RIGHTSIZING: USING SIMULATION TOOLS TO SOLVE THE PROBLEM OF OVERSIZING

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ABSTRACT

Designers oversize HVAC systems for various reasons, and some reasons are more justifiable than others. In oversizing the system, the designers are essentially asking the building owner to incur the financial penalties of oversizing throughout the life of the HVAC system in favor of the theoretical benefit of perfect occupant comfort during the combination of all possible extreme conditions. The initial and ongoing financial penalties associated with oversizing are often not communicated to the client and neither are the potential comfort trade-offs of rightsizing.

This paper presents the results of a study on the "rightsizing" of the rooftop HVAC systems. The study involves a survey and intensive interviews with HVAC designers regarding the design process to identify the factors that can lead to oversizing. The study also carried out extensive measurements on the performance of rooftop units (RTUs) under the peak cooling day design condition. The measurements were used to identify the signature of oversizing, and estimated penalty of oversizing in terms of energy consumption and peak electricity demand. This paper focuses on the results of the simulation exercise carried out as part of the study. The goal of the simulation work for the study was to extend the measured penalty estimate across the whole cooling season.

INTRODUCTION

Earlier studies show that rooftop units (RTU) are the most commonly used HVAC system, see e.g. PGE (1997) and NEEA (2004a). Packaged RTUs represent about 70% of the cooling in commercial buildings in California and about 34% in the Pacific Northwest. In California, about 80% of these buildings were constructed before 1985, and in the Pacific Northwest about 67% of them were constructed before 1987. About 45% of these buildings have RTUs that are more than 10 years old.

These studies show the widespread use of RTUs, and at the same time suggest a substantial potential for RTU replacements in California and the Pacific Northwest due to the large number of small commercial buildings that were constructed over 25 years ago. It is likely that most other areas of the United States have similar statistics.

The problem of oversizing RTUs has been identified based on the measurement result from the previous studies (Felts and Bailey, 2000; NEEA, 2004b; Cowan, 2004). Various publications has suggested ways to avoid oversizing (see e.g. Hourahan, 2004; Thomas and Moller, 2006; Burdick, 2011). Other studies quantify the effect of oversizing in terms of energy use, demand, and runtime (see e.g. James et al., 1997).

However, no previous study addressed the issue from the engineering design point of view. All of them simply state that the problem of oversizing has been found in many RTUs, without elaborating how much oversizing there is and what the strategies are to avoid oversizing. Furthermore, very little guidance was offered to individuals planning RTU replacements in order for them to determine rightsized replacements.

Our research aimed to examine oversizing from the design perspective and to provide accurate and repeatable field monitoring protocols for individuals planning rightsized RTU replacements. The measurement protocol to quantify the oversizing and the associated penalties has been reported in a separate publication (Djunaedy et al., 2011). The current paper summarizes the simulation work of the study.

SIMULATION METHODOLOGY

The main objectives of the simulation work for this study are:

1. To estimate the cooling energy penalty associated with oversizing for the whole cooling season instead of just the field monitoring period.
2. To highlight the advantages of energy simulation as an alternative sizing tool.

The simulation work was carried out in three stages:

1. The calibration stage, where the assumptions (especially the internal gains) were calibrated to the level found in field monitoring so that the runtime fraction (RTF) and the part-load ratio (PLR) of the compressor during the simulation matched the measured values. The result of this stage was the calibrated scenario, which was a set of simulation settings that represent the field monitoring conditions.

2. The sizing stage, where the RTU was sized using the simulation tool under different scenarios (including the calibrated scenario above). The result of this stage was a number of capacities that were based on different scenarios used. Four sizing scenarios were tested, resulting in four different compressor sizes.

3. The penalty estimation stage, where the energy simulations were carried out for the combination of capacities and scenarios. The four compressor capacities were used to simulate four different scenarios and output the penalty of oversizing in terms of energy consumption and peak electricity demand. This stage highlighted the sizing problem and documented the performance effects due to the fact that most RTUs of a given capacity usually operate under conditions different from what was used for sizing the capacity.

EnergyPlus is used as the calculation engine during the simulation work. EnergyPlus has gone through rigorous validation exercise (see e.g. Witte et al., 2001; Henninger et al., 2003).

Calibration Stage

The calibration stage focused on getting the simulation settings (in this case the internal gains) calibrated so that the RTU performance results closely matched the existing design conditions as found during field monitoring. Ideally, the calibration process would have included simulation of the compressor status at the same time-step as used during the field monitoring, and then compare the simulated compressor cycling profile and the temperature profile with the field measurements. If the simulated compressor cycled according to the same profile as the field monitoring data, then the simulation settings could be considered to represent the existing condition within a specified accuracy range.

However, this was not possible due to the limitations of the RTU model in EnergyPlus. It was not possible to replicate the exact on-off cycle of the compressor to be compared with the measurement data. Alternatively, the RTF over the field monitoring period was used as the parameter to compare the simulation results against. Once the RTF of the simulation and the field monitoring matched (within a certain limit), then the simulation settings were determined to represent the actual condition during the field monitoring. The calibrated scenario was important because it represented the peak cooling load condition. The capacity that is sized using this scenario is one potential candidate for the rightsized capacity.

Sizing Stage

In the sizing stage, the autosize function of EnergyPlus was employed to calculate the RTU capacities under multiple scenarios. There were two important questions answered in this stage:

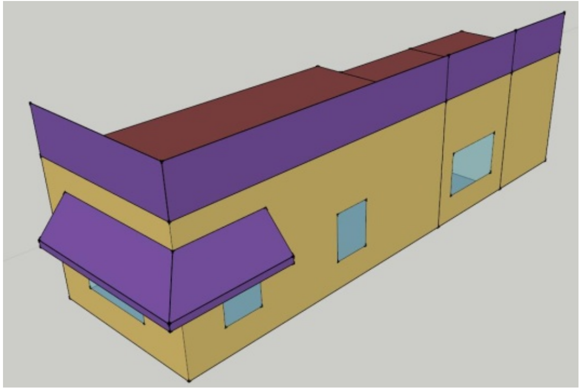

Figure 1: The simulated zones in Building A

1. Under the as-designed scenario (using the same load assumptions as set by the design engineers), can we arrive at the same RTU capacity using simulation as the sizing tool ?

2. What other capacities can be produced using other design conditions?

Before the actual sizing calculation was carried out, a load component analysis was performed. The load component analysis comprised a series of sizing simulations with a certain cooling load component activated at a given time. The cooling load components included in these analyses were (1) opaque wall, (2) glazing, (3) lighting, (4) equipment or plug-load, (5) people (including the ventilation load), and (6) external shading.

From the load component analysis we determined the dominant and less dominant load components. We also tested the sensitivity of the result relative to the boundary condition definition.

Penalty Estimation

The combination of capacities and scenarios were simulated for the whole cooling season. The penalties are calculated in terms of the cooling energy consumption and the peak electricity demand. Apart from the (energy and peak demand) penalty of oversizing, we also investigated the comfort penalty for undersizing.

SIMULATION SETTINGS

Description: The simulated space is a portion of an office building located in Boise, Idaho, USA. The space has one thermal zone served by a single RTU. The thermal zone has three rooms: a conference room, an office space, and a storage room. The zone is located in the northwest part of the building, with its north and west walls exposed to the external environment. The zone has a flat roof. Figure 1 shows the simulated zone modeled in EnergyPlus. The total area of the zone is 940 ft^2.

Construction: External walls are made up of 5/8 in. (1.6 cm) gypsum board on either side with R-19 (19 h·ft^2·°F/Btu or 3.34 K·m^2/W) insulation. The concrete floor is a 6 in. (15 cm) thick slab on grade. The roof is a concrete mass with R-30 (30 h·ft^2·°F/Btu or 5.28 K·m^2/W) insulation. The glazing area is located in the north wall (area=252 ft^2 (23.4 m^2), WWR=17%) and the west wall (area=784 ft^2 (72.8 m^2), WWR=9%). Double pane glass is used with the following thermal properties: SC=0.81 and U-value=0.59 Btu/h·ft^2·°F (3.35 W/m^2·K).

HVAC System: The RTU is modeled using the EnergyPlus template for a unitary system. There are five curves used to describe the performance of the RTU. For this simulation we used custom curves based on the manufacturer's data.

CALIBRATION STAGE

Tables 1 and 2 show the results of the calibration process for Building A. They show the RTF and the PLR for both the operating period and the period where the outside air temperature is above 90 °F. The operating period (in Tables 1 and 2) is the period when the compressor is operating from the first time it cycled ON in the morning to the last time it cycled ON during the night.

Table 1 shows the difference in the RTF between the simulation and the field monitoring data. The simulated RTF for the as-designed case is significantly higher than the measurement data, an indication that the load assumptions are higher than during the measurement period. The calibrated simulated RTF is closer to the measured RTF although it is still higher. The reason for this will be discussed below.

Table 1 shows that if all gains are eliminated, the RTF is further decreased. Even though the simulated RTF for the 'no internal gains case' is closer to the measurement, we cannot take this to represent the measurement condition because we know for a fact that there were internal gains during the measurement period as listed previously. The fact that the calibrated case still has a RTF higher than the measurement data suggests that (1) the internal gains are still too high, and/or (2) there is a heat sink that is not accounted for.

Table 2 shows the PLR between the simulated cases and the measurement. The same discussion as the RTF above also applies to the PLR result.

Figure 2 shows the simulation result with as-designed assumptions for internal gains. Comparing this with the measurement data (Figure 3) it is obvious that the as-designed assumptions are too high. The main difference (between Figure 2 and Figure 3) is that in the as-designed simulation, the compressor works continuously during the peak period between 4pm and 5pm

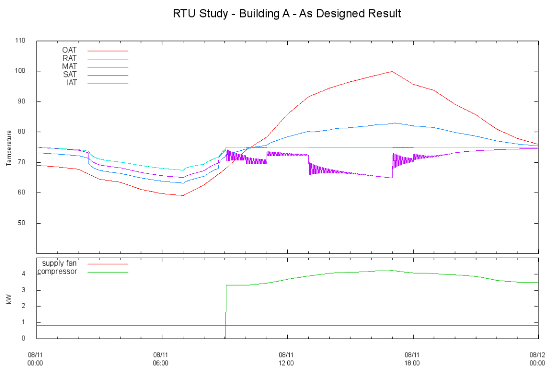

Figure 2: Simulation Result for Building A (As-Designed Condition)

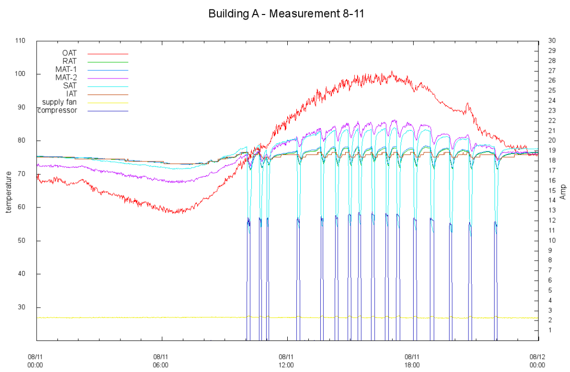

Figure 3: Measurement Result for Building A

(in fact for the whole operating period), which did not happen during the measurement. The measurement data (Figure 3) shows that the compressor cycled on and off 16 times during that period.

Figures 4 show the calibrated simulation result. The internal loads were set according to the observations made on site during the field monitoring period. Table 3 shows the difference in the internal gain assumptions between the as-designed case and the calibrated case.

To investigate further, another simulation was carried out under no-internal-gains condition. The results are

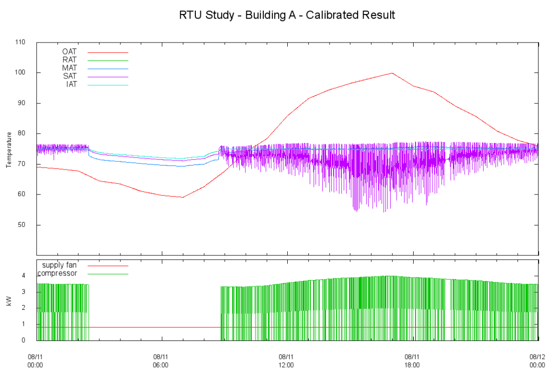

Figure 4: Simulation Result for Building A (Calibrated Condition)

Table 1: RTF Comparison for Building A

	RTF (operating period)	RTF (above 90 °F OAT)
Simulation (As Designed)	0.51	0.69
Simulation (Calibrated)	0.23	0.32
Simulation (No internal gains)	0.14	0.19
Measurement Data	0.15	0.18

Table 2: PLR Comparison for Building A

	PLR (operating period)	PLR (above 90 °F OAT)
Simulation (As Designed)	0.45	0.69
Simulation (Calibrated)	0.22	0.30
Simulation (No internal gains)	0.13	0.18
Measurement Data	0.16	0.21

also shown in 12. Both the RTF and PLR values (0.19 and 0.18 respectively for OAT above 90 °F) are close to the measurement values (0.18 and 0.21 respectively).

However, even though the RTF and PLR values for the no-gains condition are closer to the field monitoring data we know that this does not represent the condition during the measurement period. We know that there were internal gains during the field monitoring. As such, we took the internal gains as described in Table 3 as the calibrated condition. We also concluded that there was a heat sink that was not represented in the simulation.

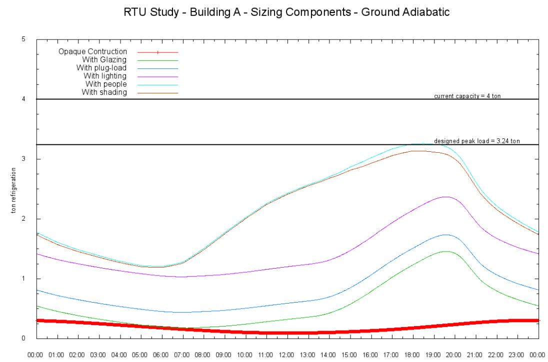

Figure 5: Peak Load Component (Adiabatic Ground)

SIZING STAGE

Load Component Analysis

Figure 5 shows the load component of the as-designed condition. The line at the bottom (red) represents the load from the opaque envelope, and the lines above it represent the inclusion of various internal gains. The comparison between the lines show the relative significance of the load component to the peak load.

There are three important notes from Figure 5:

1. The biggest contributors to the peak cooling load are the glazing and the people (including ventilation).

2. The shading has a minimal effect on the peak cooling load (the difference between the top two curves). Note that this is caused by the location of the zone, which is on the northwest corner of the building. The effect of the shading will be more dominant in the zone in the opposite corner of the building.

3. The peak cooling load estimated by EnergyPlus corresponds closely with the designed peak load for the building calculated by the mechanical engineer.

Even though Figure 5 replicates the designed peak load (as calculated by the mechanical engineer in the design stage), it should be noted that the simulation uses the assumption of an adiabatic floor, which means there is no heat loss from the floor. The same assumption was also used in the sizing calculation done by the mechanical engineer. The result of the calibration stage (see discussion in the previous section) suggests that this assumption is not correct. Under the assumption of an adiabatic floor, the simulation would produce a RTF and PLR that are significantly higher than the measurement period RTF and PLR.

A number of simulations were carried out to investigate the effect of floor heat loss to the sizing calculation. To avoid a more complicated calculation, a constant ground temperature was used for the simulations. The EnergyPlus manual suggests to set the ground temperature at 2 °C (3.6 °F) less than the set point temperature of the room.

Figure 6 show the sizing calculation based on the ground temperatures of 22 °C (71.6 °F) and 21 °C (69.8 °F) respectively.

During the calibration stage, we found that 22 °C ground temperature does not result in a RTF or PLR similar to the field monitoring data. The results of

Table 3: Internal gains for Building A

	As Designed	Calibrated
Occupancy	24 persons	6 persons
Lighting	2 W/ft^2	0.7 W/ft^2
Equipment	0.851 W/ft^2	Same as-designed (only in office)

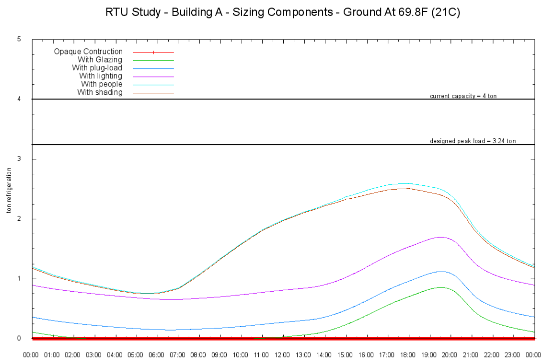

Figure 6: Peak Load Component (Ground at 21 °C or 69.8 °F)

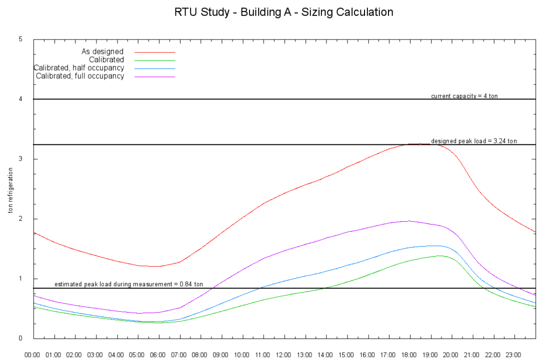

Figure 7: Sizing Calculation (Building A)

the calibration stage are all simulated using 21 °C (69.8 °F) ground temperature. The temperature 21 °C (69.8 °F) is 2.8 °C (5 °F) below the set-point temperature, slightly higher than the 2 °C suggested by EnergyPlus manual.

Even though the results from the calibration simulation (Tables 1 and 2) produce a RTF and PLR that are higher than the field monitoring, there is no attempt to decrease the ground temperature further, because the ground temperature used is already lower than what is suggested by the EnergyPlus manual (2 °C or 3.6 °F). Therefore the result from the sizing calculation (in the next section) will be relatively higher, and in turn, the estimation of the penalty due to the oversizing will be more conservative.

It is important to note that the effect of the floor heat loss in the peak load is significant. Comparing Figure 5 and Figure 6, the floor heat loss can reduce the peak cooling load by approximately 21%.

Sizing Calculation

The sizing calculations were carried out under four scenarios (Table 4). Scenario 1 represents the "as-designed" scenario, while Scenario 2 represents the calibrated scenario. Scenario 2, however, has only 5 occupants in the conference room, which is true during the field monitoring period, but may not represent the peak occupancy of the conference room. Note that Scenario 2 has one more person compared to Table 3. This is because during the measurement there was nobody in the file room, while for sizing calculation (Scenario 2) we needed to assume at least one person is in the room.

Scenarios 3 and 4 are introduced to test exactly the same scenario as Scenario 2, but with higher occupancy in the conference room.

Figure 7 and Table 5 show the sizing calculation for the four scenarios. Scenario 1 has exactly the same RTU capacity as what was designed by the mechanical engineer. Scenario 2 (the calibrated scenario) has a much smaller capacity compared to Scenario 1. Note that even if it is smaller than Scenario 1, it is considerably higher than the estimated peak cooling load during the measurement period. There is no attempt to further reduce the capacity of Scenario 1 to the estimated peak load during the measurement period because we did not do the detailed analysis on the floor heat loss and because the higher capacity will result in more conservative estimates of the energy penalty.

The capacities for Scenario 2 and 3 are lower than Scenario 1 because of the higher occupancy in the conference room (see Table 4). However, even though Scenario 4 has the same occupancy in the conference room as Scenario 1, it has a capacity that is much less than Scenario 1 (41% less). The big difference between the capacity of Scenarios 1 and 4 is caused by (1) the use of external shading in the calculation, (2) a lower lighting level, (3) slightly fewer occupants, and (4) the floor heat loss.

PENALTY ESTIMATES

To estimate the penalty associated with RTU oversizing, all four calculated capacities (as in Table 5) were simulated for the whole cooling season. Each capacity was also simulated under all four scenarios (as in Table 3). For each capacity under each scenario three types of simulation were carried out. Table 6 shows

Table 4: RTU Sizing for Different Scenario

		Scenario 1	Scenario 2	Scenario 3	Scenario 4
Ground		Adiabatic	at 21 °C	at 21 °C	at 21 °C
Shading		No	Yes	Yes	Yes
Occupancy	Conference	20	5	10	20
	Office	2	1	1	1
	File	2	1	1	1
Lighting	Conference	2	0.7	0.7	0.7
	Office	2	0.7	0.7	0.7
	File	2	0.5	0.5	0.5
Equipment	Conference	0.87	0.8	0.8	0.8
	Office	0.87	0.5	0.5	0.5
	File	0.87	0.1	0.1	0.1

Table 5: RTU Sizing for Different Scenario

Capacity	Scenario	Btu/hr	ton	CFM
Capacity 1	Scenario 1	38,424	3.20	1,553
Capacity 2	Scenario 2	16,753	1.40	684
Capacity 3	Scenario 3	18,663	1.56	745
Capacity 4	Scenario 4	22,475	1.87	867

the difference between the three types of simulation. With four capacities, four scenarios, and three simulation types, there are a total of 48 simulation runs.

Energy Penalty of Oversizing

Capacity 1 of Scenario 4 (as-designed capacity under calibrated internal gains with full capacity) is taken as the basis of the comparison. Scenario 1, which is the as-designed condition, was not taken as the basis of the comparison because it represents the maximum condition possible and will not occur all the time. It is true that Capacity 1 of Scenario 4 will not occur all the time either, but for the penalty calculation this combination will result in a conservative value of the penalty.

The other capacities use its corresponding scenario (i.e. the scenario that was used to size the capacity) for the simulation. Table 7 shows the summary of the penalties.

Depending on which capacity is used to replace the installed RTU, the energy savings range from 37% to 48%. Note that these numbers are significantly higher than the savings estimated from the measurement data (16.7% see Henderson et al., 1991), and even higher than the theoretical estimate (11%).

Peak Demand Penalty of Oversizing

Table 8 shows the estimate of the peak demand penalty for Building A. The peak demand savings is between 48% to 62%, which translates to approximately 2.4 kW to 3.1 kW.

Comfort Penalty of Undersizing

Figures 8 show the comparison of the indoor air temperature and the compressor power under different

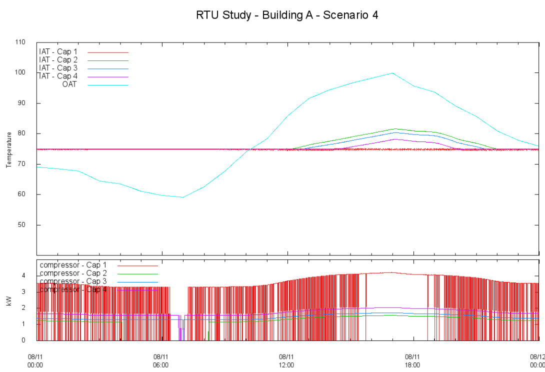

Figure 8: Simulation Results for Scenario 4

scenarios throughout a peak day. These are the results of Type 3 simulations (see Table 6). The figures show (1) how compressors with different capacities cycle under different scenarios and (2) whether the indoor air temperature rises above the set-point temperature. Because of the space limitation, only Scenario 4 will be presented here.

Figure 8 shows the result for Scenario 4. Since the occupant load is higher than in Scenario 3, only Capacity 1 can maintain the indoor air temperature near the set-point temperature. The other capacities cannot maintain the set-point temperature. For Capacity 2, the indoor air temperature started to exceed the set point around noon, while for Capacity 3 it exceed it at about 1pm. For Capacity 4, the temperature started to rise at about 3pm.

Figures 10 show the results of Type 2 simulation, which covers the whole cooling season (see Table 6 for the types of simulation). The indoor air temperature was plotted against the time of day.

Table 6: Three Types of Simulation

Type	Simulation Time	Time-step	Internal gains
Type 1	Whole cooling season (1-May through 30-Sep)	60 min	Varying over time of day with reasonable schedules
Type 2	Whole cooling season (1-May through 30-Sep)	60 min	Constant at maximum value
Type 3	One day (11-Aug), the measurement day	1 min	Constant at maximum value

Table 7: Energy Penalty Estimate for Building A

		Compressor (kWh)	Fan (kWh)	Total (kWh)	Penalty
Capacity 1	Scenario 4	1,403	3,081	4,483	-
Capacity 2	Scenario 2	764	1,581	2,344	48%
Capacity 3	Scenario 3	864	1,722	2,586	42%
Capacity 4	Scenario 4	1,094	1,722	2,586	37%

Table 8: Peak Demand Penalty Estimate for Building A

		Compressor (W)	Fan (W)	Total (W)	Penalty
Capacity 1	Scenario 4	4,227	839	5,066	-
Capacity 2	Scenario 2	1,481	430	1,911	62%
Capacity 3	Scenario 3	1,687	469	2,156	57%
Capacity 4	Scenario 4	2,095	546	2,641	48%

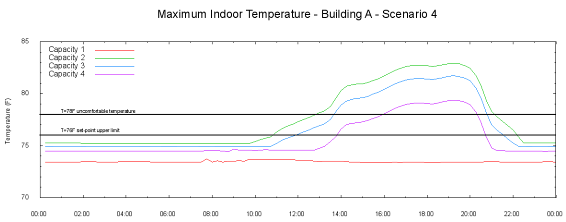

Figure 9: Maximum Indoor Air Temperature as a Function of Outside Air Temperature (Scenario 4)

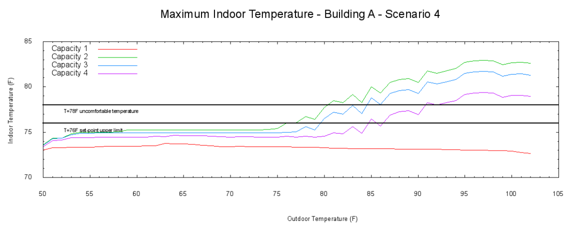

Figure 10: Maximum Indoor Air Temperature as a Function of Outside Air Temperature (Scenario 4)

What if we have 20 persons in the conference room (Scenario 4)? Figure 9 shows the maximum indoor air temperature for Scenario 4. Capacity 2 obviously cannot handle the load past 11am. Capacity 4 can maintain the set-point temperature until 2pm, and can keep the room below 78 °F until 6pm.

Table 9 shows the unmet hours of Scenario 4. Capacity 2 has 350 unmet hours, which is more than 9% of the total hours. It terms of working hours Capacity 2 has about 149 hours above 76 °F, which is almost four weeks. This is certainly not acceptable.

Capacity 4, however, has more acceptable unmet hours. With only 71 total hours (and 18 working hours) above 76 °F. Capacity 4 is a the best alternative to the as-designed capacity and is less than half of the as-designed capacity. It certainly offers savings with acceptable risk regarding human comfort.

Figures 10 show the maximum indoor temperature as a function of outdoor temperature for Scenario 4.

Figure 10 shows that for Scenario 4 (with 20 people in the conference room), Capacity 4 can maintain the indoor air temperature at the set-point temperature until the outdoor air temperature is about 85 °F, and will only be uncomfortably hot when the outdoor air temperature is above 92 °F.

PUTTING IT ALL TOGETHER

Energy simulation can be used as a sizing tool. Designers can present the client with a more complete picture of performance based on simulation results. The advantage of using energy simulation tool as a sizing tool are (1) flexibility in selecting the design conditions, (2) flexibility in presenting the sizing result in terms of load components that change dynamically throughout the design day, and (3) ability to present the different sizing scenarios with the associated penalties. The penalties that can be assessed is not only the penalty of oversizing in terms of energy consumption and peak electricity demand, but also the

Table 9: Unmet Hours for Building A (Scenario 4)

All hours	Capacity 1	Capacity 2	Capacity 3	Capacity 4
Hours above 76 °F	0	350	212	71
	0.00%	9.54%	5.77%	1.93%
Hours above 78 °F	0	147	82	14
	0.00%	4.01%	2.22%	0.37%

Office Hours	Capacity 1	Capacity 2	Capacity 3	Capacity 4
Hours above 76 °F	0	149	78	18
	0.00%	5.63%	2.94%	0.68%
Hours above 78 °F	0	49	21	2
	0.00%	1.85%	0.80%	0.06%

penalty of undersizing in terms of comfort.

Sizing calculations should be presented not only based on the maximum internal gains scenario, but also based on the likelihood or frequency that such scenarios will ever happen. Alternative scenario(s) should be presented along with the maximum internal gains scenario, and the comparison of the various penalties (energy, peak demand and comfort) should be made.

Instead of bearing all the risk and liability alone (and because of that, size the system to the maximum capacity), the designer can ask the owner to bear the consequences of choosing a smaller capacity. The owner will have first cost and energy cost savings with a certain calculated risk. The method described in this paper is particularly useful for renovation projects, where the owner has access to the existing air conditioning units that can be measured and assessed for oversizing.

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