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THE IMPACTS OF HVAC DOWNSIZING ON THERMAL COMFORT HOURS AND ENERGY CONSUMPTION

Elvin Ruya[1], and Godfried Augenbroe[2]
[1]Georgia Institute of Technology, Atlanta, GA

ABSTRACT

In current practice, HVAC designers oversize systems in order to provide the theoretical benefit of perfect occupant comfort in the consideration of all possible extreme conditions. Routine use of the autosize option of simulation tools and the assigned or implied safety factors leads to the potential oversizing that have been reported in literature. Even though the most important mandate is to reduce the risk of uncomfortable hours, current design methods and simulation tools offer only a limited way to do this. Indeed, unwanted outcomes can result from uncertainty in the parameters of the building energy model that is used.

How to overcome the negative effects of oversized HVAC systems in terms of energy use, equipment life, maintenance and financial penalties by rightsizing strategies with various perspectives has been subject of previous studies. This study focuses on an incremental downsizing approach backed up by an uncertainty analysis. A system consisting of packaged heat pump units in commercial buildings is used to demonstrate the approach. Even though a heat pump unit has both heating and cooling coils, only the capacity of cooling coils is analyzed in this paper. Acceptable risk magnitudes in terms of unmet hours, impact of modeler's ignorance, and energy & cost savings as the result of downsizing are investigated. The proposed method opens the door to selecting the appropriate system size with more flexibility and confidence in cases where comfort criteria can be relaxed.

INTRODUCTION

According to the 2011 building energy data book, the commercial building sector consumes 19% of the total energy in US, and consume 36% of electricity. Office buildings represent the highest percentage among commercial building types (19%). Space heating, cooling and ventilation (HVAC) systems constitute 42.8% of commercial sector end uses (U.S. DOE, Annual Energy Outlook 2015). Packaged units are the most commonly used HVAC systems in office buildings representing 50% (U.S. DOE, Commercial Buildings Energy Consumption Survey 2003,2006).

Oversizing rooftop units (RTU) may cause incorrect operation and control schemes which creates premature equipment failures (Yu et al. 2013).

Reducing the total energy consumption is achieved by reducing the heating/cooling and is often accomplished by advanced envelopes and glazing systems, efficient lighting and equipment selection, passive design measures and high performance mechanical systems (Bishop and Houghton 1992). In this paper we will focus on one particular aspect of the overall design, i.e. the system size. There are well established methods for system sizing, as we will elaborate below. In practice, HVAC sizing is based on load calculations that add an extra 15-25% load to accommodate uncertainties in actual loads occurring over the life of the building, and thus be on the safe side. Various studies investigate the performance of the popular RTU systems in terms of resulting occupant comfort and energy consumption. By inspecting current sizing methodologies, it is seen that many RTU's could be oversized due to the routine application of sizing factors by HVAC designers and energy modelers. It is the purpose of this paper to look at the potential to downsize systems under a more relaxed criterion for thermal comfort. This is looked at in recognition of earlier work, briefly summarized here. The reasons for oversized packaged rooftop units in Northern California were analyzed based on field measurements and inspections in previous studies (Felts and Bailey 2000). According to the authors, the capacity of 40% of the monitored units could be downsized by 25% whereas 10% of the units could be downsized by 50%. This result signals an oversizing issue in rooftop units. It should be noted that their examination is based on design (peak) day analysis. It is to be expected that use of real weather and a quantified comfort criterion would present similar or worse results. Penalties of oversizing and methodologies of rightsizing are presented in various other studies. Djunaedy et.al (2011) point to unreasonable safety factors in their study and define the consequences of oversizing in terms of high cycling rate and low run-time fraction of nine monitored RTUs in the Pacific Northwest. Djunaedy et.al also remark that oversized equipment tend to have lower PLRs and higher EER degradations (Djunaedy et al. 2011). Another study quantifies oversizing of RTU in prototypical commercial buildings by evaluating cycling behavior and run time fraction of compressors and furnace heaters (Woradechjumroen et al. 2014). A study by Jazizadeh et.al argues that in spite of most of the HVAC systems are sized to provide thermal comfort, occupants are usually not satisfied with indoor conditions in commercial buildings. The authors investigated HVAC sizing and operations from a different angle by suggesting room scale evaluation and use of building energy management system (BEMS), given that occupants might ask a warmer indoor conditions in cooling mode which would save energy and extend equipment life (Jazizadeh et al. 2014).

Systems are sized via professional tools based on load calculation methods of the ASHRAE Handbook of Fundamentals which requires design parameters, a given meteorological year data, and a design day. Because calculations are based on deterministic loads, where uncertainty parameters are not considered, actual load profiles and operations will be different from the predicted design (Gang et al. 2015).

The autosize option in energy modeling tools provides simplicity and saves time. Moreover because the background calculation algorithm uses ASHRAE standards, most users obviously prefer the autosizing option. But earlier research indicates that the outcome can lead to oversized systems.

This study explores a new framework of downsizing, based on an uncertainty analyses. UA (uncertainty analysis) supports risk-conscious decision making. It has been previously validated as a useful methodology in building design and retrofit studies (Sun et al. 2014). Conventional methodology multiplies computed peak cooling load with a safety factor to accommodate uncertainties and avoid undersizing risk. However, this is based on implied rather than quantified uncertainty and as a result, this generic “safety” may lead to HVAC size that is larger than needed (Gang et al. 2015). Various studies have used uncertainty analysis in their approach to optimum designs. In our study, uncertainty in model parameters and model discrepencies (usually referred to as model form uncertainty) will be propagated into the distribution of predicted heating and cooling demands (Sun et al. 2014). This propogation analysis is done through stochastic simulations, which can be used to determine the impact of uncertain parameters on the peak cooling load (Domínguez-Muñoz et al. 2010). The Uncertainty in building thermal comfort performance aspect was studied by de Wit and Augenbroe, (2002). According to the authors, availability of quantified uncertainty contributes to rational decision making and should be adopted in building and system sizing practices.

This paper shows outcomes of the autosizing option within the EnergyPlus simulation tool and proposes a new methodology for rightsizing RTU systems based on uncertainty analysis. EnergyPlus is selected because of it having been extensively validated. According to the empirical study of Shrestra and Maxwell, discrepancy in outcomes of EnergyPlus and experimental data is 5.4% in terms of zone cooling load (Shrestha and Maxwell 2011). However, greater differences are seen in system and plant level which could potentially contribute to the HVAC oversizing tendency if the autosizing option is used. Another study of Witte et al. confirms validation of EnergyPlus by comparison with other well-established simulation tools such as DOE-2, BLAST, TRNSYS AND ESP.

The previously developed GURA-W (Georgia Tech Uncertainty and Risk Analysis Workbench) is used for the propafation of uncertainties through Energyplus simulations (Lee et. al. 2013). In the workbench, each building input parameter is specified with a certain level of uncertainty (distribution) in a UQ repository which defines all sources of uncertainty and their distributions. GURA-W executes the UA by a Monte-Carlo method with samples generated by Latin Hypercube Sampling (LHS) (Lee et al. 2013). Each UA in this study is conducted for 100 samples from which a distribution of the outcome variables in constructed. Figure 1 shows an overview of the procedure.

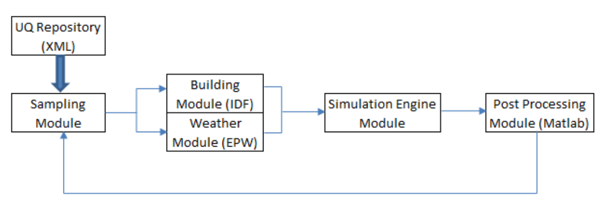


Figure 1 Workflow configuration of GURA

Our strategy is based on managing the trade-off between reduced cost and energy savings due to decreased equipment size and the expected increased in the number of uncomfortable hours. Weather, microclimate, building envelope, material parameters and operation parameters of lighting, plug load and occupancy densities are the Energyplus input parameters that add the main sources of uncertainty to the prediction.

THE PROPOSED METHOD AND CASE STUDIES

The study is carried out in three stages, (1) EnergyPlus model creation using DesignBuilder, delivering the suggested HVAC size with inbuilt autosizing approach (2) applying incremental downsizing steps and inspecting the result with deterministic as well as uncertainty analyses, and (3) comparing the results and finding the optimal allowable size reduction.. ASHRAE develops design days by filtering hourly data of 24 years (1982-2006) in order to find the worst case conditions to avoid risk of undersizing (Sun et al. 2014). To align with this approach, we use 39 years of actual meteorological year data (AMY) from 1973-2012 in our annual simulations. AMY files are selected over TMY which is created by selecting the most typical months of available years. Because TMY data can miss extreme periods, it cannot truly reproduce the actual performance during low-occurrence extreme periods. In order to reduce the risk of undersizing the system, the meximum period of available real weather data (39 years) was considered. 10% and 20% downsized models of both small and medium office buildings were run for each year and the frequency of unmet hours evaluated.

The main analysis objectives are:

1- To show the potential oversizing effect of using the autosizing option in Energyplus.

2- To verify the following approach: downsize HVAC RTU systems with certain decrements until the maximum unmet hour limit (300 hours) of ASHRAE is violated.

3- To compare outcomes of autosized and downsized cases for 39 years of actual meteorological weather data.

4- To repeat the analysis with the added effect of uncertainty.

5- To compare outcomes of deterministic and uncertainty analyses in terms of unmet hours and electricity consumption for cooling.

6- To highlight the saving potential of downsizing strategies with and without the recognition of the role of uncertainties.

CASE STUDIES

Small Office

The first case is a one story, 5500 ft2 office building consisting of 4 perimeter and 1 core thermal zones. The building is located in Atlanta, GA (climate zone 3A).

The construction consists of wood-frame external walls with layers of 1 in. stucco, 5/8 in. gypsum board, wall insulation and 5/8 in. gypsum board which has total u-value of 0.089 Btu/h-ft2-F. Attic roof has u-value of 0.027 Btu/h-ft2-F. Window-to-wall ratio is 24.4% for south façade and 19.8% for other orientations. U-value of double pane external glazing is 0.649 Btu/h-ft2-F and SHGC is 0.25.

The RTU is modeled with the unitary system template of DesignBuilder. Each zone has its own thermostat control.

Medium Office

The second case is a 53600 ft2 three story office building with 1 core and 4 perimeter zones in each floor. Total building height is 39 ft. The building is located in Atlanta, GA (climate zone 3A).

The construction consists of steel-frame external walls having layers of 0.4 in. stucco, 5/8 in. gypsum board, wall insulation and 5/8 in gypsum board which has total u-value of 0.083 Btu/h-ft2-F. Flat roof consists of 0.394 in. metal deck and 5 in. insulation board which has total u-value of 0.048 Btu/h-ft2-F. Window-to-wall ratio is 33% on each façade and u-value of double pane external glazing is 0.649 Btu/h-ft2-F with SHGC of 0.25.

The RTU is modeled with the unitary system template of DesignBuilder. Each zone has its own thermostat control.

Stage 1: Model creation

The small and medium office building models are created via DesignBuilder software as case studies. Design specifications are taken from PNNL score cards of Department of Energy (ANSI/ASHRAE/IES Standard 90.1 Prototype Building Model Package). Some of operational schedules and HVAC configurations are modified based on preferences.

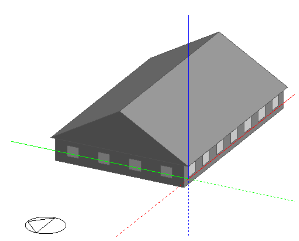


Figure 2 Small Office

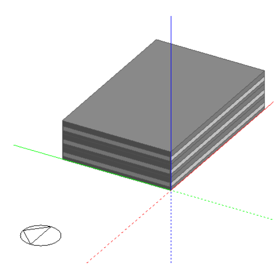


Figure 3 Medium Office

Models are exported to the EnergyPlus simulation tool for deterministic simulation and uncertainty analysis. This is performed in the GURA-Workbench which comprises sampling of parameter values from their given probability distributions and running for each sample (hundreds) an EnergyPlus simulation.

Stage 2: Downsizing and Deterministic analysis

As previously stated, a downsizing approach is employed as the way towards rightsizing the HVAC system. It is believed that HVAC equipment can be downsized based on explicit quantification of resulting uncomfortable indoor conditions,. The downsizing steps in the analysis are accomplished by adapting the HVAC system parameters. Rated total cooling capacity and rated air flow rate parameters of the DX cooling coil are modified to achieve the different configurations. This is done in consecutive steps as follows. The initial model will use the autosized HVAC parameters; it is used to see the impact of the autosizing option on the two major outcomes, i.e total facility unmet hours and cooling electricity consumption. Sizing factors of 25% for heating and 15% for cooling are then assigned to the model, as specified in ASHRAE standard 90.1 Appendix G section G4.2.2.2. A second model is also created by removing the sizing factors and keeping the model otherwise the same. From the second model, calculated capacities of each unit (by the EnergyPlus simulation) are then downsized by 10% and 20% decrements, thus generating a third and fourth model. Downsizing percentages are increased until violating the 300 allowable unmet hours, as specified by ASHRAE. Furthermore, the COP values of each coil are determined based on the nominal total cooling capacities. Referance efficiency values for each capacity are taken from ASHRAE 90.1-2010b (ANSI/ASHRAE/IESNA Standard 90.1-2010). As COP is the value of energy production divided by the energy consumption of a heat pump, coils which have larger capacities result in lower COP values thus consuming more electricity. Based on this analysis, the yearly cooling electricity consumption and related cost values are calculated. The same downsizing approach is applied for both the small and medium office buildings. Energy and cost savings by downsizing the systems are summarized in Tables 1, 2 and 3 for nominal, 30%, and 50 operational density increments, respectively. Additionally, the generated models were simulated for a 39 year period of AMY data in order to study the worst case condition.

Stage 3: Uncertainty analysis

Design specifications contain many assumptions and best guesses. Even though the ultimate goal is determining worst case scenarios, operational parameters of occupancy are the hardest to predict which can be one of the main reasons of excessive equipment sizes (Li et al. 2009). The treatment of all uncertainties, comprising operational uncertainties, weather, building envelope and material uncertainties is well explained in studies of Lee et al. (2013) and Sun et. al.(2014) and the UQ repository with standard, "vanilla" uncertainty ranges of all Energyplus parameters has been integrated in the GURA workbench to perform generic uncertainty analyses. Both studies advocate the probabilistic approach over the deterministic one for best decision making. In this paper, the range of operational uncertainties are based on some level of presumed "modeler's ignorance" especially when it comes to choosing occupancy variables (presence, lighting and appliances). In order to reflect potential deviations from an original guess, occupancy, lighting and plug load densities are increased by 30% and 50% increment factors each representing a safety factor that a modeler could apply to cover ignorance of what the actual densities will be in the realized building. As a result of the increased densities, the cooling demand of the building will change drastically which requires a new sizing calculation of the cooling equipment. The impact of modeler's ignorance is analyzed via deterministic and uncertainty analyses.

RESULTS AND DISCUSSION

Small Office

Tables 1, 2 and 3 show the deterministic simulation results in terms of unmet hours and electricity consumption based on HVAC capacity downsizing the small office building. According to the results shown in Table 1, if the allowance for modeler's ignorance and other (parameter) uncertainties are ignored, the total capacity can be downsized by 20% without violating the 300 unmet hour limitation. In doing so, 12% energy and 13% electricity related cost are saved. When it is assumed that occupancy, lighting and plug load densities are 30% more than what is in the design specification, only 10% downsizing is applicable and the total consumption increase would be 20% more than the initial case (Table 4). Allowing for large usage ignorance, i.e. 50% increase in densities causes an energy consumption increase of 30% whereas downsizing is limited to 10% to stay within the acceptable unmet hour limit (Table 5).

Table 1 Deterministic simulation results of Small office models without operational density increments

		Autosized with SF	Autosized without SF	10% Downsized	20% Downsized
DETERMINISTIC SMALL OFFICE	Dx cooling coil capacity (ton)	10	9	8	7
	Total unmet hours (h)	13.5	34	140	299
	Cooling electricity consumption (J)	25255.1	24365.96	23391.81	22269.73
	Capacity saving (%)	-	11%	20%	29%
	Consumption saving (%)	-	4%	7%	12%
	Annual electricity cost	$ 643.15	$ 610.24	$ 585.66	$ 557.02
	Cost saving (%)		5%	9%	13%

Table 2 Deterministic simulation results of Small office models with 30% operational density increments

		Autosized with SF	Autosized without SF	10% Downsized	20% Downsized
SMALL OFFICE OCCUPANCY-LIGHTING-PLUG LOAD 30% INCREMENT	Dx cooling coil capacity (ton)	12	10	9	8
	Total unmet hours (h)	14.5	35	156	352
	Cooling electricity consumption (J)	31468.95	30517.99	29277.84	27816.84
	Capacity saving (%)	-	12%	21%	30%
	Consumption saving (%)	-	3%	7%	12%
	Annual electricity cost	$ 791.56	$ 756.00	$ 724.99	$ 687.98
	Cost saving (%)		6%	10%	16%

Table 3 Deterministic simulation results of Small office models with 50% operational density increments

SMALL OFFICE OCCUPANCY-LIGHTING-PLUG LOAD 50% INCREMENT		Autosized with SF	Autosized without SF	10% Downsiz
	Dx cooling coil capacity (ton)	13	11	
	Total unmet hours (h)	17.5	57	20[illegible]
	Cooling electricity consumption (J)	36068.94	34722.72	33269.[illegible]
	Capacity saving (%)	-	11%	2[illegible]
	Consumption saving (%)	-	4%	[illegible]
	Annual electricity cost	$ 890.58	$ 854.34	$ 818.[illegible]
	Cost saving (%)		4%	[illegible]

Table 4 Impact of operational density in terms of cooling electricity consumption

	Cooling electricity consumption (J)		
	Autosized with SF	Autosized without SF	10% Downsized
Without Ignorance	25255.1	24365.96	23391.81
30% Ignorance Involved	31468.95	30517.99	29277.84
Extra	20%	20%	20%
Without Ignorance	25255.1	24365.96	23391.81
50% Ignorance Involved	36068.94	34722.72	33269.01
Extra	30%	30%	30%

Table 5 Impact of operational density in terms of unmet hours

	Total unmet hours (h)		
	Autosized with SF	Autosized without SF	10% Downsized
Without Ignorance	13.5	34	140
30% Ignorance Involved	14.5	35	156
Difference	7%	3%	10%
Without Ignorance	13.5	34	140
50% Ignorance Involved	17.5	57	202.5
Difference	23%	40%	31%

The 10 and 20% downsized models are simulated for a 39-year period (1973-2012) in order to see the risk of unmet hours over a longer actual weather period. According to the results, only 1980 exceeds allowed unmet hour range for the 10% downsized model (352 hr.). Higher unmet hour counts occur for the 20% downsized model which are found to occur in 1980 (525.5 hr.), 1990 (335 hr.), 1991(336.5 hr.) and 2010 (451 hr.).

Table 6 Deterministic simulation results of Small office for 39-year period

Unmet hours	Frequency 10% Downsize	Frequency 20% Downsize
0-20	6	1
20-40	9	2
40-60	6	2
60-80	2	4
80-100	4	4
100-120	0	5
120-140	2	1
140-160	3	4
160-180	3	3
180-200	2	1
220-240	1	2
240-260	1	2
260-280	0	1
280-300	0	2
>300	1	6

Medium office

The same analysis is applied to the medium office building. According to the results, 20% downsizing is possible for all three cases which are shown in Table 6, 7 and 8. By accepting 216 unmet hours, 29% capacity and 19% energy and cost saving can be achieved in the case of maximum allowance of 50% density increase (Table 9).

Table 7 Deterministic simulation results of Medium office models without operational density increments

DETERMINISTIC MEDIUM OFFICE				
	Autosized with SF	Autosized without SF	10% Downsized	20% Downsized
Dx cooling coil capacity (ton)	100	90	81	72
Total unmet hours (h)	58	165	169.5	174
Cooling electricity consumption (J)	423806.66	401145.75	381825.9	364483.68
Annual electricity cost	$ 9,962.91	$ 9,446.41	$ 8,967.25	$ 8,548.81
Consumption saving (%)	-	5%	10%	14%
Cost saving (%)	-	5%	10%	14%

Table 8 Deterministic simulation results of Medium office models with 30% operational density increments

DETERMINISTIC MEDIUM OFFICE OCCUPANCY-LIGHTING-PLUG LOAD 30% INCREMENT				
	Autosized with SF	Autosized without SF	10% Downsized	20% Downsized
Dx cooling coil capacity (ton)	125	111	100	89
Total unmet hours (h)	90.5	187.5	190	196.5
Cooling electricity consumption (J)	514999.73	481563.82	468223.76	453258.11
Annual electricity cost	$ 12,062.71	$ 11,282.85	$ 10,955.50	$ 10,598.28
Consumption saving (%)	-	6%	9%	12%
Cost saving (%)	-	6%	9%	12%

Table 9 Deterministic simulation results of Medium office models with 50% operational density increments

DETERMINISTIC MEDIUM OFFICE OCCUPANCY-LIGHTING-PLUG LOAD 50% INCREMENT				
	Autosized with SF	Autosized without SF	10% Downsized	20% Downsized
Dx cooling coil capacity (ton)	137	122	109	97
Total unmet hours (h)	109	208.5	210	216
Cooling electricity consumption (J)	625971.28	591237.83	525488.2	506712.64
Annual electricity cost	$ 14,626.79	$ 13,789.57	$ 12,245.01	$ 11,797.28
Consumption saving (%)	-	6%	11%	4%
Cost saving (%)	-	6%	16%	19%

According to Table 10, the 39 year simulation results for the medium office shows 0 years exceedance for 10% downsizing, whereas 20% downsizing exceeds 300 hr. range for 3 years, 1980 (409 hr.), 1993 (301 hr.) and 2010 (330 hr.). It could be concluded that even 20% downsizing could be accepted with minimum risk of having uncomfortable hours. It will lead to substantial saving in energy and costs of 19 % (Table 9).

Table 10 Deterministic simulation results of Medium office for 39-year period

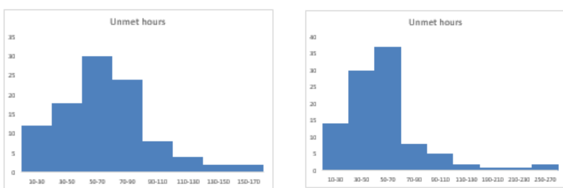
Unmet hours	Frequency 10% Downsize	Frequency 20% Downsize
0-20	0	0
20-40	3	1
40-60	4	2
60-80	8	4
80-100	4	9
100-120	7	1
120-140	3	8
140-160	2	2
160-180	4	4
180-200	1	0
200-220	0	3
220-240	1	2
240-260	1	0
260-280	1	0
280-300	1	1
>300	0	3

Uncertainty Results

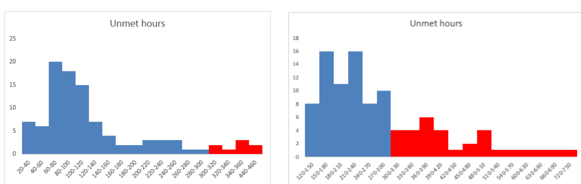
As the aim of the study is to verify our rightsizing approach in worst case conditions, all possible uncertainty parameters are included in the analyses. This includes building material, microclimate, thermal bridge, infiltration, and operational uncertainties (occupancy, lighting, and equipment). The UA results are shown below.

Small office

The 10% downsizing gives the optimum result. When operational uncertainties are excluded, the risk of uncomfortable hours above 300 is only 8% (Figure 4) which is lower than the reasonable threshold of 10%. It should be noted that a threshold of 10 % means that there is only a 1 in 10 risk that the building will exceed 300 unmet hours. Similarly, when operational densities are increased 30% the calculated risk is 10% (Figure 5). Only a 50% increase of operational densities show the increased risk of 20% for the 10% downsized system (Figure 6).

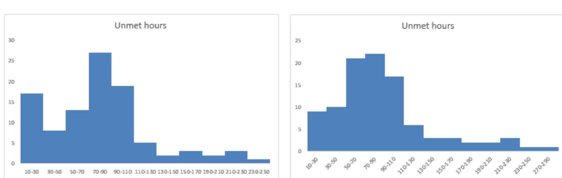


Autosized with SF Autosized w/o SF



10% Downsized 20% Downsized

Figure 4 Uncertainty outcomes of small office models without operational density increments



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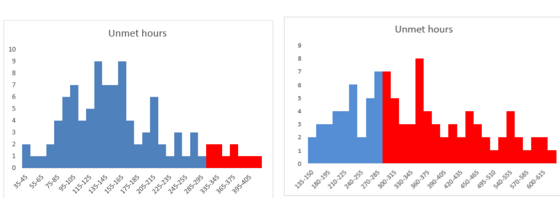
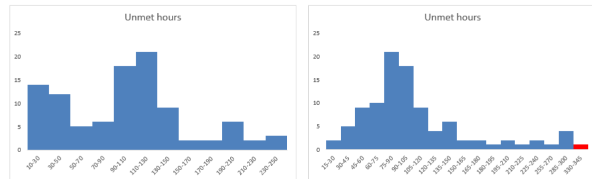
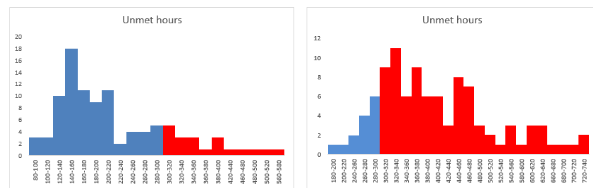


10% Downsized 20% Downsized

Figure 5 Uncertainty outcomes of small office models with 30% operational density increments



Autosized with SF Autosized w/o SF

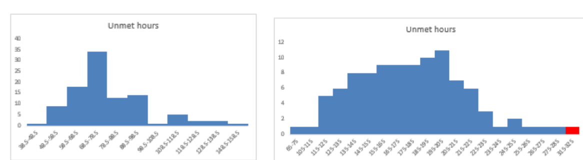


10% Downsized 20% Downsized

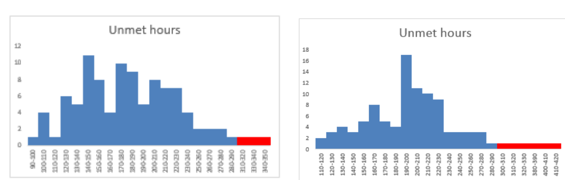
Figure 6 Uncertainty outcomes of small office models with 50% operational density increments

Medium office

Outcomes show that 20% downsizing is possible if the risk (14%) of uncomfortable hours are considered (Figure 8). If operational loads are not part of the considered uncertainty the calculated unmet hour risk is 6% (Figure 7). However, 50% operational density increase disables downsizing possibilities (Figure 6). Maximum energy saving could be achieved with excluding sizing factor in that case (Table 9).

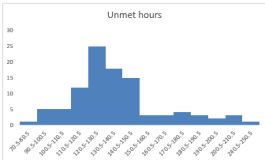


Autosized with SF Autosized w/o SF

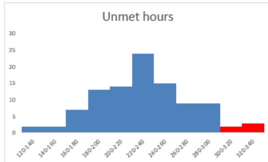


10% Downsized 20% Downsized

Figure 7 Uncertainty outcomes of medium office models without operational density increments



Autosized with SF



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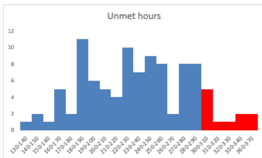
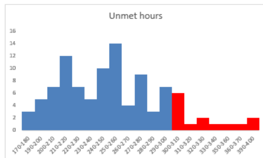
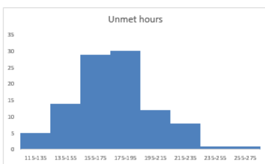


10% Downsized

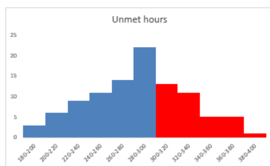


20% Downsized

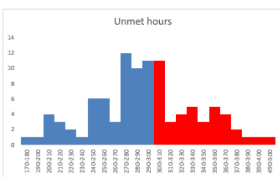
Figure 8 Uncertainty outcomes of medium office models with 30% operational density increments



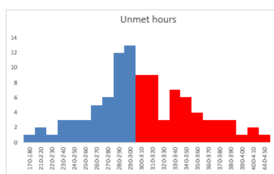
Autosized with SF



Autosized w/o SF



10% Downsized



20% Downsized

Figure 9 Uncertainty outcomes of medium office models with 50% operational density increments

CONCLUSION

Existing HVAC system sizing relies on design day methods or sizing factors to meet the desired performance level. We argue that both generic approaches can cause oversizing in many cases. Subsequently, oversized systems consume superfluous energy and shorten the equipment life. Where these established methods do not cause oversizing, they do not guarantee that the required comfort level expressed in unmet hours is met. Hence, sizing calculations should include an uncertainty analysis which enables a more realistic inspection of the risks to HVAC designers and other decision makers.

Energy modeling tools are time consuming due to the large amounts of input data required, especially for the HVAC system. It is clear that the autosizing option saves time and extra effort in this case. However, it should be noted that non expert use of the autosize option can cause oversizing. This study analyzes the impact of autosizing of DX cooling coils in RTU for climate zone 3A, in various situations of ignorance of operational usage and other sources of uncertainty. It is found that the impact of autosizing in energy modeling tools is signifcant if one wants to design for acceptable risks in unmet hours. The results show that autosizing and use of the routine sizing factors cause 12% extra electricity consumption for the small office and 14% for the medium office.

Another conclusion is that relying on deterministic simulations to evaluate thermal performance of the building is misleading because of false confidence in the calculated unmet hours. Uncertainty analyses provide the quantified risk of the occurrence of unmet hours above a certain thershold. This UA methodology provides robust and realistic input to the consideration of the trade-off between reduced comfort guarantees and accrued savings from HVAC downsizing.

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