2018 Building Performance Analysis Conference and
SimBuild co-organized by ASHRAE and IBPSA-USA
Chicago, IL
September 26-28, 2018

EXPLORING THERMAL COMFORT ACCEPTANCE CRITERIA IN ENERGY MODELING

Elvin Ruya[1], and Godfried Augenbroe[2]
[1]Bractlet Inc., Austin, TX
[2]Georgia Institute of Technology, Atlanta, GA

ABSTRACT

Thermal comfort dominates the decisions on the HVAC (heating, ventilation, air conditioning) sizing and operations. Despite industry standards aim to achieve the perfect occupant comfort, they mostly fail in occupant satisfaction and cause superfluous energy consumption. Similar to design practices, energy modeling tools also depend on the predefined standards to determine the acceptable thermal comfort levels which leads to system oversizing.

In the first paper, we demonstrated the impact of the autosize option in system sizing and explored the use of uncertainty analysis with the consideration of the offsets between energy consumption decrease and unmet hours increase. This paper analyzes the impact of different tolerances that has been widely used in energy modeling industry, inspects unmet load hour calculation methods of energy simulation tools and discusses the robustness of the 300 hour limitation of ANSI/ASHRAE/IES Standard 90.1. Finally, it explores a new framework to guide the unmet hour acceptance criteria and demonstrate energy saving possibilities through downsizing approach.

INTRODUCTION

Buildings account for around 40% of the energy consumption and assumingly it will increase around 5% by 2040. According to data surveys office buildings represent the highest percentage among other building types. Space heating, ventilation, air conditioning (HVAC) systems constitute around 40% of the commercial sector end use (U.S DOE, Annual Energy Outlook 2017). One of the very known reasons of this high contribution is referred to equipment oversizing (Woradechjumroen et al. 2013). Various researches show that design engineers, HVAC engineers tend to consider extreme conditions and use safety factors to mitigate the potential risk of undersizing and occupant discomfort (Djunaedy et al. 2010).

Energy modeling tools base on the same underlying principle which often results in the oversizing of HVAC systems while not guaranteeing the occupant comfort (Ruya and Augenbroe 2016). Oversizing issue regarding to outdated thermal comfort standards and its negative outcomes on energy, occupant comfort and equipment life has been discussed for years, however no previous study addressed the issue from energy modeling standpoint. Moreover, guidelines and standards are vague when defining the unmet hour reporting tolerances which lead modelers, practitioners to set different tolerances in order to achieve 300 maximum allowable limit of ANSI/ASHRAE/IES Standard 90.1 Some of the commonly used default tolerances are 0.2K for “OpenStudio” and “DesignBuilder” and 1.1C (U.S. DOE EnergyPlus version 8.7 Input Output Reference) for “IES VE” (Unmet Load Hours Troubleshooting Guide 2013).

ASHRAE 90.1-2007 Appendix G defines “Unmet load hour” as “an hour in which one or more zones is outside of the thermostat setpoint range” (ASHRAE 90.1-2007). However, the definition has changed in ASHRAE 90.1-2010 Appendix G to “an hour in which one or more zones is outside of thermostat setpoint plus or minus one half of the temperature control throttling range. Any hour with one or more zones with an unmet cooling load or unmet heating load is defined as an unmet load hour.” Lastly, 300 maximum allowable limit is imposed on unmet load hours for both the proposed design and baseline building designs (ASHRAE 90.1-2010).

As thermal comfort becomes the main influence of HVAC sizing and operations, it is important to understand its underlying principles and how it can be interconnected with building energy consumption (Jazizadeh et al.2013). ASHRAE 55 defines thermal comfort as “that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation (ASHRAE Standard 55). According to Nicol and Humphreys success of a building thermal comfort should involve right decisions on energy consumption and sustainability as well as comfort (Nicol and Humphreys 2002).

Kumar et al. also point to energy saving potentials by properly predicting actual thermal comfort which will avoid oversizing issues (Kumar et al. 2010).

The PMV/PPD is probably the most commonly used thermal model which has been developed through extensive laboratory experiments in 70’s by Fanger

© 2018 ASHRAE (www.ashrae.org) and IBPSA-USA (www.ibpsa.us).
For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE or IBPSA-USA's prior written permission.

(Fanger 1970). It is a static model where occupant is assumed to be a passive recipient (deDear and Brager 1998).Fanger developed the PMV (predicted mean vote) index for the HVAC engineers to be able to predict the acceptable thermal environment through a comprehensive experimental work. Study established relationships between skin temperature, activity levels and sweat secretion which then used in heat balance equations to determine the comfort equation. Predicted mean vote (PMV) is derived from the comfort equation which is a function of air temperature, mean radiant temperature, relative air velocity, air humidity, activity level and clothing insulation (Yang et al. 2013). According to this study, these six primary factors are substantial to quantify the thermal comfort. ASHRAE 55 defines acceptable environment as "an environment that substantial majoritty of the occupants would find thermally acceptable" (ASHRAE 55-2010). Substantial majority can be referred to at least 80% of the occupants based on the comfort zone limits of ASHRAE 55.

When considering the variations in a large group of people, there will always a percentage of people who are dissatisfied with the climatic conditions. Therefore, a PPD index (predicted percent dissatisfied) which is also based on thermal sensations scale was developed to represent the dissatisfaction (Brager et al. 1993).

Various studies discuss solutions for better thermal comfort assessments. In addition to commonly used standards (ASHRAE 55, ISO 7730, EN 15251), different methods are analyzed such as adaptive comfort strategies, smart sensors, uncertainty analysis and leveraged empirical data to obtain more reliable and predictable thermal comfort acceptance criteria. The adaptive comfort principle assumes that people would react in ways to restore their comfort. This could be through changing their clothing or using air movement to adjust their comfort level which does not depend on the HVAC system (Nicol and Humphreys 2002). Because the PMV/PPD model does not account for the thermal adaptation to indoor climate, it is not applicable to naturally ventilated buildings (deDear - Brager 1998). Occupants of centrally ventilated buildings are treated as passive recipients of their indoor environment controls and they tend to prefer feeling cooler than neutral in warm climates and warmer than neutral in colder climates (deDear and Brager 1998). While Adaptive Comfort Standard (ACS) of ASHRAE is mainly used by naturally ventilated buildings, Kampelis et al. proposes a discomfort score (DS) which based on ACS of ASHRAE to evaluate demand response and thermal comfort. The correlation between the mean outdoor air temperature and indoor operative temperature is used to set the optimum temperature and allowable acceptability criteria for the mixed-mode buildings. (Kampelis et al. 2017). Studies relying on occupant feedback address conventional assumptions when occupants are keeping out of the loop as the reason of inadequate thermal comfort and excessive use of energy (Sanguinetti et al. 2016). Findings of Jazizadeh et al. show that standardized temperature setpoints for a given space do not guarantee a perfect occupant comfort; 65% of the occupant perceptions were different from neutral conditions. Thus, continuous and real-time data would provide more effective results (Jazizadeh et al. 2011). While thermal sensing programs can be very convenient for the participants as they are accessible via mobile web applications or web portals, these programs need to be maintained regularly (Yang et al. 2013). Uncertainty analysis is another method that can be chosen over deterministic analysis which mostly relies on the safety factors and unrealistic assumptions, to quantify the risk of unmet hour occurrences (Ruya and Augenbroe 2016). Occupant behavior which is dependent on the cultural and psychological factors is an unknown for buildings, especially for naturally ventilated buildings where occupant has control over thermal condition and air change of the building. Chen et al. emphasized that unrealistic occupant behavior models might cause large discrepancies which will mislead the implications (Chen et al. 2017).

In the absence of dynamic occupant feedback, facility managers, building engineers tend to set building set points aggressively which decrease efficiency of building systems and occupant satisfaction (Jazizadeh et al. 2013). ASHRAE RP-884 field study database showed that narrow setpoint temperature ranges do not result in higher occupant satisfaction than wider ranges of 4-6K. However, its more common to see very narrow ranges in practice such as 2K (Hoyt et al. 2014). We aim to demonstrate energy saving potentials which is the result of downsizing possibilities when wider setpoint ranges are considered. Results of many studies prove that extending thermostat setpoints will have significant impacts on building energy consumption by not over heating/cooling spaces and letting passive componenets to play a role in the air conditioning while maintaining the overall thermla comfort of the building. 12-20% savings were achieved for large office buildings across different climate regions (16 U.S cities) by increasing the ranges by 2degrees on both heating and cooling side (Fernandez et al. 2012). Another report of PNNL which uses same prototype buildings that were used in their previous report (Fernandez et al. 2012), shows that wider deadband and night setbacks was the top performing energy efficiency measure for both natural gas and overall site energy savings (Fernandez et al. 2017).

This paper employs a downsizing approach to the main cooling and heating equipment of the selected buildings

© 2018 ASHRAE (www.ashrae.org) and IBPSA-USA (www.ibpsa.us).
For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE or IBPSA-USA's prior written permission.

in order to quantify the energy saving opportunities. Various downsizing strategies has been analyzed for the typical commercial office HVAC equipment to inform designers, manufacturers that conventional sizing methods lead to oversizing. For instance, Woradechjumroen et al. conducted their study on oversized RTUs which result in short-time running cycles at design conditions whereas they can run continuously at smaller capacities (Woradechjumroen et al. 2013). Similar to the issue mentioned above, conventional chiller sizing method is also based on the peak cooling load assumptions which lead to chiller oversizing, decrease in system efficiency and increase in initial and maintenance cost (Kang et al. 2017). Our study integrates downsizing aspect of different heating and cooling equipment which are commonly used in commercial office buildings with a new method of thermal comfort assessment. We further analyzed the impact of the climate region (8 cities in US) and building scale. The aim is to clarify the acceptable unmet hour ranges for the building energy simulation practitioners, to show the trade-off between energy savings and decreased thermal comfort, and to discuss the effect of downsizing to energy saving in different climates.

METHODOLOGY AND CASE STUDIES

This study introduces a new method for evaluating thermal comfort acceptance criteria for commercial office buildings in different scale and climates. There are five main steps that build up the main framework of the paper.

1- Building models

90.1 Commercial prototype building models are used for the analysis. Three different office types (small, medium and large) in 8 climate regions (1A-2A-3A-4A-5A-6A-7-8) are selected as case study models. In order to make fair comparisons, availability schedules of AHU's (air handling unit) are changed from night cycle to fixed schedules and timestep intervals are fixed to 10 min (timestep 6) for all models. Additionally, thermostat setpoints are set to 70-72F (21.11-22.22C) which are described as the most commonly used setpoint range in practice and thermostat setbacks are removed from the model (Hoyt et al. 2014). Nightcycle (optimal start) and thermostat setback could be counted as energy saving measures which may not represent the majority of the HVAC operations (Fernandez et al. 2017). Lastly, supply fan typology is also standardized and some of the variable speed fans are changed to constant volume which eliminates the uncontrolled fan consumption increase in return to cooling capacity decrease for the downsizing step.

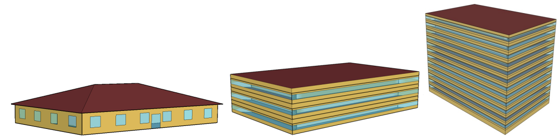

Figure 1 Small-Medium-Large Office Buildings

2- Model Runs

Tuned models were run annually via EnergyPlus simulation engine with related AMY (actual meteorological year) weather files based on their climate region. AMY data were particularly chosen over the TMY (typical meteorological year) weather data due to TMY's lack of ability to represent the actual conditions and capture the extreme periods (Ruya and Augenbroe 2016). In order to show the magnitude in terms of unmet hours, commonly used reporting tolerances of 0.2C (0.56F) and 1.11C (2F) applied to the models and results are compared.

3- Analyzing Thermal Comfort

Unmet hours are reported as "Time setpoint not met during occupied hours" or "Time setpoint not met during unoccupied hours" in EnergyPlus. Occupied time unmet hour calculation considers the hours based on the occupancy schedule. However, HVAC operation might follow a different schedule which probably will cause the zones not meeting their setpoints for these hours. Therefore, our assumptions consider HVAC operation schedule for occupied hours. Secondly, calculation of total facility unmet hour is changed. While ASHRAE 90.1-2010 dictates "Any hour with one or more zones with an unmet cooling load or unmet heating load is defined as unmet load hour" it is assumed to be unfair for a single zone to share the same unmet fraction for a given timestep with indefinite number of zones if they coincide. Ignoring number of zone factor and scale of the building leads unfair comparisons which probably will lead toward system oversizing. Our proposed method sums all the unmet fractions (heating and cooling separately) for each zone and for whole year, then calculates a percentage based on the number of total operational hours and number of zones. Unmet hour calculation is iterated for different temperature tolerances of 0.2C, 1.11C, 2.5C and 4C.

Unmet hour for timestep t in T

t = timestep

T = total hours

T_a = zone mean air temperature

T_{htg} = zone thermostat heating setpoint

T_{clg} = zone thermostat cooling setpoint

O_t = HVAC operation hours

© 2018 ASHRAE (www.ashrae.org) and IBPSA-USA (www.ibpsa.us).
For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE or IBPSA-USA's prior written permission.

$\propto$ = acceptability tolerance
η = t/hour; in our case $\eta = 1/6$
U_{htg} = heating unmet hour
U_{clg} = cooling unmet hour
n = number of zones

$$\frac{I(O_t)I((T_a - T_{htg}) < \propto)}{\eta} = U_{htg} \quad \frac{I(O_t)I((T_a - T_{clg}) < \propto)}{\eta} = U_{clg}$$

$$\frac{\sum_{i=1}^{n} \frac{\sum_{t}^{T}(U_{htg} + U_{clg})}{O_t}}{n}$$

Contrary to 300 maximum allowable unmet hour limitation of ASHRAE 90.1-2010, we set acceptability threshold which gives more transparency and flexibility to thermal comfort analysis. Acceptability ranges:
<5% = acceptable
5%-10% = moderately acceptable
>10% = not acceptable

4- Downsizing

Incremental downsizing steps (10-20-30%) are applied to chosen equipment for each building and climate region. Small and medium office building HVAC designs consist of DX heating and cooling coils for primary heating and cooling while large office has chiller and boiler as main equipment for air conditioning. Downsizing is applied to each major equipment and their associated parameters based on manufacturers example specifications such as COPs and air flow rates are adjusted based on the capacity decrements. As our primary focus is demonstrating the possibility of downsizing for HVAC equipment, our downsizing assumptions are not very detailed. Results are inspected deterministically and optimal size reduction is analyzed based on different unmet hour tolerances. the paper.

5- Energy and Cost Saving Analyzes

Motivation of this study is to show the impact of more robust thermal comfort assessments in terms of equipment sizing and energy and cost saving potentials. Our cost analysis only considers the average utility rates for each climate region. Thus, impact of the utility purchase rates, equipment initial and maintenance costs are ignored for this paper. Based on the average utility rates, energy consumption and associated cost for each simulation are calculated. Impacts of the climate region and scale of the building are discussed comperatively.

Results and Discussion

All publ Study aims to clarify the ambiguity in unmet hour reporting tolerance selection in energy modeling industry. Figure 2-3-4 illustrate the total hours of "time setpoint not met during occupied heating and cooling" for small, medium and large office buildings by using the conventional calculation of unmet hours. ine above the figure and below the caption.

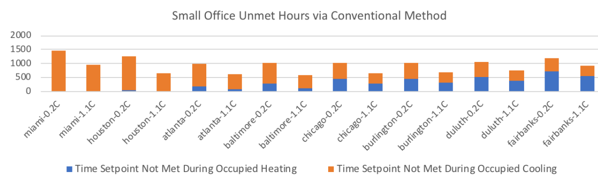

Figure 2 Small Office Unmet via Conventional Method

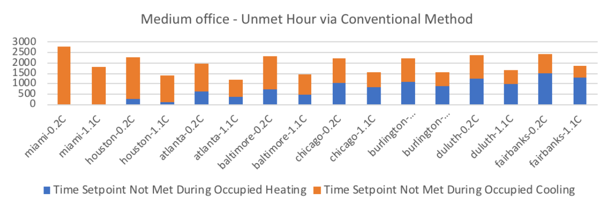

Figure 3 Medium Office Unmet via Conventional Method

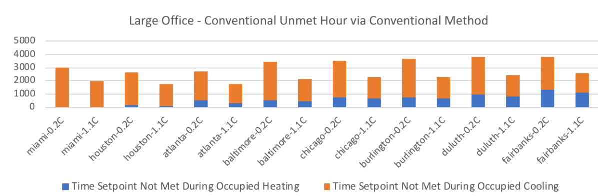

Figure 4 Large Office Unmet via Conventional Method

As its also shown in the graphs, larger buildings have higher unmet hours even though the hours that are shared by multiple zones were not taken into account. However, they still need to comply with 300 maximum allowable unmet limitation which brings up another discussion on finding the right reporting tolerance. Figure 2-3-4 show the significant reduction in both heating and cooling unmet hours when tolerance is changed from 0.2C to 1.11C. In this paper, we analyzed impacts of different tolerances (0.2C, 1.11C, 2.5C and 4C) through a more realistic framework. We aim to demonstrate that keeping acceptability tolerance too narrow will cause system oversizing while it does not guarantee the occupant comfort which has already been proven by many researchers through empirical and deterministic studies. According to the results shown in table 1-2-3 downsizing can be achieved up to 30% for all three building types when narrow tolerances are ignored (0.2C and 1.1C). However, more conservative approach still enables downsizing possibility.

© 2018 ASHRAE (www.ashrae.org) and IBPSA-USA (www.ibpsa.us).
For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE or IBPSA-USA's prior written permission.

Table 1 Small Office Original Unmet Hours

	Small Office Original							
	miami	houston	atlanta	baltimore	chicago	burlington	duluth	fairbanks
Facility Total Unmet Hours (0.2C)	723	385.16667	173	200.83333	187.33333	174.16667	190.16667	144.33333
	4%	2%	1%	1%	1%	1%	1%	1%
Facility Total Unmet Hours (1.11C)	153.83333	85.333333	26	26.166667	26.5	27.833333	39.5	44.166667
	1%	1%	0%	0%	0%	0%	0%	0%
Facility Total Unmet Hours (2.5C)	16.333333	7.8333333	1.6666667	2.3333333	3.5	2.6666667	10.5	10
	0%	0%	0%	0%	0%	0%	0%	0%
Facility Total Unmet Hours (4C)	0	0	0	0	0.5	0	1.6666667	1
	0%	0%	0%	0%	0%	0%	0%	0%

Table 2 Small Office 10% Downsized Unmet Hours

	Small Office 10% downsized							
	miami	houston	atlanta	baltimore	chicago	burlington	duluth	fairbanks
Facility Total Unmet Hours (0.2C)	1561.5	846	383.333	365.333	223	198.667	204	403.3333
	10%	5%	2%	2%	1%	1%	1%	2%
Facility Total Unmet Hours (1.11C)	368	181	42.5	44.8333	32.3333	34.6667	44.1667	166.8333
	2%	1%	0%	0%	0%	0%	0%	1%
Facility Total Unmet Hours (2.5C)	23	11.3333	2.83333	3.5	4.33333	2.83333	10.5	51.33333
	0%	0%	0%	0%	0%	0%	0%	0%
Facility Total Unmet Hours (4C)	0.5	0.16667	0	0	0.5	0	1.66667	13
	0%	0%	0%	0%	0%	0%	0%	0%

Table 3 Small Office 20% Downsized Unmet Hours

	Small Office 20% downsized							
	miami	houston	atlanta	baltimore	chicago	burlington	duluth	fairbanks
Facility Total Unmet Hours (0.2C)	3383.5	2012.33	939	804.833	430.667	321.833	238.833	412.6667
	21%	12%	6%	5%	3%	2%	1%	3%
Facility Total Unmet Hours (1.11C)	1121.33	582.5	155.667	167.667	73.5	43	55.1667	170.3333
	7%	4%	1%	1%	0%	0%	0%	1%
Facility Total Unmet Hours (2.5C)	76.6667	44.8333	5.5	8.33333	4.5	3.16667	11	51.66667
	0%	0%	0%	0%	0%	0%	0%	0%
Facility Total Unmet Hours (4C)	2.83333	0.5	0	0	0.5	0	1.66667	13
	0%	0%	0%	0%	0%	0%	0%	0%

Table 4 Small Office 30% Downsized Unmet Hours

	Small Office 30% downsized							
	miami	houston	atlanta	baltimore	chicago	burlington	duluth	fairbanks
Facility Total Unmet Hours (0.2C)	5475	3613.5	1935	1763.5	825.667	679.167	427.833	437.5
	33%	22%	12%	11%	5%	4%	3%	3%
Facility Total Unmet Hours (1.11C)	3066.67	1775.67	618.667	515.833	123.667	97.5	77.8333	175.8333
	19%	11%	4%	3%	1%	1%	0%	1%
Facility Total Unmet Hours (2.5C)	425.5	210.5	22.6667	41.1667	8.16667	7.5	13.8333	51.83333
	3%	1%	0%	0%	0%	0%	0%	0%
Facility Total Unmet Hours (4C)	8.66667	6.16667	0.16667	0.16667	0.5	0	1.66667	13
	0%	0%	0%	0%	0%	0%	0%	0%

According to the results, climate zones have significant impact on equipment sizing. Miami (1A) shows the highest sensitivity to downsizing throughout all building types while heating dominated regions enable more aggressive downsizing percentages. Results also show that besides climate factor, sensitivity level is also dependent on the HVAC design. While small and medium offices (packaged air-conditioning/heat pump), follow a similar pattern, large office buildings (chiller/boiler) react differently.

Table 5 Medium Office Original Unmet Hours

	Medium Office Original							
	miami	houston	atlanta	baltimore	chicago	burlington	duluth	fairbanks
Facility Total Unmet Hours (0.2C)	3468.5	1829.5	1068.167	1649.167	1767	1662.833	1661.833	2331.167
	7%	4%	2%	3%	4%	3%	3%	5%
Facility Total Unmet Hours (1.11C)	1099.167	505.5	211.5	351.5	643.3333	526.1667	587.6667	1160.833
	2%	1%	0%	1%	1%	1%	1%	2%
Facility Total Unmet Hours (2.5C)	112.3333	119	81.66667	97.66667	218.3333	250.1667	313	666.3333
	0%	0%	0%	0%	0%	1%	1%	1%
Facility Total Unmet Hours (4C)	2.833333	11.5	35.83333	33.83333	100.1667	147	178.5	423.3333
	0%	0%	0%	0%	0%	0%	0%	1%

Oversized figures and tables. approach still enables downsizing possibility.

Table 6 Medium Office 10% Downsized Unmet Hours

	Medium Office 10% downsized							
	miami	houston	atlanta	baltimore	chicago	burlington	duluth	fairbanks
Facility Total Unmet Hours (0.2C)	4602	2373.167	1308.5	1947.167	2100	1570.167	1609.833	2338.5
	9%	5%	3%	4%	4%	3%	3%	5%
Facility Total Unmet Hours (1.11C)	1591.333	647.5	265.1667	494	858.1667	496.5	576.5	1176.333
	3%	1%	1%	1%	2%	1%	1%	2%
Facility Total Unmet Hours (2.5C)	163.8333	129	83.16667	103.6667	257.3333	249.3333	315	677.3333
	0%	0%	0%	0%	1%	1%	1%	1%
Facility Total Unmet Hours (4C)	9	13.33333	36	34.5	103	147	178.5	426.6667
	0%	0%	0%	0%	0%	0%	0%	1%

Table 7 Medium Office 20% Downsized Unmet Hours

	Medium Office 20% downsized							
	miami	houston	atlanta	baltimore	chicago	burlington	duluth	fairbanks
Facility Total Unmet Hours (0.2C)	10390.17	6013.167	2746.167	3316.333	3184.5	1955.833	1609.833	2402
	21%	12%	6%	7%	6%	4%	3%	5%
Facility Total Unmet Hours (1.11C)	4217.667	1982.833	763.5	1131	1375.667	633.6667	576.5	1205.167
	9%	4%	2%	2%	3%	1%	1%	2%
Facility Total Unmet Hours (2.5C)	645.8333	332.8333	107	208.5	471.3333	254.6667	315	695.6667
	1%	1%	0%	0%	1%	1%	1%	1%
Facility Total Unmet Hours (4C)	40.83333	46.5	36	35.66667	111.1667	147	178.5	434.3333
	0%	0%	0%	0%	0%	0%	0%	1%

Table 8 Medium Office 30% Downsized Unmet Hours

	Small Office 20% downsized							
	miami	houston	atlanta	baltimore	chicago	burlington	duluth	fairbanks
Facility Total Unmet Hours (0.2C)	3383.5	2012.33	939	804.833	430.667	321.833	238.833	412.6667
	21%	12%	6%	5%	3%	2%	1%	3%
Facility Total Unmet Hours (1.11C)	1121.33	582.5	155.667	167.667	73.5	43	55.1667	170.3333
	7%	4%	1%	1%	0%	0%	0%	1%
Facility Total Unmet Hours (2.5C)	76.6667	44.8333	5.5	8.33333	4.5	3.16667	11	51.66667
	0%	0%	0%	0%	0%	0%	0%	0%
Facility Total Unmet Hours (4C)	2.83333	0.5	0	0	0.5	0	1.66667	13
	0%	0%	0%	0%	0%	0%	0%	0%

Our strategy is based on managing the trade-off between energy&cost saving due to the downsizing and increased unmet hour. We propose that 2.5C unmet tolerance is optimal for thermal comfort analysis and by applying it to our study, 30% downsizing is achievable for all buildings in each climate except medium and large office buildings in climate zone 1A whereas 20% downsizing is still achievable.

Table 9 Large Office Original Unmet Hours

	Large Office Original							
	miami	houston	atlanta	baltimore	chicago	burlington	duluth	fairbanks
Facility Total Unmet Hours (0.2C)	9512.833	6686	5421.667	6852.333	6498.5	6342.667	6172.333	5585.167
	18%	13%	10%	13%	12%	12%	12%	11%
Facility Total Unmet Hours (1.11C)	5593.5	2468.667	1392	1976.333	1993.167	1640.333	1412	1631
	11%	5%	3%	4%	4%	3%	3%	3%
Facility Total Unmet Hours (2.5C)	385.1667	119.6667	62.5	136.3333	378.3333	117.6667	162.8333	385.1667
	1%	0%	0%	0%	1%	0%	0%	1%
Facility Total Unmet Hours (4C)	47.33333	14.83333	8.833333	11.16667	41.66667	13.5	42.33333	181.6667
	0%	0%	0%	0%	0%	0%	0%	0%

Table 10 Large Office 10% Downsized Unmet Hours

	Large Office 10% downsized							
	miami	houston	atlanta	baltimore	chicago	burlington	duluth	fairbanks
Facility Total Unmet Hours (0.2C)	10155.67	6872.333	5288.667	7001	6873.667	6172.333	6482.5	5951.5
	19%	13%	10%	13%	13%	12%	12%	11%
Facility Total Unmet Hours (1.11C)	6106.833	2600	1378.667	2130	2309	1412	1606.667	1835.667
	12%	5%	3%	4%	4%	3%	3%	4%
Facility Total Unmet Hours (2.5C)	530.5	146.3333	68	173.8333	545.1667	162.8333	197.5	468
	1%	0%	0%	0%	1%	0%	0%	1%
Facility Total Unmet Hours (4C)	53.5	17	10	12.33333	78.66667	42.33333	43.16667	225.8333
	0%	0%	0%	0%	0%	0%	0%	0%

Table 11 Large Office 20% Downsized Unmet Hours

© 2018 ASHRAE (www.ashrae.org) and IBPSA-USA (www.ibpsa.us).
For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE or IBPSA-USA's prior written permission.

	Large Office 20% downsized							
	miami	houston	atlanta	baltimore	chicago	burlington	duluth	fairbanks
Facility Total Unmet Hours (0.2C)	12554.83	7768.5	5383.167	7785.333	7749.167	7960.167	7029.333	6645.667
	24%	15%	10%	15%	15%	15%	13%	13%
Facility Total Unmet Hours (1.11C)	7560.333	3162	1470	2636.833	2981.833	2750.333	1946.167	2276.833
	14%	6%	3%	5%	6%	5%	4%	4%
Facility Total Unmet Hours (2.5C)	990.5	262.6667	90.5	345.6667	837.6667	401	283.3333	675.5
	2%	1%	0%	1%	2%	1%	1%	1%
Facility Total Unmet Hours (4C)	72.5	18.5	11	23.33333	142.3333	22.66667	50.33333	315.3333
	0%	0%	0%	0%	0%	0%	0%	1%

Table 12 Large Office 30% Downsized Unmet Hours

	Large Office 30% downsized							
	miami	houston	atlanta	baltimore	chicago	burlington	duluth	fairbanks
Facility Total Unmet Hours (0.2C)	22294.83	11900.67	6339.833	10364	9309	9814.5	8090.833	7197
	43%	23%	12%	20%	18%	19%	15%	14%
Facility Total Unmet Hours (1.11C)	13940.17	5498.333	2033.833	4423.333	4232.667	4144	2589.333	2578.833
	27%	10%	4%	8%	8%	8%	5%	5%
Facility Total Unmet Hours (2.5C)	3500.833	843.6667	201.8333	902	1474	872.5	441.3333	649.1667
	7%	2%	0%	2%	3%	2%	1%	1%
Facility Total Unmet Hours (4C)	362.6667	45.83333	17.16667	57.16667	320.1667	79.16667	94.5	217.5
	1%	0%	0%	0%	1%	0%	0%	0%

Table 13 shows that, energy saving opportunities are obtained in warmer climates align with unmet hour results. It should be noted that even though downsizing approach is applied to main heating and cooling equipment, this paper only analyzes outcomes related to electricity as it has bigger impacts in each climate region than natural gas. Further analyzes is needed to include saving analyzes for natural gas. While warmest climate shows the highest savings, smaller buildings show higher energy saving potentials then larger buildings which could be explained by the different HVAC configuration they have. Thus, improving the operation sequence of large offices might help to save more energy.

Table 13 Energy Saving Results of Small-Medium-Large Office Buildings

City	Climate Zones	small office			medium office			large office		
		10%	20%	30%	10%	20%	30%	10%	20%	30%
Miami	1A	2.9%	4.6%	6.6%	3.0%	3.5%	3.7%	1.0%	1.6%	1.9%
Houston	2A	2.3%	3.7%	5.3%	2.5%	3.1%	3.4%	0.8%	1.3%	1.6%
Atlanta	3A	1.7%	2.7%	3.7%	1.9%	2.5%	2.5%	0.8%	1.2%	1.5%
Baltimore	4A	1.5%	2.4%	3.3%	1.6%	2.1%	2.2%	0.5%	0.8%	1.0%
Chicago	5A	1.2%	1.9%	2.6%	1.2%	1.5%	1.5%	0.4%	0.7%	0.9%
Burlington	6A	1.1%	1.8%	2.5%	1.1%	1.5%	1.6%	0.3%	0.5%	0.7%
Duluth	7	1.0%	1.6%	2.2%	0.8%	1.0%	1.0%	0.3%	0.4%	0.6%
Fairbanks	8	0.8%	1.2%	1.8%	0.4%	0.4%	-0.1%	0.2%	0.2%	0.3%

Similar to energy saving results, cost savings are also very significant for a single building based on the scale factor (Table 14).

Table 14 Cost Saving Results of Small-Medium-Large Office Buildings

City	Climate Zones	small office			medium office			large office		
		10%	20%	30%	10%	20%	30%	10%	20%	30%
Miami	1A	$ 170.75	$ 276.05	$ 397.23	$ 2,115.54	$ 2,533.54	$ 2,663.43	$ 12,643.97	$ 19,633.90	$ 23,112.51
Houston	2A	$ 108.59	$ 172.73	$ 246.06	$ 1,384.41	$ 1,718.60	$ 1,881.18	$ 7,988.46	$ 12,267.88	$ 15,399.06
Atlanta	3A	$ 82.11	$ 128.36	$ 179.56	$ 1,041.43	$ 1,367.82	$ 1,420.60	$ 7,554.09	$ 12,030.42	$ 15,447.44
Baltimore	4A	$ 91.31	$ 141.66	$ 197.80	$ 1,088.74	$ 1,422.75	$ 1,503.66	$ 6,313.61	$ 10,083.48	$ 12,445.45
Chicago	5A	$ 55.70	$ 88.38	$ 119.94	$ 605.84	$ 765.48	$ 811.30	$ 3,876.87	$ 6,240.13	$ 8,035.30
Burlington	6A	$ 76.62	$ 126.81	$ 175.87	$ 885.91	$ 1,156.05	$ 1,286.56	$ 4,529.81	$ 7,368.76	$ 9,716.05
Duluth	7	$ 47.07	$ 75.49	$ 104.80	$ 406.84	$ 529.02	$ 556.44	$ 2,410.41	$ 4,034.65	$ 5,387.01
Fairbanks	8	$ 67.60	$ 106.97	$ 150.25	$ 426.79	$ 407.83	$ (74.75)	$ 2,705.52	$ 4,165.33	$ 5,692.33

Lastly, cost saving results are normalized based on the building area to be able to make a fair comparison between models (Table 15). downsizing is still achievable.

Table 15 Normalized Cost Savings for Small-Medium-Large Office Buildings

City	Climate Zones	small office			medium office			large office		
		10%	20%	30%	10%	20%	30%	10%	20%	30%
Miami	1A	$ 0.03	$ 0.05	$ 0.07	$ 0.04	$ 0.05	$ 0.05	$ 0.03	$ 0.04	$ 0.05
Houston	2A	$ 0.02	$ 0.03	$ 0.04	$ 0.03	$ 0.03	$ 0.04	$ 0.02	$ 0.02	$ 0.03
Atlanta	3A	$ 0.01	$ 0.02	$ 0.03	$ 0.02	$ 0.03	$ 0.03	$ 0.02	$ 0.02	$ 0.03
Baltimore	4A	$ 0.02	$ 0.03	$ 0.04	$ 0.02	$ 0.03	$ 0.03	$ 0.01	$ 0.02	$ 0.02
Chicago	5A	$ 0.01	$ 0.02	$ 0.02	$ 0.01	$ 0.01	$ 0.02	$ 0.01	$ 0.01	$ 0.02
Burlington	6A	$ 0.01	$ 0.02	$ 0.03	$ 0.02	$ 0.02	$ 0.02	$ 0.01	$ 0.01	$ 0.02
Duluth	7	$ 0.01	$ 0.01	$ 0.02	$ 0.01	$ 0.01	$ 0.01	$ 0.00	$ 0.01	$ 0.01
Fairbanks	8	$ 0.01	$ 0.02	$ 0.03	$ 0.01	$ 0.01	$ (0.00)	$ 0.01	$ 0.01	$ 0.01

Study of Jazizadeh et al. highlighted that majority of the dissatisfied occupants prefer warmer indoor environments which which gives more opportunity to downsizing of cooling equipment (Jazizadeh et al 2013). In conjunction with the results of our study, downsizing the cooling equipment creates great potentials to energy (electricity) and cost saving.

CONCLUSION

Existing HVAC system design and operations rely on outdated thermal comfort assumptions which inevitably lead to a chain of issues of system oversizing, excessive energy consumption, uncomfortable indoor environments and dissatisfied occupants. As its proven by various deterministic and empirical studies that narrow thermostat ranges do not provide perfect occupant comfort, moreover they reduce equipment life and increase energy consumption. Standards dictate to achieve a certain threshold for the acceptable thermal comfort, while not clearly defining the acceptability tolerance for the modeling industry which cause ambiguity among users. Furthermore, calculation algorithm of energy simulation tools treats all building scales in the same manner which does not represent the reality. Instead of targeting to achieve a predefined value (300 maximum allowable limit of ASHRAE 90.1), a percentage should be considered which puts different factors into account. A new framework for integrating these mentioned issues was presented in this paper. First objective is to provide a fair and transparent platform which will help to maintain a standard throughout the community. Secondly, to show the saving potentials when wider thermostat ranges are accepted. Lastly, to highlight the sensitivity level of climate zones to different sizing approaches. Comparison of the magnitude of the unmet hour risk based on the downsizing percentages, climate and building scale helps to optimize the design decisions to find rightsizing of the equipment.

REFERENCES

ANSI/ASHRAE/IESNA Standard 90.1-2007, Energy standard for buildings except low rise residential

© 2018 ASHRAE (www.ashrae.org) and IBPSA-USA (www.ibpsa.us).
For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE or IBPSA-USA's prior written permission.

buildings. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ANSI/ASHRAE/IESNA Standard 90.1-2010, Energy standard for buildings except low rise residential buildings. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE Standard 55-2010, Thermal Environment Conditions for Human Occupancy, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Brager, G.S., M.E. Fountain, C.C. Benton, E.A. Arens, and F.S. Bauman. 1993. A Comparison of Methods for Assessing Thermal Sensation and Acceptability in the Field. Proceedings of Thermal Comfort: Past, Present and Future, Watford, United Kingdom.

Chen, J., Augenbroe, G., Wang, Q. and Song, X. 2017, Uncertainty Analysis for Thermal Comfort Evaluation in Naturally Ventilated Buildings, Proceedings of ASCE International Workshop on Computing in Civil Engineering 2017.

deDear, R. and Brager, G. 1998, Developing an adaptive model of thermal comfort and preference, ASHRAE Transactions 1041:1-18.

Djunaedy, E., Van den Wymelenberg, K., Acker, B. and Thimmana, H. 2011. Rightsizing: Using simulation tools to solve the problem of oversizing, Proceedings of Building Simulation 2011, Sydney, Australia.

Fanger, P.O. 1970. Thermal Comfort Analysis and Applications in Environment Engeering

Fernandez, N., Katipamula, S., Wang, W., Huang, Y. and Liu, G. 2012. Energy Savings Modeling of Standard Commercial Building Re-tuning Measures: Large Office Buildings, Pacific Northwest National Laboratory, Richland, Washington.

Fernandez, N., Katipamula, S., Wang, W., Xie, Y., Zhao, M. and Corbin, C. 2017. Impacts of Commercial Building Controls on Energy Savings and Peak Load Reduction, Pacific Northwest National Laboratory, Richland, Washington.

FHP (Florida Heat Pump), Technical documentation of Heat Pump DX heating and cooling coils. Retrieved January 2018, from https://www.bosch-climate.us/files/CA_Series_US.pdf

IES Virtual Environment, 2013, Unmet Load Hours Troubleshooting Guide

Jazizadeh, F., Ghahramani, A., Becerik-Gerber, B., Kichkaylo, T., and Orosz, M. 2014. Human-Building Interaction Framework for Personalized Thermal Comfort-Driven Systems in Office Buildings, Journal Of Computing In Civil Engineering, 28(1), 2-16."

Jazizadeh, F., Kavulya, G., Klein, L. and Becerik-Gerber, B. 2011. Continuous Sensing of Occupant Perception of Indoor Ambient Factors, Proceedings of ASCE International Workshop on Computing in Civil Engineering 2011.

Kampelis, N., Ferrante, A., Kolokotsa, D., Gobakis, K., Standardi, L. and Cristalli, C. 2017, Thermal comfort evaluation in HVAC Demand Response control, Energy Procedia 134:675-682.

Kang, Y., Augenbroe, G., Li, W. and Wang, Q. 2017, Effects of scenario uncertainty on chiller sizing method, Applied Thermal Engineering 123.

Kumar, A., Singh, I. and Sud, S. 2010. AN APPROACH TOWARDS DEVELOPMENT, International Journal on Smart Sensing and Intelligent Systems 3(4).

Nicol, F. and Humphreys, M. 2002. Adaptive Thermal Comfort and Sustainable Thermal Standards for Buildings, Energy and Buildings 34(6):563-572.

Official Nebraska Government Website. 2015. Annual Average Electricity Price Comparison by State. Retrieved January 2018, from http://www.neo.ne.gov/statshtml/204.htm.

Ruya, E. and Augenbroe, G. 2016. THE IMPACT OF HVAC DOWNSIZING ON THERMAL COMFORT HOURS AND ENERGY CONSUMPTION, Proceedings of ASHRAE and IBPSA-USA SimBuild, Salt Lake City, UT.

Sanguinetti, A., Pritoni, M., Salmon, K. and Morejohn, J. 2016, TherMOOstat: Occupant Feedback to Improve Comfort and Efficiency on a University Campus, Proceedings of ACEEE Summer Study on Energy Efficiency in Buildings, Asilomar, CA.

U.S DOE, Energy Efficiency and Renewable Energy, Building energy Codes Program, Commercial Prototype Building Models, in: ANSI/ASHRAE/IES Standard 90.1 Prototype Building Model Package.

U.S. DOE, Energy Information Administration (EIA), in: Annual Energy Outlook 2017.

U.S DOE EnergyPlus Version 8.7 Input Output Reference, 2016, University of Illinois & Ernest Orlando Lawrence Berkeley National Laboratory.

Trane, Technical documentation of Water-cooled Centrifugal Chiller.

© 2018 ASHRAE (www.ashrae.org) and IBPSA-USA (www.ibpsa.us).
For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE or IBPSA-USA's prior written permission.

Woradechjumroen, D., Yu, Y., Li, H., Yu, D., Yang. H. 2014. Analysis of HVAC System Oversizing in Commercial Buildings through Field Measurements, Energy and Buildings 69:131-143.

Yang, L., Yan, H. and Lok, C. 2014, Thermal comfort and building energy consumption implications – A review, Applied Energy 115:164-173.

© 2018 ASHRAE (www.ashrae.org) and IBPSA-USA (www.ibpsa.us).
For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE or IBPSA-USA's prior written permission.