Energy System Simulation
Task 2

AREN 4010, HVAC Modeling and Controls

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Abstract

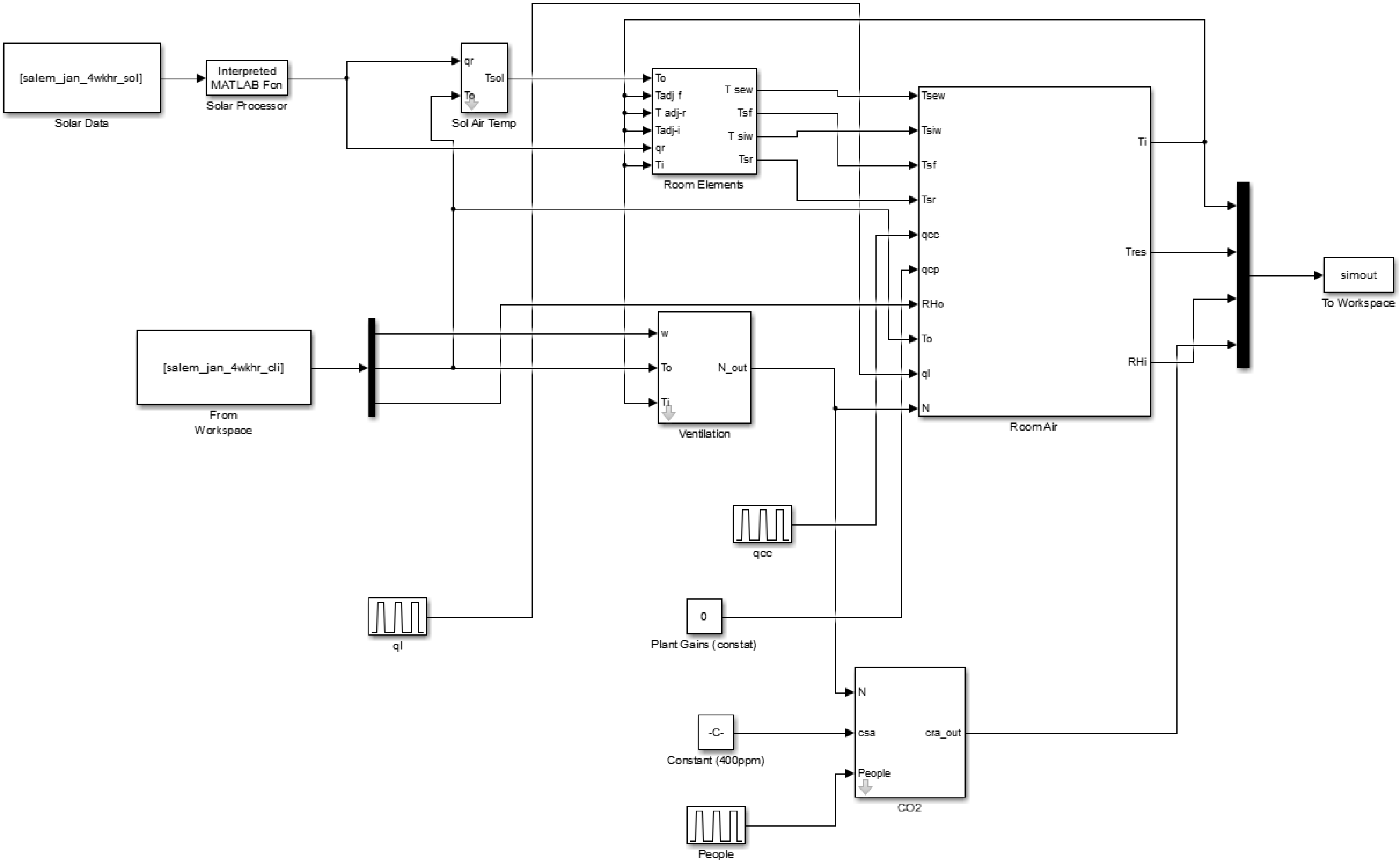
It was of interest to develop a model for passive building performance in both Salem Oregon and Omaha Nebraska for both winter and summer months and study the effect of varying different building parameters on building performance. The following report details how this was done using MATLAB's Simulink plugin as well as discusses the results of changing different building features. Overall, it was possible to show improvement to building performance and in, some cases, achieve the ASHRAE recommended thermal comfort zone with an entirely passive design.

Introduction

This report describes the development and use of a Simulink model to model interior conditions in a building in Omaha Nebraska, and another in Salem Oregon. The model includes considerations for quantity and location of thermal mass, transient heat transfer conditions, window gains, infiltration, and internal sensible and latent loads. Once a base line model was established, a parametric study was done to optimize building performance for the given weather conditions.

The purpose of this phase of the energy system simulation is to develop a Simunlink thermal model that can take weather data for a given site and time, and output interior temperature for the time specified by the model user. The model accepts as input 2 climate file, one that describes outdoor temperature, relative humidity and windspeed, and another that describes global horizontal radiation.

The first file allows for the conduction component of heat transfer through the walls to be calculated using a simple energy balance. Additionally, using the wind speed and the user specified standard infiltration rate, the model is able to incorporate the effect of infiltration gains and losses. The second file allows for the effect of solar radiation to be considered for the effect it has on heat gain through the southern façade. This data, in conjunction of the ambient outdoor temperature data, allows for the calculation of sol-air temperature using the method prescribed by ASHRAE. A schematic view of the model is shown in the figure on the following page..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simout
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To
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N_out
Ventilation
qcc
ql
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Plant Gains (constat)
N
csa
People
cra_out
CO2
-C-
Constant (400ppm)
People

Methodology

Room air temperature calculation

The room temperature was modeled using the first law of thermodynamics to derive an energy balance equation. The basic idea of this methodology is captured below in equation 1.1.

$$qcc + qcp - Wall\ Heat\ loss - Window\ Heat\ Loss - Infiltration\ Losses - Ci\frac{dT_i}{dt} = 0 \qquad [1.1]$$

Where qcc is the convective internal heat gain in the space and qcp is the plant gain created by a potential HVAC system. For this particular analysis, the plant gain was taken to be 0 as this was intended to be a passive analysis only. Based on the room air volume of 630 cubic meters, specific heat capacity of air of 1005 J/K, and air density of 1.2 kg/m^3 a Ci value of 759,780 [J*kg/K] was determined. The heat loss components in equation 1.1 were calculated as,

$$Wall\ Heat\ Loss = \frac{Aew(Ti - Tsew)}{R_s} + \frac{Aiw(Ti - Tisw)}{R_s} + \frac{Af(Ti - Tsf)}{R_s} + \frac{Ar(Ti - Tsr)}{R_s} \qquad [1.2]$$

$$Window\ Heat\ Loss = Ag * Ug * (Ti - To) \qquad [1.3]$$

$$Infiltration\ Losses = ACH * Room\ Volume * (Ti - To) * \rho_{air} * Cp_{air} \qquad [1.4]$$

Substituting known air property values into equation 1.4 and converting air changes per hour into air changes per second makes it approximately equal to

$$Infiltration\ Losses = \frac{NV(Ti - To)}{3} \qquad [1.5]$$

Note that equation 1.5 assumes that air density and specific heat are constant throughout the modeling period, while in reality these properties vary with temperature and humidity. The error introduced by this assumption is acceptable, however, for HVAC modeling purposes.

Substituting equations 1.2, 1.3 and 1.5 into equation 1.1 gives the sensible energy balance shown in equation 1.6 below.

$$Ci\frac{dT_i}{dt} = qcc + qcp - [\frac{Aew(Ti - Tsew)}{R_s} + \frac{Aiw(Ti - Tisw)}{R_s} + \frac{Af(Ti - Tsf)}{R_s} + \frac{Ar(Ti - Tsr)}{R_s} + Ag * Ug * (Ti - To) + \frac{NV(Ti - To)}{3}]$$

Room humidity calculation

The humidity in the room was modeled using the principal mass conservation, the basic idea of which is shown in equation 2.1.

$$Infiltration\ Moisture + Interal\ gains\ moisture - Room\ Air\ Mass * \frac{dgi}{dt} = 0 \qquad [2.1]$$

It should be noted that this methodology ignores surface moisture absorption which was done for model simplicity. Solving for each of the terms in equation 2.1 properly gives the equations below.

$$Infiltration\ Moisture = \rho_{air} * ACH * \frac{V}{3600} \qquad [2.2]$$

$$Interal\ gains\ moisture = \frac{q_{latent}}{Latent\ heat\ of\ vaporization\ for\ water} \qquad [2.3]$$

Substituting equations 2.2 and 2.3 into equation 2.1 results in the following mass balance.

$$M\frac{dgi}{dt} = \frac{1.2NV(go - gi)}{3600} + \frac{q_{latent}}{h_{fg}} \qquad [2.4]$$

The parameter g in the above equations is the moisture concentration in the air measured in kg/kg. It is more convenient, however, to express humidity as relative humidity which was doing using the method prescribed in the *CIBSE Guide Book A, Section A1.*

Room CO2 concentration calculation

To evaluate the indoor air quality in the space, carbon dioxide concentration was used as a proxy for indoor air pollutants, as is commonly done for IAQ analysis. Carbon dioxide was modeled using the same mass balance principle used for the humidity ratio which is described by equation 3.1.

$$V_{room}\frac{dc_{ra}}{dt} = \dot{V}_{sa}c_{sa} - \dot{V}_{ra}c_{ra} + S_{occupants} \qquad [3.1]$$

For this modeling task, a ventilation rate of zero was assumed, so the supply air volumetric flow rate is equivalent to the infiltration rate described in the weather files. Further, it was assumed that the CO2 concentration of the supply air (c_{sa}) was constant at a level of 400 parts per million. It was given that humans produce carbon dioxide at a rate of 0.02323 m^3 per hour. Further, for modeling purposes, it was assumed that the building is occupied by 15 people for 10 hours per day, 7 days per week. So when the building is occupied $S_{occupants}$=0.34845 m^3 per hour or 9.679 E -05 m^3 per second, and when it is not occupied $S_{occupants}$=0. Using the known parameters for the model and converting everything to per second, equation 3.1 reduces to equation 3.2.

$$\frac{dc_{ra}}{dt} = \frac{N(.0004 - c_{ra}) + \frac{S}{V}}{3600} \qquad [3.2]$$

The differential equation of equation 3.2 could then be trivially solved using the built in integrator block in Simulink.

Parametric Analysis

The first design that was modeled was the baseline design prescribed in the assignment. It had the following properties.

- Internal space with single exterior wall facing due south.
- 30m x 3m x 7m
- 35% window to wall ratio on south wall
- Glass transmissivity of 0.6
- Glass U-value of 3.2 $Wm^{-2}K^{-1}$
- Sensible internal heat gain of 20 W/m^2
- Latent heat gain of 4 W/m^2

The baseline space was modeled to be constructed with the following materials.

Table 1

External South Facing Wall				
Code No.	**Construction Component**	**Rt [m^2 K/W]**	**Ct [kJ/m^2 K]**	**Ct [J/m^2 K]**
E0	inside surface resistance	0.121	0	0
E1	20mm light plaster	0.026	25.8216	25821.6
C3	100mm heavy concrete block	0.125	83.2104	83210.4
B24	70mm mineral wool insulation	1.584	5.3256	5325.6
B1	25mm air gap	0.16	0	0
A2	100mm outer brick	0.076	187.22	187220
A0	outside surface resistance	0.059	0	0
Total		**2.2**	**301.6**	**301577.6**

Table 2

Internal Wall				
Code No.	**Construction Component**	**Rt [m^2 K/W]**	**Ct [kJ/m^2 K]**	**Ct [J/m^2 K]**
E0	inside surface resistance	0.121	0	0
E1	20mm light plaster	0.026	25.8216	25821.6
C2	100mm light concrete block	0.266	52.0632	52063.2
E1	20mm light plaster	0.026	25.8216	25821.6
E0	inside surface resistance	0.121	0	0
Total		**0.6**	**103.7**	**103706.4**

Table 3

Floor/Ceiling				
Code No.	**Construction Component**	**Rt [m^2 K/W]**	**Ct [kJ/m^2 K]**	**Ct [J/m^2 K]**
E0	inside surface resistance	0.121	0	0
C10	Heavycast concrete	0.117	382.8636	0
B1	300 mm Airgap	0.16	0	0
E1	20mm light plaster	0.026	25.8216	25821.6
E0	inside surface resistance	0.121	0	0
Total		**0.5**	**408.7**	**25821.6**

Subsequent to the derivation of this base line structure, different parameters were then varied to see if they improved building performance, by bringing the indoor psychrometric properties into the comfort zone for more hours per day. The details of what was changed are summarized in table 4.

Table 4

	Base	**Higher**	**Lower**
South Glazing Fraction	35%	50%	10%
Mass Level of Exterior Wall [J/m^2 K]	301577.6	603155.2	150788.8
Mass Level of Interior Wall [J/m^2 K]	103706.4	207412.8	51853.2
Mass Level of Ceiling and Floor [J/m^2 K]	301577.6	603155.2	150788.8
Glazing U-Value [W/m^2K]	3.2	5.8	1.6
Standard ACH	1	1.5	0.5

These parameters were varied and modeled in both Omaha, Nebraska and Salem, Oregon under winter and summer conditions to qualitatively evaluate their impact on building thermal performance. It was chosen to perform the parametric study using summer conditions, as it is typically more expensive to cool a space than it is to heat it. Once an optimal design was reached for summer conditions, the same construction was modeled under winter conditions. The results of this analysis is discussed in the results section of this report.

Results

The results of making the changes described in table 4 are summarized below and tables 5 and 6 along of the construction values used for the improved model.

Table 5. Key, MW=much worse, SW=slightly worse, NC=no change, SB=slightly better, MB=much better.

Omaha Summer Parametric Study			
		Effect of change	
	Improved Design	Higher	Lower
South Glazing Fraction	10%	MW	MB
Mass Level of Exterior Wall [J/m^2 K]	150788.8	NC	SB
Mass Level of Interior Wall [J/m^2 K]	103706.4	NC	NC
Mass Level of Ceiling and Floor [J/m^2 K]	301577.6	NC	NC
Glazing U-Value [W/m^2K]	5.8	SB	SW
Standard ACH	1.5	SB	MW

Table 6. Key, MW=much worse, SW=slightly worse, NC=no change, SB=slightly better, MB=much better.

Salem Summer Parametric Design			
		Effect of change	
	Improved Design	Higher	Lower
South Glazing Fraction	10%	SW	MB
Mass Level of Exterior Wall [J/m^2 K]	150788.8	SW	NC
Mass Level of Interior Wall [J/m^2 K]	103706.4	NC	NC
Mass Level of Ceiling and Floor [J/m^2 K]	301577.6	NC	NC
Glazing U-Value [W/m^2K]	5.8	MB	MW
Standard ACH	1.5	MB	MW

Temperature plots

Subsequent to the modification to the building parameters beyond the baseline design, it was of interest to analyze the effects of the modifications on the building's operative temperature. The base line and modified designs are compared below.

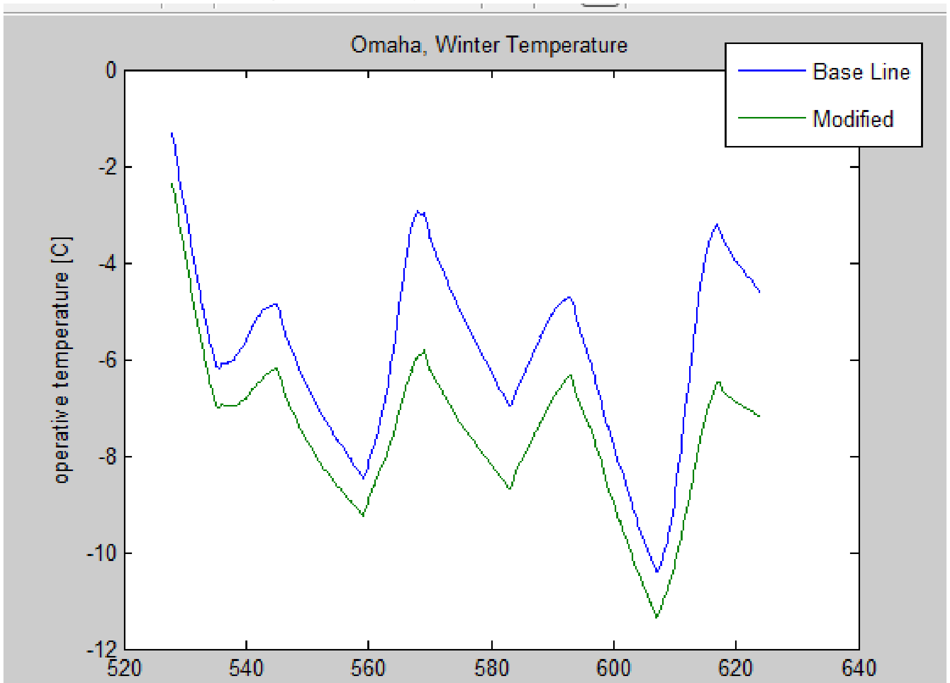

Figure T.1

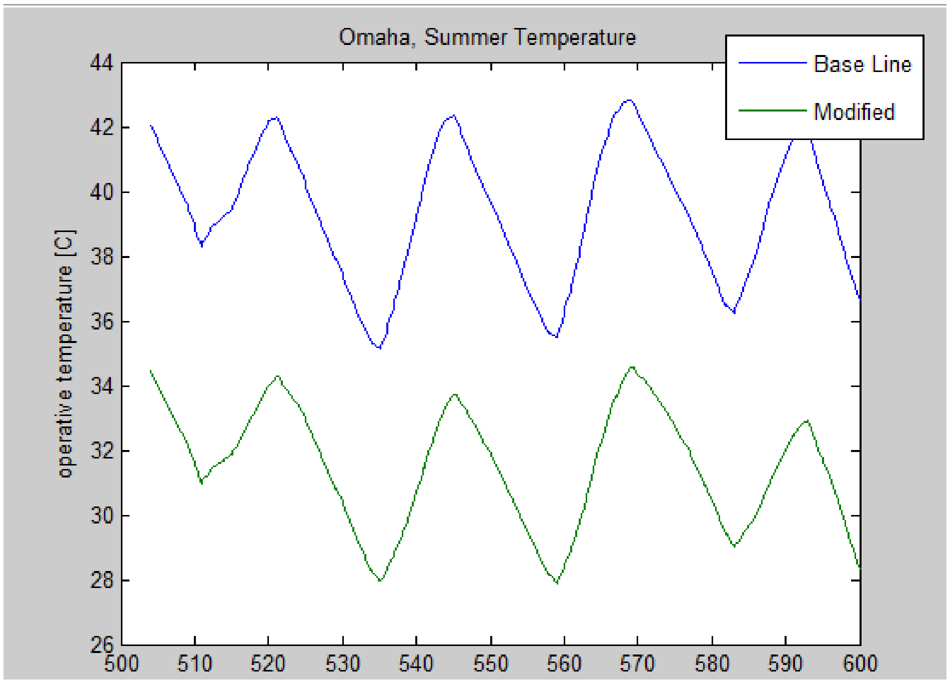

Figure T.2

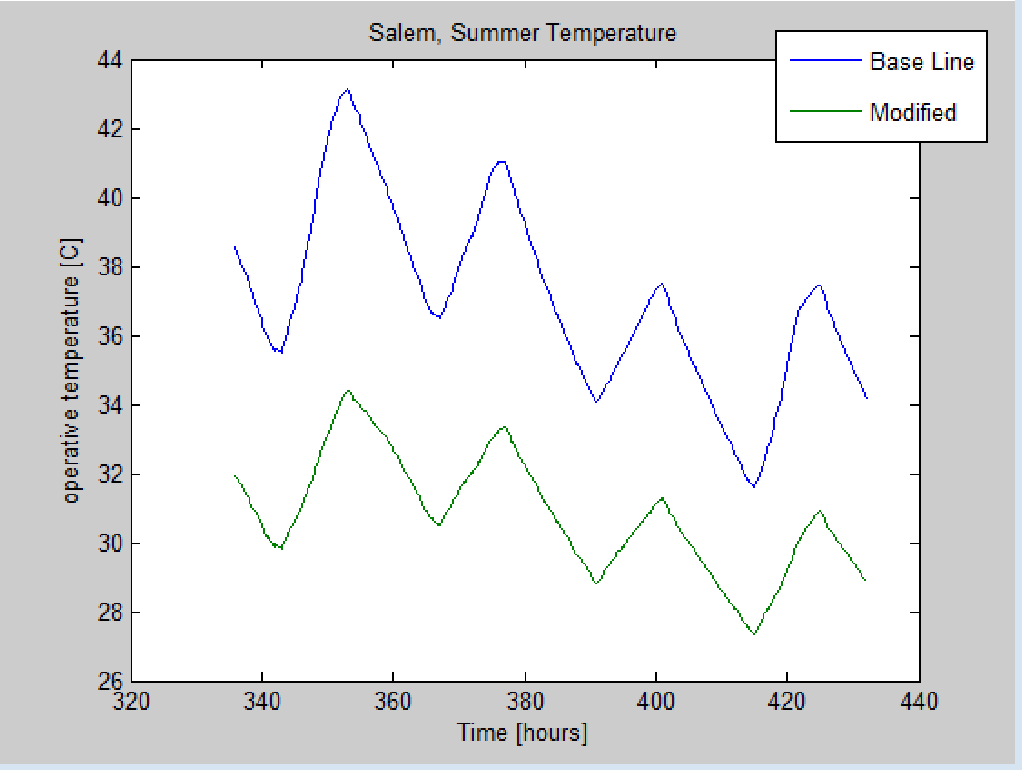

Figure T.3

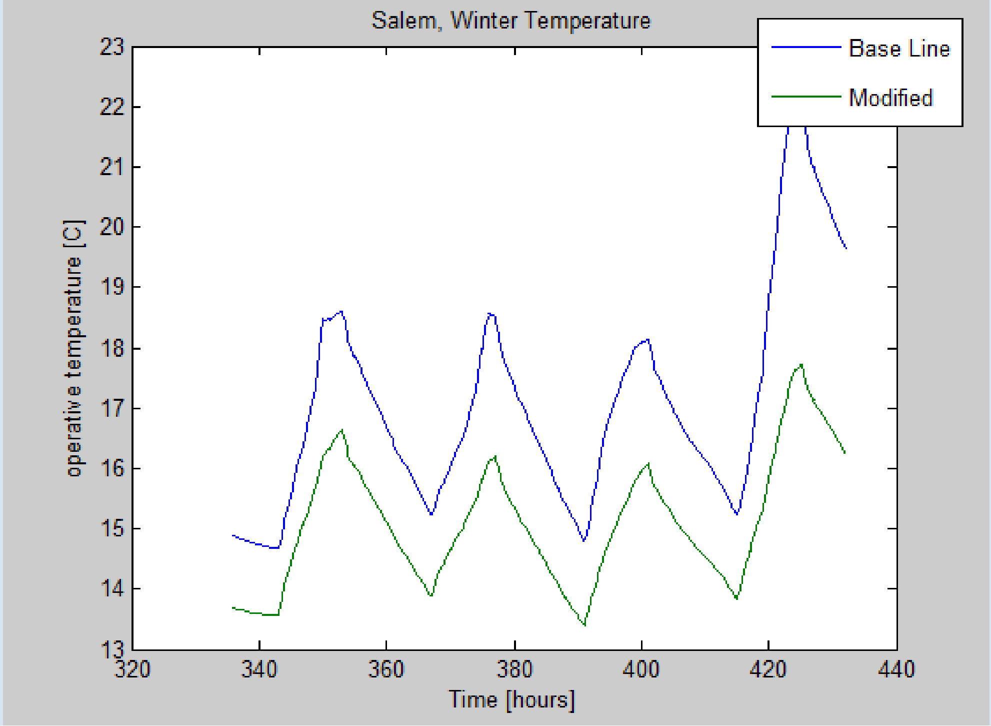

Figure T.4

Psychrometric plots

To analyze compliance with ASHRAE Standard 55, Fig 5.2.1.1, the resulting humidity ratios and drybulb temperatures were plotted on the Psychrometric chart along side the ASHRAE comfort zone as indicated by the gray square box. For purposes of psycrometric plotting, it was assumed that both sites were located at sea level, which is an appropriate approximation for Omaha and Salem.

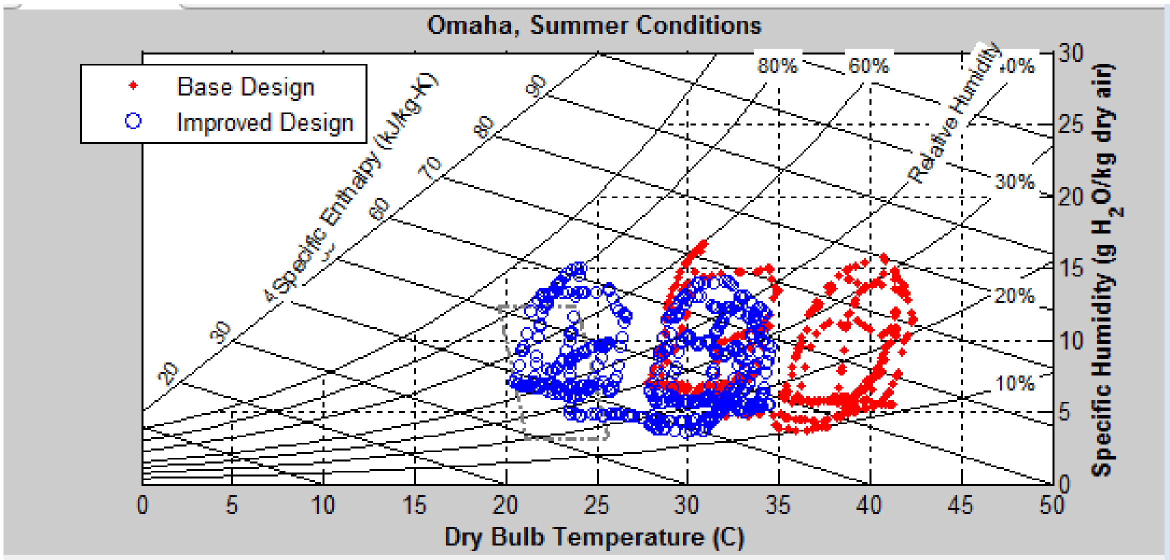

Figure P.1. Data shown for last 2 weeks of the month.

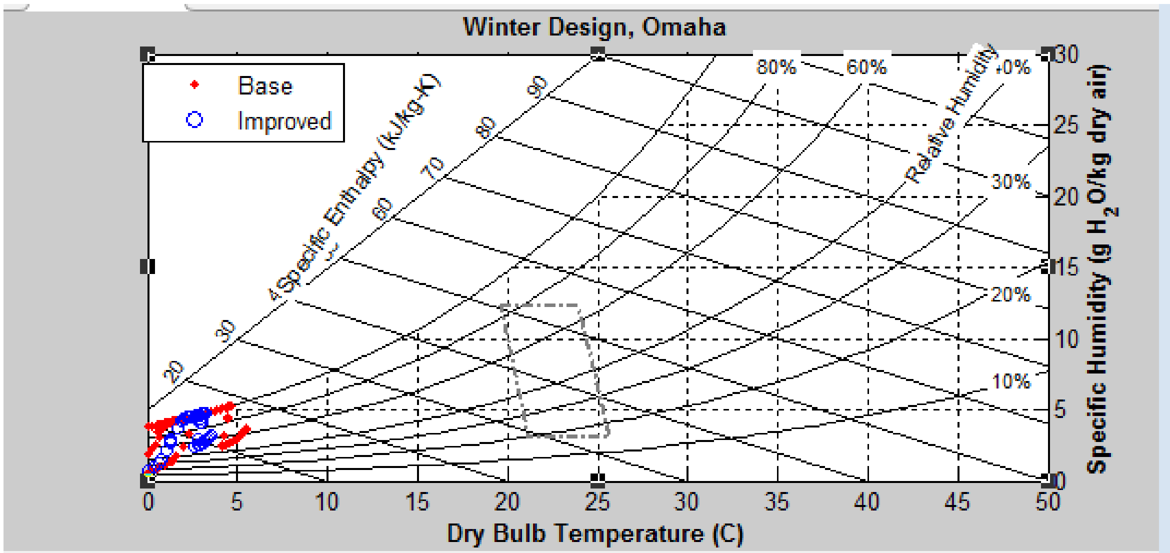

Figure P.2. Data shown for last 2 weeks of the month.

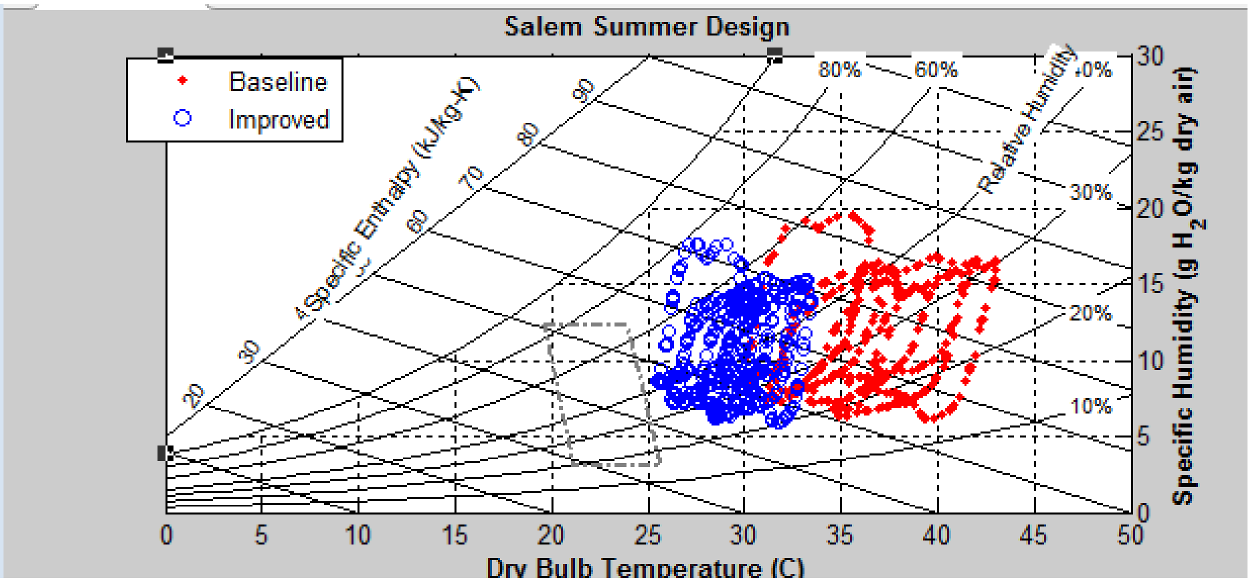

Figure P.3. Data shown for last 2 weeks of the month.

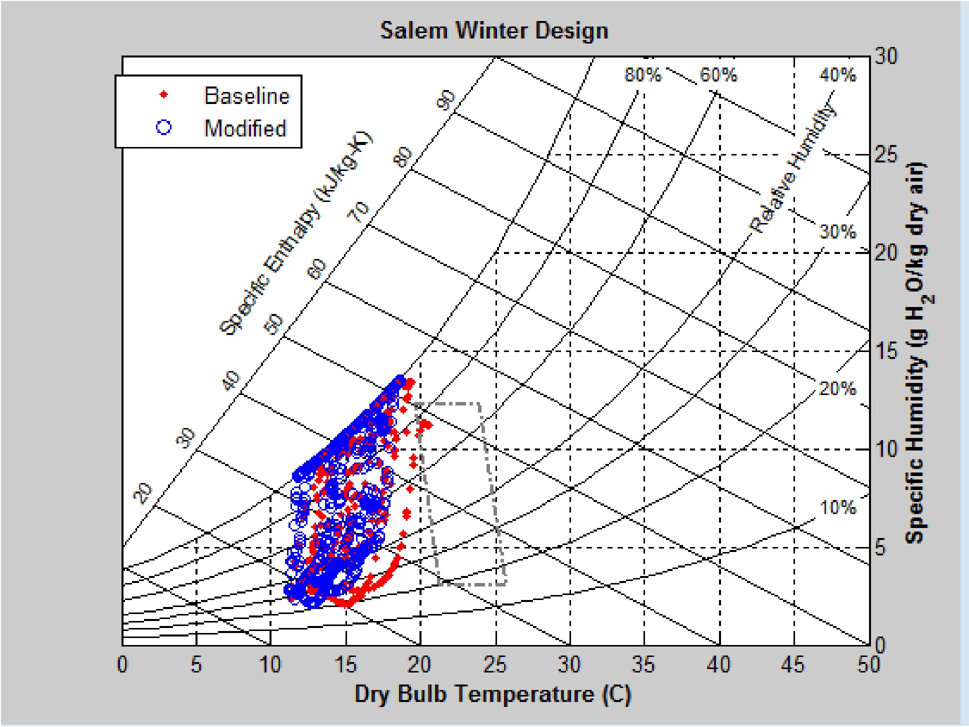

Figure P.4 Data shown for last 2 weeks of the month.

CO2 Concentration

Another interesting parameter in buildings is the indoor air quality. It is often convenient to use indoor carbon dioxide concentration as a proxy for other indoor pollutants to analyze IAQ. The plots below show the levels of CO2 for each design, assuming an outdoor concentration of 400 ppm and 15 people occupying the space for 10 hours per day, 7 days a week.

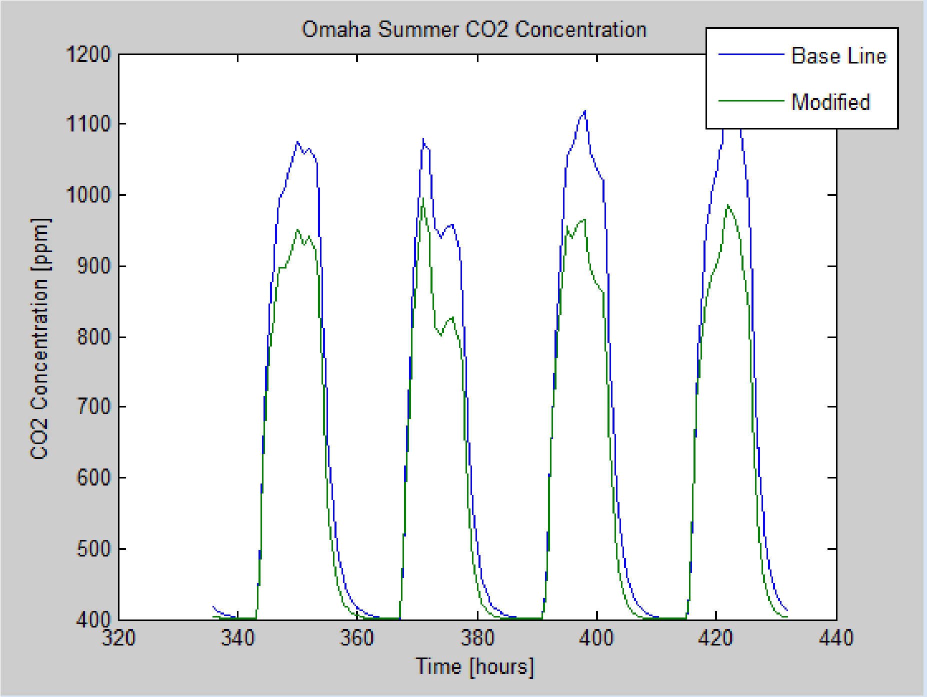

Figure C.1

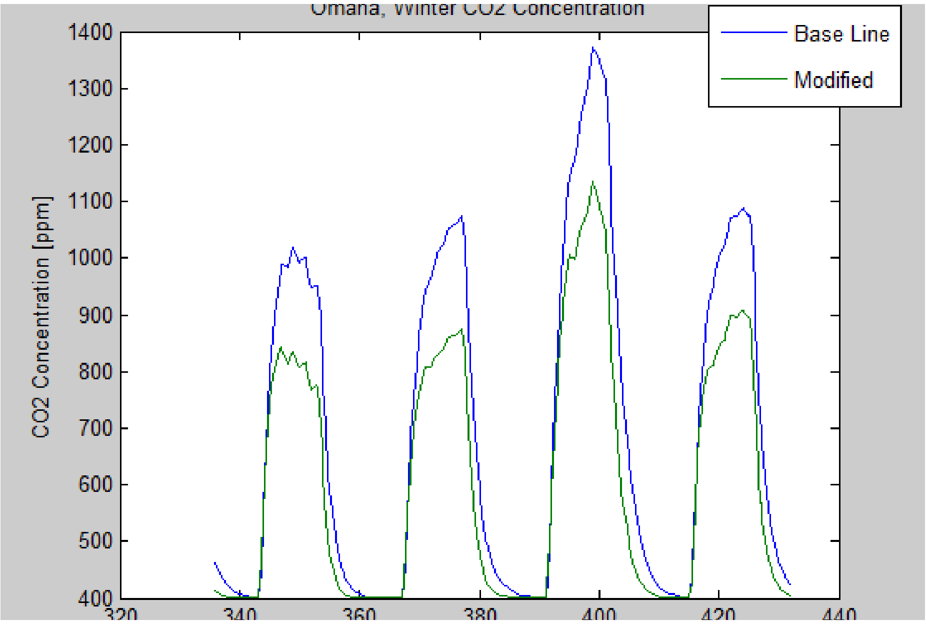

Figure C.2

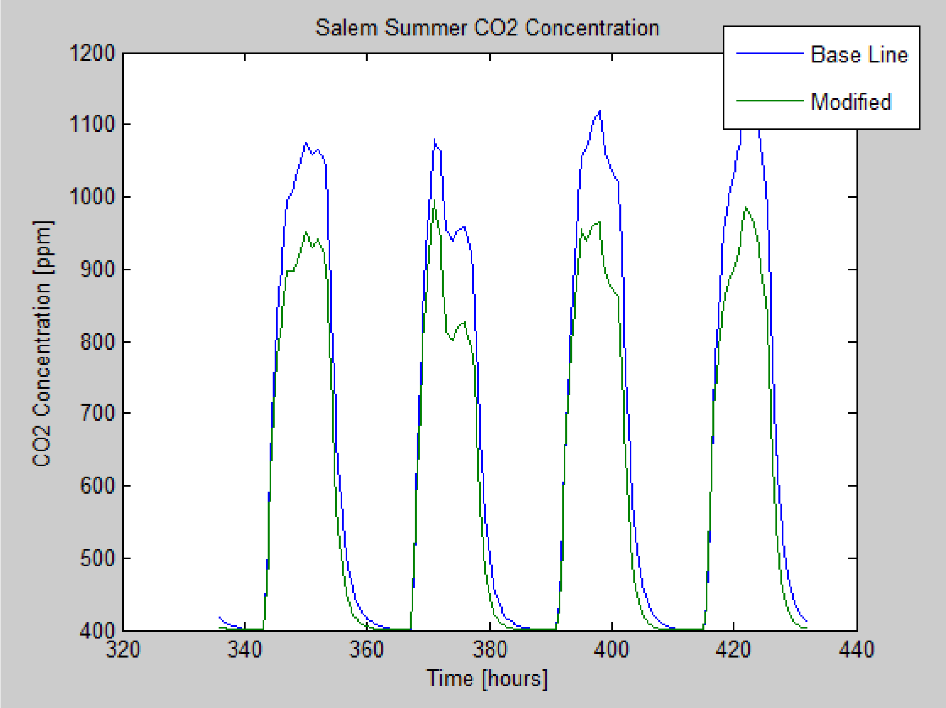

Figure C.3

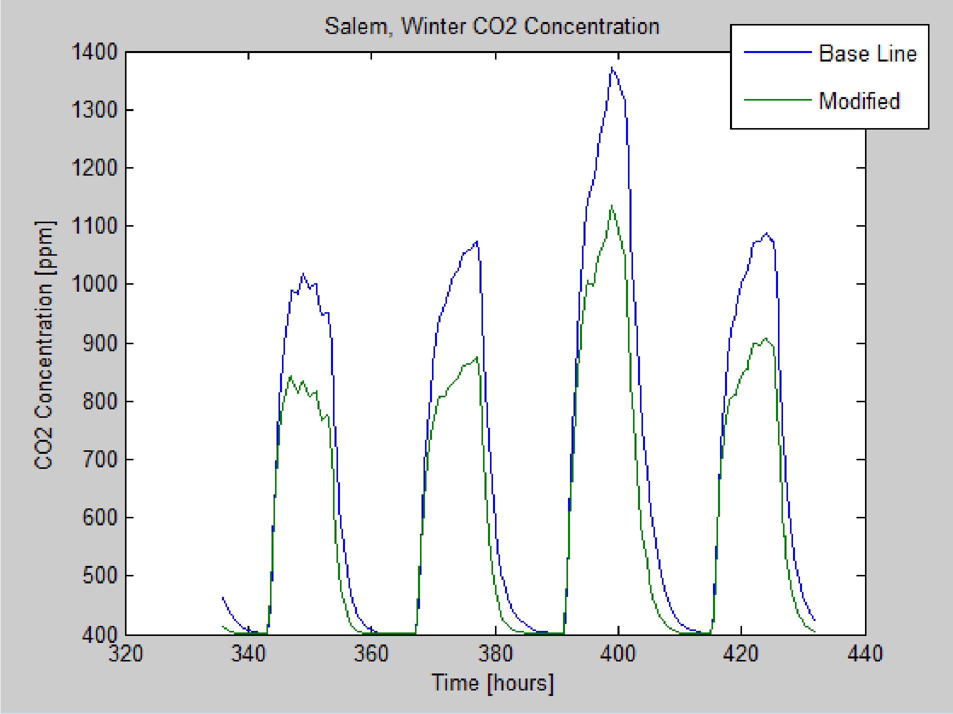

Figure C.4

Analysis and Conclusions

Omaha

The temperatures shown in figure T.2 shows that, by making the modifications described in table 5, the interior operative temperature was reduced by approximately 8 degrees Celsius for the days modeled in August. This effect can further be seen in the psycrometric chart of figure P.1 which indicates indoor conditions shifted closer to the comfort zone for the modified design. This is due to a number of reasons.

- By reducing the glazing fraction of the southern wall, the space gained less heat throughout the day, thereby reducing the peak temperature.
- By increasing the ventilation rate of the space, more heat was rejected during the nighttime hours, leading to lower overall. This also had the effect of reducing interior carbon dioxide concentrations.
- Increasing the U-value of the window (changing from double-pane to single-pane) allowed more heat to be rejected during the evening hours, thereby lowering overall temperatures.

Though making the changes described in table 5 caused the building to perform better in the summer months, those changes had the unfortunate effect of making the building perform worse under winter conditions. The operative temperature fell by about 2 degrees Celsius, on average, and the data points on figure P.2 shifted slightly away from the comfort zone. The modest reduction in comfort during winter months is justified, however, due to the substantial gains seen for the summer model.

Salem

After the changes described in table 5, the Salem structure saw improvements similar to Omaha during the summer months. Temperatures dropped by about 7 degrees on average and the data points in the psycrometric chart of figure P.3 demonstrated a clear shit towards the comfort zone prescribed by ASHRAE 55. This is for the same reasons described in the Omaha section.

Also like Omaha, the improvement to the building performance for summer caused the building to perform less will in winter months, though not in a very dramatic way. Temperatures dropped by approximately 2.5 degrees Celsius, on average, which is an acceptable amount. Overall improvements to building performance were highly successful.