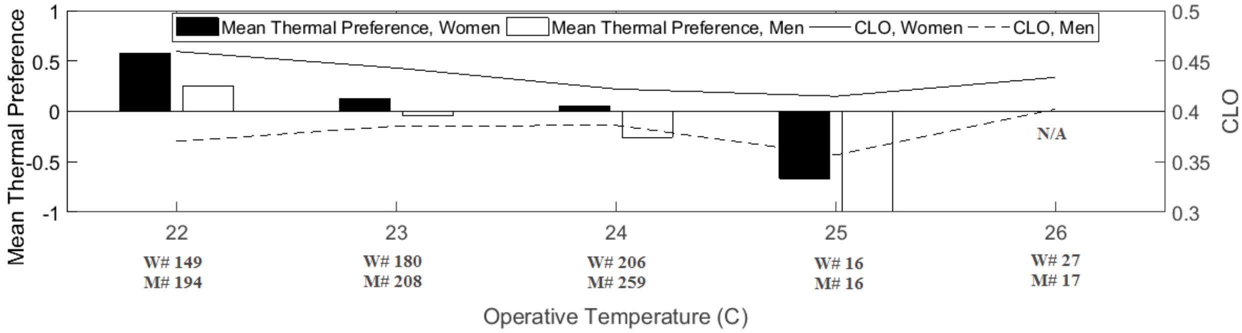


Figure 3.16 A comparison between men and women's mean thermal preference votes (left axis) and their CLO values (right axis) vs. the indoor operative temperatures (°C)

3.2.4. Summary and Conclusions

This study focuses on investigating the impact of demand response events on building occupant thermal comfort. Demand response in this study is implemented through increasing cooling temperature set point in parts of the building that are considered public spaces and are not occupied for long hours by each individual occupant, such as in campus classrooms. The investigated indoor spaces in this study were campus classrooms and were generally occupied temporarily, meaning between 60 and 90 minutes. The normal operating temperature in these classrooms is typically around 21-22° C. Since the operative temperatures in other parts of the building remained the same as normal practices during the test periods, this study subjects were exposed to increased cooling temperature only in one class section and in one classroom. However, since the room's thermal environment was stable during the test period and occupants were surveyed after at least 15 minutes exposure to the room temperature, the occupants' responses are considered as steady-state.

Building occupants were college age students, generally undergraduates. They were asked to answer four important questions about their thermal sensation (based on the ASHRAE seven-point scale for thermal sensation), thermal preferences (based on a five-point scale), if the thermal environment is acceptable or unacceptable for them, and if they have involved in any behavioral adaptation to maintain their thermal comfort, through verbal questionnaires. A total of 1336 survey responses were collected.

The results of this study revealed that there is a good potential for increasing cooling temperature setpoint in classrooms on this campus while possibly improving, or at least maintaining occupants' thermal comfort. Some of the most important results derived from this study are:

- By temporarily increasing the cooling temperature set points in classrooms from the typical 21-22º C (70-71º F) up to 25º C (77º F) the occupant's AMV did tend to increase but for most cases the class averages remained in an acceptable thermal comfort range ($-0.5 < AMV < 0.5$).
- Occupant's AMV values tended to marginally decrease as ambient temperature increased in cooling seasons, due to the different clothing levels worn or different thermal expectations, or perhaps both.
- In this field study, almost 50% of the subjects expressed preferences for a non-neutral thermal conditions, more of them generally preferring a cooler thermal environment.
- Women in this study generally perceived the thermal environment cooler than men in the same thermal environment while wearing a slightly lighter level of clothing.
- Around 20% of the survey participants were involved in some sort of adaptive behavior while still in a public space on campus with limited control options. This indicates that occupants' engagement in adaptive behavior could be more significant in buidling with

more adaptive and control options. These options could include personalized conditioning systems or operable windows that could potentially engage a larger percentage of occupants in adaptive behavior.

- The thermal environment in classrooms was acceptable for more than 80% of building occupants during the studied DR events. AMV values remained within ASHRAE's specified comfort zone ($-0.5 < AMV < 0.5$) when the indoor operative temperature was temporarily increased from 22 up to 25° C. Occupants generally preferred a "Slightly Warmer" or "Slightly Cooler" thermal environment or that "No Change" should be made within this temperature range.
- Occupants' average thermal preference votes equal zero (or "no change") when the indoor operative temperature is around 23.5° C. This indicates that this temperature could, on average, be the most preferred and comfortable temperature for classrooms on this campus. Thermal acceptability for this temperature was above 90% and occupants' thermal sensation was almost neutral ($AMV = 0$).
- The percentage of building occupants involved in any form of adaptive behavior to minimize their thermal discomfort always remained less than 30% for each individual class, and less than 20% for overall class averages within each thermal category in this study. Occupants' adaptive behavior includes changing clothing level and type, having a cold or hot drink, changing the position in the room, changing posture, etc. Occupants' adaptive options were limited in this campus as there were no ceiling fans and personalized conditioning systems, with limited or no control over the HVAC system operation. The

occupants also may be conditioned to not expect “warm” conditions based on their prior experience on the campus.

- The heat balance model over-predicts the percentage of dissatisfied occupants for thermal environments perceived cooler than neutral (room operative temperature less than 24° C). The model under-predict dissatisfaction for thermal environments perceived warmer than neutral, compared to the actual expressions of dissatisfaction from the survey results.
- The average AMV values for women were lower compared to those for men, while the average clothing level (CLO) for women was marginally higher than for men. Correspondingly, women generally preferred a warmer thermal environment in the same environmental conditions.

3.3. The assumption of equidistance in the seven-point thermal sensation scale and a comparison between categorical and continuous metrics

In 1967, Gagge et al. proposed the seven-point scale for thermal sensation (currently known as the ASHRAE seven-point scale for thermal sensation) and a four-point scale for thermal comfort sensation (Gagge et al. 1967). Until then, researchers would normally use one single scale to evaluate both dimensions of occupants’ thermal perception, i.e. thermal sensation and thermal comfort sensation. One of the most well-known thermal comfort evaluation scales that would mix the two dimensions is known as the Bedford scale (Nicol and Humphreys 2002). This scale would ask subjects to determine how they felt about the surrounding thermal environment based on a mixed scale. Table 3.3 summarizes various scales that have been widely used in various research and studies thus far (ASHRAE 2017, Schweiker et al. 2017, Nicol and Humphreys 2002, ASHRAE 1968).

Table 3.3 Various thermal sensation and thermal comfort sensation scales

Scale Name or Developer	*Measured Dimension*	*Scale Markers*
ASHRAE Seven-Point Scale (2017)	Thermal Sensation	Cold- Cool- Slightly Cool- Neutral- Slightly Warm- Warm- Hot
ASHRAE Four-Point Scale (1968)	Thermal Comfort Sensation	Comfortable- Slightly Comfortable- Uncomfortable- Very Uncomfortable
Bedford Scale (1936)	Mixed Scale	Much Too Cool- Too Cool- Comfortably Cool- Comfortable- Comfortably Warm- Too Hot- Much Too Hot
Houghten et al. Scale	Mixed Scale	Cold- Cool- Slightly Cool- Comfortable- Slightly Warm- Warm- Hot
Houghten and Yagloglou Scale (1923)	Mixed Scale	Too Cold- Comfortably Cool- Very Comfortable- Comfortably Warm- Too Warm

One question that arises for field survey administrators is that which dimension of thermal comfort should be evaluated in order to provide the best thermal environment for the building's occupants. The heat balance model incorporates the predicted mean vote (PMV) index to predict occupants' thermal comfort. The PMV index is the 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 (Fanger 1970)." It is based on a non-linear equation that incorporates six parameters that are dry bulb temperature, relative humidity, air speed, mean radiant temperature, metabolic rate, and clothing insulation level. The adaptive approach, on the other hand, incorporates the occupants' actual mean vote as the primary index to assess thermal sensation. AMV represents the average of the room occupants' subjective evaluation of a thermal environment.

It should be noticed that in Table 3.3 the middle votes or Neutral thermal sensations are represented by “Comfortable” or “Very Comfortable” labels for mixed scales. The PMV index is also based on the assumption that the neutral thermal environment equals the optimal or comfortable thermal environment. The AMV index needs to be based upon a similar assumption as well to be able to evaluate occupants’ thermal sensation versus a comfortable condition. This assumption has been challenged by various studies so far, as summarized in Aghniaey and Lawrence (2018c). Occupants’ thermal preference and acceptability votes and their thermal comfort perception vote are among the other dimensions of thermal perception that could be evaluated in a field study.

ASHRAE Standard 55 (2017) states that a thermal environment in a building is considered comfortable if it is acceptable for at least 80% of building occupants. The PMV values in such an environment are expected to range between -0.5 and 0.5. However, several studies revealed that occupants could find thermal comfort beyond this range, as summarized in Aghniaey and Lawrence (2018b). Thermal acceptability, by itself, could never reveal what kind of changes could be made to a thermal environment in order to improve occupants’ thermal comfort. The study reported in this section brings up questions on the idea of using the mean thermal preference vote as the best predictor of occupants’ thermal comfort. Thermal comfort range based on mean thermal preference vote are also discussed in this section.

The type of the scale that is used to evaluate occupants’ thermal perception (categorical or continuous) has also been a source of discussion and debates for some time. Among all categorical or numerical scales, ASHRAE seven-point scale for thermal sensation is the primary scale used to evaluate occupants’ thermal sensation (ASHRAE standard 55-2017, EN 15251:2007). The application of continuous scales to evaluate thermal sensation or thermal comfort, satisfaction, and acceptability is also widespraed in various field studies. This would allow a non-integer thermal sensation rating without basing on the assumption of equidistance between scale markers (Cena and de Dear 1999). The assumption of equidistance expresses that occupants' thermal sensation votes change at the same rate as the room operative temperature and that the seven-point thermal sensation scale markers are distributed equally alongside the scale and around the neutral thermal sensation vote (Schweiker et al. 2017). Incorporating continuous scales in field studies would also reduce voting error through enabling occupants to precisely rate their sensation even with small changes in environmental stimuli (Tian and Love 2008). A major challenge when using two different types of scales is determining if the categorical and continuous scales are compatible and how results from them are comparable to each other.

The difficulties in making comparison between a continuous and a numerical scale might limit the ability of researchers to take advantage of the results of other studies or to compare with their own study results. One contributor to this discrepancy could be the assumption of equidistance when using categorical scales. In a categorical scale, such as the seven-point scale, all scale markers are positioned in equal distances from each other. This assumes that a thermal environment changes with equal rate when occupants' thermal comfort sensation goes from 'Cold' (-3) to 'Cool' (-2) compared to going from Neutral or '0' to Slightly Warm (+1).

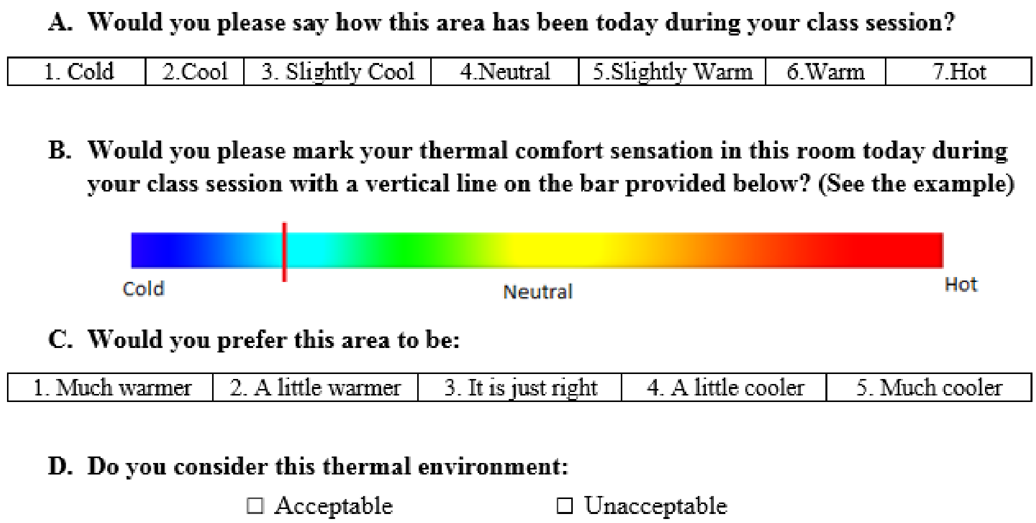
Unfortunately, the number of studies focusing on verifying the assumption of equidistance has been limited so far. A study by Schweiker et al. (2017) indicated that the majority of subjects did not consider an equidistance distribution of scale labels or markers for the categorical scale. Although the distance between the numerical values are equal on the categorical scale, the distance between occupant's perception votes or scale markers are not equal when evaluated on the continuous scale. They also realized that there was a non-linear relationship between the rating of thermal sensation and the room temperature. The current study reported here challenges the assumption of equidistance between the various labels on the seven-point scale for thermal sensation. The thermal sensation votes based on the ASHRAE seven-point scale and the location of occupants' votes based on a continuous scale are compared. The results revealed valuable information regarding the validity of the assumption of equidistance.

3.3.1. Methodology

The survey questionnaire that was used during this research evaluates the occupant's thermal sensation, thermal preference, and thermal comfort acceptability, with a portion of this questionnaire shown in Figure 3.17. Students in classrooms were asked to express their thermal sensations based on a categorical scale or the seven-point scale specified for "point-in-time surveys" in ASHRAE Standard 55 (2017). The same question was asked using a continuous scale for thermal sensation and students were asked to mark their vote on that scale. They were also requested to express their thermal preferences based on a five-point scale (I want: Much Cooler, Slightly Cooler, No Change, Slightly Warmer, or Much Warmer than the current setting), as defined in Humphreys and Nicol (2004) and McCartney and Nicol (2002). They also were asked if they considered the current thermal environment to be "Acceptable" or "Unacceptable". They were asked to report limited demographic information like age and gender, if they felt healthy or sick, time of exposure to the thermal environment in the room, and information regarding their clothing type and level, as discussed in Section 3.2.

3.3.2. Results and Discussion

Figure 3.17 shows how the occupants' thermal sensation votes were gathered based on a categorical scale (part A of Figure 3.17) and on a continuous scale (shown in part B of Figure 3.17). In order to allow a comparison of the occupants' votes based on both scales, the continuous scale was transformed numerically and assumed to range between -3 and +3 as well. Values assigned for each survey result were based on the physical distance along the continuous scale.



A. Would you please say how this area has been today during your class session?

1. Cold	2.Cool	3. Slightly Cool	4.Neutral	5.Slightly Warm	6.Warm	7.Hot

B. Would you please mark your thermal comfort sensation in this room today during your class session with a vertical line on the bar provided below? (See the example)

C. Would you prefer this area to be:

1. Much warmer	2. A little warmer	3. It is just right	4. A little cooler	5. Much cooler

D. Do you consider this thermal environment:

☐ Acceptable ☐ Unacceptable

Figure 3.17 Part of the thermal comfort survey questionnaire concerning occupants' thermal sensation, thermal preference, and thermal acceptability votes

The boxplot shown in Figure 3.18 depicts the distribution of occupants' thermal sensation votes based on the continuous scale versus their votes based on the seven-point scale. Occupants' thermal sensation votes based on the continuous scale are categorized according to their seven-point thermal sensation votes. The red lines in the middle of boxes show the median of votes within each category. Top and bottom of the boxes show the 25th and the 75th percentile values. The whiskers (dashed lines) extend to the extreme data points, excluding outliers. The "+" shown in red represent the outliers. Outliers are votes that are more than three scaled median absolute deviations (MAD) away from the median (MathWorks).

The vertical axes or the continuous scale is divided into seven regions shown by different color shades. The color shades represent the same colors used for the continuous scales that appear in question B of the survey questionnaire, as shown in Figure 3.17. Each color shade ranges within a seven-point scale marker (-2, -1, 0, etc.) ±0.5, except for the extreme votes (-3 for Cold and 3 for Hot) that are limited from one side. Thus, each color indicates how occupants are expected to vote on the continuous scale based on their seven-point thermal sensation votes on the categorical scale, if the assumption of equidistance is valid. To illustrate, all occupants voting for Neutral based on the seven-point scale are expected to choose a point between -0.5 and 0.5 on the continuous scale. Similarly, those voting for Hot, Warm and Slightly Warm are expected to vote between 3 and 2.5, 2.5 and 1.5, and 1.5 and 0.5, respectively. Likewise, occupants are anticipated to vote between -3 and -2.5, -2.5 and -1.5, and -1.5 and -0.5 if they have voted for Cold, Cool, and Slightly Cool based on the seven-point scale, respectively.

It is clear from the figure that votes are focused around the median (zero) for Neutral thermal sensation categorical group. However, as votes expand to the warmer or cooler side of the seven-point scale, occupants' votes within each category spread over a broader range around the median. The median of votes also diverges from the seven-point scale markers (-3, -2, -1, etc.) within each category by moving towards the warmer or cooler side of the seven-point scale.

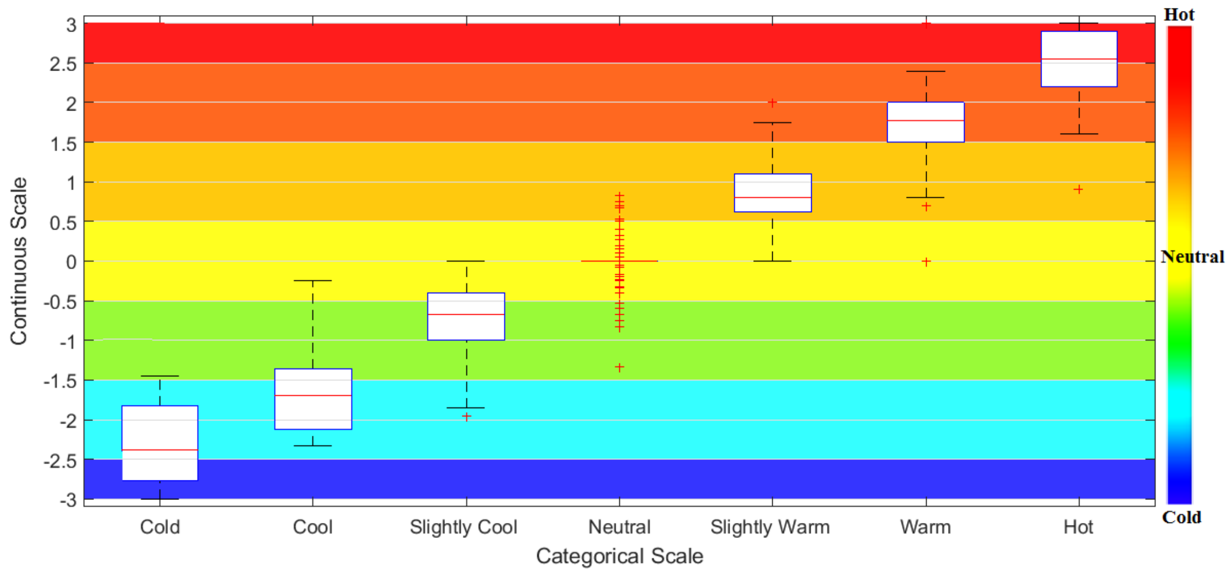


Figure 3.18 The box plot of distribution of occupants' thermal sensation votes based on a continuous scale versus their votes based on the categorical or seven-point scale

As Figure 3.18 indicates occupants' votes within each category varied across up to two different color shades. There is at least 50% overlap between adjacent, non-Neutral categories showing that the interpretation of scales might be different from one person to another. For example, among those who voted in the aqua or light blue region (between -2.5 and -1.5), some voted for Cool, some for Cold, and a small number of occupants voted for Slightly Cool. As a result, two persons voting the same on the continuous scale might vote differently on the seven-point scale or vice versa. Occupant's thermal sensation votes might also differ from one scale to another since their interpretation of scales differ from one scale to another. We observe that more than 75% of those voted for the extreme thermal sensation based on the seven-point scale, did not choose the maximum possible value on the continuous scale. These differences make the comparison of results from various field studies that use different thermal sensation scales very difficult or problematic at the least.

Table 3.4 reveals the number of occupants responding in each category and the average value of their votes within that category. Almost 59% of subjects were within the Neutral category, 34% fell within the Slightly Cool or Slightly Warm categories, and the others voted for Cold or Hot on the seven-point scale. Due to the very different sample sizes and the small number of occupants voting for the extreme thermal sensation (Cold or Hot), an ANOVA test (Analysis of Variance) was conducted to identify if there is a significant relationship between occupants' thermal sensation votes based on the continuous scale and based on the seven-point scale. The results showed a P-value of 0.002 in this study. Therefore, even with unequal sample sizes for different categories, a conclusive comparison can be made that the thermal sensation votes based on the continuous scale within different categories in Figure 3.18 are statistically different. Thus, we can safely make generalizations from these results.

Table 3.4 Comparison of thermal sensation votes based on a continuous scale for respondents in each categorical group

Categorical Group	Voter's Count	Average Vote	25th Percentile	75th Percentile
Cold (-3)	8	-2.30	-2.76	-1.94
Cool (-2)	19	-1.63	-2.08	-1.39
Slightly Cool (-1)	60	-0.73	-1	-0.4
Neutral (0)	144	-0.03	0	0
Slightly Warm (1)	43	0.88	0.63	1.1
Warm (2)	17	1.78	1.6	2
Hot (3)	10	2.36	2.2	2.85

The term ΔM was derived to show the absolute value of differences between seven-point scale markers and the average vote from the continuous scale within each category shown in Table 3.4. It is aimed to compare the two scales and indicate how the occupants' average votes on the continuous scale differ from their votes based on the categorical scale. To illustrate, if the mean thermal sensation vote based on the continuous scale for a group of occupants is -0.7 and they have voted for "Slightly Cool" or "-1" based on the seven-point scale, then ΔM is equal to $\vert -1 -$

$(-0.7)\,\big| = 0.3$. Figure 3.19 shows the ΔM and variance of votes within each category as thermal sensation changes from Neutral to a warmer or cooler sensation.

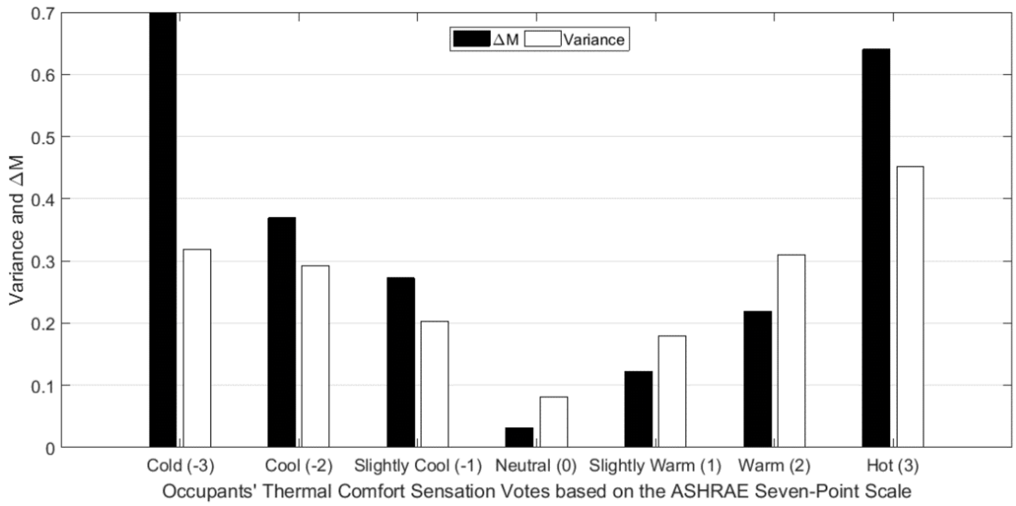


Figure 3.19 The variance of thermal sensation votes based on the continuous scale and ΔM within each category

Figure 3.19 indicates that ΔM and the variance increase as thermal sensation goes from Neutral towards the cooler or warmer side of the categorical scale. For occupants who voted for Hot or Cold, the variance and ΔM is maximum. ΔM tends to be marginally larger on the cooler region, compared to the warmer region, while the variance tends to be marginally higher in the warmer side of the scale. The results of this study show that the manifestation of differences between occupants' thermal sensation votes within each category is more visible for extreme votes; there is a larger discrepancy among occupants in positioning their votes on the continuous scale as their thermal sensation diverges from Neutral and especially for extreme votes. The location of seven-point scale markers also considerably differ from occupants' average vote on the continuous scale for extreme votes (by more than 0.6). Therefore, the position of seven-point scale markers and locating them within equal distances from each other has not been supported by this study.

Figure 3.20 depicts the particular trend for step changes in the average thermal sensation votes on the continuous scale for the corresponding categorical groups. Each point or black circle in this figure shows the position of occupants' average thermal sensation vote on the continuous scale within each category. Numbers between points show the physical distance between them. The point in the middle represents the "Neutral" category. The other six points represent the remaining six thermal sensation categories respectively. Note that if there were actually even step changes in the thermal sensation votes as assumed with the categorical changes, the difference values would be expected to be all close to approximately 1.0. From Table 3.4 and Figure 3.20 it could be concluded that the average value of votes on the continuous scale diverge from the seven-point scale markers (-3, -2, etc.) as thermal sensation goes from Neutral to the Warmer or Cooler sides of the scale, and that the difference is slightly greater on the cooler side. Therefore, the assumption of equal distance between thermal comfort markers on the seven-point scale is challenged by this study.

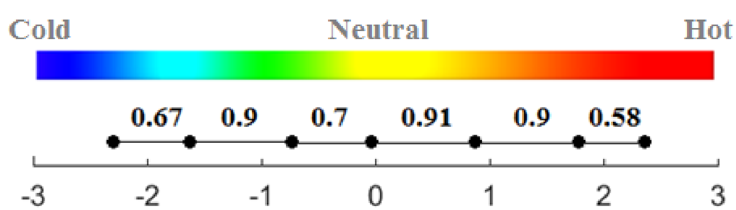


Figure 3.20 The position of occupants' average thermal sensation votes on the categorical and continuous scales and the distance between them

The results of the field surveys in this study revealed that even the same group of people in the same room and thermal environment might perceive the thermal environment differently on two different days. Surveying occupants' thermal preferences might be necessary in pinpointing the optimal thermal conditions for a specific group of occupants in a built environment. This dimension of thermal comfort, per se, also indicates what changes could be made to the thermal environment to improve occupants' comfort. This feature makes thermal preference vote distinguished from the thermal sensation and acceptability votes. If δ represents the occupants' mean thermal preference vote, a thermal environment could be considered optimal when |δ| is minimum.

In order for a thermal environment to be acceptable for at least 80% of building occupants (ASHRAE 2017), |δ| needs to be at or around the 'minimum' level. The results of this study showed that students on UGA campus perceive the thermal environment as acceptable even when the thermal environment is outside the ASHRAE comfort zone. It was also evident that all those who perceive the thermal environment as Slightly Cool (-1), Neutral (0), and Slightly Warm (1), deem the thermal environment as acceptable (Aghniaey and Lawrence 2018c). Therefore, there is a potential for expanding thermal comfort zone, either temporarily, or permanently as a building's energy efficiency measure.

Figures 3.9 and 3.10 in section 3.2.3 depict occupants' mean thermal preference vote and their thermal comfort acceptability for different indoor operative temperatures. These figures make it clear that when occupants' average thermal preference vote is between -0.5 and 0.5, thermal acceptability is above 80%. Thus, it could be concluded that for the specific population on UGA campus, thermal acceptability is above 80% for $-0.5 < |\delta| < 0.5$. As |δ| converges to zero thermal acceptability becomes maximum.

3.3.3. Summary and Conclusions on the Study of Equidistance

The number of factors that are at play in the way occupants perceive a thermal environment and feel comfortable in it necessitates extensive field studies and thermal comfort surveys conducted in a built environment under a variety of conditions. However, in order for the results to be credible and useful in determining and creating an optimum thermal environment, appropriate questions and thermal comfort scales should be incorporated into the study and basic assumptions should be validated, if any. In this study, the assumption of equidistance between ASHRAE seven-point thermal sensation scale markers were evaluated and ultimately challenged. Survey subjects were asked to express their thermal sensation votes based upon a seven-point scale and a continuous scale with only three markers in the middle and two ends (Cold, Neutral, and Hot). The survey results were compared and contrasted and the most important conclusion are as follows:

- There is no equal distance between occupants' mean thermal sensation votes based on the continuous scale, categorized based on their seven-point scale thermal sensation votes. The distance is considerably smaller between extreme and the adjacent mean thermal sensation votes (between Cold and Cool or Hot and Warm).
- Occupants' average thermal sensation votes based on the continuous scale diverge from their votes on the categorical scale as their votes move from the Neutral towards the warmer or cooler side of the scale.
- The interpretation of the thermal sensation scales and positioning of thermal sensation votes on the continuous scale considerably varies among occupants, especially for those who perceive the thermal environment as Cold and Hot.
- The mean thermal preference vote could be an alternative proxy to evaluate occupants' thermal comfort. This proxy is not based upon the assumption of thermal neutrality being equal to thermal comfort. This proxy also indicates what changes could be made to improve

thermal comfort in an environment. An optimum thermal environment could be achieved by minimizing the absolute mean thermal preference vote.

- Thermal environment is acceptable for more than 80% of occupants if the absolute value of their mean thermal preference vote ($|\delta|$) is between -0.5 and 0.5.

CHAPTER 4

A LITERATURE REVIEW ON THE ADAPTIVE THERMAL COMFORT MODELING IN AIR-CONDITIONED BUILDINGS

As discussed in previous chapters, the heat balance model often fails to take into consideration the impact of various contextual, psychological, cultural, demographic, geographic, and adaptive factors affecting occupants' thermal comfort perception in real buildings (except for the four environmental and two personal factors included in the PMV equation). PMV and PPD indices are developed to predict occupants' mean thermal sensation votes for a large group of building occupants in a steady state and almost uniform thermal environment. In real buildings, however, occupants are exposed to a dynamic thermal environment where they are continuously interacting with the thermal environment and the building itself (Enecsu 2017, Oseland 1995). Many researchers found discrepancies between the PMV values and occupants' actual mean votes for thermal sensation (AMV) in naturally ventilated (mostly) and in air-conditioned buildings. In this chapter some of the most important studies concerning modeling building occupants' thermal comfort based on field studies or the adaptive approach is presented.

4.1. Literature Review

In 2011, Azizpour et al. conducted a field study to compare the predicted mean vote from the heat balance model with the actual thermal sensation votes from field studies. They compared the PMV values with building occupants' AMV values in a university hospital in Malaysia (Azizpour et al. 2011). They realized that the AMV values were generally less than the PMV values during their research. They concluded that the neutral temperature in a hot and humid climate is larger than what is specified by current standards for occupants' thermal comfort such as the ASHRAE standard 55, using the heat balance model.

Kaj'tar et al. (2016) compared the PMV and AMV values under steady-state conditions in several office buildings in Hungary. AMV was achieved through averaging occupants' real thermal sensation votes gathered through field surveys. They proposed the following relationship between the PMV and AMV values for PMVs between -1.7 and 0.5:

$$AMV = PMV + 0.275 \quad (4.1)$$

Other researchers tried to correct the PMV index based on the results from field studies in naturally ventilated buildings. They proposed the adaptive predicted mean vote (aPMV) and the extended predicted mean vote (ePMV) indices as alternatives to the PMV index. The aPMV index includes an adaptive coefficient (β) that is the ratio between the impact of occupants' psychological and behavioral state on their thermal sensation and the corresponding impact of physical stimuli (thermal environmental conditions). The aPMV index is defined as Equation 4.2 (Yao et al. 2009):

$$aPMV = (PMV^{-1} + \beta)^{-1} \quad (4.2)$$

Where β could vary from one building to another depending mostly on the occupants' psychological and demographic features, the geographic location of the building, and the adaptive options given to the building occupants. The ePMV index equals the PMV index multiplied by an expectancy factor (e_p) that is supposed to account for occupants' expectation from the built environment based on the local climate and the popularity and availability of the air-conditioning systems (Gao et al. 2015, Fanger and Toftum 2002):

$$ePMV = e_p \cdot PMV \qquad (4.2)$$

Humphreys and Nicol (2002) proposed the new predicted mean vote (nPMV) index to apply for the air-conditioned buildings. This model was developed based on the adaptive model and compensates for the discrepancies between the PMV index and building occupants' AMV values. The nPMV index is defined as:

$$nPMV = \gamma \ \cdot [PMV - f_{PMV-ASHRAE}] \qquad (4.4)$$

Where $\gamma = 0.8$, and

$$f_{PMV-ASHRAE} = -4.03 + 0.0949.T_{op} + 0.00584.RH\% + 1.201.MET.I_{cl} + 0.00083.{T_{out}}^2 \qquad (4.5)$$

In the Equation 4.5, T_{op} and T_{out} represent the operative temperature in the room and the outside air temperature respectively. RH%, MET and, I_{cl} are the indoor relative humidity, occupants' average metabolic rate, and their average clothing insulation. T_{op} is defined as the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat through radiation and convection as in the actual non-uniform thermal environment. T_{op} is presented as the following equation:

$$T_{op} = \frac{(T_{db}+T_{mrt})}{2} \qquad for \ (v < 0.2 \ ^{m}/_{s}) \qquad (4.6)$$

Where air speed in the building is less than 0.2 m/s, and the absolute value of the difference between the mean radiant temperature and the air temperature is less than 4 ºC (Enescu 2017). In this equation T_{db} is the room air or dry bulb temperature, T_{mrt} is the mean radiant temperature of the room, and ν is the air speed.

To find the comfortable and neutral temperature range in buildings, some researchers conducted some field or laboratory studies and analyzed the collected datasets from real buildings or climate control chambers to find an indoor neutral temperature range for buildings. EN ISO 7730 (as cited in Olesen and Parsons 2002) recommends 24.5° C to be the neutral temperature in office buildings during cooling seasons. This temperature could vary between 24.5±0.5, 24.5±1.5, and 24.5±2.5° C corresponding to different categories from A to C (for 6%, 10%, and 15% dissatisfaction level or PPD, respectively), as shown in Table 4.1. The neutral temperature is calculated using PMV-PPD indices and the related thermal comfort votes within each category. The proposed humidity range is 30-70%.

Table 4.1 ISO EN 7730 recommended neutral temperature range during the cooling season in office buildings (Olesen and Parsons 2002)

Category	PPD	Neutral Temperature (°C)	Air Velocity (m/s)
A	< 6%	24.5±0.5	0.18
B	< 10%	24.5±1.5	0.22
C	< 15%	24.5±2.5	0.25

Occupants' expectations from a thermal environment varies from one building to another, specifically based on the geographical location and application of the building (Aghniaey and Lawrence 2018b). Thus, modeling occupants' thermal sensation and preference votes using building occupants' actual thermal sensation and preference votes, collected in real world conditions, is expected to better represent the thermal comfort of the specific population in the building. Buildings with different application type (residential, commercial, and industrial) have thermal environmental requirement different from each other, considerably depending on the adaptive and control options that are provided to the building occupants and the cultural environment and regulations of the building. Some studies correlated occupants' thermal sensations and building's neutral temperature to the recent outdoor temperature. This mostly happens in naturally ventilated and conditioned buildings or buildings with more adaptive opportunities. Others related occupants' thermal sensation to the prevailing indoor operative or effective temperature (Peeters et al 2009, Nicole 1995, Nicole et al. 1999).

Peeters et al. (2009) investigated the comfortable temperature range based on the outdoor air temperature in residential buildings for naturally ventilated, air-conditioned, and mixed mode buildings. In residential buildings, there are more control options over the thermal environment and more adaptive options for occupants to make themselves comfortable. Thus, the thermal environment in residential buildings could vary within a wider range compared to public spaces such as offices and classrooms. For the same reason, the neutral (or comfort) temperature in residential buildings is also more dependent on the outside air temperature. They concluded that for spaces in residential buildings, other than bathrooms and bedrooms, the neutral temperature is defined as:

$$T_n = 20.4 + 0.06 \cdot T_{e,ref} \quad for \quad T_{e,ref} < 12.5°\,C \tag{4.7}$$

$$T_n = 16.63 + 0.36 \cdot T_{e,ref} \quad for \quad T_{e,ref} \geq 12.5°\,C \tag{4.8}$$

Where the weighted average of the outdoor air temperature is defined as:

$$T_{e,ref} = \frac{(T_{Today} + 0.8\, T_{Today-1} + 0.4\, T_{Today-2} + 0.2\, T_{Today-3})}{2.4} \tag{4.9}$$

In Equation 4.9, T_{Today} is today's average outdoor air temperature and $T_{Today-n}$ represents the average outdoor air temperature "n" days before today. All outdoor air temperature values are the dry bulb temperature in °C in this equation.

An indoor environment, however, especially in residential building, is a dynamic system that changes according to the outside air conditions, internal heat gain, and the ventilation rate. Even with the most complicated control systems it is hard to guarantee one single operating temperature inside the buildings. Practically, the indoor thermal environment would fluctuate around the comfort or neutral temperature. Therefore, Peeters et al. (2009) considered the upper and lower limits for the neutral or comfort temperature indoors to be according the following equations:

$$T_{upper} = T_n + \mu\alpha \tag{4.10}$$

$$T_{lower} = T_n - (1 - \mu)\alpha \tag{4.11}$$

Where T_{upper} and T_{lower} are the upper and lower limits of the comfort band (°C), and

$$\mu = 5°\,C\,, \alpha = 0.7 \quad for \quad 10\%\,PPD \tag{4.12}$$

$$\mu = 7°\,C\,, \alpha = 0.7 \quad for \quad 20\%\,PPD \tag{4.13}$$

α could equal to 0.5 if thermal sensation was symmetric around the neutral thermal conditions. However, the preferred thermal sensation was 0.2 scale unit above the neutral thermal sensation in their research. Occupants were also less adaptive to the cold rather than the hot environment. These factors caused the thermal comfort band to split in an asymmetric way (30 to 70%) around the neutral comfort conditions.

In 1995, Nicol (Nicol 1995) conducted a longitudinal study to estimate building occupants' thermal comfort vote or comfort temperature as a function of the outdoor and black globe temperature (or simply globe temperature) in summer and winter. Globe temperature in this study was used as a measure of the indoor temperature. Globe temperature or black globe temperature (T_g) is the temperature inside a black globe (almost 15 centimeters in diameter) as discusses in Chapter 1. A longitudinal study surveys a small sample of occupants' thermal experience over a continuous period. They surveyed occupants in naturally ventilated and mechanically heated or cooled (air-conditioned) buildings in five different cities in Pakistan, representing five different climate regions. The survey questionnaires included questions about occupants' thermal comfort vote (based on a seven-point scale), their thermal preference vote (based on a five-point scale), their skin moisture content (based on a four- point descriptive scale), their clothing type by item, and their activity level (based on a five-point descriptive scale). They concluded that, in summer, only occupants' thermal comfort vote, their thermal preference vote, and their skin moisture content are correlated with the comfort temperature. They stated that there is a continuous feedback between occupants' thermal comfort vote and the outdoor thermal environment resulting in occupants' physiological and psychological adaptation. This adaptation or feedback loop flattens the regression line between occupants' comfort vote and the comfort temperature in the room (McCartney and Nicol 2002). Thus, they predicted the buildings' comfort temperature based on the outdoor air temperature using linear regression methods. The resulting model is shown in Table 4.2. Auliciems and deDear (1986), as cited in Nicole 1995 and Humphreys et al. 2013, also achieved almost the same result in their study in air-conditioned buildings.

In another study, Nicol et al. (1999) conducted a transverse study through surveying occupants' monthly, over a year, in five different cities in Pakistan with four of them being the same as the previous study. A transverse study surveys a relatively larger number of subjects in smaller number of occasions, compared to a longitudinal study. They surveyed sedentary working occupants in five to seven buildings in each city and 10 to 30 occupants in each building. The results of this extensive study are also presented in Table 4.2. The comfort temperature indoors equals the globe temperature where comfort vote equals 4 or thermal condition is neutral. Linear regression method is applied to predict comfort temperature (T_c) as a function of the daily outdoor temperature (T_o) and the monthly mean outdoor or outdoor long-term temperature (T_{olt}). Thermal comfort vote (C) as a function of the globe temperature indoors (T_g) is also presented in this table.

Table 4.2 Results from a longitudinal and a transverse study in Pakistan (Nicol 1995)

	Longitudinal Study	**Transverse Study**
Comfort Vote (C) vs. Globe Temperature (T_g)	$C = 0.09 + 0.154\,T_g$ (4.14)	$C = 0.11 + 0.151\,T_g$ (4.15)
Comfort Temperature (T_c) vs. Globe Temperature (T_g)	$T_c = 11.7 + 0.55\,T_g$ (4.16)	$T_c = 11.5 + 0.53\,T_g$ (4.17)
Comfort Temperature (T_c) vs. Globe Temperature (revised Griffiths slope)	$T_c = 7.8 + 0.70\,T_g$ (4.18)	$T_c = 7.8 + 0.70\,T_g$ (4.19)
Comfort Temperature vs. Outdoor Daily Temperature (T_o)	$T_c = 17.3 + 0.37\,T_o$ (4.20)	$T_c = 19.0 + 0.34\,T_o$ (4.21)
Comfort Temperature vs. Outdoor Daily Temperature (T_o), (revised Griffiths slope)	$T_c = 15.3 + 0.46\,T_o$ (4.22)	$T_c = 17.1 + 0.43\,T_o$ (4.23)
Comfort Temperature vs. Monthly Mean Outdoor Temperature (T_{olt})	$T_c = 18.0 + 0.33\,T_{olt}$ (4.24)	$T_c = 18.5 + 0.36\,T_{olt}$ (4.25)
Comfort Temperature vs. Monthly Mean Outdoor Temperature (T_{olt}), (revised Griffiths slope)	$T_c = 16.2 + 0.41\,T_{olt}$ (4.26)	$T_c = 16.5 + 0.46\,T_{olt}$ (4.27)

As is clear from Table 4.2, the results from the two studies, i.e. longitudinal and transverse, are in a close agreement. Due to the interdependency between T_g and T_o or T_{olt} (from the meteorological reports), the prediction of occupants' comfort vote based on the both indoor and outdoor air temperature is avoided in this study. This will prevent any regression error that might exist because of the occupants' adaptive behavior and corresponding adjusted comfort vote following the changing globe temperature. During this study, Nicole et al. (1999) realized that the comfort temperature slightly differs for buildings located in one city to another. However, especially within the globe temperature range of between 20 and 30° C, this difference is negligible. Figure 4.1 shows their predicted comfort temperature versus the mean indoor globe temperature for different cities. The bold lines in the figure show the overall regression line for comfort temperature in buildings located in any one city.

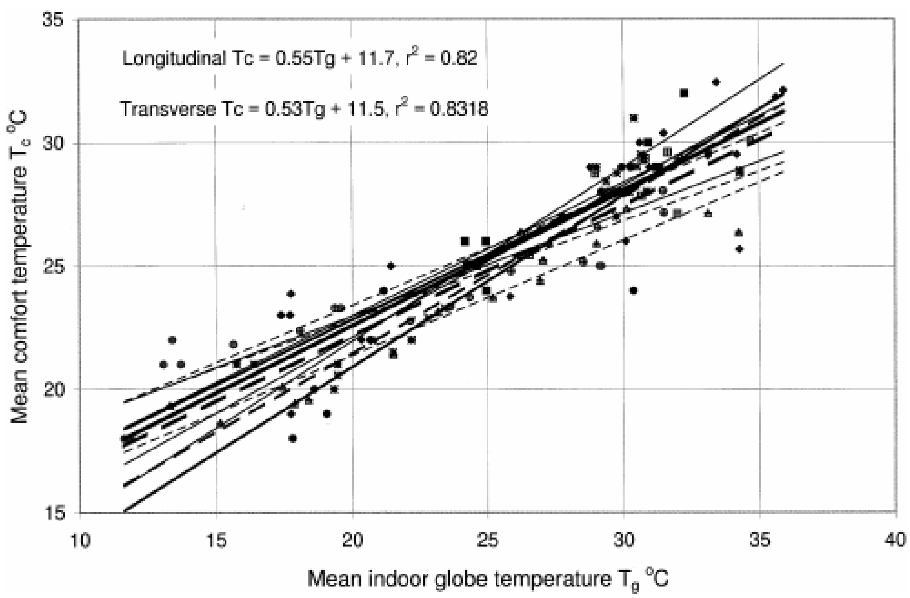


Figure 4.1 Regression lines for the comfort temperature in relation to the mean indoor globe temperature for each city from the longitudinal (continuous lines) and the transverse (dashed lines) surveys (Nicol et al. 1999)

The comfort temperature in Table 4.2 is calculated using Griffiths' original and revised slopes or equations (as cited in Nicol et al. 1999 and Nguyen 2012). Griffith assumed that comfort vote would increase by one scale unit (based on a seven-point scale ranging from 1 to 7, using Bedford's scale) for every 3° C rise in the indoor temperature. He proposed the following equation for comfort temperature (T_c) as a function of the Indoor air temperature (T_{in}) and the corresponding comfort vote (C):

$$T_c = T_{in} + 3(4 - C) \tag{4.28}$$

Later, Humphreys et al. (2013) revised the Griffiths equation proposing a higher occupants' sensitivity to the changing indoor temperature in a short time interval. The revised Griffiths equation suggests that comfort vote changes by one scale unit for any 2° C rise in the indoor temperature.

$$T_c = T_{in} + 2(4 - C) \tag{4.29}$$

Humphreys (1978) conducted a critical review concerning the relationship between the thermal comfort indoors and the outdoor thermal environment in naturally conditioned and ventilated (free running), air-conditioned, and mixed-mode buildings. He analyzed the collected datasets from more than thirty field studies around the world, using meta-analysis techniques. He quantified the relationship between the comfort or neutral temperature (T_n) and the outdoor monthly mean temperature ($T_{o,m}$). Equations 4.31 and 4.32 show these relations for naturally conditioned and ventilated, and air-conditioned buildings, respectively. He assumed that the neutral thermal environment would be the preferred or comfortable thermal environment for building occupants. As is clear from the following equations, the correlation coefficient (r) between the neutral temperature and the outdoor air temperature in air-conditioned buildings (r=0.72) is lower than the corresponding value for naturally ventilated buildings (r=0.97). Figure 4.2 depicts occupants' neutral temperature collected from field studies and the fitted regression lines for both building types. As is clear from the figure, the relationship in naturally ventilated building is linear while it is more complicated with a smoother curvilinear function in air-conditioned buildings.

$$T_n = 11.9 + 0.534\, T_{o,m}\ for\ Naturally\ Ventilated\ Buildings \tag{4.30}$$

$$T_n = 23.9 + 0.295(T_{o,m} - 22).\exp\left(-\left[{(T_{o,m} - 22)}/{24\sqrt{2}}\right]^2\right) \qquad for\ Air - Conditioned\ Buildings \tag{4.31}$$

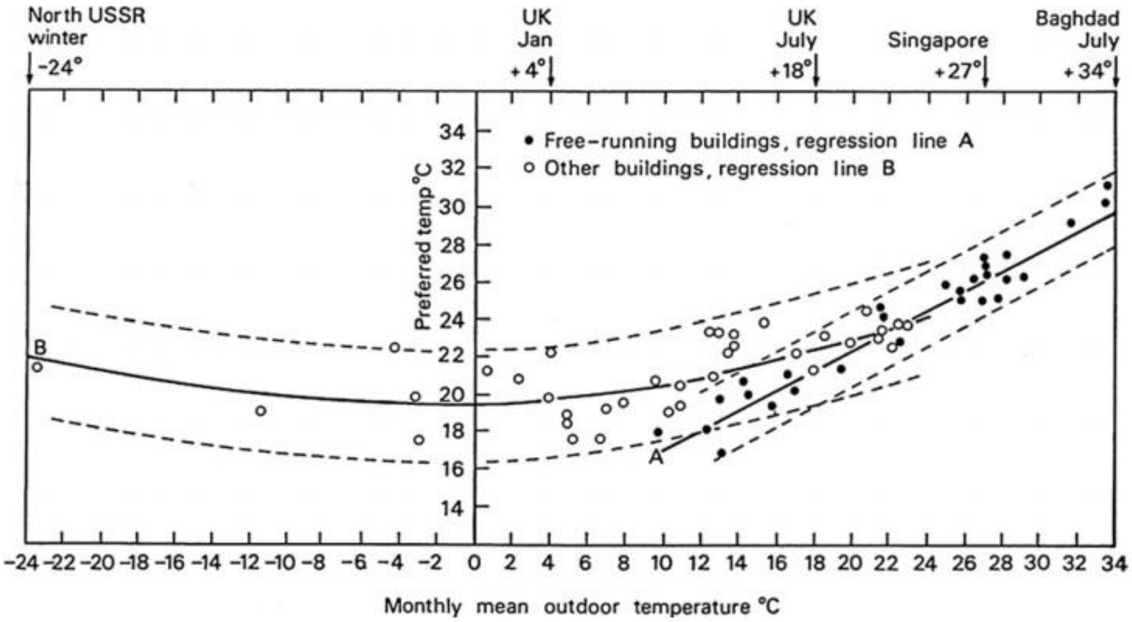


Figure 4.2 The scatter diagram for neutral/comfort temperature and the monthly mean outdoor temperature (Humphreys 1978)

Auliciem (1981), as referenced by Humphreys et al. (2013), revised the relationship between the neutral temperature indoors and the outdoor air temperature (Equations 4.30 and 4.31) using only monthly mean outdoor temperature above 0° C. The proposed equation (Equation 4.32) applies to both naturally conditioned and ventilated, and air-conditioned buildings. Thus, the regression line falls between the regression equations that Humphreys proposed for naturally ventilated and air-conditioned building and its slope depends on what percentage of datasets were collected in each type of buildings. This equation closely agrees with findings from Nicol (1995), presented in Table 4.2.

$$T_n = 17.7 + 0.27\ T_{o,m} \qquad where\ T_{o,m} < 0°\ C \tag{4.32}$$

Humphreys et al. (2013) achieved almost the same results as Humphreys (1978) after analyzing SCATs data point collected from air-conditioned office buildings in Europe (Figure 4.3). They used 253 blocks of datasets including 71,150 single observations in France, Greek, UK, Sweden, and Portugal. The prevailing mean outdoor temperature in this study was calculated using Equation 4.33:

$$T_{rm,Tomorrow} = 0.8\ T_{rm,Yesterday} + 0.2\ T_{m,Today} \tag{4.33}$$

Where T_{rm} is exponentially weighted running mean temperature as shown in Equation 4.9 and T_m is the average of the minimum and maximum daily outdoor temperature values.

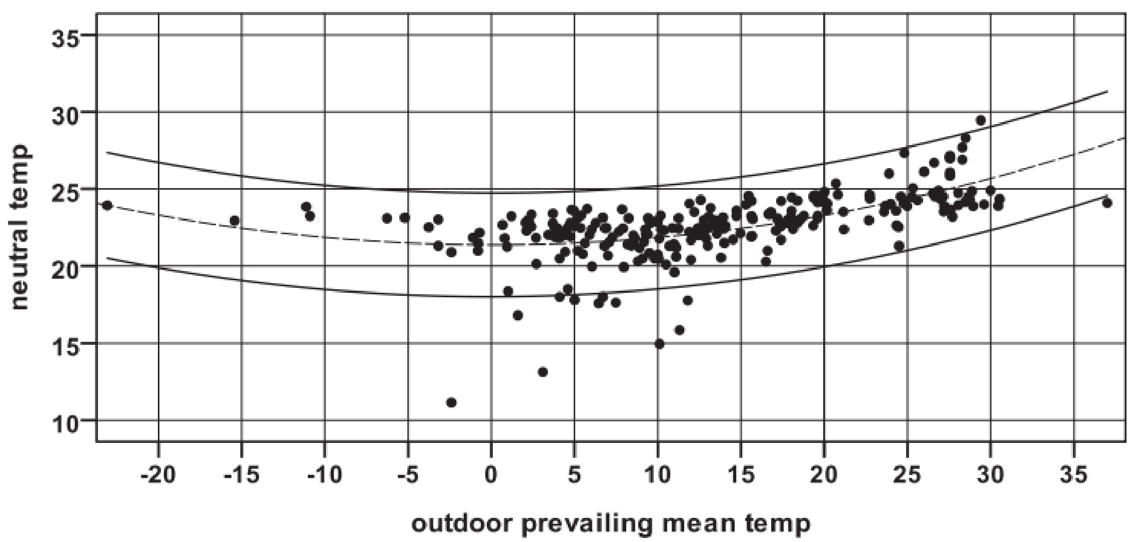


Figure 4.3 The scatter plot correlating the neutral temperatures (°C) and the prevailing mean outdoor temperatures (°C), (Humphreys et al. 2013)

Through careful analysis of SCADs database, Humphreys et al (2013) concluded that the preferred metric for the outdoor air temperature is the exponentially weighted running mean of the daily mean temperature where more weight is given to the recent thermal experience (Equation 4.9). They also realized that people are sensitive to temperature changes that occur in a working day and for each 1 K temperature change is such a situation, occupants' thermal sensation changes by 0.5 scale unit using the ASHRAE seven-point scale.

De Dear and Brager (1998) observed a strong evidence of human adaptation in built environment and in real-world conditions rather than in the climate control chambers. They used ASHRAE RP-884 database to analyze occupants' thermal comfort. This database contains almost 21,000 raw data sets collected from field studies in four continents, nine countries, and 160 buildings (naturally ventilated, air-conditioned, and mixed-mode). Through analyzing those data sets using meta-analysis techniques, they achieved the following relationship for occupants' mean thermal sensation vote (MTSV) versus the operative temperature (T_{op}) in air-conditioned buildings:

$$MTSV = -11.9 + 0.51\, T_{op} \tag{4.34}$$

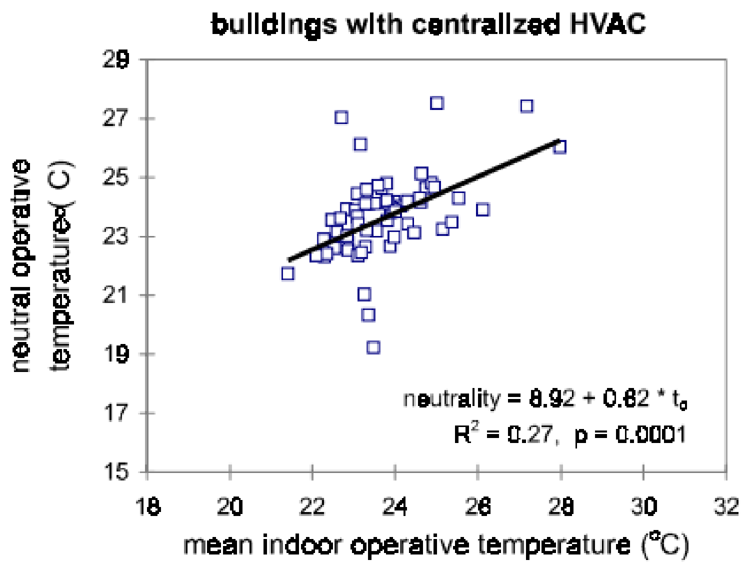
They realized that occupants' sensitivity to temperature deviation from the optimal conditions in air-conditioned buildings is twice of that value in naturally ventilated buildings. They also found the relationship between the neutral or comfort temperature and the operative temperature indoors as well as the mean outdoor effective temperature.

$$T_n = 8.92 + 0.82\, T_{op} \tag{4.35}$$

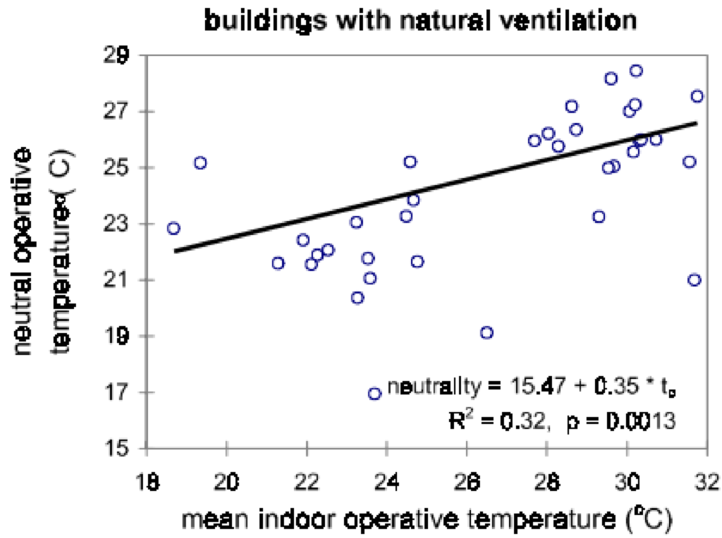
$$T_n = 21.5 + 0.11\, ET^{*}{}_{out} \tag{4.36}$$

Effective temperature or the new effective temperature is defined as the temperature of an imaginary uniform enclosure with 50% relative humidity at which occupants would feel the same level of warmth, acceptability, or coolness as they would in the actual environment (Mangum and Hill 1977).

Figure 4.4 depicts the neutral temperature indoors versus the mean indoor operative temperature for air-conditioned (a) and naturally ventilated buildings (b), based on the findings from De Dear and Brager (1998). They realized that the range of the average neutral temperature in air-conditioned buildings was between 21 and 25 ° C. This range was detected to vary between 20 and 27° C for naturally ventilated buildings.



(a)

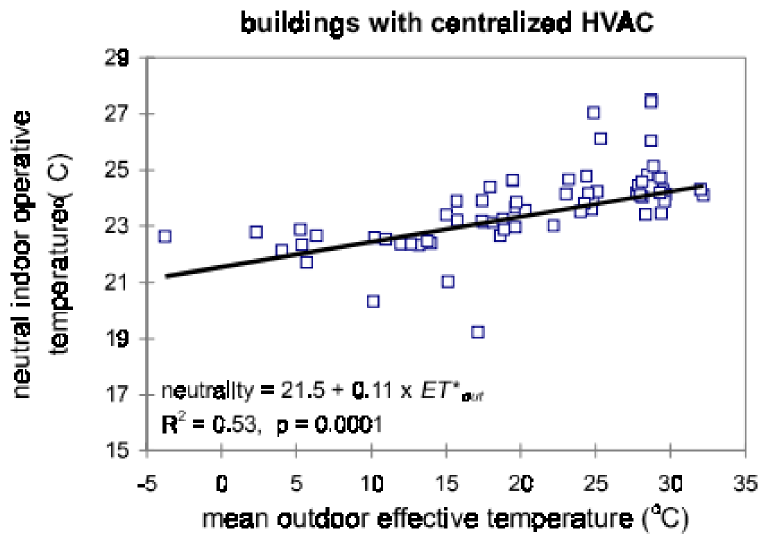


(b)

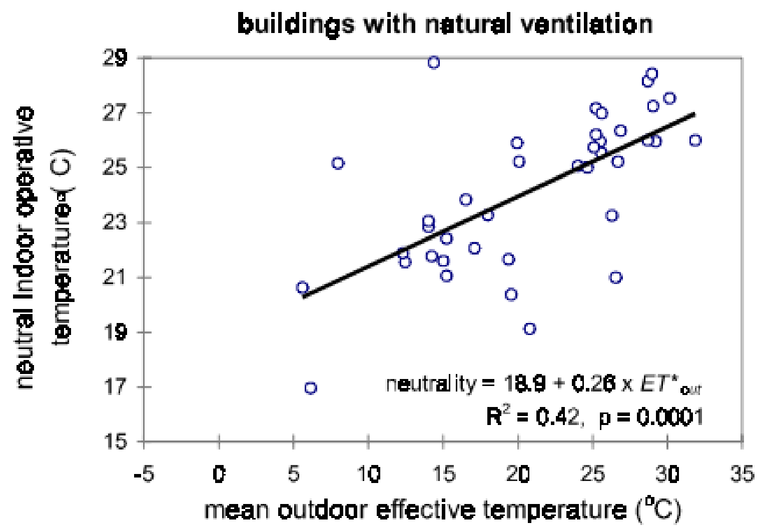
Figure 4.4 The relationship between the neutral indoor operative temperature and the mean indoor operative temperature for (a) air-conditioned and (b) naturally ventilated buildings (De Dear and Brager 1998)

Figure 4.5 depicts the indoor neutral temperature versus the mean outdoor effective temperature for air-conditioned (a) and naturally ventilated buildings (b). As the figure reveals, the regression line gradient is more than twice higher in naturally ventilated buildings (4.5a) compared to the air-conditioned buildings (4.5b). In other words, the slope of the regression line is smoother for air-conditioned buildings showing that the neutral temperature does not significantly follow the ambient thermal conditions in air-conditioned buildings.

The survey questionnaires they used in some of the buildings also included questions about the occupants' thermal preference votes. Based on the occupants' responses, they investigated the adaptive hypothesis suggesting that occupants in warmer climate regions would prefer a cooler than neutral indoor thermal environment. Similarly, occupants in cooler climate regions would prefer a warmer than neutral thermal environment as their comfort conditions. Based the collected



(a)



(b)

Figure 4.5 The neutral indoor operative temperature vs. mean outdoor effective temperature in (a) air-conditioned and (b) naturally ventilated buildings (De Dear and Brager 1998) data sets they developed a semantic discrepancy between the neutral and comfort operative temperature, as shown in Equation 4.37. This discrepancy was statically significant only in air-conditioned buildings (r=0.62, p=0.0001).

$$Semantic\ Discepancy\ in\ Air - Conditioned\ Buildings = -0.95 + 0.07(\ ET^{*}_{out}) \qquad (4.37)$$

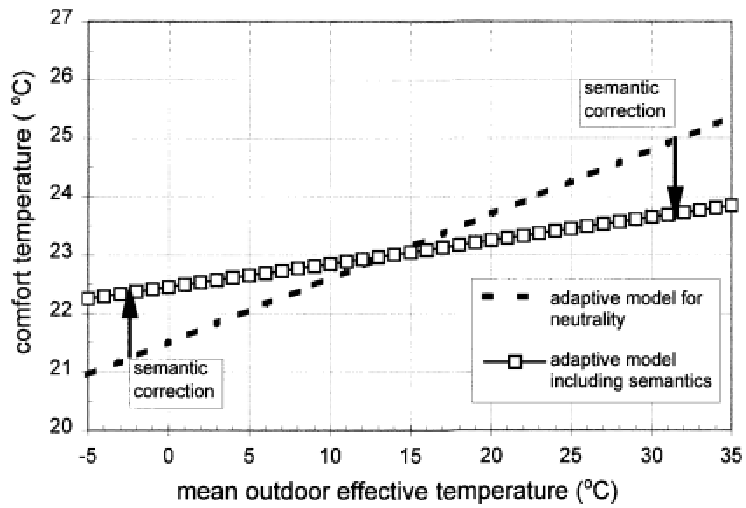


Figure 4.6 The effect of semantic artefact on comfort temperatures inside buildings with centralized HVAC systems (De Dear and Brager 1998)

The effect of the semantic artefact on comfort temperatures inside buildings with centralized HVAC systems is to decrease occupants' sensitivity to the outdoor air temperature. Based on the Equation 4.37, De Dear and Brager (1998) corrected the comfort temperature (as opposed to the neutral temperature) versus the outdoor mean effective temperature as shown in Figure 4.6. The adaptive neutrality in Figure 4.6 comes from the Figure 4.5a and values for semantic discrepancy come from Equation 4.37. It is clear from the figure that occupants living in warmer climate regions (mean outdoor effective temperature beyond 13° C) preferred cooler than neutral thermal environment as their comfort conditions and vice versa.

Mui and Chan (2003) developed an adaptive comfort temperature (ACT) algorithm in air-conditioned buildings located in humid-subtropical climate in Hong Kong. Their research was focused on reducing the heat shock and thermal dissatisfaction resulting from energy conservation measures. They intended to optimize the energy consumption for space cooling while maintaining the desired thermal acceptance range among occupants. They developed a model for the comfort temperature indoors as a function of the outdoor air temperature and based on the survey results and field measurements. They conducted two different studies; 1) a cross-sectional (or transverse) study performed in 55 office buildings in Hong KONG, and 2) a detailed investigation in an office building in Hong Kong over a year (longitudinal study). After analyzing the results, based on the subjective thermal acceptability votes, they found the acceptable indoor operative temperature to fall between 21 and 25° C in summer. Figure 4.7 shows the percentage of unacceptable votes versus the indoor operative temperature. In this figure, PPDF represents Fanger's predicted percentage of dissatisfied, PPDG is Gagge's predicted percentage of dissatisfaction, and PD is the percentage of dissatisfaction based on their own studies. Poly shows the fitted line to the scatter data. Gagge's predicted mean vote or predicted percentage of dissatisfaction replaces the operative temperature with ASHRAE's standard effective temperature (SET*) in Fanger's PMV/PPD equation (Gagge et al. 1986).

Figure 4.8 also depicts occupants' thermal sensation votes versus the indoor operative temperature in some the surveyed office buildings in Hong Kong, based on the study by Mui and Chen (2003). As is clear from the figure, the neutral temperature (or temperature corresponding to the thermal sensation vote equal to zero) equals 23.7 ° C (Mui and Chan 2003).

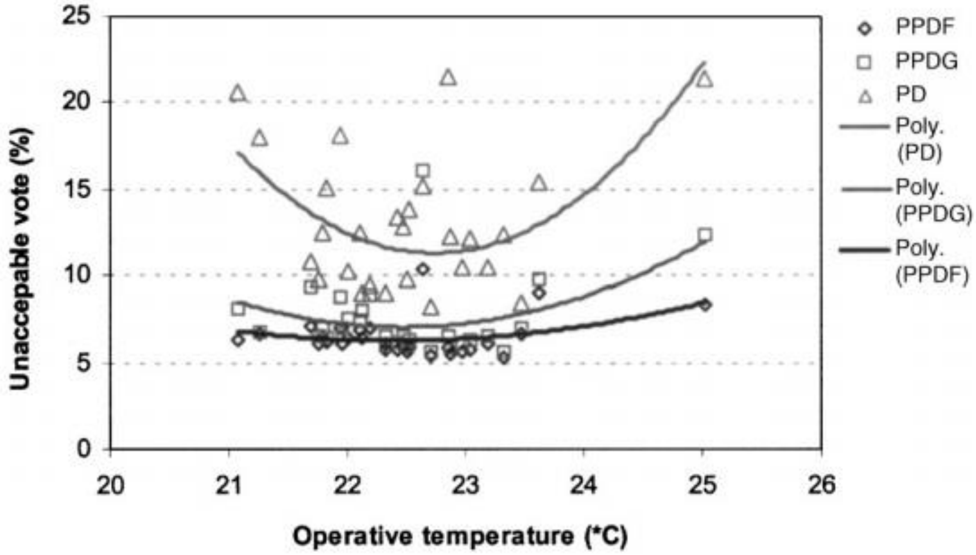


Figure 4.7 The unacceptable votes against the operative temperature in office buildings in Hong Kong in summer (Mui and Chan 2003)

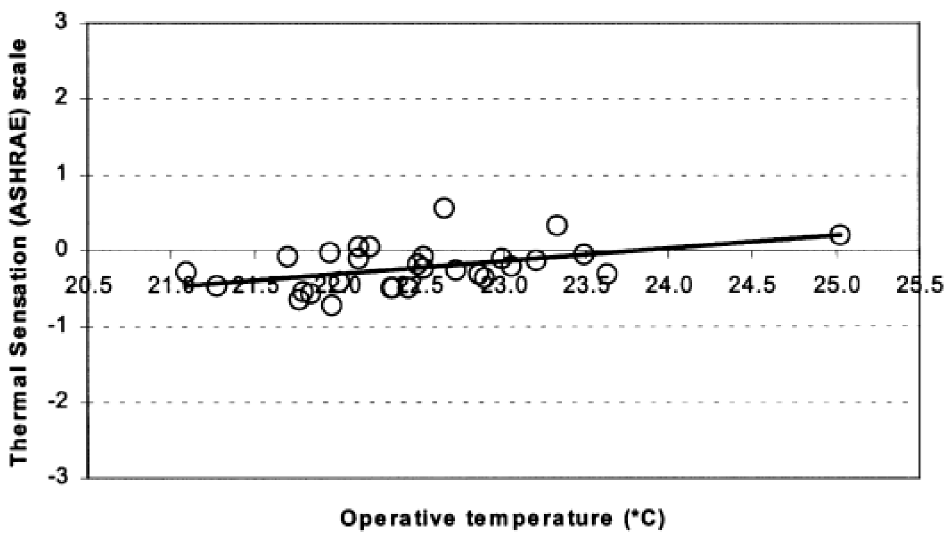


Figure 4.8 The thermal sensation scale against the operative temperature in summer (Mui and Chan 2003)

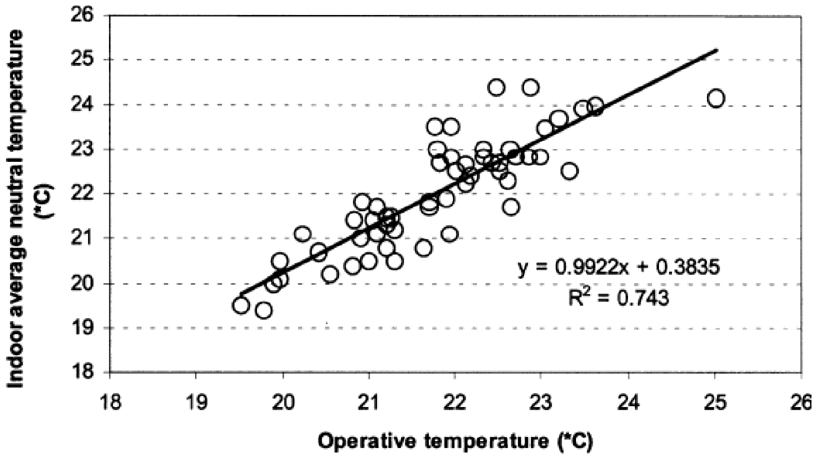


Figure 4.9 The relationship between the indoor neutral temperatures and the indoor average operative temperature (Mui and Chan 2003)

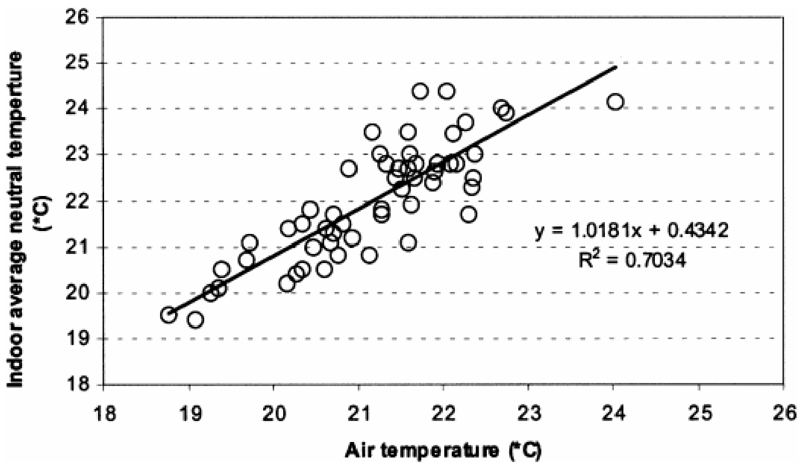


Figure 4.10 Dependence of indoor neutral temperatures against the indoor average air temperature (Mui and Chan 2003)

They also correlated the indoor average neutral temperature to the indoor average operative temperature and indoor average air temperature, shown in Figures 4.9 and 4.10, respectively. The adaptive hypothesis is clearly visible in these figures. According to the adaptive hypothesis, occupants' neutral temperature should drift toward the mean indoor temperature that they usually experience. Therefore, the dependence of the neutral temperature on the mean indoor temperature creates a support for the adaptive hypothesis in this research. Mui and Chan assumed that the occupants' clothing insulation, their metabolic rate, and the air speed in the building are predictors of occupants' adaptive behavior happening through changing clothing type or level, changing activity or using elevated fan speed. They also quantified occupants' average neutral temperature versus the outdoor air temperature, shown in Equation 4.38. Figure 4.11 depicts this correlation.

$$T_n = 18.3 + 0.158\ T_{out} \tag{4.38}$$

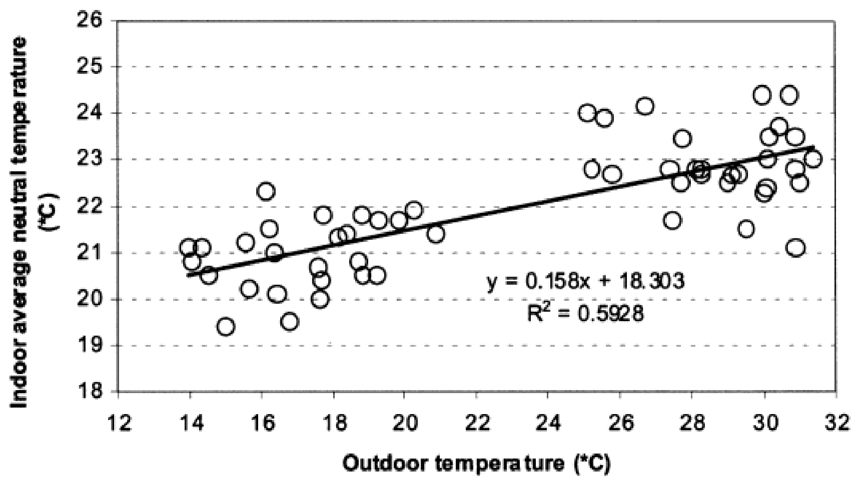


Figure 4.11 The adaptive neutral temperature vs. the outdoor air temperature for a humid sub-tropical climate zone, Hong Kong (Mui and Chan 2003)

Figure 4.11 reveals that the indoor average neutral temperature in this study is correlated with the ambient air temperature. However, compared to Figure 4.10, the neutral temperature only slightly varies with considerable variation in the outdoor air temperature. In other words, the rate of changes of neutral temperature is much lower versus the ambient temperature compared to the indoor average air or operative temperature. Based on several studies some of which are mentioned in this chapter, this trend is expected in air-conditions buildings, especially those with less control and adaptive options.

4.2. Summary and Conclusions

Several field and laboratory studies have been conducted thus far to estimate building occupants' thermal sensation or thermal comfort votes and/or the neutral or comfort temperature in naturally conditioned and ventilated, air-conditioned, and mixed-mode buildings. Most of these studies were based upon the thermal neutrality assumptions that assumes that building occupants are thermally comfortable in a neutral thermal environment. The majority of these studies also consider a symmetrical thermal sensation around the neutral conditions, meaning that occupants' sensitivity to the cold thermal environment is the same as the hot thermal conditions. Some other researchers, however, reported results that are not compatible with those assumptions.

The most important results from several studies covered in this chapter are summarized as follows:

- There is a significant correlation between the outdoor ambient air temperature (or average, weighted average, exponentially weighted average, or effective outdoor temperature) and occupants' neutral or comfort temperature in naturally ventilated and conditioned buildings. This relationship for air-conditioned buildings is less significant.
- There is a substantial correlation between the neutral or comfort temperature in buildings and the average indoor air or operative temperature (the adaptive hypothesis or thermal acclimatization).
- Because of the building occupants' psychological and behavioral adaptations, the AMV values in buildings are expected to be different form the PMV values. This discrepancy could be more significant in buildings with more control or adaptive options for occupants to adapt to the thermal environment or to adjust it.

CHAPTER 5

SENSITIVITY ANALYSIS AND ADAPTIVE THERMAL COMFORT MODELING

This chapter concerns with occupants' adaptive thermal comfort modeling based on the data collected from field studies and thermal comfort surveys on UGA campus. The methodology and details about this field study along with the associated statistic results were presented in Chapter 3. In this chapter, all measured environmental and personal objective parameters (such as air temperature and relative humidity, and clothing insulation), as well as the collected subjective responses (such as thermal sensation and thermal preference votes) are analyzed. A sensitivity analysis is conducted to evaluate the statistical significance of the impact of different environmental and personal parameters on the occupants' mean thermal sensation and preference votes. Meta-analysis technique is used to analyze the average values for occupants' thermal sensation and thermal preference votes for each class session. Finally, the mathematical models for occupants' mean thermal sensation and mean thermal preference votes on UGA campus, as a function of the most important predictors, are presented.

5.1. Response Variables

A response variable in this study is a variable that is being used as a proxy to gauge occupants' thermal comfort. To be able to develop a mathematical model for occupants' thermal comfort, all potential input and output variables should be evaluated and the most correlated variables should be identified. Initially, the response variable or the parameter that will be used to gauge the building occupants' thermal comfort should be identified. As discussed in the literature review in Chapter 1 and 4, most of the researchers thus far have used the neutral temperature indoors to be the representative of thermal comfort in buildings (De Dear and Brager 1998, Mui and Chen 2003, Humphreys et al. 2013). They considered the neutral thermal environment to be equal to thermal comfort. Most thermal comfort standards also use occupants' mean thermal sensation vote such as the predicted mean vote (PMV) and, occasionally, the actual mean vote (AMV) to evaluate occupants' thermal comfort state. Mean thermal preference vote and thermal acceptability percentage are among the other variables that could be used as proxies to evaluate occupants' thermal comfort in buildings. All abovementioned parameters measure different dimensions of thermal comfort and may not be replaced by each other. Therefore, one should be cautious in choosing and using each of this parameters for thermal comfort evaluation.

In this section, occupants' actual mean thermal sensation votes or AMVs and their mean thermal preference votes will be evaluated. Fortunately, AMV values and the mean thermal preference votes are strongly correlated and are the functions of the same input variables. However, mean thermal preference vote better reflects the subjectivity of thermal comfort, compared to AMV, and it is independent of the assumption of thermal neutrality being equal to thermal comfort. Furthermore, thermal preference reflects what type of adjustment should be made to the room thermal environment to alleviate thermal discomfort or to improve thermal comfort.

In a field study for occupants' thermal comfort evaluation, the dimension of thermal comfort that is being evaluated and the type of questions that the building occupants are being asked play a major role in the survey outcome. The heat balance model assumes that occupants feel comfortable at neutral thermal conditions or when PMV values equal to zero where occupants feel neither cold, nor hot (Aghniaey and Lawrence 2018b). Surveying occupants' mean thermal sensation votes or their AMVs usually needs to be based on the same assumption. However, based on the valid and sufficient evidence in the literature, not all occupants would necessarily prefer a neutral thermal environment as the optimum thermal environment in buildings (Aghniaey and Lawrence 2018b). The results of the field surveys in this study revealed that even the same group of people in the same room and thermal environment might perceive the thermal environment differently on two different days. Thus, surveying occupants' thermal preferences might be necessary in pinpointing the optimal thermal conditions for a specific group of occupants in a built environment. This dimension of thermal comfort, per se, also indicates what changes could be made to the thermal environment to improve occupants' thermal comfort. This feature makes the thermal preference vote distinguished from the thermal sensation vote and the thermal acceptability percentage.

If δ represents occupants' mean thermal preference vote, a thermal environment could be considered optimal when $|\delta|$ is minimum. In this study, $|\delta|$ or the absolute value of mean thermal preference vote (called Pref in this study) and the AMV index are considered to gauge occupants' thermal comfort on UGA campus. To avoid basing the optimization on the assumption of equidistance, however, the optimization of thermal comfort and energy cost/consumption in the next chapter, is only based on the mean thermal preference vote or Pref.

5.2. Predictors

During this filed study, various environmental and personal parameters were measured and/or collected. These parameters could be divided into four major categories, as shown in Table 5.1; environmental, subjective or judgmental, personal, and Demographic. Environmental parameters associated with the indoor thermal environment are measured using the described devices in Table 3.2. The sampling time and locations are also presented in Table 3.1 of Chapter 3. Subjective parameters are collected using online or in-print survey questionnaires on UGA campus and represent occupants' subjective evaluation of their surrounding thermal environment. The questionnaire is presented in Appendix B. Personal factors, account for occupants' non-subjective, physiological or behavioral factors that may be reflecting their interactions with the thermal environment. Finally, demographic information evaluates occupants' physical conditions. The influence of each measured or collected variable shown in Table 5.1 in predicting occupants' mean thermal sensation and preference vote is discussed hereafter.

Table 5.1 The measured and collected environmental and personal parameters from the field studies on UGA campus

Environmental Parameters					
Air temperature (T_{in})	Mean radiant temperature (T_{mr})	Indoor relative humidity (RH_{in})	Ambient temperature (T_{out})	Ambient relative humidity (RH_{out})	CO_2 level
Subjective Parameters					
Mean thermal sensation or actual mean vote (AMV)		Mean thermal preference vote (Preference)		Thermal acceptability (Acc)	
Personal Factors					

Clothing insulation (CLO)	Metabolic rate (MET)	Time of exposure to the room thermal environment (TOE)	The percentage of people who are involved in some sort of adaptive behavior (Adp)
	Demographic Information		
Age Group (Student, Faculty, Parent)		Gender (Male, Female, N/A)	Health Status (Healthy or Sick)

5.2.1. Sensitivity Analysis of Ambient or Outdoor Air Temperature

In this section, the relationship between occupants' mean thermal sensation and preference vote with ambient air temperature is evaluated. The main goal of this discussion is to understand the mechanism through which the ambient air temperature affects building occupants and their adaptation either behavioral (through changing their clothing level or adjusting their interactions with the building) or psychological and physiological (through affecting occupants' expectations or their thermoregulatory system). Based on the literature review presented in Chapter 4, researchers have applied various indices as the representatives of the ambient air temperature that might be affecting occupants' thermal comfort (Humphreys et al. 2013, Humphreys 1978, Peeters et al. 2009). Some of these indices reflect occupants' very recent experience of ambient air temperature. Among them is monthly, weekly, and 24-hour average, maximum, and minimum ambient temperature, exponentially weighted running mean ambient temperature, and day-ahead average ambient temperature (Peeters et al. 2009).

A sensitivity analysis in conducted to find the most relevant ambient air temperature index, through evaluating the correlation between occupants' mean thermal sensation vote (AMV) and their mean thermal preference vote (Preference) and the abovementioned variables, as shown in Table 5.4 and Table 5.5. A new index called "Day Ahead 12hr Average" is introduced in Table 5.6. This index averages the ambient air temperature between 8:00 am and 8:00 pm on the day ahead of the survey day. Since it is more probable that building occupants (students in this survey) to be exposed to the outdoor environment during this period (between 8:00 am and 8:00 pm), compared to the nighttime, it might be possible that their thermal comfort is more affected by this 12hr average index. This index could potentially adjust building occupants' anticipation of the ambient temperature during the next day and their expectations from the thermal environment indoors.

Table 5.2 shows the correlation between occupants' mean thermal sensation votes or AMVs, their mean thermal preference votes (Preference), the percentage of people who were involved in some sort of adaptive behavior in each classroom (Adp), and students' mean clothing insulation (CLO) values versus monthly and weekly outdoor ambient temperature indices. Based on the literature, it is expected that occupants' clothing insulation or CLO values to be affected by ambient air temperature either directly or through their adjusted expectations. The influence of the ambient air temperature on occupants' adaptive behavior or the percentage of people who claimed to be involved in some sort of adaptive behavior (Adp) might also be a representative of building occupants' psychological adaptation to seasonal, diurnal, or random variations in outdoor ambient conditions. In these chapter, Max and Min represent the maximum and minimum outdoor ambient air temperature, respectively.

*Table 5.2 The **Correlation Coefficient** between AMV, Preference, Adp, and CLO, and the outdoor ambient weekly and monthly average, minimum, and maximum air temperature*

	Weekly Max	**Weekly Min**	**Weekly Average**	**Monthly Max**	**Monthly Min**	**Monthly Average**
AMV	-0.204	0.080	**-0.292**	-0.086	0.042	-0.009
Preference	0.220	-0.051	0.290	0.028	-0.067	-0.059
Adp	-0.198	-0.258	-0.158	0.100	-0.116	-0.027
CLO	-0.055	-0.269	-0.030	-0.037	0.033	0.161

Table 5.3 represents these correlation coefficient values for the day-ahead minimum, maximum, and average, and exponentially weighted mean outdoor air temperatures, as shown in Equations 5.1 and 5.2. T_{exp1} as discussed in the literature review in Chapter 4 (Peeters et al. 2009) is an exponentially weighted combination of one-day ahead and two-day ahead average outdoor air temperatures. T_{exp2}, however, takes into account the mean outdoor temperatures related to three consecutive days prior to the test day and the test day itself. Tm shows the mean temperature of the corresponding day, which is the average of the maximum and minimum air temperature of that day (24-hour average). Tm_{n} represents the mean outdoor air temperature for the day "n", which is the test day or the day occupants' thermal comfort is being evaluated. Therefore, Tm_{n-1}, Tm_{n-2}, Tm_{n-3} represent, one-day, two-days, and three-days ahead of the test day, respectively.

$$T_{exp1} = (Tm_{(n)} + 0.8\,Tm_{(n-1)} + 0.4\,Tm_{(n-2)} + 0.2\,Tm_{(n-3)})/2.4 \quad (5.1)$$

$$T_{exp2} = 0.8\,Tm_{(n-1)} + 0.2\,Tm_{(n-2)} \quad (5.2)$$

Table 5.3 The ***Correlation Coefficient*** *between AMV, Preference, Adp, and CLO, and the day ahead minimum, maximum, and 24-hour average outdoor air temperature*

	Day-Ahead Max	**Day-Ahead Average**	**Day-Ahead Min**	**T_{exp1}**	**T_{exp2}**
AMV	**-0.351**	-0.100	-0.139	-0.219	-0.224
Preference	0.219	0.096	0.095	0.237	0.217
Adp	-0.220	-0.258	-0.114	-0.287	-0.208
CLO	-0.286	**-0.356**	-0.197	-0.214	-0.257

Table 5.4 depicts the correlation coefficient values between the "Day-Ahead 12hr Average" outdoor air temperature and occupants' actual mean vote, their thermal preference vote, their adaptive behavior, and their clothing insulation values. The two exponentially weighted mean temperatures presented in Table 5.4, using Equations 5.1 and 5.2, are also calculated using 12-

hour averages temperature of each day (or simply 12hr), versus the 24-hour average temperatures. The “Day-Ahead 12hr Average” temperature shows the average air temperature between 8:00 am and 8:00 pm for the previous day. It is clear that all correlation coefficients corresponding AMV, Preference, and Adp are at least marginally increased using the 12hr averages, compared to 24-hour averages. However, considering the CLO values, only the correlation between CLO and T_{exp1} has marginally improved compared to Table 5.3 and among the three outdoor air temperature indices presented in Table 5.4.

Table 5.4 The ***Correlation Coefficient*** *between AMV, Preference, Adp, and CLO, and the outdoor air temperature 12hr indices*

	Day-Ahead 12hr Average	**T_{exp1}, 12hr Average**	**T_{exp2}, 12hr Average**
AMV	0.236	-0.266	-0.258
Preference	**0.419**	0.255	0.343
Adp	**-0.321**	-0.317	-0.331
CLO	-0.257	-0.266	-0.258

Table 5.5 indicates the impact of the same day outdoor air temperature on building occupants’ thermal sensation, preference, adaptive behavior, and their clothing insulation. Daily minimum temperature (24-hour Min) usually occurs around 7:30 am on each day. As shown in Table 5.5 this index has the most significant correlation with AMV and Preference. This could be the temperature that students are exposed to early in the morning while leaving their homes to school. Thus, this might be the most influential factor affecting their thermal expectations. Occupants’ adaptive behavior, however, is mostly correlated with the maximum and the average outdoor air temperature and also the air temperature values around the time of the survey (which is close to the Max). This might be explained by occupants pro-actively or reactively behaving to alleviate the expected or experienced thermal discomfort during almost the warmest times of the

day. When expecting or experiencing higher temperatures outdoors, occupants could more actively react to reduce thermal discomfort indoors, even with the same indoor environmental conditions. In Table 5.5, T_{out} shows the outdoor air temperature as the survey is being conducted. Max, Min, and Average show the maximum, minimum, and the average outdoor air temperature values of the test day (24-hour).

Table 5.5 The ***Correlation Coefficient*** *between the same day outdoor air temperature and occupants' AMV, Preference, Adp, and CLO values*

	Max	**Min**	**Average**	**12hr Average**	**T_{out}**
AMV	-0.029	**-0.365**	-0.209	-0.008	0.043
Preference	0.021	**0.512**	0.256	0.049	-0.064
Adp	**-0.365**	-0.228	**-0.330**	**-0.371**	**-0.425**
CLO	-0.260	-0.056	-0.192	-0.266	-0.174

Table 5.6 shows the R-Squared values, p-values, and the root mean square error (RMSE) corresponding to the linear regression models between AMV, Preference, Adp, and CLO, and relatively the most significant outdoor ambient air temperature indices, based on the results presented in Tables 5.2 through 5.5. Correlation coefficient is a measure of linear dependency between two random variables. R^2 indicates the proportionate amount of variations in the response variable (y) explained by the independent variable (x) in the linear regression model, as explained in Chapter 3 and APPENDIX C. The model shows a better accuracy when the R^2 values are closer to 1 (Mathworks.g).

The p-value tests the null hypothesis that the regression coefficient for the independent variable is equal to zero. In other words, p-values are the probability that the relationship between the output and input(s) parameters is random. A p-value lower than 0.05 rejects the null hypothesis. Root mean square error (RMSE) shows the average difference between the predicted and the actual responses and it measures how concentrated the actual data sets are around the regression line. The model's accuracy increases as RMSE diverges to 0. APPENDIX C shows how the correlation coefficient between two variables is calculated. The calculation of R^2 and RMSE are also presented in APPENDIX C.

As is clear from Table 5.6, although most of the p-values for the linear regression models between the most correlated variable are lower than 0.05, R-squared values are so small and RMSE values are too high for all correlations. To illustrate, AMV values are based on a seven-point scale and vary between -3 and +3. A RMSE value of 5.86 out of 7 is significantly high for a linear regression model. Therefore, the impact of the outdoor air temperature on occupants' thermal sensation, preferences, adaptation, and clothing insulation values could be neglected for this study on UGA campus. This was expected since in most air-conditioned buildings in US, the indoor environment is completely isolated from the outdoor ambient conditions and the temperature set point does not follow the ambient air condition patterns, as discussed in Chapter 4. This lack of adaptation in air-conditioned buildings significantly affects the occupants' thermal expectations and their thermal experience.

Table 5.6 The R^2, P-Values, and RMSE values for the linear regression model corresponding to the most correlated parameters

Linear Regression	**R^2**	**P-Value**	**RMSE**
AMV vs. Min	0.133	0.0126	5.86
AMV vs. Day-Ahead Max	0.124	0.0166	4.81
CLO vs. Day-Ahead Max	0.0819	0.0538	4.92
Preference vs. Day-Ahead 12hr Average	0.175	0.0661	6.55
Preference vs. Min	0.262	0.021	5.78

5.2.2. Sensitivity Analysis for the Other Factors

The relationship between the response variables (AMV and Preference) and the other predictors is discussed in this section. Table 5.7 and 5.8 show the correlation coefficient (Corr Coef), R^2, p-values, and RMSE values for the linear regression models simulating the AMV and Preference values, respectively, versus CO_2 level, time of exposure to the indoor thermal environment (TOE), clothing insulation (CLO), the percentage of occupants who were involved in some sort of adaptive behavior (Adp), outdoor and indoor relative humidity (RH_{out} and RH_{in}), the operative temperature indoors (T_{op}), and the percentage of thermal acceptability (Acc).

*Table 5.7 The correlation coefficients, R^2, RMSE, and P-Values between **AMV** and various environmental and personal variables*

Parameter	Corr Coef	R^2	P-Value	RMSE
CO_2	0.129	0.033	0.53	0.714
TOE	0.096	0.019	0.668	0.69
CLO	-0.103	0.042	0.398	0.682
Adp	-0.121	0.0315	0.481	0.795
RH_{out}	**-0.550**	**0.302**	**0.000**	**0.576**
RH_{in}	**-0.67**	**0.630**	**0.000**	**0.608**
T_{op}	**0.653**	**0.510**	**0.000**	**0.522**
Preference	**-0.970**	**0.940**	**0.000**	**0.226**
Acc	**-0.787**	**0.619**	**0.000**	**0.543**

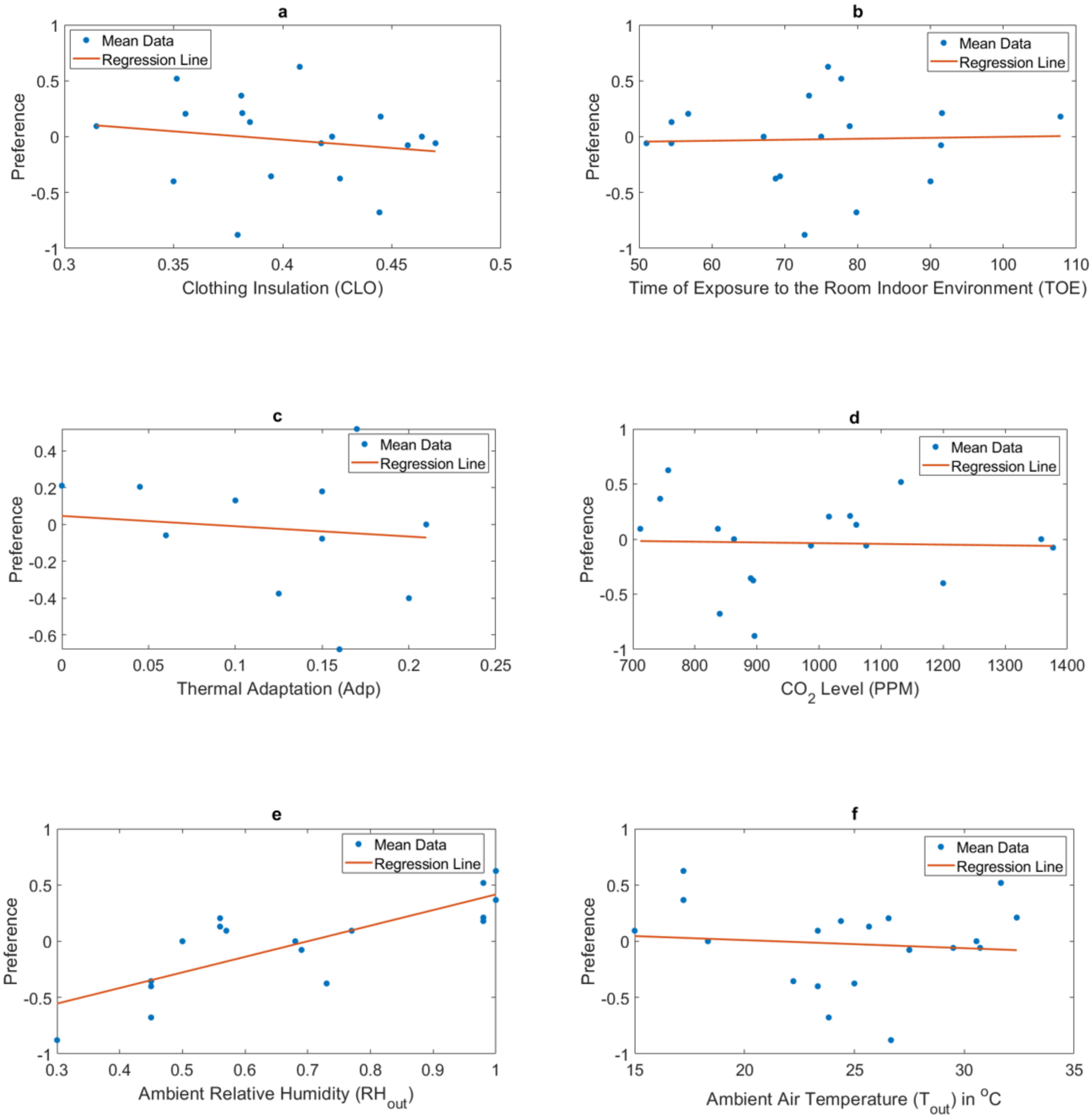
*Table 5.8 The correlation coefficients, R^2, RMSE, and P-Values between **Preference** and various environmental and personal variables*

Parameter	Corr Coef	R-Squared	P-Value	RMSE
CO_2	0.094	0.009	0.701	0.525
TOE	-0.178	0.032	0.454	0.509
CLO	-0.110	0.012	0.643	0.514
Adp	-0.284	0.081	0.325	0.503
RH_{out}	**0.751**	**0.615**	**0.000**	**0.352**
RH_{in}	**0.78**	**0.500**	**0.000**	**0.471**
T_{op}	**-0.715**	**0.511**	**0.000**	**0.362**
AMV	**-0.970**	**0.949**	**0.000**	**0.126**
Acc	**0.834**	**0.686**	**0.000**	**0.280**

As shown in Tables 5.7 and 5.8, RH_{in} and T_{op} are the most important factors affecting occupants' thermal comfort, i.e., AMV, Preference, and thermal acceptability or Acc. The AMV, Acc, and Preference are all strongly correlated and one can be calculated using the other. These are all response variables, showing different dimension of thermal comfort and all are a function of the same predictors or input variables.

Although there is a high correlation coefficient between AMV or Preference and RH_{out}, the outdoor relative humidity affects occupants' thermal comfort mostly through influencing the relative humidity indoors. Thus, these two parameters are significantly correlated (Correlation Coefficient= 0.6) and this could be the reason for relatively high correlation coefficient between RH_{out} and AMV or Preference. When developing the AMV or Preference model based on the RH_{out} (using also RH_{in} and T_{op}) the model results in unrealistic predicted values. One should be specifically avoid using both RH_{in} and RH_{out} in modeling occupants' thermal comfort in buildings to avoid multicollinearity in the regression model.

Figure 5.1 illustrates the linear regression models between occupants' thermal preference votes and the studied environmental and personal parameters shown in Tables 5.7 and 5.8. As is also clear from the figure, occupants' thermal preference vote only changes significantly with indoor and outdoor relative humidity and the air or operative temperature indoors.


a
Mean Data
Regression Line
Preference
Clothing Insulation (CLO)
b
Mean Data
Regression Line
Preference
Time of Exposure to the Room Indoor Environment (TOE)
c
Mean Data
Regression Line
Preference
Thermal Adaptation (Adp)
d
Mean Data
Regression Line
Preference
CO_2 Level (PPM)
e
Mean Data
Regression Line
Preference
Ambient Relative Humidity (RH_{out})
f
Mean Data
Regression Line
Preference
Ambient Air Temperature (T_{out}) in ^oC

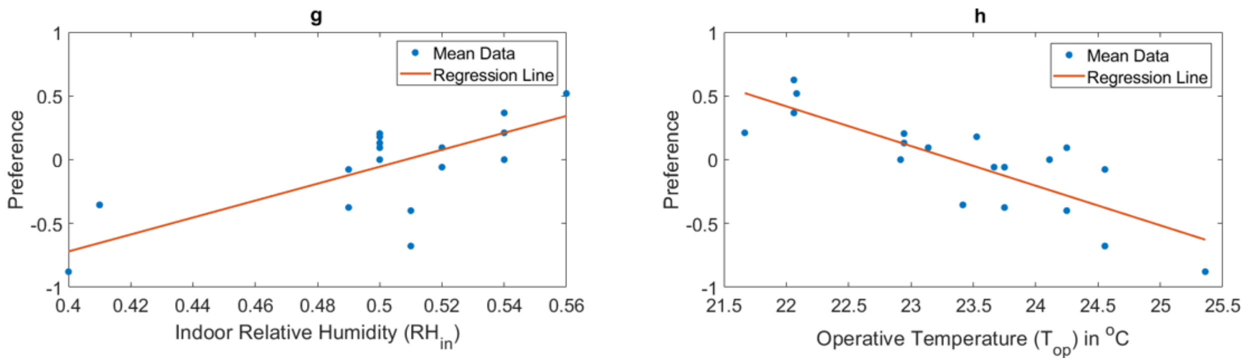


Figure 5.1 The linear regression between occupants' mean thermal preference vote on UGA campus and a) Occupants' Clothing Insulation, b) Time of Exposure, c) Adaptation, d) CO_2 Level, e) Outdoor Ambient Relative Humidity, f) Ambient Air Temperature, g) Indoor Relative Humidity, and h) Indoor Operative Temperature

5.3. The Adaptive Thermal Comfort Model based on Field Studies on UGA Campus

Finally, the thermal comfort models are developed based upon RH_{in} and T_{op} as predictors, and AMV and actual mean vote for thermal preference (Preference) as two separate response variables. Table 5.9 shows the R^2, Adj-R^2, RMSE, and p-values for each model. The adjusted R^2 (Adj-R^2), adjusts the R^2 Values based on the number of independent variables in the model, as discussed in APPENDIX C.

Table 5.9 The statistical significance of the linear regression models developed for AMV and Preference

Parameter	R^2	Adjusted R^2	RMSE	P-value
AMV	0.745	0.648	0.362	0.001
Preference	0.777	0.691	0.212	0.001

The mathematical models for occupants' AMV and Preference based on the indoor operative temperature and relative humidity in cooling season on the UGA campus are presented in Equations 5.3 and 5.4. These models show how values for occupants' mean thermal sensation and thermal preference votes change on UGA campus, as a function of the indoor environmental conditions. Figures 5.2 and 5.3 depict the simulated AMV and Preference values versus the operative temperature indoors.

$$AMV = 2.34\, T_{op} + 12.48\, RH_{in} - 1.33\, T_{op} RH_{in} - 0.03\, {T_{op}}^2 + 11.05\, {RH_{in}}^2 - 32.66 \quad (5.3)$$

$$Preference = 3.30\, T_{op} + 23.90\, RH_{in} - 0.90\, (T_{op} . RH_{in}) - 0.06\, (T_{op}^2) + 1.80\, (RH_{in}^2) - 43.42 \quad (5.4)$$

Where

$$0.3 \leq RH_{in} \leq 0.7$$

And

$$21 \leq T_{op} \ll 27\, °C$$

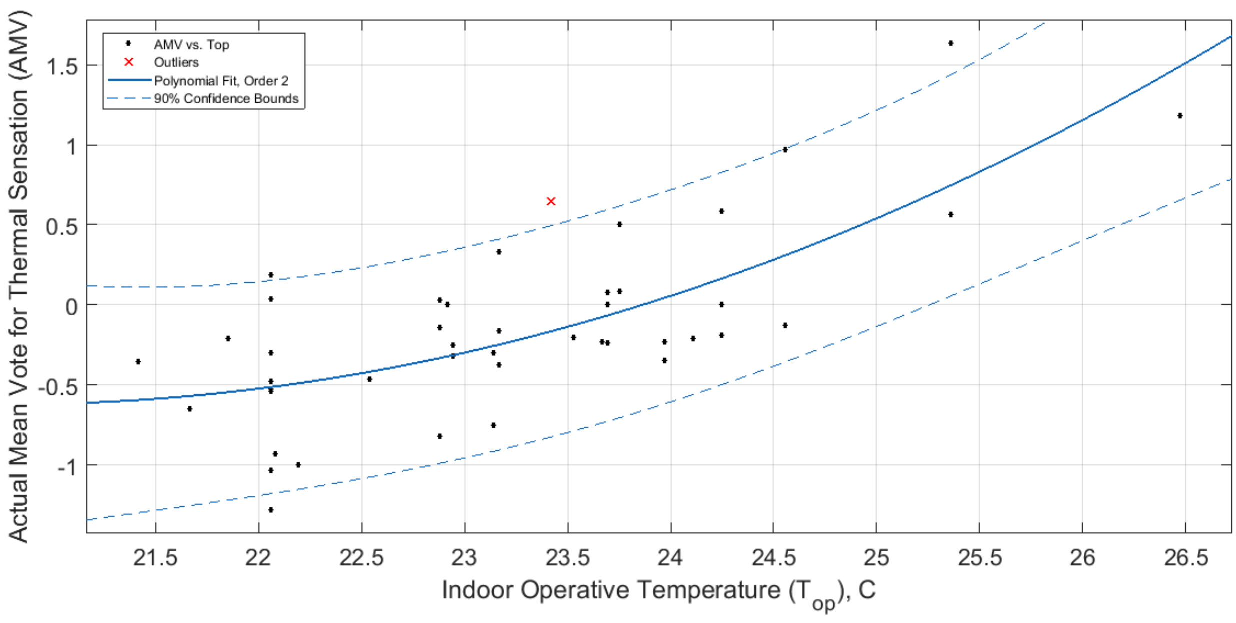


Figure 5.2 The regression model for occupants' actual mean vote for thermal sensation vs. the indoor operative temperature on UGA campus

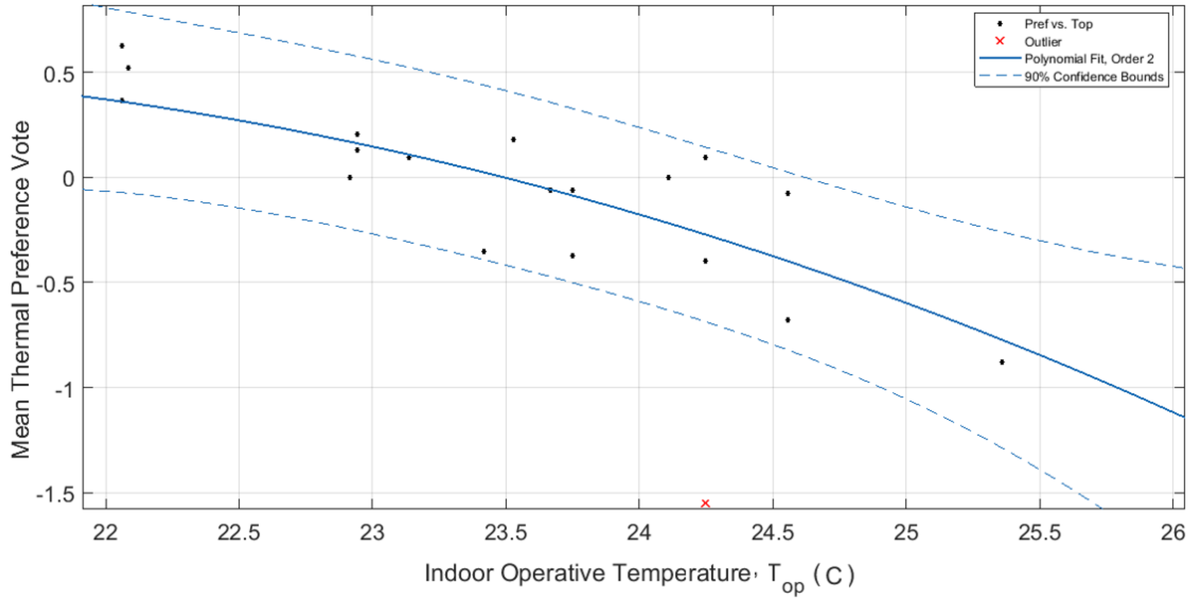


Figure 5.3 The regression model for occupants' actual mean thermal preference vote vs. the indoor operative temperature on UGA campus

Figure 5.4 depicts the occupants' thermal acceptability percentage versus the indoor operative temperature as also discussed in Chapter 3. ASHRAE standard 55 considers a thermal environment to be comfortable if it is acceptable for at least 80% of building occupants. This figure helps to understand the acceptable range for AMV and mean thermal preference vote. Based on the Figures 5.3 and 5.4, for thermal preference votes between 0.5 and -0.5 the thermal environment is acceptable for more than 80% of building occupants. However, there is not enough data sets related to occupants' thermal acceptability for thermal preference values beyond 0.5 or indoor operative temperature values beyond almost 24.5 °C.

Comparing Figures 5.2 and 5.4 also reveals that for AMV values below 0.5 on UGA campus, thermal acceptability is above 80%. However, the lower bound of AMVs for 80% acceptability cannot be identified since there are not enough data sets for indoor operative temperature values below 21° C. For AMV values equal to -0.6 the thermal environment is still in the 80% thermal acceptability range which is slightly lower than the ASHRAE Standard 55 specified thermal comfort range (-0.5 < AMV < 0.5), implying that occupants on UGA campus might generally prefer a slightly cooler than neutral thermal environment.

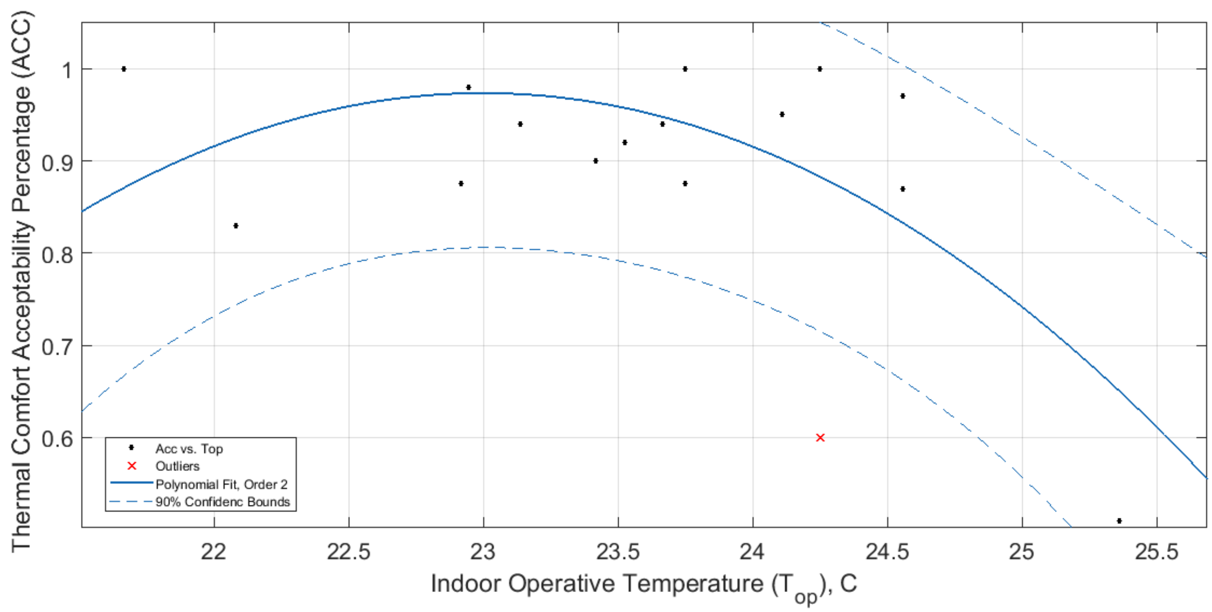


Figure 5.4 The regression model for occupants' thermal acceptability vs. the indoor operative temperature on UGA campus

5.4. Summary and Conclusion

This chapter focuses around a sensitivity analysis for all collected data sets during the extensive thermal comfort survey conducted on UGA campus between July 2015 and October 2017. Thermal environmental parameters such as the temperature and relative humidity indoors were temporally and spatially averaged for each class section. All subjective data sets such as the thermal sensation and preference votes were averaged for each class section to represent the corresponding mean vote for the large group of occupants in each classroom. Various outdoor ambient air temperature indices were examined concerning their correlation with the AMV and thermal preference votes. These indices include the day ahead maximum, minimum, and average outdoor air temperature, the same day maximum, minimum, and average outdoor air temperature, and exponentially weighted mean ambient air temperature over the 3 or 4 consecutive days. All average values were based on the daily 12-hour or/and 24-hour time periods. The most important conclusions are presented as follows:

- Neither of the indices corresponding the outdoor ambient air temperature were found to significantly affect the occupants' mean thermal sensation or preference votes in the surveyed air-conditioned building on UGA campus.
- Outdoor relative humidity mostly affects building occupants through influencing the indoor relative humidity. Because of the multicollinearity between the indoor and outdoor relative humidity values, using both variables in developing the thermal sensation or preference models leads to a substantial decrease in models' quality.
- Indoor relative humidity and the indoor air temperature (or the indoor operative temperature) are the most correlated parameters to the occupants' mean thermal sensation and preference votes.
- None of the remaining variables, i.e., occupants' clothing insulation, their time of exposure to the room thermal environment, the percentage of occupants involved in some sort of adaptive behavior, and the CO_2 level in the classrooms, considerably correlate with the occupants' AMV or Preference values in this study.

- The Preference, AMV, and thermal acceptability percentage are strongly correlated, as expected, and represent the different dimensions of occupants' thermal states in classrooms.

CHAPTER 6

OPTIMIZING BUILDING OCCUPANTS' MEAN THERMAL PREFERENCE VOTE WITH BUILDING ENERGY CONSUMPTION FOR SPACE COOLING ON UGA CAMPUS

Optimizing buildings' energy consumption has been a topic for numerous studies around the world. Considering the current global warming challenges and the huge amount of energy that is being consumed by HVAC systems in buildings (almost 20% of total energy consumption worldwide), energy saving opportunities in buildings can considerably contribute to alleviating climate change. Demand side management techniques, including demand response and energy efficiency measures, could substantially reduce energy consumption and utility costs along with the associated environmental impacts. Alternatively, it could at least shift the load from peak-electricity-demand hours (peak load) to off-peak hours (Motegi et al. 2007). However, since the HVAC system's operation substantially contributes to building occupants' health and well-being, it is essential to find a tradeoff between energy consumption by HVAC systems and occupants' thermal comfort in buildings. People spend nearly 90% of their time in buildings (Klepeis et al. 2001). Therefore, it is particularly important that the indoor environment supports the occupants' health, wellbeing, and productivity (Freire et al. 2008). Among different factors contributing to building occupants' wellness in buildings, thermal comfort and indoor environmental quality (IEQ) have the most significant impact on occupants, as discussed earlier in this work.

Unfortunately, if demand response and energy efficiency measures are not accompanied by proper thermal comfort and IEQ control, then short and long-term health issues, thermal dissatisfaction, decreased overall performance by the occupants, and changes of mood can occur (Zhang et al. 2011). These impacts could be more severe in spaces where the occupants spend longer time periods in the environment, have less control over the thermal environment, and deal with more sensitive tasks, such as in office buildings or university campuses (Kotopouleas and Nikolopoulou 2016). In order to avoid these ramifications, multiple researchers have tried to optimize a building's energy consumption and/or cost with the occupants' thermal comfort. As a general practice in air-conditioned buildings, HVAC systems are controlled through keeping the zone temperature within a desired range (Gouda et al. 2001). Since temperature feedback is the only predictor of occupants' thermal comfort, a lack of scaling occupant preferences, their thermal sensation, and their behavioral feedback could cause a reduced thermal satisfaction level in buildings.

In this chapter some of the most recent control strategies for HVAC systems in buildings and methods for optimizing building energy consumption and thermal comfort are reviewed. Energy consumption modeling and the optimization method used for this study are described. Results from the optimization using genetic algorithm method and the corresponding conclusions are presented in the last section of this chapter.

6.1. Literature Review of Control Strategies

Numerous control strategies have been proposed in recent years to optimize and improve occupants' thermal comfort and reduce HVAC systems' energy cost/consumption in buildings.

Among those are: occupancy-based control; model-predictive control (MPC); adaptive and non-adaptive proportional-integral-derivative (PID) or proportional-derivative (PD) control; and fuzzy logic control strategies (Korkas et al. 2016, Freire et al. 2008, Kolokotsa et al. 2001, Gouda et al. 2001). PID and MPC controllers are well-suited for most commercial and industrial HVAC applications. However, some level of knowledge about HVAC plant's dynamics is required for tuning PID gain constants (Gouda et al. 2001). MPC, as is clear from the name, operates based on the predicted performance developed from models of the HVAC plant's dynamics. Fuzzy logic controllers evaluate thermal comfort (usually PMV or PPD) as a fuzzy concept that varies within a fuzzy range instead of using a single-point limit for thermal comfort. The term 'fuzzy' refers to the fact that one or more of the variables or concepts can have a value of 'partially true' as opposed to true or false (0 or 1). In other words, this is a computing method based on the degree of truth where the truth values of variables could be any number between 0 and 1.

When optimizing occupants' thermal comfort and energy cost/consumption, the primary concern is choosing the appropriate indices to gauge thermal comfort and energy cost/consumption. Identifying proper objective functions, weights, and/or constraints for the optimization problem as well as a solver that better suites the nature of the problem are among the factors that significantly affect the final optimization and control results. Most of the related studies thus far have used PMV/PPD indices and the ASHRAE comfort zone ($-0.5 < PMV < 0.5$ and/or $PPD < 10\%$), ASHRAE Standard 55 psychometric chart comfort zone for temperature, air speed, and relative humidity, or the Effective Temperature (ET*) index to evaluate and optimize occupants' thermal comfort while minimizing energy cost/consumption (Korkas et al. 2016, Freire et al. 2008).

Korkas et al. (2016) developed a novel, occupancy-based, control algorithm to optimize thermal comfort in micro grids equipped with renewable energy and energy storage facilities during demand response events. Their primary goal was to guarantee occupants' thermal comfort in mixed mode or air-conditioned buildings and to manage energy generation and consumption based on occupants' behavior. They proposed a two-level supervisory control strategy consisting of a controller, processing local measurement for each building in the first level. The second level optimizes energy cost and thermal comfort and updates the controllers embedded in the first level. Thermal comfort is optimized through minimizing PPD values and keeping that below 10%. They compared two different control strategies for maintaining thermal comfort and reducing energy cost/consumption; 1) A rule-based control strategy that would keep each zone' set point temperature below 24 or 25° C, and 2) minimizing a performance index consisting of a weighted energy score and a thermal comfort score. Energy score represented the normalized energy cost (E_i) while thermal comfort score reflected normalized PPD values (C_i) as shown in equation (6.1). In this equation, 'n' is the number of buildings in the micro grid and 'k' represents the weighting factor.

$$M(t) = \sum_{i=1}^{n} (k * E_i(t) + (1-k) * C_i(t)) \tag{6.1}$$

Freire et al. (2008) proposed two model predictive control strategies for air-conditioned buildings: one for thermal comfort optimization and the second one for minimizing energy consumption while maintaining adequate thermal comfort. Thermal comfort is addressed using the PMV index and ASHRAE Standard 55 graphical comfort zone. They examined five different control approaches to implement the abovementioned MPC strategies; 1) temperature signal lies within the comfort zone while energy consumption is minimized, 2) temperature signal lies within the comfort zone while the relative humidity is optimized, 3) HVAC system input power is optimized using a cost function optimization combining temperature and relative humidity, 4) the PMV index is optimized using a PMV-based predictive, and 5) energy consumption is optimized while maintaining the acceptable PMV level. The results showed that all control strategies were successful in maintaining occupants' thermal comfort and decreasing energy consumption. However, the proposed PMV-based controller was able to provide better global performance in terms of both thermal comfort and energy consumption. This was attributed to the fact that PMV index adapts to individual parameters such as the occupants' metabolic rate and better predicts a thermally comfortable environment.

Kolokotsa et al. (2001) evaluated different control strategies to maintain indoor air quality and occupants' thermal and visual comfort while reducing building energy consumption. They compared and contrasted a non-adaptive PID, a non-adaptive PD, an adaptive PD, and an on-off controller. The results showed that although all controllers are applicable to buildings, the adaptive, PMV-based, PID controller led to a lower energy consumption. This control strategy, by eliminating overshooting and oscillation of PMV values, results in reduced energy consumption.

Gouda et al. (2001) investigated a PMV-based fuzzy logic controller (FLC) that could maximize occupants' thermal comfort and reduce building energy consumption by 20% in typical winter days. Fuzzy logic controllers have been identified as potential alternatives to the traditional PID controllers and they better alleviate the overshooting problem inherent to the traditional controllers. They concluded that FLC provided a better control tracking and robustness compared to PID controllers. Linag and Du (2005) proposed a thermal comfort control system based on a direct neural network (NN), using the PMV index. This control system provides optimum thermal comfort for a specific user through learning the occupants' preferred comfort zone. Energy saving strategy and variable air volume (VAV) system is adopted to reduce HVAC system energy consumption. The NN is used to overcome the nonlinearity of PMV index. Using a thermal comfort controller, as opposed to temperature controller, provides an improved thermal comfort in buildings and leads to a higher energy saving.

Ascione et al. (2016) proposed a simulation-based model predictive control (MPC) procedure that includes optimizing occupants' thermal comfort with HVAC system operation cost using a multi-objective genetic algorithm (GA) optimization method. HVAC system operation cost is optimized with PPD values in a model predictive controller. Compared to the conventional control strategies, this control method resulted in 56% energy saving in a typical day in heating season in the Italian city of Naples. The optimization results is a pareto front (a set of optimum solutions) that goes through a multi-criteria decision-making process by the user and based on the occupants' requirements.

6.2. Optimization Methodologies: Literature Review and Selection

The optimization problem in this study is a constraint, nonlinear, multi-objective optimization problem with nonlinear constraints and objective functions. For solving this problem there might be various methods with *Fmincon* function, multi-objective genetic algorithm (GA), and weighted-sum method GA being the most well-known methods (Mathworkds.d). Genetic algorithm is a population based method that uses random numbers as the initial population and creates random results. While multi-objective GA finds a pareto front or a set of optimized solutions, the weighted-sum method GA finds the global minimizer. Similar to GA, *Fmincon* is a function for solving nonlinear problems, subject to equality or inequality nonlinear constraints and bounds. *Fmincon* is a gradient-based method that solves problems where the objectives and constraints are continuous and have continuous first derivatives. For infeasible problems, *Fmincon* adjusts the constraints. Although *Fmincon* is a useful function in finding local minima, sometimes it fails to find the global minima and it may only identify the local minimizer. Thus, it could underperform GA in finding the global solution.

Particle swarm optimization (PSO) is another common method for solving optimization problems, however, it mostly applies to bound-constraint problem with an objective function that can be non-smooth. Same as the genetic algorithm, PSO is a population-based algorithm. Surrogate optimization is another solver that has applications in bound-constraint, time-consuming (expensive), and smooth objective functions. This function does not require a start point but it requires finite bounds to solve the optimization problem. It approximates the values for the objective function, evaluates the surrogates on thousands of points and takes the best value as an approximation to the minimizer. None of the particle swarm and surrogate optimization methods apply to the optimization problem in this study since they only apply to bound-constraint problems (Mathworks.e). Based on the literature review, GA has been found to be the most promising tool in solving the optimization problem in this study. In the following section a brief introduction to this method is presented.

6.2.1. Genetic Algorithm (GA)

Genetic algorithm (GA) is a method to solve constraint and non–constraint optimization problems (Mathworks.a). This method applies to solve discontinuous, non-differentiable, stochastic, and highly nonlinear problems. This method is different from the classical derivative-based optimization methods in different ways. A classical optimization algorithm would create a single point in each iteration and the sequence of points would approach an optimal solution. The GA, however, creates a population of points in each iteration and the best point in the population will approach an optimal solution. The GA selects the next population based on random number generation while the classical method selects the next point in the sequence using deterministic calculations.

To solve a problem using GA a fitness function ($F(x_i)$) should be defined. Fitness function (or objective function) is a function that needs to be minimized (optimized). Each individual (x_1, x_2, x_3) is a point to which the fitness function could apply. The value of fitness function for an individual or point ($F(x_1, x_2, x_3)$) is called the score or fitness value of that individual. An array of individuals or genomes creates a population. The average distance between individuals in a population is called diversity. The smallest fitness value for any individual in a population represents the best fitness value in that population. At each step, GA selects individuals with best fitness values (parents) to create the next generation (Mathworks.b).

This method mimics natural selection that happens during biological evolution. At first, the algorithm generates a random initial population. Then, a sequence of new populations is generated in various steps. At each step, this algorithm selects individuals from the current population to produce the individuals for the next population. After sufficient iterations, the population would evolve towards the optimum solutions. The algorithm stops when one of the stopping criteria are met.

GA performs the following steps to create a new population for the next step:

- Calculating the raw fitness scores of each individual in the current population. In this step, the algorithm scores the members of current population based on their fitness values.
- Scales the raw fitness scores to convert them into a more usable range of values. These scaled values are called expectation values.
- Selects members based on their expectations. These members are called parents.
- Elite, crossover, and/or mutation children are created.
- Finally, the algorithm replaces the parents with the children to create the next generation.

As mentioned above, GA could create three types of children; elite, crossover, and mutation children. Elite children are the individuals in the current population that have the best or smallest fitness values. These individuals automatically pass to the next population. Crossover children are created by combining a pair of individuals or parents. The mutation children, on the other hand, are created through making random changes or mutation to a single parent or individual. Figure 6.1 shows these three types of children (Mathworks.c).

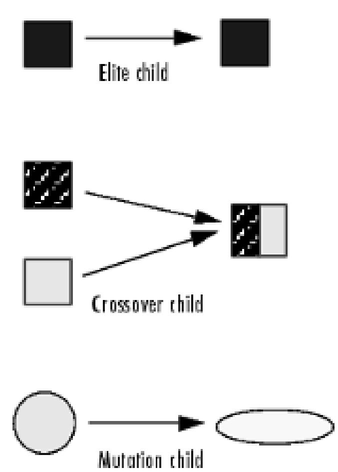


Figure 6.1 The Elite, Crossover, and Mutation children in each iteration of Genetic Algorithm (Mathworks.c)

6.3. Energy Consumption Modeling

An eQuest model for Correll Hall building's energy consumption was developed. eQuest is a tool for conducting sophisticated and professional-level building energy consumption analysis. This is a freeware tool that uses today's most sophisticated energy use simulation techniques. It combines building creation wizard, an energy efficiency measure wizard and a graphical result display (Energy Design Resources). Through this model, the energy consumption for space cooling versus indoor temperature setpoint is predicted in this study. Since mean radiant temperatures in all tests conducted during this study were almost equal to the indoor air (dry bulb) temperature, the operative temperature was assumed to be equal to the room air temperature in this study.

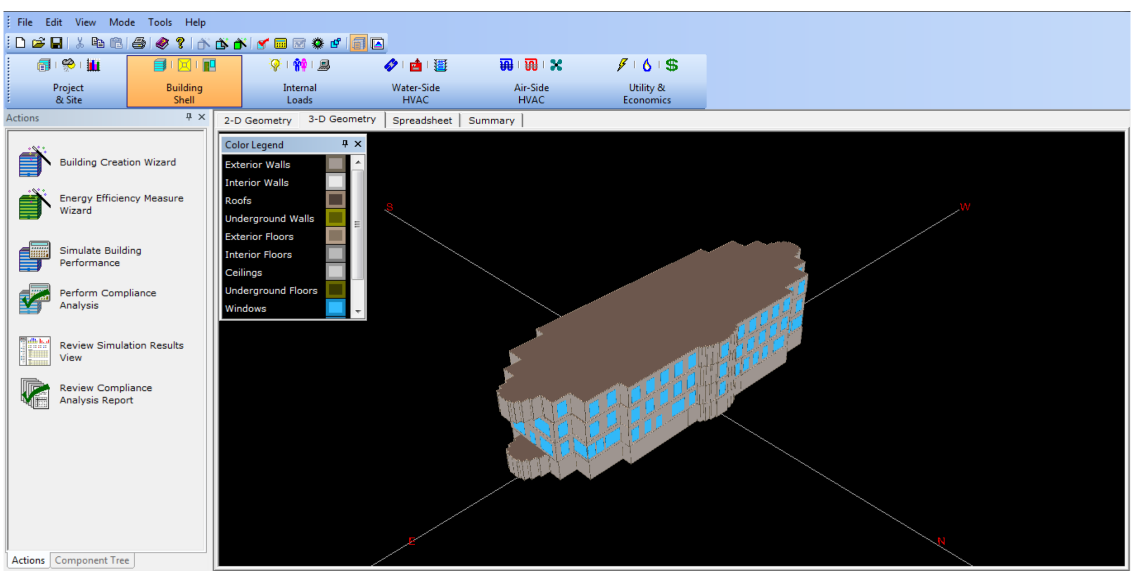


Figure 6.2 A screenshot from the eQuest software interface, building creation wizard, Correll Hall on UGA campus

Figures 6.2 shows a screenshot of the building creation wizard for the simulated Correll Hall building on UGA campus. Figures 6.3 and 6.4 show the graphical results and the corresponding values for electric consumption by various end users in Correll Hall from the eQuest model, when room set point temperature is 21° C (70° F). As is clear from Figure 6.3, electric consumption for space cooling has a greater value than other end users in the cooling season, between the months of May through October. Energy consumption for space cooling reaches a maximum in July and August.

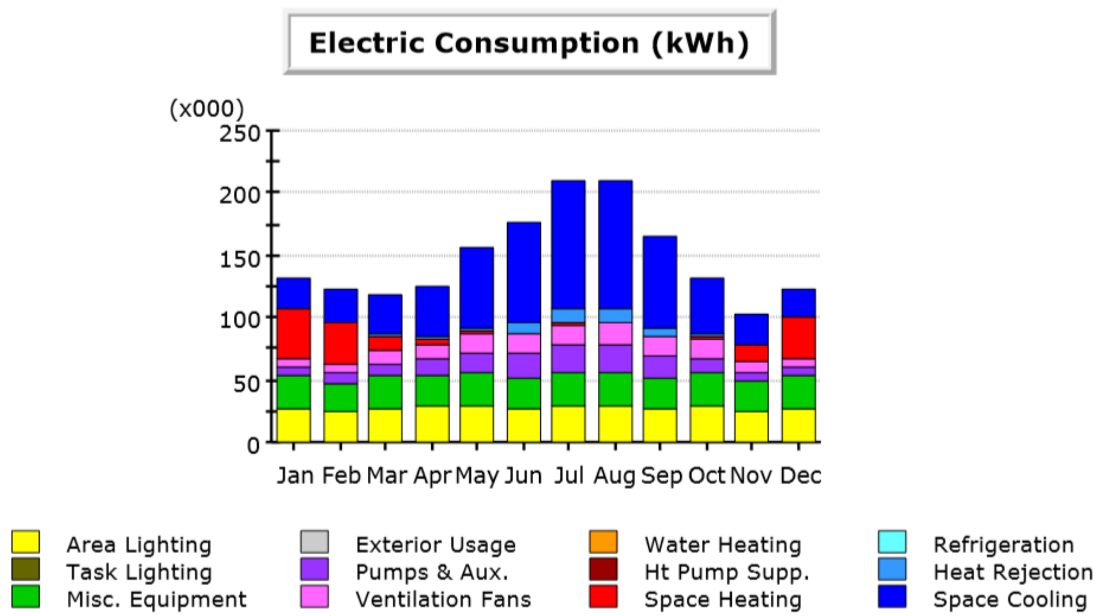


*Figure 6.3 the **monthly** electric consumption (kWh × 1000) per different end users. Values are predicted for set point temperature equal to 21° C (70° F) in Correll Hall building on UGA campus*

File Edit View Window Help

Report: ATTN Simulation Messages For Review | Component: | Hourly Results

HOURLY REPORT- Hourly Report HVAC WEATHER FILE- Athens GA TMY2 Pg: 196 - 1

	EM1 LIGHT END USE KWH ----(1)	EM1 TASK END USE KWH ----(2)	EM1 EQUIP END USE KWH ----(3)	EM1 HEAT END USE KWH ----(4)	EM1 COOL END USE KWH ----(5)	EM1 HTREJ END USE KWH ----(6)	EM1 AUX END USE KWH ----(7)	EM1 VENT END USE KWH ----(8)	EM1 REFG END USE KWH ----(9)	EM1 SUPP END USE KWH ----(10)
715 1	4.170	0.000	11.011	0.000	57.481	1.190	27.742	0.970	0.000	0.000
715 2	3.954	0.000	10.937	0.000	56.115	0.938	27.742	0.970	0.000	0.000
715 3	4.302	0.000	11.060	0.000	56.309	1.103	27.742	0.970	0.000	0.000
715 4	14.145	0.000	17.647	0.123	55.330	0.881	27.742	0.970	0.000	0.000
715 5	55.824	0.000	48.487	0.000	121.212	14.417	29.323	26.202	0.000	0.000
715 6	68.371	0.000	58.992	0.000	130.544	16.274	30.214	23.780	0.000	0.000
715 7	70.840	0.000	61.509	0.000	134.267	16.887	30.487	26.309	0.000	0.000
715 8	71.169	0.000	61.844	0.000	155.861	21.411	33.342	27.321	0.000	0.000
715 9	71.169	0.000	61.376	0.000	172.134	23.822	34.289	28.722	0.000	0.000
71510	71.169	0.000	58.679	0.000	184.143	25.786	35.020	28.047	0.000	0.000
71511	71.169	0.000	56.451	0.000	191.317	27.133	35.400	26.483	0.000	0.000
71512	71.169	0.000	56.464	0.000	197.067	27.757	35.546	26.963	0.000	0.000
71513	71.169	0.000	58.653	0.000	212.483	28.510	35.576	32.704	0.000	0.000
71514	71.169	0.000	60.933	0.000	219.900	28.822	35.563	39.801	0.000	0.000
71515	71.169	0.000	61.753	0.000	219.358	28.795	35.471	42.019	0.000	0.000
71516	71.169	0.000	61.844	0.000	215.368	28.625	35.305	41.040	0.000	0.000
71517	71.169	0.000	61.844	0.000	215.400	28.629	35.152	42.246	0.000	0.000
71518	71.041	0.000	61.801	0.000	198.484	26.575	34.545	41.622	0.000	0.000
71519	69.889	0.000	61.410	0.000	182.320	24.475	33.911	40.234	0.000	0.000
71520	66.688	0.000	60.325	0.000	175.304	24.021	33.652	37.321	0.000	0.000
71521	58.239	0.000	53.624	0.000	162.247	23.014	33.032	32.125	0.000	0.000
71522	28.896	0.000	24.326	0.000	132.020	17.993	30.960	19.108	0.000	0.000
71523	12.884	0.000	14.191	2.437	120.889	9.803	28.814	5.108	0.000	0.000
71524	6.162	0.000	11.695	0.006	119.640	9.872	28.904	5.108	0.000	0.000

Figure 6.4 The predicted ***hourly*** *electric consumption (kWh) for different end users in Correll Hall building on UGA campus. Values are associated with the temperature set point equal to 21° C (70° F) in classrooms and over 24 hours in July 15 (7 15 1, 7 15 2, etc.)*

The **Hourly** electric consumption for space cooling in Correll Hall building on UGA campus (EnCon) is predicted for temperature set points ranging from 21 to 28° C (69 to 82° F). Then, a quadratic multiple linear regression model is developed to predict electric consumption using the air temperature in room (T_{in}), outdoor ambient air temperature and relative humidity (T_{out} and RH_{out}), and the operation month and hour of the day (M, hr), as shown in Equations 6.2 and 6.3.

Equation 6.2 represents EnCon for outdoor ambient temperature values beyond 20° C or for the cooling season and Equation 6.3 shows this model for ambient temperature values below 20 °C or for the transient season. All temperature values in Equations 6.2 and 6.3 are in degrees

Celsius. T_{in} represents the indoor air temperature in °C that is assumed to be equal to the operative temperature indoors. T_{out} is the ambient or outdoor air temperature in °C. RH_{in} is the indoor relative humidity and RH_{out} shows the outdoor relative humidity. The units for the energy consumption is kWh of electricity consumption for Correll Hall.

In these Equations, "M" shows the month of the year (1 through 12) and "hr" shows the time of the day (1 through 24). Since this model only represents the energy consumption for cooling season, the "M" values could only vary between 4 and 10 representing the months of April through October (the tests were only conducted during these months). Also, the hours of HVAC system operation in Correll Hall building are between 6:00 am and 6:00 pm (and occasionally until 7:00 pm). Therefore, "hr" only varies between 6 and 19 in these equations ($4 < M < 10 \; and \; 6 < hr < 19$).

$$For\ T_{out} > 20°\ C$$

$$\begin{aligned} EnCon\ (kWh) &\\ = 117.65 &- 0.61\, T_{out} - 42.21\, RH_{out} + 0.38\, T_{in} - 0.4\, hr + 4.65\, M \\ &+ 2.84\, T_{out} \cdot RH_{out} - 0.13\, T_{out} \cdot T_n + 0.02\, T_{out} \cdot hr - 0.05\, T_{out} \cdot M \\ &- 1.5\, RH_{out} \cdot T_{in} + 0.2\, RH_{out} \cdot hr - 0.23\, RH_{out} \cdot M + 0.01\, T_{in} \cdot hr \\ &- 0.06\, T_{in} \cdot M - 0.02\, hr \cdot M + 0.06\, T_{out}^2 + 14.4\, RH_{out}^2 + 0.08\, T_{in}^2 \\ &+ 0.01\, hr^2 - 0.11\, M^2 \end{aligned} \tag{6.2}$$

$$For\ T_{out} < 20°\ C$$

$$En\ Con\ (kWh) = 118.57 - 0.03\, T_{out} + 0.74\, RH_{out} - 0.09\, T_{in} + 0.14\, hr + 0.04\, M \tag{6.3}$$

6.4. Methodology

A weighted-sum, genetic algorithm (GA) method is used to optimize the absolute values of occupants' mean thermal preference votes (Pref) in conjunction with the building energy cost/consumption. The absolute values of occupants' mean thermal preference votes in this study is called Pref and could vary between 0 and 3 (mean thermal preference vote varies between -3 and 3). Although the mean thermal preference vote in field surveys for this study was evaluated based on a five-point scale ranging from -2 to 2, votes equal to -3 and 3 show the thermal preference for extremely colder and extremely hotter thermal environment, respectively.

Energy cost significantly affects customers' energy consumption behavior and stimulates and incentivizes building owners and managers to participate in demand response programs. Some researchers thus far have optimized occupant thermal comfort with energy cost. However, minimizing energy cost, as opposed to energy consumption, may cause heating/cooling and ventilation or other necessary services in buildings to be overlooked. This happens because the energy cost could escalate rapidly and change in a wide range while energy consumption does not significantly vary and cannot decrease under a certain limit. For example, on a university campus, even if the electricity prices increase dramatically, energy consumption cannot be reduced below a specific limit to maintain the necessary services. Depending on a building's application, some devices need to continue operating and cannot be shut down or postponed to another time. An example of this is the monitors, projectors, some laboratory devices and computers in an educational building. Some building services are also essential in supporting health, productivity, and overall well-being of students and staff. Therefore, energy consumption could be a more realistic and occupant-oriented parameter to be optimized along with occupants' thermal comfort.

However, electrical energy consumption in a building can be affected by electricity prices, either through time-dependent tariffs for electric utility or demand response programs, or through occupants' consumption pattern and adaptive behavior to reduce utility bills. To consider the influence of real time price (RTP) for electricity on energy consumption and occupants' thermal comfort in this optimization study, the weighting factors (ω and 1- ω) for the two objective functions are defined as the function of current RTP for electricity. A fitness function for this optimization problem combines the weighted objective functions for energy consumption and thermal preference and is defined as follows:

$$ObjectiveFunction = \omega \cdot EnCon_N + (1-\omega) \cdot Pref_N \tag{6.2}$$

$$ObjectiveFunction = \omega.(((117.65 - 0.61\,T_{out} - 42.21\,RH_{out} + 0.38\,T_{in} - 0.4\,hr + 4.65\,M + 2.84\,T_{out} \cdot RH_{out} - 0.13\,T_{out} \cdot T_n + 0.02\,T_{out} \cdot hr - 0.05\,T_{out} \cdot M - 1.5\,RH_{out} \cdot T_{in} + 0.2\,RH_{out} \cdot hr - 0.23\,RH_{out} \cdot M + 0.01\,T_{in} \cdot hr - 0.06\,T_{in} \cdot M - 0.02\,hr \cdot M + 0.06\,T_{out}^2 + 14.4\,RH_{out}^2 + 0.08\,T_{in}^2 + 0.01\,hr^2 - 0.11\,M^2) - 128)/18.5) + (1-\omega).\left(3.30\,T_{in} + 23.90\,RH_{in} - 0.90\left(T_{op} \cdot RH_{in}\right) - 0.06\,(T_{in}^2) + 1.80\,(RH_{in}^2) - 43.42\right)/3 \tag{6.3}$$

Where Pref $_N$ is the normalized ($_N$) absolute value of mean thermal preference vote, EnCon $_N$ shows the normalized hourly energy consumption for space cooling in the building, and ω is the weighting factor as a function of RTP for electricity as shown in equation 6.4.

$$\omega = f(RTP) \tag{6.4}$$

The operative temperature inside the classrooms were limited to within the range of 20 and 30° C and are not allowed to exceed 30° C. It is recognized that a set point temperature equal to or beyond 30° C is above the normal expected range and is intolerable for majority of building occupants, but was set to illustrate the trend. Relative humidity indoors is assumed to be equal to 50%. "M" and "hr" in this optimization study are assumed to be 7 and 15 respectively. Generally, ambient air condition is assumed to be around the worst-case scenario in cooling season for Athens GA, i.e., 3:00 pm in the afternoon of July with ambient air temperature of 35° C and ambient relative humidity of 70%.

Hourly energy consumption for space cooling versus the indoor air temperature set point for the study in Correll Hall building was derived using the eQuest building energy simulation pack software described above, as a function of the indoor air temperature. Since the mean radiant temperature values in this study are almost equal to the air temperature values, it is assumed that indoor air temperature is equal to the operative temperature in this model (the operative temperature was described earlier in Equation 3.1). Considering that the scales of Pref and energy consumption are substantially different, these parameters need to be normalized before being combined into an objective function. To normalize each of these objective functions, the Utopia ($EnCon^U$ and $Pref^U$) and Nadir ($EnCon^N$ and $Pref^N$) points are calculated for each objective function as follows (Kim and De Weck 2006):

$$EnCon_{Norm} = \frac{EnCon - EnCon^U}{EnCon^N - EnCon^U} \tag{6.5}$$

And

$$Pref_{Norm} = \frac{Pref - Pref^U}{Pref^N - Pref^U} \tag{6.6}$$

In these Equations, "Norm" shows the normalized parameters. Utopia point or ideal objective vector provides the lower bound of the pareto optimal set where both objective functions are minimum. However, it is not normally feasible because of the conflicting nature of the individual objective functions (Grodzevich and Romanko 2006). A Nadir point provides the upper bound of the pareto optimal set. Nadir and Utopia points give us the length of the intervals where the optimal objective functions vary within the pareto optimal set. Utopia and Nadir point values for Pref and energy consumption (EnCon) reflect the minimum and maximum values for each objective function within the studied range and are as shown in Table 6.1:

Table 6.1 The Utopia and Nadir point values for Pref and EnCon (EnCon in kWh)

	Utopia	Nadir
Pref	0	3
EnCon	128	146.5

6.5. Results and Discussion

On the UGA campus, DR measures are implemented as a step function of RTP for electricity. When the electricity price is less than 20 cents per kWh, no DR measures are initiated. As RTP increases beyond 20 cents up to 50 cents, some DR measures are initiated, such as turning off lights, projectors and monitors, and computer systems in unoccupied spaces. When the RTP is between 50 cents and $1, more stringent measures will be taken, such as postponing the cleaning and janitorial services. For RTP more than $1, dimmed lighting and reduced HVAC services are set to be applied. Various DR strategies associated with different mathematical correlations between RTP and the weighting factor or ω are examined in this research. This includes a step function (as implemented on UGA campus), a linear function, and an exponential function. Various constraints for occupants' thermal preference values are also investigated to examine how satisfying different comfort ranges for mean thermal preference vote in classrooms may affect energy consumption. The following section presents each DR strategy with the associated impacts on the hourly energy consumption for space cooling in the cooling season and occupants' thermal comfort represented as Pref. Optimization results per different variables and the investigated ranges that are discussed hereafter are summarized as below:

- RTP for values between 0 and $1.
- ω as a function of RTP for three different DR strategies corresponding to ω as a step function (as is implemented on UGA campus), a linear function, and an exponential function of RTP.
- Pref or the absolute value for mean thermal preference vote against four different constraints ranges, i.e., -0.5 to 0.5, -1 to 1, -2 to 2, and -3 to 3.
- The hourly energy consumption for space cooling in Correll Hall building on UGA campus (kWh).

6.5.1. Demand Response Strategy on UGA Campus: Weighting Factor (ω) as a Step Function of RTP

In this section the DR strategy on UGA campus is evaluated and its impact on energy consumption and occupants' mean thermal preference vote is identified. Various constraints for occupants' mean thermal preference votes associated with different thermal comfort levels are examined. Table 6.2 shows how DR is normally being implemented based on the RTP for electricity on UGA campus. Weight or ω in section 6.4 is a step function of RTP for electricity.

Table 6.2 The demand response strategy on UGA campus based on the RTP for electricity

RTP	**ω**	**Common DR Measure on UGA Campus**	**DR Measure with Continuous HVAC Adjustment on UGA Campus**
< $ 0.20	0	None	None
$ 0.2 ≤ RTP < $ 0.50	0.5	Turning off lights and electric devices not in use	Turning off lights and electric devices not in use, HVAC adjustments

$ 0.5 ≤ RTP < $ 1	0.7	Postponing unnecessary tasks like cleaning	Postponing unnecessary tasks like cleaning, HVAC adjustments
RTP ≥ $1	1	Light dimming and reduced HVAC services (increased temperature set point)	Light dimming and reduced HVAC services (increased temperature set point)

Table 6.2 indicates that, on UGA campus, no adjustments is made to the HVAC system unless the RTP passes the $1 threshold. The HVAC system adjustment as a part of the DR program below this threshold does occasionally happen on UGA campus. However, the concerns of the increased thermal comfort complain rates and decreased thermal satisfaction level among building occupant prevents this strategy from becoming a common practice on the campus. The facility management on UGA campus that supported this study is interested in implementing the HVAC system adjustments during DR event if it does not adversely affect building occupants. The earlier results of this study (Chapter 3) revealed the potentials for implementing DR measures with increased cooling temperature set point for HVAC system on UGA campus that resulted in a slightly improved occupants' thermal satisfaction level when implemented properly. This study hereafter focuses on the "DR Measure with Continuous HVAC Adjustment on UGA Campus" and optimizing the hourly energy consumption for space cooling with occupants' thermal comfort with respect to this strategy.

Table 6.3 shows how the optimal room operative temperature changes based on the values for RTP and ω. As RTP increases, ω increases accordingly and more weight will be given to the objective function for energy consumption (EnCon). This will result in a higher room operative temperature or temperature set point in classrooms. An increased temperature set point would result in a higher thermal preference vote. The variations in Pref and EnCon values based on the RTP are also shown in Table 6.3 when mean thermal preference vote is restricted to a wide range of between -3 and 3. As a reminder, EnCon represents the hourly energy consumption for space cooling in Correll Hall building in kWh. Figures 6.5 depicts these correlations.

Table 6.3 The DR strategy on UGA campus where ω is a step function of RTP for electricity, as shown in Table 6.2. Preference is constrained to -3 and 3 (Pref is constraint to 0 and 3).

RTP ($)	**ω**	**T_{op} (°C)**	**Pref**	**EnCon (kWh)**	**Electricity Cost ($/hr)**
0	0	23.5	0	137.33	0
0.1	0	23.5	0	137.33	13.73
0.2	0.5	24	0.19	136.04	27.21
0.3	0.5	24	0.19	136.04	40.81
0.4	0.5	24	0.19	136.04	54.42
0.5	0.5	24	0.19	136.04	68.02
0.6	0.7	27.2	1.86	129.72	77.83
0.7	0.7	27.2	1.86	129.72	90.81
0.8	0.7	27.2	1.86	129.72	103.78
0.9	0.7	27.2	1.86	129.72	116.75
1	1	28.7	3.00	127.26	127.26

Figure 6.5.b shows that before initializing the demand response program (RTP < $0.2), the optimum operative temperature equals to almost 23.5° C that corresponds to the thermal preference or Pref value of zero. This is the optimum thermal preference vote that could be achieved in a building where occupants would not like any changes to be made to the thermal environment. The weight for energy consumption (EnCon) is zero at this range and thermal comfort is the only objective function to be optimized.

When RTP increases to beyond $0.2, the optimum indoor operative temperature increases to 24° C and Pref increases to almost 0.2, yet remains within the 80% acceptability range. According to ASHRAE Standard 55, a thermal environment is considered as comfortable if it is acceptable for more than 80% of building occupants. Based on the results from this study presented

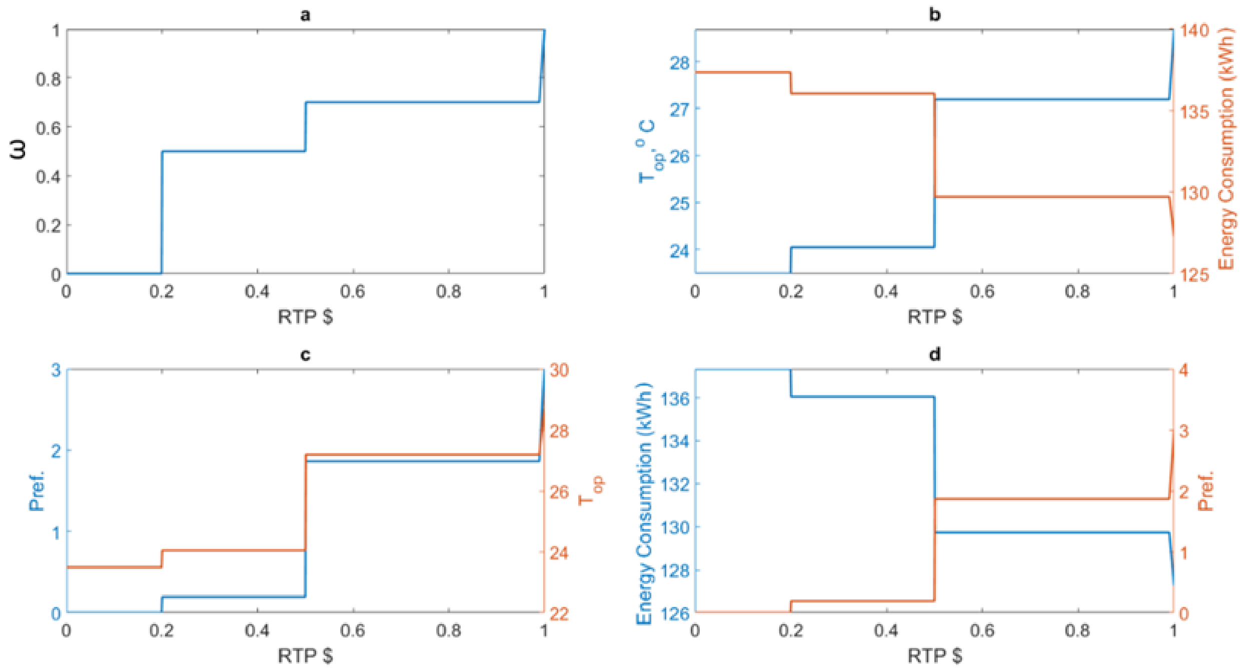


Figure 6.5 Variations of (a)weights or ω, (b) the optimized T_{op}, (c) the optimized Pref, and (d) the optimized EnCon vs. RTP during DR events. Pref changes between 0 and 3 (Preference changes between -3 and 3).

in Figures 3.9, 3.10, 5.3, and 5.4, a thermal environment is acceptable for more than 80% of building occupants if the mean thermal preference vote remains between -0.5 and 0.5 ($0 \leq$ Pref $\leq$ 0.5). Beyond this range thermal acceptability might substantially decrease although more data sets in room operative temperature values beyond 25° C is required to confirm this. These results may only be applicable to UGA campus.

When RTP values are greater than $0.5, the optimum operative temperature increases to 27° C and mean thermal preference vote increases to 2. Thus, the thermal environment would not be in the ASHRAE specified comfort range anymore. For RTP values equal or above $1, the optimum operative temperature increases to around 29° C and the corresponding value for mean thermal preference vote equals 3. This is the maximum possible value for Pref since it is constrained to remain between 0 and 3, and occupants would feel extremely hot (would prefer a much colder thermal environment) at this point. Energy consumption for this optimization problem and constraints varies between almost 137 and 127 kWh for RTP values equal to 0 and 1 respectively.

When mean thermal preference vote is constrained between -3 and 3 (Pref between 0 and +3), the optimum room operative temperature varies between almost 23.5 and 29° C. This ranges shrinks to between 23.5 and almost 25° C when mean thermal preference vote is limited to the range of between -0.5 and 0.5. If mean thermal preference vote is constrained to remain between -0.5 and 0.5 (representing at least 80% acceptability) the variations of room operative temperature and energy consumption with RTP is not significant (1.3° C and around 3 kWh), as shown in Table 6.4 and Figure 6.6. This means that the optimum thermal comfort on UGA campus could happen when indoor operative temperature in classrooms are kept between 23.5 and almost 25° C. Energy consumption for cooling in Correll Hall in this range varies between almost 137.3 to 134.4 kWh. The energy consumption in the range was increased by almost 5% (7.1kWh) by changing the mean thermal preference range constraints from between -3 and 3 to between -0.5 and 0.5.

Table 6.4 The DR strategy on UGA campus where ω is a step function of RTP, as shown in Table 6.2. Preference is constrained between –0.5 and 0.5.

RTP ($)	**ω**	**T_{op} (° C)**	**Pref**	**EnCon (kWh)**	**Energy Cost ($/hr)**
0	0	23.5	0	137.332	0
0.1	0	23.5	0	137.332	13.73
0.2	0.5	24	0.19	136.048	27.21
0.3	0.5	24	0.19	136.048	40.81
0.4	0.5	24	0.19	136.048	54.42
0.5	0.5	24	0.19	136.048	68.02
0.6	0.7	24.8	0.5	134.416	80.65
0.7	0.7	24.8	0.5	134.416	94.09

0.8	0.7	24.8	0.5	134.416	107.53
0.9	0.7	24.8	0.5	134.416	120.97
1	1	24.8	0.5	134.416	134.41

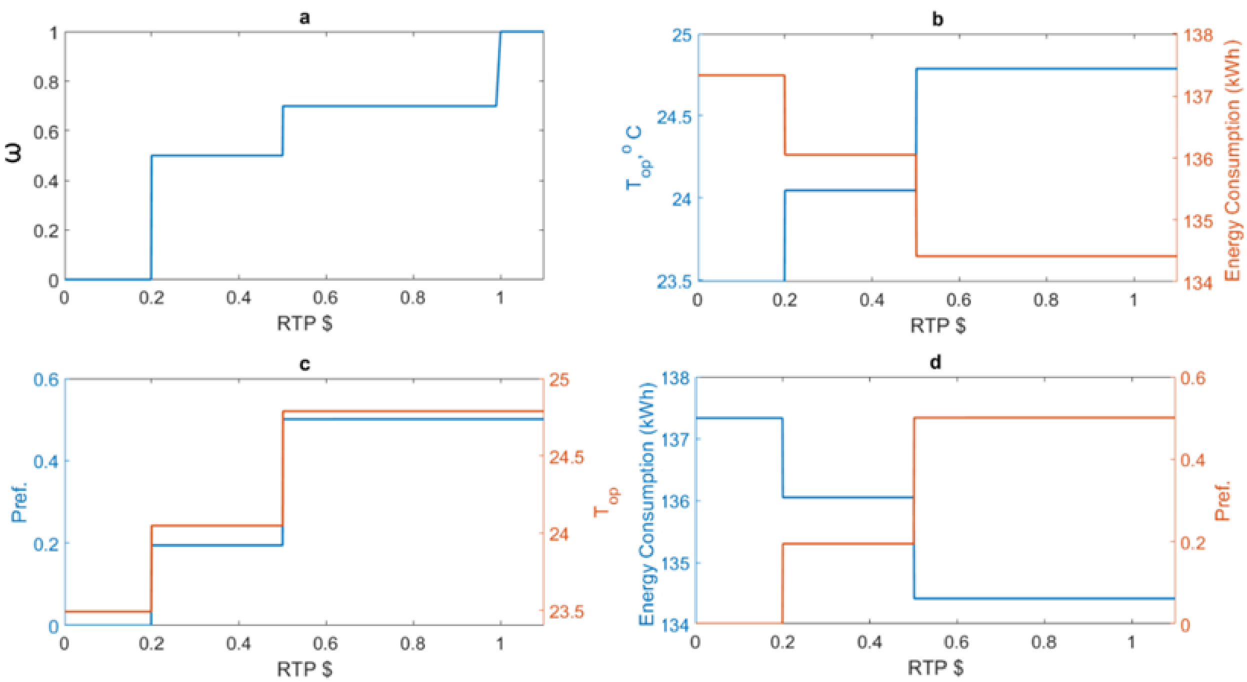
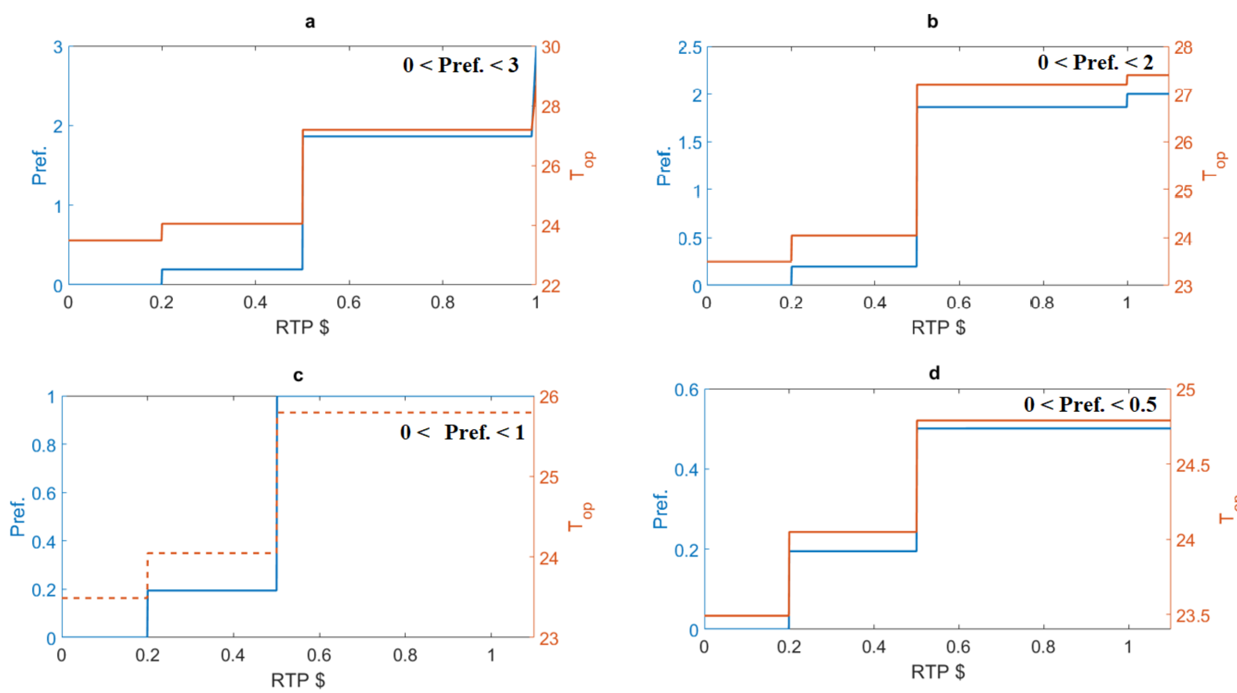


Figure 6.6 The variation of (a)weights or ω (b) the optimized T_{op}, (c) the optimized Pref, and (d) the optimized EnCon vs. RTP during DR events. Preference changes between -0.5 and 0.5.

Figures 6.7 and 6.8 reveal how optimized indoor operative temperature, and the corresponding Pref and EnCon vary versus RTP, with different constraints being chosen for Pref. Figure 6.7.e shows that if there is no constraint chosen for occupants' thermal preference vote, the operative temperature inside the classrooms could reach 30° C for RTP values beyond $1. Since the temperature is defined to remain between 20 and 30° C, this would be the maximum temperature that could be achieved during a demand response event in this study. We realized that for indoor operative temperatures beyond 30° C, there is a significantly increased thermal discomfort complaint rate from building occupants and the thermal environment is intolerable for majority of students. For this reason, the upper bound for the indoor operative temperature was chosen to be 30°C. Pref would be around 4 for this temperature that means that occupants would be extremely hot and uncomfortable in the warmer side of the scale and some health impacts and decreased concentration and productivity level might be expected. Occupants' thermal preference vote was studied based on a five-point scale ranging from -2 to 2 corresponding to Colder to Warmer. However, -3 and 3 were added to the scale later to represent Much Cooler and Much Warmer thermal preference votes. Any number beyond this range (-4 or below and 4 or beyond) is assumed to represent an intolerable environment where occupants' preferences is for an Extremely Colder or Extremely Hotter thermal environment.



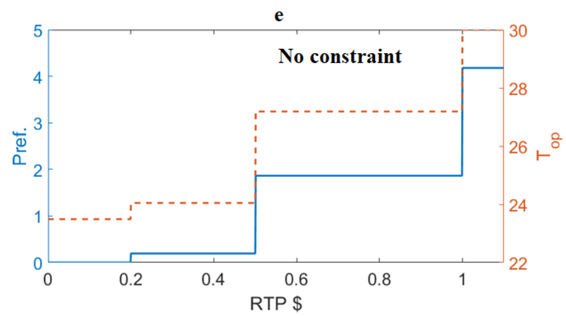


Figure 6.7 A comparison of the optimum T_{op} and Pref for different constraints for Preference vs. RTP

By stretching the thermal preference range from between -0.5 and 0.5 to between -1 and 1, the upper bound for the optimal operative temperature indoors reaches around 26° C, as shown in Figure 6.7.c. The maximum optimal energy consumption would decrease by 1.5% (or 2.0 kWh or kW per Hour for Correll Hall) and cost saving would be at least $2.0 per hour if RTP equals to $1. The impact of widening thermal preference range to between -1 and 1 might not be significant and this might still satisfy ASHRAS Standard 55 approved thermal acceptability range. More field studies are required to be conducted at indoor operative temperature ranges beyond 25.5° C to investigate the actual impact of this DR strategy on building occupants. There are not sufficient collected data sets at this temperature range in this study to draw valid conclusions.

The energy saving potential from increasing the operative temperature to 30° C (no constraint for Pref.), as shown in picture 6.8.e, is around 5.58 kWh or 4% compared to 24.8° C (corresponding to Pref equal to 0.5). Cost saving potential, provided that RTP is equal to 1$, would be $5.5 per hour.

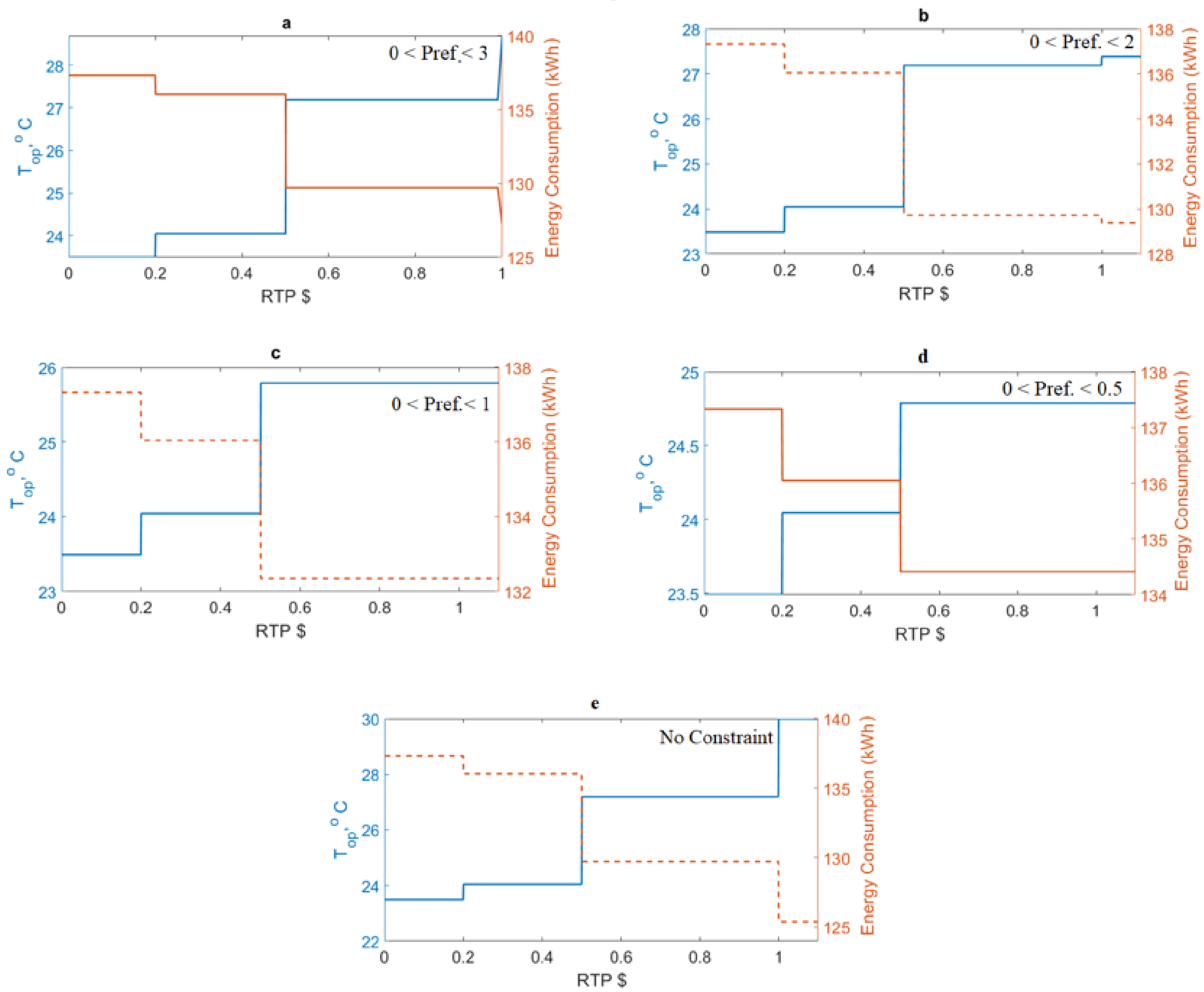


Figure 6.8 A comparison of the optimum T_{op} and EnCon for different constraints for Preference vs. RTP

6.5.2. Other Demand Response Strategies

In this section two other DR strategies are investigated and compared to the abovementioned strategy on the UGA campus; The first considers ω as a linear function of RTP while the second has ω as an exponential function of RTP. For the former DR strategy, ω is equal to RTP (as shown in Equation 6.7 and Figure 6.9.a) and the values for ω and RTP increase or decrease simultaneously. This strategy associates with a smooth and continuous adjustments in in

HVAC temperature set point and electricity consumption as RTP increases. Table 6.5 and Figure 6.9 show the weighting factor (ω), the optimized operative temperature (T_{op}), the absolute value for occupants' mean thermal preference vote (Pref), and the hourly energy consumption for space cooling in Correll Hall building versus RTP for electricity if this demand response strategy is implemented on UGA campus. The last column in the Table 6.5 shows the energy cost for space cooling where mean thermal preference vote is maintained between -0.5 and 0.5.

Figures 6.9.b and c show how the optimized energy consumption decreases and the optimized thermal preference increases as the optimized operative temperature goes up with increased RTP price. Clearly, the operative temperature and energy consumption change in the opposite direction meaning that a warmer classroom in the summer results in a decreased energy consumption. The mean thermal preference vote, however, moves in the same direction as T_{op} and a warmer classroom results in a higher mean thermal preference vote or higher desire for decreased air temperature indoors.

$$\omega = RTP \tag{6.7}$$

Figure 6.9.d depicts the trade-off between optimized Pref and EnCon and shows how their values change in conflicting directions. Since mean thermal preference vote only varies between -0.5 and 0.5 (Pref varies between 0 and 0.5), this Figure depicts the comfort zone for building occupants on UGA campus classrooms where thermal environment is acceptable for at least 80% of building occupants. The maximum optimal operative temperature in this range is around 25° C (77° F).

Table 6.5 A DR strategy where ω equals the RTP. Preference varies between -0.5 and 0.5.

RTP	ω	T_{op}	Pref	EnCon (kWh)	Energy Cost ($/hr)

0	0	23.5	0	137.332	0
0.1	0.1	23.5	0	137.332	13.73
0.2	0.2	23.5	0	137.332	27.46
0.3	0.3	23.5	0	137.332	41.20
0.4	0.4	23.5	0	137.332	54.93
0.5	0.5	24	0.19	136.049	68.02
0.6	0.6	24.8	0.50	134.416	80.65
0.7	0.7	24.8	0.50	134.416	94.09
0.8	0.8	24.8	0.50	134.416	107.53
0.9	0.9	24.8	0.50	134.416	120.97
1	1	24.8	0.50	134.416	134.41

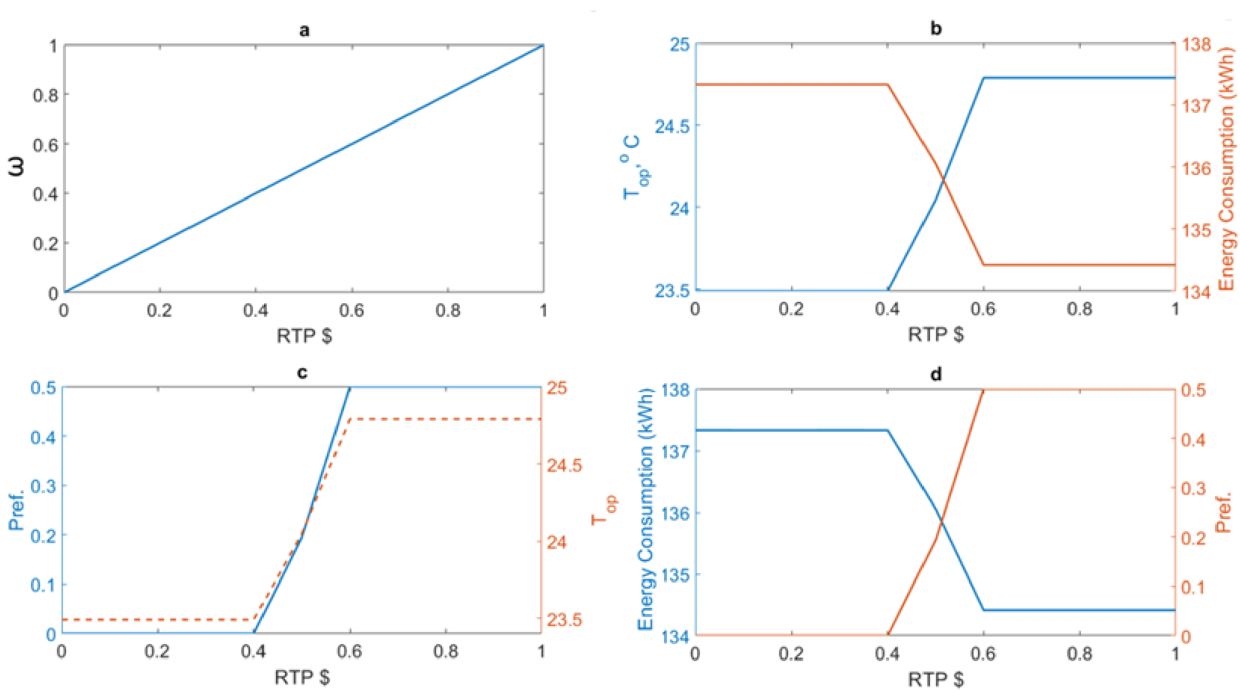
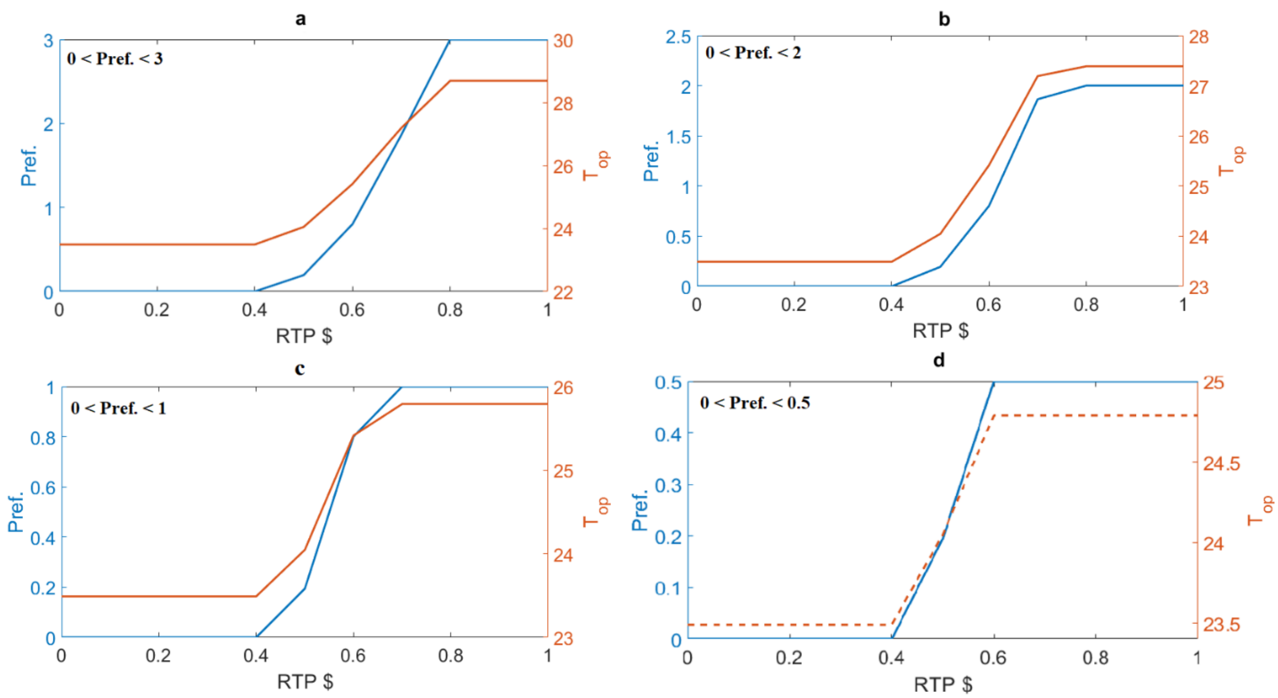


Figure 6.9 The variation of (a) weights or ω (b) the optimized T_{op}, (c) the optimized Pref, and (d) the optimized EnCon vs. RTP during DR event with ω=RTP. Preference changes between -0.5 and 0.5.

Figure 6.10 compares the optimized values for the absolute mean thermal preference vote and the room operative temperature versus different RTP values and for various ranges of mean thermal preference vote. Figure 6.11 shows the optimized solutions for Pref and EnCon versus

RTP for electricity. It depicts that widening the constraint range for thermal preference would result in a decreased energy consumption especially for higher RTP values (more than $0.5).

It is clear from the figures that the upper bound for the optimal operative temperature ($associated\ with\ RTP = \$1$) decreases from 30° C, where there is no constraint for thermal preference, to around 25° C, where mean thermal preference is constraint to between -0.5 and 0.5 and remains in the comfort zone. With RTP equal to $1, the predicted reduction in energy consumption for increasing the operative temperature indoors from around 25 to 30° C is approximately 7% with 9.0 kWh energy saving associated with $9.0 cost saving per hour. However, occupants' thermal comfort would substantially decrease for T_{op} equal to 30° C.



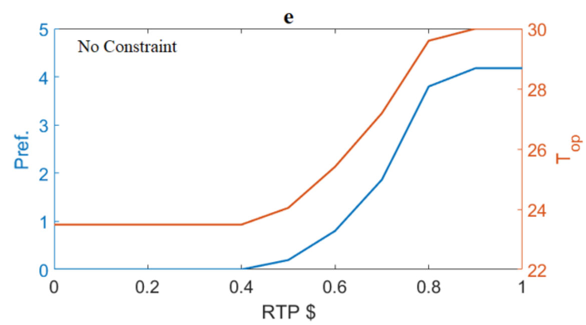


Figure 6.10 A comparison of the optimum T_{op} and Pref for different Preference constraints vs. RTP where ω equals RTP

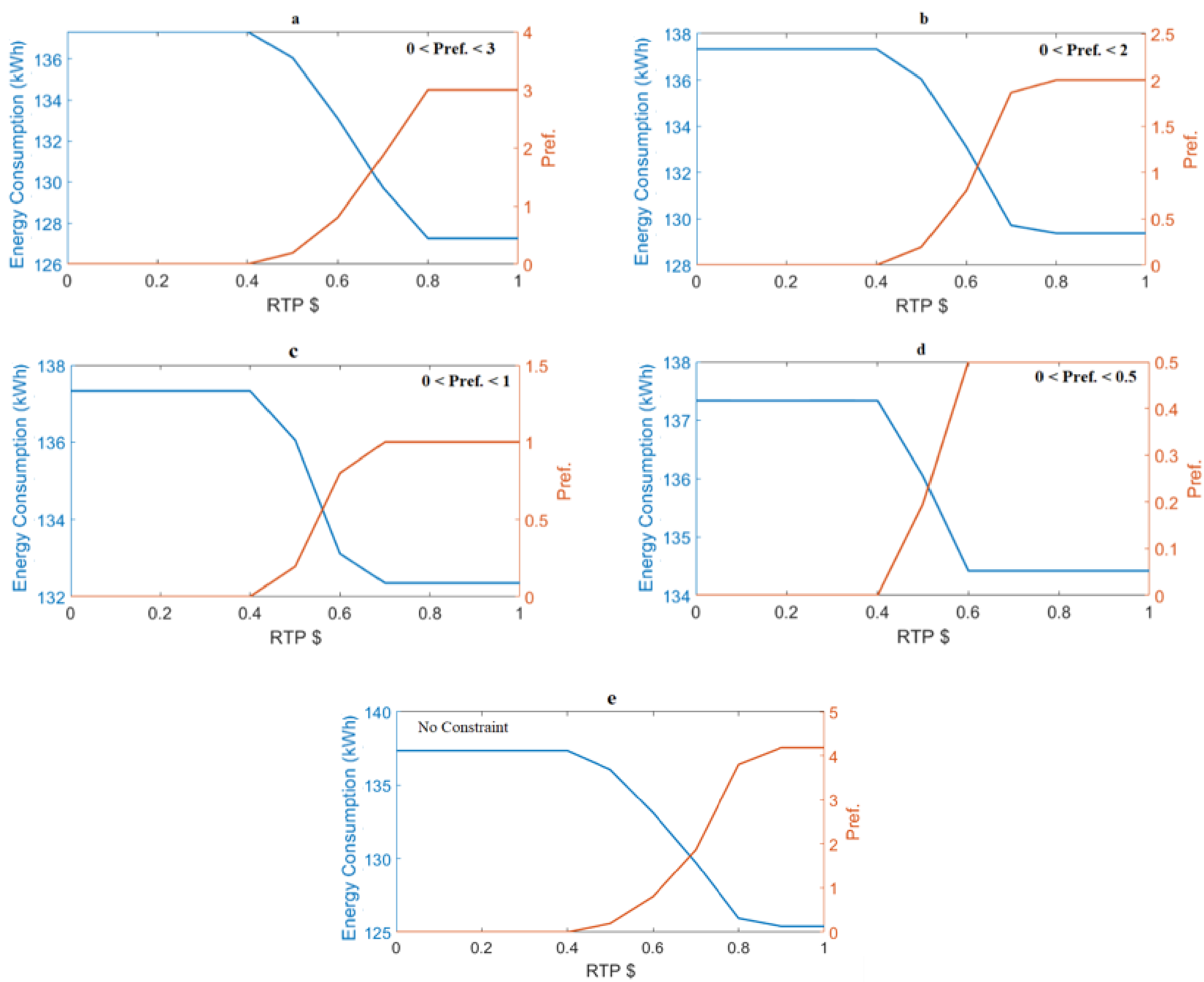


Figure 6.11 A comparison of the optimum T_{op} and Pref for different Preference constraints vs. RTP where ω equals RTP

Figures 6.12, 6.13 and 6.14 depict another DR strategy where ω increases exponentially with RTP. Figure 6.12 shows the exponential correlation between ω and RTP shown in equation 6.8. With this strategy, more weight is given to the energy consumption when RTP values are between 0 and 1, compared to the former strategy. This strategy is also concerned with continuous adjustments in building services and cooling temperature set point as RTP for electricity increases. The optimized values for the room operative temperature or T_{op}, Pref, and EnCon versus RTP for various constraints for occupants' mean thermal preference vote (Preference) are shown in Figures 6.13 and 6.14. It is clear from the Figures that the optimized values for operative temperature, Pref, and EnCon at the two extremes for RTP are the same as the former DR strategy where ω equals RTP. However, the corresponding values for different RTPs within the range are slightly different. Generally, there is no significant differences between the two strategies in this section while there are considerable differences with the DR strategy on UGA campus where ω is a step function of RTP. On UGA campus, the adjustments in building services as a part of the DR strategies are discontinuous and none smooth.

$$\omega = (-\exp(-\mathrm{RTP}) + 1)/0.6 \tag{6.8}$$

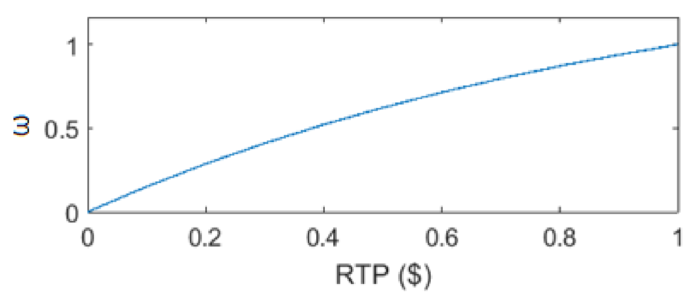


Figure 6.12 The exponential correlation between ω and RTP for the abovementioned DR strategy

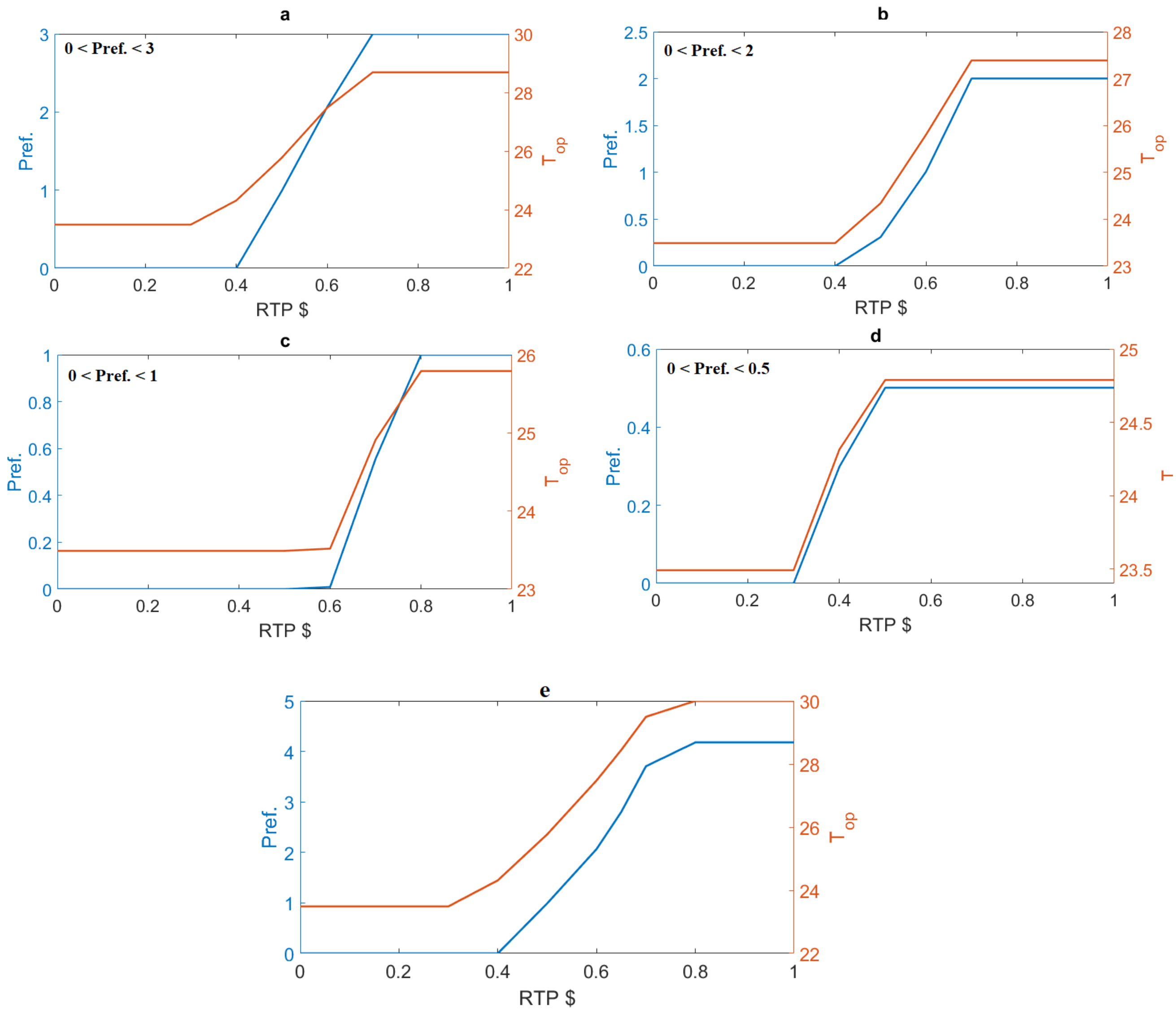


Figure 6.13 A comparison of the optimum T_{op} and Pref for different constraints for Preference vs. RTP where ω is an exponential function of RTP

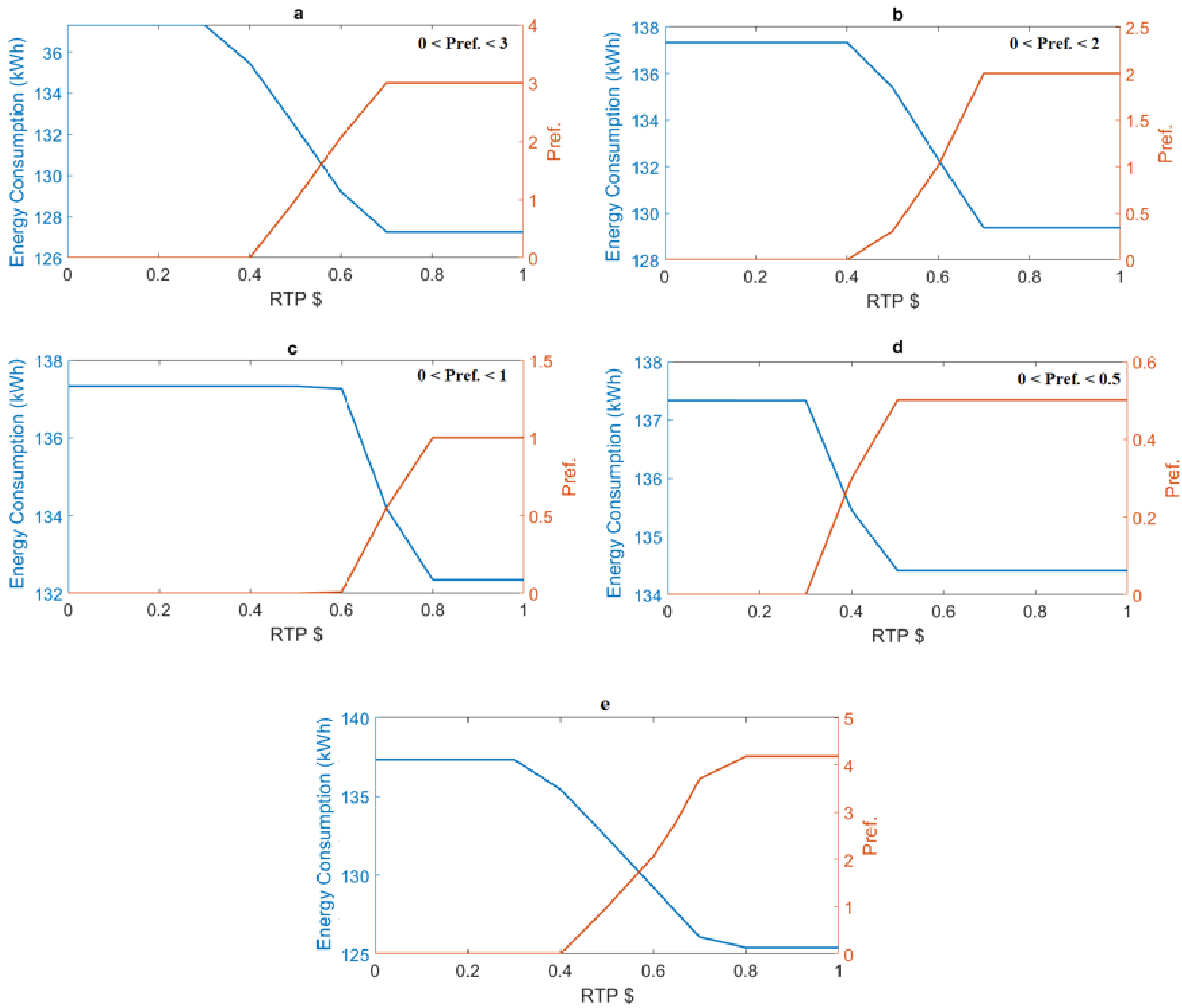


Figure 6.14 A comparison of the optimum EnCon and Pref for different constraints for Preference vs. RTP where ω is an exponential function of RTP

From the Figures in this section it could be noticed that for the discussed DR strategies, the T_{op}, EnCon, and Pref values for RTPs less than \$0.4 remain constant for all thermal preference constraints. This might be associated with the specific shape of the two objective functions (Equation 6.2), EnCon and Pref, and the resulting weighted-sum fitness function. At this RTP range, it is only the thermal preference function or Pref that specifies the minimum value for the fitness function that is being optimized. Both EnCon and Pref are parabolas, however, among the two objective functions only Pref has a vertex (minimum) in the evaluated RTP range. Since Pref represents the absolute value for the mean thermal preference vote, the vertex occurs around Pref equal to zero or T_{op} equal to 23.5° C. As RTP moves beyond $0.4, the EnCon gains more weight and the optimum values for the fitness function moves away from the vertex for Pref. Figure 6.15 depicts these interactions.

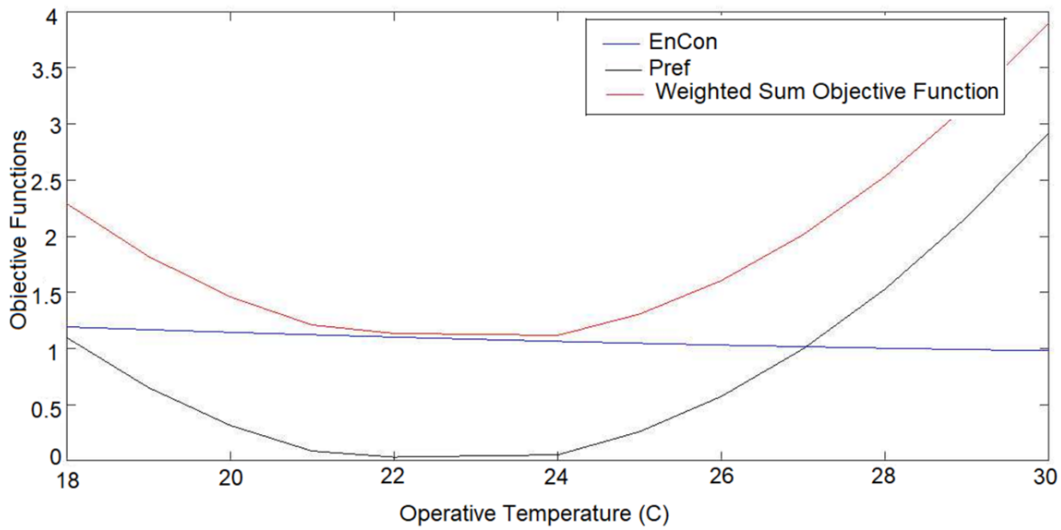


Figure 6.15 The objective functions for Pref and EnCon and the associated weighted-sum fitness function. The optimized value depends only on the minimum value of Pref for RTPs less than $0.4.

The demand response strategy on UGA campus demands less labor work or a less complicated control system since DR measures only happen in three or four different steps. This makes the DR control system simpler and easier. However, the two other DR strategies need a continuous adjustment in end-users' operating set pints and a complicated control system to achieve this. For example, a continuous adjustment in HVAC system temperature setpoint or a continuous light dimming, as RTP increases during peak hours, might happen as a part of the two latter DR strategies. Demand response measures on UGA campus for some RTP values within each step might be less or more stringent, compared the other two strategies, that could result in a lower or higher energy saving and associated impacts on occupants' thermal comfort. Therefore, the DR strategy on UGA campus less closely follows the RTP variations.

6.6. Multi-Objective Optimization

In this section, a multi-objective optimization method for optimizing occupants' mean thermal preference vote and energy consumption for space cooling on UGA campus classrooms is presented, as opposed to the weighted-sum GA method. This is another common optimization method for multi-objective problems. This method uses two separate objective functions, one for energy consumption and the other one for thermal preference. The optimization result is a Pareto Front or a set of optimized solutions. Pareto front reflects different optimized solutions based on various weights that the algorithm uses to create a set of optimized solution. Weights are not user-defined, therefore, there is no control over choosing the weighting factors by the users. Engineers or facility managers could decide which optimized solution to use, based on the values for both objective functions and/or other criteria. One of the drawbacks for this method in this study is that the impact of RTP for electricity is not considered in this optimization method. Thus, the impact of DR and the associated adjusted occupant behavior in response to the increased RTP values on energy consumption is not emphasized in this method.

However, electricity price or utility cost is usually the most important reason for consumers to adjust their consumption behavior. Electricity cost reduction is a primary incentive for customers to participate in DR programs while the amount of energy consumption and peak electricity demand are significantly important for power plants and energy providers, especially during peak demand hours. Figures 6.16 shows the pareto front for Pref and EnCon in Correll Hall building on UGA campus where Preference varies between -3 and 3. Depending on the energy consumption or thermal comfort limits, one could decide which optimized solution to use and T_{op} could be calculated accordingly. For example, in a hospital where maintaining patients' health and comfort is of a paramount importance, facility managers might decide to keep the thermal preference around zero regardless of the amount of energy consumption or electricity cost. On the other hand, in a residential building where building occupants could accept higher temperature variations (because of more adaptive options), facility managers might want to keep the utility cost (or the energy consumption) below a certain limit, for example $100 (or 130 kWh). Energy cost could be calculated by multiplying energy consumption into the RTP for electricity.

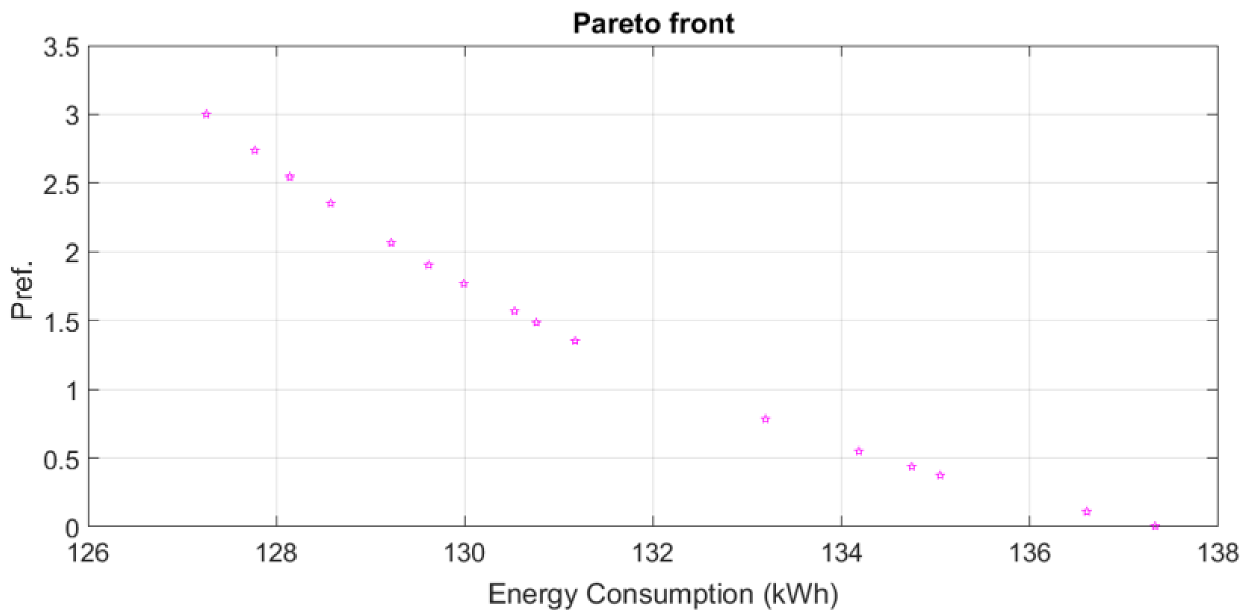


Figure 6.16 The Pareto Front for EnCon and Pref in Correll Hall Building on UGA campus. Mean thermal preference vote remains between -3 and 3.

As is clear from Figure 6.16, there is no dependency between the weighting factors for the two objective functions and RTP, since user has no control over choosing the weighting factors. Therefore, it is not possible to evaluate different demand response strategies using the GA multi-objective optimization method. This makes decision making process more complicated and time-consuming where the impact of energy price on energy consumption is not explicitly reflected. However, the weighted-sum method GA enables users to find the optimal solution based on various demand response strategies and RTP for electricity.

6.7. Summary and Conclusion

In this chapter, different HVAC control strategies were briefly introduced. The literature for optimizing energy cost or consumption with building occupants' thermal comfort was briefly reviewed and the associated thermal comfort indices used for those optimization methods were discussed. Most of the studied optimization methods were found to be either based upon the static PPM/PPD indices or using the graphical comfort zone method from ASHRAE Standard 55. In search of the most appropriate optimization method to optimize energy cost or consumption versus thermal comfort in this study, various optimization methods were benchmarked. Considering the nonlinear nature of the objective functions in this study, subject to nonlinear constraints, the weighted-sum GA as the most suitable method for solving the optimization problem in this study was chosen and the method was concisely described.

The hourly energy consumption for space cooling model for Correll Hall building, where the field studies were conducted on UGA campus, that was developed using eQuest software is also presented in this chapter. The thermal comfort model for students in classrooms, developed using data collected from field studies on UGA campus, is summarized. Each model (energy consumption or thermal comfort) represents an objective function that needs to be minimized. Utopia and Nadir point are used to normalize each objective function. The weighted sum of the normalized objective functions represents the cost function for the GA optimization problem. The demand response strategy implemented on UGA campus during peak demand hours is discussed in detail. For this strategy, ω (and 1-ω) which is the weighting factor for the objective functions changes as a step function of RTP for electricity. Two other demand response strategies are introduced where ω is a linear and an exponential function of RTP. Finally, the optimization problem is solved using a multi-objective GA method and the results are discusses. The most important conclusions in this chapter are made as follows:

- By decreasing the thermal preference constraint range on UGA campus, the upper bound for the optimized operative temperature in classrooms during DR events decreases and the energy consumption increases accordingly. This maximum optimized operating temperature equals 25, 26, 27.5 ,29 and 30° C for mean thermal preference values between -0.5 and 0.5, -1 and 1, -2 and 2, -3 and 3, and no constraint, respectively. The lower bound is 23.5° C associated with the mean thermal preference vote equal to zero for all constraint ranges.
- By increasing thermal comfort constraint range from between -0.5 and 0.5 to between -3 and 3, 7% energy saving could be achieved on UGA campus during peak demand hours with RTP equal or more than $1. This associates with almost at least $9.00 cost saving per hour for RTP equal to $1. However, this significantly and adversely affects occupants' thermal comfort.
- By widening the constraint range for mean thermal preference vote from between -0.5 and 0.5 to between -1 and 1 on UGA campus, 1.5% energy saving during peak demand hours could be achieved with RTP equal to or more than $1. There would

be at least \$2.00 cost saving per hour for Correll Hall alone. The impact on human thermal comfort needs more investigation and field studies to be conducted in the associated temperature range.

- With multi-objective optimization method, the impact of RTP for electricity and the associate adjustments in occupants' consumption behavior on the optimization results cannot be simply evaluated. The optimization result will be a set of optimal solutions or pareto front (instead of a single optimized solution). Therefore, consumers or facility managers would be responsible for decision making based on values for different objective functions (energy consumption and mean thermal preference vote in this study).

EPILOGUE

This study was initiated in 2014 with the aim of evaluating the potential for demand response (DR) implementations in air-conditioned buildings on UGA campus. The HVAC system adjustment and increasing the cooling temperature set point in commercial buildings during peak hours in summer afternoons was the focus of demand response program in this study. The capability of the HVAC systems on UGA campus to be involved in DR events and the potential energy savings was evaluated as well as the impact of the DR implementations on building occupants. Demand response, while saving energy and reducing peak electricity demand, could substantially and adversely affect building occupants if not implemented properly. HVAC system adjustment as a part of the DR program could result in reduced occupant thermal comfort. An impaired thermal comfort would adversely affect building occupants' health and wellbeing, their performance and productivity, and their mood and psychological state.

Initial field experiments in 2014 and 2015 verified the significant potential for energy saving (almost 12%) as a result of implementing DR on UGA campus. This was followed by extensive field measurements and thermal comfort surveys in Correll Hall building on UGA campus, over two years between Spring 2015 and Fall 2017, to evaluate the impact of DR on building occupants. Almost 1350 individual data sets were collected and analyzed in this study. The results revealed that building occupants on UGA campus have limited adaptive options and control over the thermal enviroemnmnt. This might have led to the isolation of buildings' indoor environment from the outdoor environment. This results in reduced occupants' seasonal and diurnal adaptive capabilities in buildings and accordingly, a larger amount of energy to be consumed for providing occupants' thermal comfort and maintaining the indoor operative temperature in a narrow range.

The results of this study also complied with other similar studies conducted all over the world, as discussed in Chapter 2 and Chapter 4, with occupants' neutral temperature being around 23.5° C. There was also some evidence of occupants' mean thermal preference for a cooler than neutral thermal environment on UGA campus, however, more field studies are required to be conducted to verify this result. It was also concluded that more than 80% of students on UGA campus would accept the thermal environment if their mean thermal preference votes remain between -0.5 and 0.5 based on a five-point scale for thermal preference.

Two adaptive thermal comfort models were developed based on the data collected during these field surveys, simulating occupants' mean thermal preference and their mean thermal sensation votes. It was argued that since mean thermal preference vote is not based upon the assumption of thermal neutrality being equal to thermal comfort, it outperforms the mean thermal sensation vote indices (AMV or PMV). Building energy consumption model was developed to simulate the real-time energy consumption for space cooling in Correll Hall building on UGA campus, using e Quest software. The weighted-sum genetic algorithm method was used to optimize occupants' mean thermal preference vote with building energy consumption for space cooling with respect to the real-time price (RTP) for electricity and for the DR strategy implemented on UGA campus. Results revealed the energy saving and cost saving potential of DR strategy against its impact on occupants' thermal preference. The weights for objective functions (thermal preference and energy consumption) could be adjusted based on the desired DR strategy or to emphasize one of the objective functions over another, depending on the building application or occupancy type or occupants' demographic features.

Further field studies and future works could investigate the impact of DR and the adjusted HVAC temperature set points on building occupants in a broader range of indoor operative conditions and also for buildings with more adaptive and control options. It is also encouraged to investigate the impact of energy informatics and occupants' environmental awareness on their adaptive behavior and their thermal comfort perception.

ACRONYMS

ACT	Adaptive Comfort Temperature
Adj-R2	Adjusted R-Squared or Adjusted Coefficient of Determination
AMV	Actual Mean Vote for Thermal Sensation
aPMV	Adaptive Predicted Mean Vote for Thermal Sensation
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ANOVA	Analysis of Variance
C	Comfort Vote (Thermal)
CBE	Center for Built Environment
CLO	Clothing Insulation ($1\ CLO = 0.155\ m^2.℃/W$)
DLC	Direct Load Control
DR	Demand Response
EnCon	Hourly Energy Consumption for Space Cooling in Correll Hall Building on UGA campus (kWh)
e_p	Expectancy Factor
ePMV	Extended Predicted Mean Vote for Thermal Sensation
ET *	Effective Temperature
ET^*_{out}	Mean Outdoor Effective Temperature
FLC	Fuzzy Logic Controller
GA	Genetic Algorithm
hr	Hour of the Day
HVAC	Heating, Refrigerating, and Air Conditioning
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
M	Month of the Year
MET	Metabolic Rate ($1\ MET = 58.2\ W/m^2$)
MPC	Model Predictive Control
MTSV	Mean Thermal Sensation Vote for Thermal Comfort
N	Nadir Point
NN	Neural Network
Norm	Normalized Value
nPMV	New Predicted Mean Vote for Thermal Sensation
OB	Occupant Behavior
PCS	Personalized Conditioning Systems
PMC	Phase Change Material
PD	Proportional-Derivative
PD	Percentage of Dissatisfaction
PEC	Personal Environmental Control

PID	Proportional-Integral-Derivative
PMV	Predicted Mean Vote for Thermal Sensation
PPD	Predicted Percentage of Dissatisfied
PPDF	Fanger's Predicted Percentage of Dissatisfied
PPDG	Gagge's Predicted Percentage of Dissatisfied
Pref	The Absolute Value of Mean Thermal Preference Vote
Preference	Thermal Preference Vote
PSO	Particle Swarm Optimization
r	Correlation Coefficient
R^2	R-Squared or the Coefficient of Determination
RH_{in}	Indoor Relative Humidity
RH_{out}	Ambient or Outdoor Relative Humidity
RMSE	Root Mean Square Error
RTP	Real Time Price for Electricity
SET	Standard Equivalent Temperature
SET*	Standard Effective Temperature
SSR	Sum Squared Regression
SST	Sum Squared Total
STDEV	Standard Deviation
T_c	Comfort Temperature (°C or F)
T_{db}	Dry Bulb Temperature (°C or F)
T_{exp}	Exponentially weighted Mean Ambient Air Temperature (°C or F)
$T_{e, ref}$	The weighted Average of Outdoor Ambient Air Temperature (°C or F)
T_g	Globe Temperature (°C or F)
T_{in}	Indoor Air Temperature (°C or F)
T_{lower}	The Lower Limit of The Comfort Band (°C or F)
Tm	Daily Average of Ambient Air Temperature (°C or F)
T_m	Average of Minimum and Maximum Daily Outdoor Temperature (°C or F)
T_{mr}	Mean Radiant Temperature (°C or F)
T_n	Neutral Temperature (°C or F)
T_{out}	Ambient or Outdoor Air Temperature (°C or F)
T_o	Daily Outdoor Temperature (°C or F)
T_{olt}	Outdoor Long-Term Temperature (°C or F)
$T_{o,m}$	Outdoor Monthly Mean Temperature (°C or F)
T_{op}	Operative Temperature (°C or F)
T_{rm}	Weighted Running Mean Outdoor Air Temperature (°C or F)
T_{upper}	The Upper Limit of The Comfort Band (°C or F)
TOE	Time of Exposure to the Room Thermal Environment
U	Utopia Point
UGA	University of Georgia
δ	Mean Thermal Preference Vote
ν	Air Speed (fpm or m/s)
ω	Weight

ΔM	The Absolute Value of Differences between the Seven-Point Scale Markers (for Thermal Sensation) and the Average Vote from the Continuous Scale within Each Category

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APPENDICES

APPENDIX A: Predicted Mean Vote and Predicted Percentage Dissatisfied (PMV/PPD) Calculation

The heat balance model uses the predicted mean vote (PMV) index as the predictor of mean thermal sensation for a large group of building occupants. This index was developed based on a seven-point scale ranging from -3 for Cold to +3 for Hot. PMV is calculated using the following equation:

$$PMV = [0.303\,.\exp(-0.036\,.MET) + 0.028].\{(MET - W) - 3.05\,.10^{-3}.[5733 - 6.99(MET - W) - p_a] - 0.42\,.[(MET - W) - 58.15] - 1.7\,.10^{-5}.MET.(5867 - p_a) - 0.0014.MET.(34 - t_a) - 3.96\,.10^{-8}.f_{cl}.[(t_{cl} + 273)^4 - (\overline{t_r} + 273)^4] - f_{cl}.h_c.(t_{cl} - t_a)\}$$

Where

$$t_{cl} = 35.7 - 0.028.(MET - W) - I_{cl}.\{3.96\,.10^{-8}.f_{cl}.[(t_{cl} + 273)^4 - (\overline{t_r} + 273)^4] + f_{cl}.h_c.(t_{cl} - t_a)$$

$$h_c = \begin{cases} 2.38\,.|t_{cl} - t_a|^{0.25} & for \quad 2.38\,.|t_{cl} - t_a|^{0.25} > 12.1\,.\sqrt{v_{ar}} \\ 12.1\,.\sqrt{v_{ar}} & for \quad 2.38\,.|t_{cl} - t_a|^{0.25} < 12.1\,.\sqrt{v_{ar}} \end{cases}$$

$$f_{cl} = \begin{cases} 1.00 + 1.290\,I_{cl} & for\ I_{cl} \leq 0.078\,m^2.K/W \\ 1.00 + 1.645\,I_{cl} & for\ I_{cl} > 0.078\,m^2.K/W \end{cases}$$

And

$MET = Metabolic\ rate\ \left({}^{W}/_{m^2}\right)$

$W = The\ effective\ mechanical\ power\ (W/m^2)$

$I_{cl} = Clothing\ Insulation\ (m^2.K/W)$

$f_{cl} = Clothing\ surface\ area\ factor$

$t_a = Air\ temperature$ (℃)

$\overline{t_r} = Mean\ radiant\ temperature$ (℃)

$v_{ar} = Relative\ air\ velocity\ (m/s)$

$p_a = Water\ vapor\ partial\ pressure\ (P_a)$

$h_c = Convective\ heat\ transfer\ coefficient\ (W/(m^2.K))$

$t_{cl} = Clothing\ surface\ temperature$ (℃)

$1\ MET = 58.2\ W/m^2$

$1\ CLO = 0.155\ m^2.℃/W$

The predicted percentage dissatisfied (PPD) represents the percentage of people who are dissatisfied with the thermal environment in a large group of building occupants. PPD is calculated using the equation below:

$$PPD = 100 - \exp(-0.0335\ .PMV^4 - 0.2179.PMV^2)$$

APPENDIX B: Survey Questionnaire

The survey questionnaire used for this study on UGA campus is shown below. This questionnaire first asks about occupants' thermal sensation vote based on the ASHRAE seven-point scale for thermal sensation (A). The next two questions ask about occupants' thermal preference votes based on a five-point scale and their thermal acceptability votes based on a binary scale (B and C respectively). Question "D" investigates the occupants' most recent thermal experience before reporting their subjective votes that might have affected their thermal expectations or perceptions. Question "E" concerns with occupants' demographic and physiological information. Part "F" surveys occupants' clothing insulation level or CLO values. Finally, the last question, "G", surveys occupants' adaptive behavior or their interactions with the building that could help improving their thermal comfort or alleviating their thermal discomfort.

Date: ----------------------- *Time:* ----------------------- *Location:* -----------------

Voluntary Thermal Comfort Survey

I am with the college of engineering and we are conducting a survey of the thermal comfort in this building. This is an IRB approved survey.

A. **Would you please say how this area has been today during your class session?**

1. Too hot	2.Warm	3. Slightly warm	4.Just right	5.Slightly cool	6.Cool	7.Too cold

B. **Would you prefer this area to be:**

1. Much warmer	2. A little warmer	3. It is just right	4. A little cooler	5. Much cooler

C. **Do you consider this thermal environment:**

☐ Acceptable ☐ Unacceptable

D. **Where have you been at least 15 minutes prior to entering this room?**

☐ Inside the building ☐ Outdoor environment

E. **Personal Information**

Gender: Male, Female, NA	3.Health Status: Healthy or Sick	4.Age Group (Student, Faculty, Parents)	5. Time of Exposure: How long have you been in this room today?

F. **Would you please briefly describe what are you wearing right now? Just describe your outfit (example: hat+ short sleeve shirt +walking shorts+ sneakers +socks)**

Response: ____

G. **Have you involved in any behavioral adjustments (like putting on or taking off clothes, changing location, etc.) in order to make this thermal environment more favorable? If so, please briefly explain it.**

Response: ____

Thank you!

APPENDIX C: Statistics

In this section, it is descried how the correlation coefficient between two variables, and the R-Squared or R^2, adjusted R^2 (adj-R^2), and the root mean square error (RMSE) are calculated for any regression model.

Correlation Coefficient is the measure of the linear dependence between any two variables (Mathworks.f). If the scalars “A” and “B” have “n” observation each, the correlation coefficient between them is calculated as:

$$r = \frac{1}{n-1}\sum_{i=1}^{n}(\frac{A_i - \mu_A}{\sigma_A})(\frac{B_i - \mu_B}{\sigma_B})$$

Where μ is the mean and σ is the standard deviation of each variable. Alternatively, it is defined based on the covariance (Cov) of A and B as:

$$r = \frac{Cov(A, B)}{\sigma_A \sigma_B}$$

Coefficient of determination or R-Squared (R^2) indicates the proportionate amount of variations in the response variable (y) explained by the independent variable (x) in a linear regression model (Mathworks.g). A larger R^2 values indicated the larger variability in the linear regression model. If SSR is the sum of squared regression and SST is the sum of squared total defined as:

$$SST = \sum_{i=1}^{n}(y_i - \bar{y})^2$$

$$SSR = \sum_{i=1}^{n} (y_i - f_i)^2$$

Where y is the response variable in the data set and “f” is the fitted or predicted value for response variable by the model. $\bar{y}$ is the mean of the observed data. Finally, R^2 is defined as:

$$R^2 = \frac{SSR}{SST}$$

The Adjusted R^2 (Adj-R^2) adjusts the R^2 for the number of variables in the model and is defined as:

$$Adj - R^2 = \left(\frac{n-1}{n-p}\right) R^2$$

Where p is the number of regression coefficients including the intercept in the linear regression model. Root Mean Square Error or RMSE is also calculated using the following equation:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (f_i - y_i)^2}{n}}$$