A Comparison of EnergyPlus to DOE-2.1E: Multiple Cases Ranging from a Sealed Box to a Residential Building

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ABSTRACT

EnergyPlus (EPlus) is becoming widely used for building simulation. Previous studies have compared the performance of EPlus with other simulation programs including DOE-2 for a variety of cases. These studies identified the different results of programs for the same cases defined in ANSI/ASHRAE Standard 140. This study expanded upon the previous comparisons to include the simplest case scenario where the building was a sealed box without infiltration, internal load, system or plant. The simulations were then extended to include incremental changes on the building load by adding people, lights, equipment and infiltration. EPlus and DOE-2 were compared using multiple base case buildings in Austin from the simplest case to a fully inhabited residential building. With zero infiltration, EPlus calculated 16-17% lower total building load than calculated by DOE-2 as incremental loads were added. Infiltration decreased the difference between DOE-2 and EPlus by 27% and lead to an 11% lower total building load in EPlus when compared to DOE-2.

Keywords: building simulation, EnergyPlus, EPlus, DOE-2, thermal load, infiltration.

INTRODUCTION

DOE-2 has been widely used for 30 years and the simulation community is familiar with this simulation program. DOE-2.1E, referred to as DOE-2 in this study, has been used for building design studies, analysis of retrofit opportunities and developing and testing building energy standards (Crawley et al 2005). With the introduction of EnergyPlus (EPlus), DOE-2 is no longer maintained by the Department of Energy (DOE) or any public or private entity, except for minor software fixes (Huang et al 2006).

The U.S. Department of Energy initiated support for the development of EPlus in 1996 (Crawley et al 2004). The EPlus team combined the best features and capabilities of predecessor programs DOE-2 and BLAST. A primary difference between DOE-2 and BLAST is the load calculation method. DOE-2 uses a room weighting factor approach, while BLAST uses the heat balance approach (Crawley et al 2002). The development team chose the heat balance method for the thermal load calculations of EPlus.

For the heating and cooling load calculations of a building, the heat balance method is a more accurate method compared to the weighting factor method. The weighting factor method imposes simplifications on the solution technique, while the heat balance method accounts for all energy flows (Strand et al 1999). Weighting factors are calculated for typical constructions in a preprocessor (ASHRAE 1997) and applied to hourly instantaneous heat gains from solar radiation, conduction, lights and people/equipment in order to calculate the space cooling load. This approach assumes time-invariant room properties, while the heat balance technique uses time-varying room properties. The heat balance solution technique can model varying inside air film conductance which depends on the surface-to-air temperature differences, the direction of heat flow and the supply air flow rate. The heat balance method can model walls containing phase-change materials or walls whose conductance is temperature / moisture dependent. The heat balance method can also model varying solar radiation absorbed by the inside surfaces depending on sun position, sky condition and deployment of window shades. These advanced features add to the accuracy of the heat balance solution technique (Strand et al 1999).

Previous studies compared EPlus with other whole building simulation programs in terms of building load. The studies also compared EPlus with the ASHRAE 1052-RP toolkit in terms of individual modes of heat transfer. This study expanded the previous studies by examining the simplest case scenario where the building was a sealed box without infiltration or internal load. EPlus was compared to DOE-2 in terms of the incremental changes on building heating and cooling load by adding infiltration, people, lights and equipment.

BACKGROUND

EPlus has been compared to 8 other building simulation programs for 13 cases for the Building Thermal Envelope and Fabric Load Tests where cooling/heating loads are calculated and compared with respect to ANSI/ASHRAE Standard 140-2007 (Henninger and Witte 2008a). The studied programs were ESP, BLAST, SRES/SUN, SERIRES, S3PAS, TRNSYS, TASE, DOE-2.1D and DOE-2.1E. The 13 test cases varied in mass, windows, overhangs and fins. The results showed that EPlus was within the range of the other programs for 5 of the 13 cases. For the remaining 8 cases, the ranges for the other programs varied between 0.5MWH and 1.4MWH. For these cases, EPlus results were all less than 5.2% out of the bounds. For all 13 test cases, both the heating and cooling loads from EPlus were lower than those of DOE-2 (Henninger and Witte 2008a).

Individual modes of heat transfer in EPlus have been compared to the ASHRAE 1052-RP Toolkit for 16 different envelopes specified in the ASHRAE 1052-RP report. EPlus compared within 7.2% with the results of ASHRAE 1052-RP Toolkit in terms of infiltration, convection, conduction, radiation, solar gains, shading and long wave radiation. Significant differences between EPlus and the ASHRAE 1052-RP toolkit were indicated in 4 major areas: 1) window heat gains, 2) treatment in external long wave radiation, 3) treatment of ground-coupled heat transfer for slabs, and 4) tests where the 1052-RP hourly weather data had to be interpolated into sub-hourly data for 10 minute time steps (Henninger and Witte 2008b).

The first quantitative comparison of DOE-2 and EPlus was made using the Alternate Compliance Method (ACM) certification suite which was used to test different building shells, equipment, and operations in different California climates. Table 1 summarizes the conclusions of the study and shows how EPlus results differed from those of DOE-2 in terms of heating and cooling energy use for various wall assemblies (WA), window-to-wall ratios (WWR), lighting levels (LL) and ventilation rates (VR) (Huang et al 2006).

Table 1. Summary of EPlus results compared to DOE-2 results (Huang et al 2006).

	heating	cooling
variable	EPlus is:	EPlus is:
WA	Lower (within 20%)	Higher (within 10%)
WWR	Lower (30% - 60%)	identical
LL	Lower (60% - 70%)	Higher (15% - 20%)
VR	Lower (15% - 20%)	Higher (15%)

WA: wall assembly
WWR: window-to-wall ratio
LL: lighting level
VR: ventilation rate

SIMULATIONS

The study completed and documented three sets of simulations: 1) the simulation of an empty sealed enclosed space (Sim-1), 2) a base case building (Sim-2), and 3) the incremental addition of people, lights, equipment and infiltration to the base case building (Sim-3). For these simulations, EPlus 2.2.0.023 and DOE-2.1E Version-119 were used.

The first set of simulations (Sim-1) compared DOE-2 and EPlus results in terms of the relationship between the building's dimensions and the corresponding heating and cooling load. Four sets of Sim-1 spaces with constant wall height and a different floor area were simulated in DOE-2 and EPlus. All Sim-1 wall heights were 2.4m, while the square floor area varied from 5m x 5m to 20m x 20m in 5m increments. All Sim-1 spaces were located over a conditioned space. Figure 1 shows the largest Sim-1 space with dimensions of 2.4m x 20m x 20m. All four Sim-1 spaces and the space below were conditioned with heating and cooling setpoints of 24ºC, which decoupled the ground temperature. For this purpose, throttling-range of DOE-2 was set to its minimum (0.1). The enclosed spaces were simulated using the same weather data. The DOE-2 TMY2 weather file for Austin, Texas (.bin) was converted into an EPlus weather file (.epw) by using the EPlus weather converter. Custom weighting factors were used in DOE-2 for the simulation of the building envelope. In both DOE-2 and EPlus, the enclosed space had the layers given in Table 2 for the walls, floors and ceilings / roofs. The ground reflectance coefficient around the building was assumed as 0.18 for all cases. Only the results for the second story (Sim-1 space) were used in the comparisons.

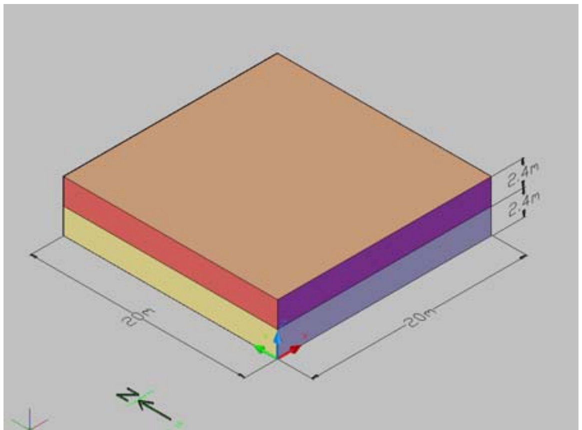


Figure 1. The largest Sim-1 space (2nd floor) over a conditioned space.

Table2. Roof, wall and floor / ceiling layers from outside to inside.

ROOF			
	RG01: roof gravel/slag	**BR01:** built-up roofing	**CC03:** heavy weight concrete
t	0.0127	0.0095	0.1016
ρ	881	1121	2243
c	1674	1464	837
σ	1.442	0.162	1.31

WALL			
	SC01: stucco	**BK01:** brick	**GP03:** gypsum or plaster board
t	0.0254	0.1016	0.0190
ρ	2659	1922	801
c	837	837	837
σ	0.721	0.721	0.16

FLOOR	
	CC03: heavy weight concrete
t	0.1016
ρ	2243
c	837
σ	1.31

t is thickness in meters,
ρ is density in kg/m^3,
c is specific heat in J/kg-K,
σ is conductivity in W/m-K.

In DOE-2, default values were used for the interior surface film resistance and the interior surface solar absorptance values. Internal film R-value was 0.68 for all interior surfaces. The inside solar absorption coefficient was 0.5 for the walls, 0.3 for the ceilings and 0.8 for the floors. The outside surface emissivity coefficient was 0.65 for the walls and 0.29 for the roof. SUM was entered as the system-type for the calculation of building loads. The DOE-2 SS-A reports were used for the simulation results.

The EPlus detailed inside and outside convection algorithms were used for the simulations. Rain and snow indicators were used from the weather data file. Country was selected as the terrain. Loads convergence value was 0.04 and temperature convergence tolerance value was 0.4. The time step in hour was 4 and the solution algorithm was CTF with maximum surface temperature limit of 200. EPlus assumes that emissivity, ε, of the materials equals to their absorption coefficient, α (EPlus Engineering Reference 2008). The outside emissivity values used in DOE-2 for exterior surfaces were entered in EPlus as the thermal absorptance of the outermost layers of related constructions. For all simulations, purchased air was used as the system type, which supplied cooling/heating air to the zone in sufficient quantity to meet the zone load (EPlus Engineering Reference 2008). The report variable for zone/sys sensible heating load and zone/sys sensible cooling load were used for the simulation results.

The Sim-2 set of simulations incrementally added windows (Sim-2 Step1) and a conditioned upper story (Sim-2 Step2) to the Sim-1 space shown in Figure 1. As a result, the Sim-2 base case building shown in Figure 2 was obtained. For comparisons, only the loads for the second story (Sim-2 space) were considered. The first and third floors served as adiabatic isolation for the floor and ceiling. All floors had the same space temperature (24ºC).

Windows were added on all four sides of the second and third floors of the building with window-to-wall ratios of 25%. The Window 5.2a v5.2.17a program was used to design the windows and generate reports describing the window properties. These reports were then copied into DOE-2 and EPlus window libraries as a new window type. DOE-2 and EPlus used these reports from their libraries and simulated the same windows.

The Sim-3 set of simulations added people, lights, equipment and infiltration to the second floor of the Sim-2 base case building shown in Figure 2. The number of people, lighting wattage, equipment wattage and air changes per hour of infiltration were increased sequentially only in the second floor.

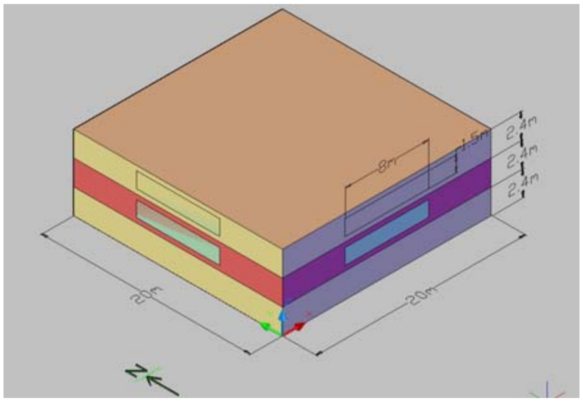
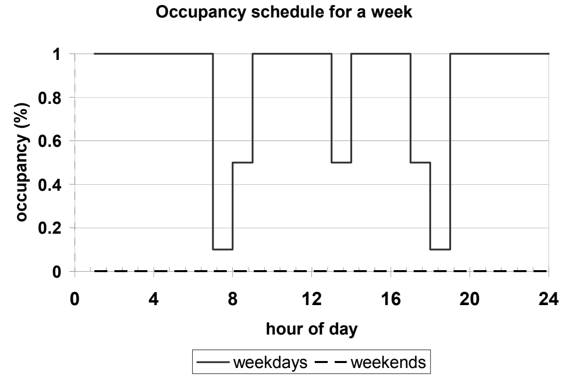


Figure 2. The Sim-2 base case building (Sim-2 Step2).

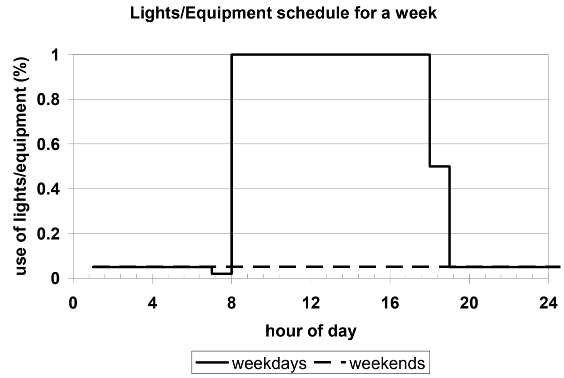
For the simulation of people, 450 Btu/hr was assumed as PEOPLE-HEAT-GAIN in DOE-2. In EPlus, an equal number in SI units, 131.8 Watts / person, was entered as the activity level of the people. The occupancy schedule for the people was the schedule shown in Figure 3a in both DOE-2 and EPlus simulations. Since DOE-2 assumes 70% of the heat generated by people and equipment is distributed by radiation, 0.7 was assumed to be the fraction radiant for both people and equipment in EPlus. The number of people increased from 0 to 5. The schedule shown in Figure 3b was used as the lighting/equipment schedule. Wattage of equipment increased from 0 Watts to 500 Watts in increments of 100 Watts.

For the simulation of lighting, the surface mount luminaire configuration was used as described in the Lighting Handbook: Reference and Application (1993). The radiant fraction was assumed as 0.72, return air fraction was 0 and visible fraction was 0.18. The same values for radiant and return air fractions were entered into the EPlus and DOE-2 input files. The wattage of lights was increased from 0 Watts to 1000 Watts in increments of 200 Watts.

EPlus and DOE-2 simulated identical infiltration conditions by the use of AIR-CHANGES/HR (ACH). In both DOE-2 and EPlus, the infiltration was enabled at all times and ACH was increased from 0 to 0.375 in increments of 0.09375.



(a)



(b)

Figure 3. (a) Occupancy, (b) Lights/equipment schedule for the building.

RESULTS & DISCUSSION

The results for the Sim-1 simulations showed that DOE-2 used about 20% additional heating and cooling energy as compared to EPlus when the floor area increased from 25 m^2 to 400 m^2. The 400 m^2 Sim-1 building had 12.3% lower cooling load and 16.7% lower heating load in EPlus when compared to DOE-2 (Table 3, Table 4 and Figure 8). With increasing floor area, the heating and cooling load per m^2 decreases in both DOE-2 and EPlus (Figures 4 and 5). DOE-2 calculated 36.2% lower heating load per m^2 and 39.9% lower cooling load per m^2 for the 400 m^2 house when compared to 25 m^2 house. EPlus calculated 46.2% lower heating load and 34% lower cooling load per m^2 for the same increase in floor area.

Table 3. Cooling loads calculated by DOE-2 and EPlus for sealed boxes with varying base areas.

Base Area (m^2)	DOE-2 (GJ)	EPlus (GJ)	Δ=DOE-2 - EPlus (GJ)
25	14.94	11.30	3.64
100	42.57	34.37	8.20
225	82.91	70.15	12.76
400	135.96	119.19	16.77

Table 4. Heating loads calculated by DOE-2 and EPlus for sealed boxes with varying base areas.

Base Area (m^2)	DOE-2 (GJ)	EPlus (GJ)	Δ=DOE-2 - EPlus (GJ)
25	14.65	13.70	0.95
100	43.16	38.32	4.84
225	85.57	73.26	12.31
400	141.89	118.16	23.73

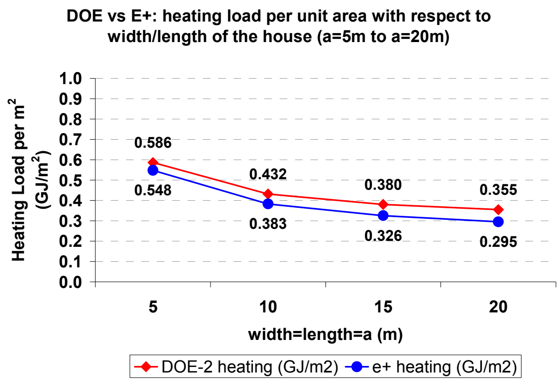


Figure 4. Increased floor area impact on heating load per unit area.

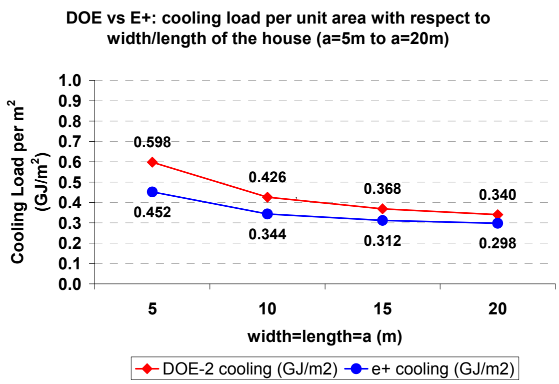


Figure 5. Increased floor area impact on cooling load per unit area.

The Sim-2 simulation results are given in Figure 6 in two steps: the results for the incremental addition of 1) windows (Sim-2 step1) and 2) an unconditioned upper story (Sim-2 step2). The addition of windows increased the cooling load and decreased the heating load in both DOE-2 and EPlus. Windows increased the cooling load by 26.2% in DOE-2 and by 29% in EPlus. Windows decreased the heating load by 1.9% in DOE-2 and by 3.4% in EPlus. The addition of a conditioned upper story decreased heating and cooling loads both in DOE-2 and EPlus. The conditioned upper story decreased the cooling load by 36.9% in DOE-2 and by 41% in EPlus. The conditioned upper story decreased the heating load by 73.5% in DOE-2 and by 73.9% in EPlus. Eventually, for the base case building shown in Figure 6 (Sim-2 step2), EPlus showed 16.2% lower cooling load and 19.29% lower heating load when compared to DOE-2. The Sim-2 Step2 building obtained by Sim-2 simulations had lower heating and cooling loads than the largest sealed box both in EPlus and DOE-2 (Figure 8).

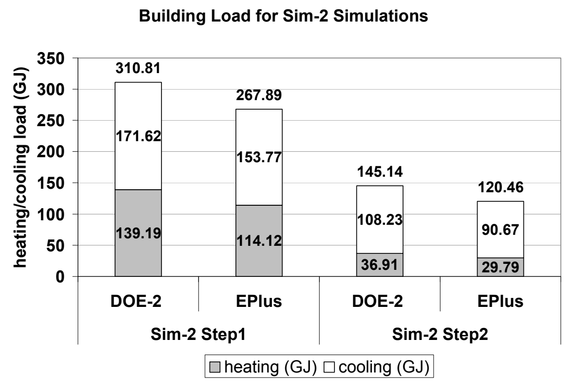
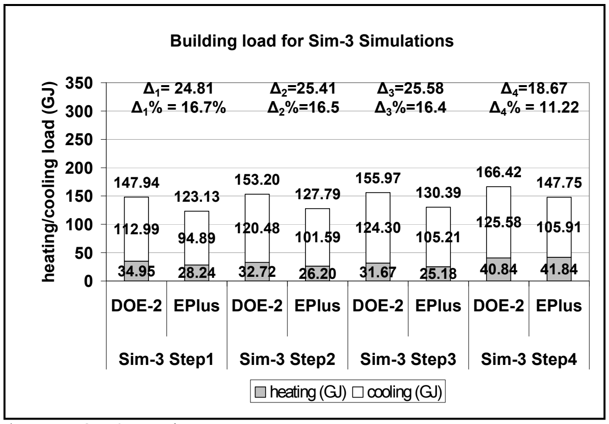


Figure 6. The building heating and cooling load for Sim-2 simulations.

The Sim-3 results are given in Figure 7 and in Tables 5, 6, 7 and 8. The results showed that there are linear relationships between building load and each of the incrementally added features except infiltration. Infiltration showed a polynomial relationship with building load in both EPlus and DOE-2. The relationship equations obtained for the each of the incrementally added feature fit to the real data with an R^2 value of 0.99 or higher. The changes in load due to the addition of people, lights, equipment and infiltration are expressed in percentages and discussed below. For comparisons, the Sim-2 Step2 building shown in Figure 6 was used as the base case.

Increasing the number of people and the lighting/equipment wattage decreased the heating load and increased the cooling load in both EPlus and DOE-2. Five people were added to the base case building (Sim-2 Step2) to obtain Sim-3 Step1 building shown in Figure 7. With the addition of 5 people, the heating load decreased by 5.3% in DOE-2 and by 5.2% in EPlus. The corresponding cooling load increased by 4.4% in DOE-2 and by 4.6% in EPlus. The linear equations showing the relationship between the number of people and the building load is given in Table 5. 1000 Watts of lighting was then added to Sim-3 Step1 building to obtain Sim-3 Step2 building (Figure 7). 1000 Watts of lighting and 5 people in Sim-3 Step2 building decreased the heating load and increased the cooling load by 11.3% in DOE-2 and by 12% in EPlus with respect to the base case building. The change in building load of Sim-3 Step1 building with increasing lighting wattage is given in Table 6. A 500Watts of equipment was then added to Sim-3 Step2 building to obtain Sim-3 Step3 Building (Figure 7). Five people, 1000 Watts of lighting and 500 Watts of equipment in Sim-3 Step3 building lead to a 14.2% lower heating load in DOE-2 and 15.47% lower heating load in EPlus when compared to the base case building. Sim-3 Step3 building also had 14.8% higher cooling load in DOE-2 and 16% higher cooling load in EPlus than the base case building. The linear relationship between the building load of Sim-3 Step2 building and increasing equipment wattage is given in Table 7.



Δ_n = DOE-2 – EPlus
Δ_n% = 100* (DOE-2 –EPlus) / DOE-2

Figure 7. The building heating and cooling load for Sim-3 simulations.

Infiltration (0.375ACH) was then introduced into the Sim-3 Step3 building to obtain Sim-3 Step4 building. Sim-3 Step3 building already contained five people, 1000 Watts of lighting and 500 Watts of equipment. With the addition of 0.375 ACH, the Sim-3 Step4 building represented a fully inhabited residential building. This fully inhabited residential building (Sim-3 Step4) showed 10.6% higher heating load in DOE-2 and 40.4% higher heating load in EPlus when compared to the base case building. The cooling load of the Sim-3 Step4 building was also higher than the base case building by 16% in DOE-2 and by 16.8% in EPlus. The relationship between the building load of Sim-3 Step3 building and increasing ACH and is given in Table 8.

Table 5. Equations for the number of people (P) versus the heating (Q_H) and cooling (Q_C) loads.

Q_H =**Heating load (GJ)**	
DOE-2.1E version 119	Q_H = -0.3917*P + 36.903
EnergyPlus 2.2.0.023	Q_H = -0.31*P + 29.784

Q_C =**Cooling load (GJ)**	
DOE-2.1E version 119	Q_C = 0.9518*P + 108.22
EnergyPlus 2.2.0.023	Q_C = 0.8436*P + 90.666

P= number of people from 0 to 5.

Table 6. Equations for the lighting wattage (L) versus the heating (Q_H) and cooling (Q_C) loads.

Q_H =**Heating load (GJ)**	
DOE-2.1E version 119	Q_H = -0.0022*L + 34.938
EnergyPlus 2.2.0.023	Q_H = -0.002*L + 28.228

Q_C =**Cooling load (GJ)**	
DOE-2.1E version 119	Q_C = 0.0075*L + 112.97
EnergyPlus 2.2.0.023	Q_C = 0.0067*L + 94.878

L= lighting wattage from 0W to 1000W.

Table 7. Equations for the equipment wattage (E) versus the heating (Q_H) and cooling (Q_C) loads.

Q_H =**Heating load (GJ)**	
DOE-2.1E version 119	Q_H = -0.0021*E + 32.718
EnergyPlus 2.2.0.023	Q_H = -0.002*E + 26.198

Q_C =**Cooling load (GJ)**	
DOE-2.1E version 119	Q_C = 0.0077*E + 120.47
EnergyPlus 2.2.0.023	Q_C = 0.0072*E + 101.59

E=equipment wattage from 0W to 500W.

Table 8. Equations for the air changes per hour (ACH) versus the heating (Q_H) and cooling (Q_C) loads.

Q_H =**Heating load (GJ)**	
DOE-2.1E	Q_H = 2.2378*ACH^2 + 23.636*ACH + 31.665
EnergyPlus 2.2.0.023	Q_H = 7.5612*ACH^2 + 41.615*ACH + 25.173

Q_C =**Cooling load (GJ)**	
DOE-2.1E	Q_C = 2.2721*ACH^2 + 2.5476*ACH + 124.3
EnergyPlus 2.2.0.023	Q_C = 7.5898*ACH^2 – 0.9562*ACH + 105.21

ACH= air changes per hour from 0 to 0.375.

The results for Sim-1, Sim-2 and Sim-3 simulations are given together in Figure 8. At the end of the Sim-3 simulations, a higher heating and cooling load were obtained when compared to the base case building. The results of the Sim-3

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simulations indicated that the most substantial difference between the base case building (Sim-2 Step2) and the fully occupied residential building (Sim-3 Step4) was in heating load due to infiltration. With the introduction of the same air changes per hour into the Sim-3 Step3 building, EPlus calculated a 4 times higher percentage increase in heating load compared to DOE-2.

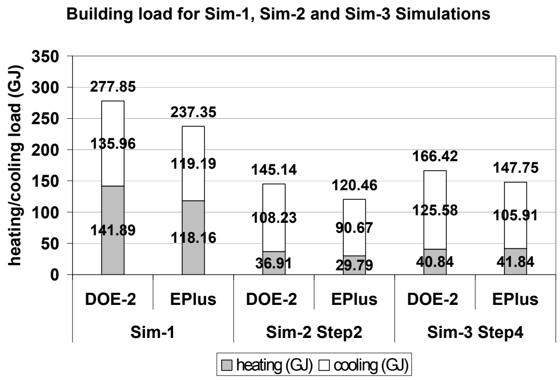

Figure 8. The building heating and cooling load for Sim-1, Sim-2 & Sim-3 simulations.

Peak heating and cooling loads of the fully occupied residential building (Sim-3 Step4) is given in Figure 9. DOE-2 calculated 39.8% higher peak heating load and 26.6% higher peak cooling load when compared to EPlus.

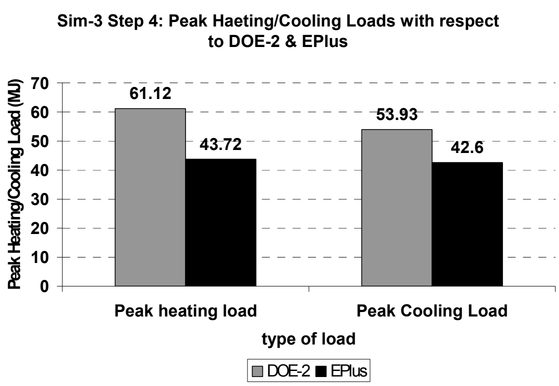

Figure 9. Peak heating and cooling loads for Sim-3 Step4 building.

The results of the study were compared to the studies in literature. Windowless sealed box over the conditioned space (Sim-1) and the sealed box with windows over the conditioned space (Sim-2 Step1) indicated similar difference in results between EPlus and DOE-2 to those concluded in EPlus testing with Building Thermal Envelope and Fabric Load Tests from ANSI/ASHRAE Standard 140-2007 (Henninger and Witte, 2008a). Both studies concluded that EPlus showed 10-20% lower heating and cooling loads when compared to DOE-2. Huang (2006) identified 30% higher infiltration in EPlus than DOE-2 when the same infiltration condition was simulated in the two programs. He stated that this difference was because the EPlus Simple Air Flow Model did not adjust for wind speed, while DOE-2 reduced the wind speed on the weather tape to account for local terrain effects. The results of this study are in agreement with Huang's conclusions with ~2 times higher increase in heating load in EPlus due to the same increase in ACH (Figure 7). Different from this study, Huang (2006) included systems in his test cases for comparisons. To keep this study focused on investigating the impact of envelope, windows, internal loads and infiltration, purchased air was used for EPlus and the SUM function was used in DOE-2. The effect of systems was thus isolated from the results. With the differences seen in the calculations between DOE-2 and EPlus, further studies are needed to understand the resulting differences in the results to make comparisons with previous studies in literature.

CONCLUSIONS

EPlus 2.2.0.023 (EPlus) and DOE-2.1E Version-119 (DOE-2) were compared through three sets of simulations. The simulations included multiple test cases ranging from an enclosed space without windows (Sim-1), to adding windows and a conditioned upper story (Sim-2 Step2) and finally to where lighting, people, equipment and infiltration were added (Sim-3 Step4). All simulations used the same Austin, Texas weather data.

The first set of simulations (Sim-1) showed that DOE-2 used about 20% additional heating and cooling energy than EPlus for a 400 m^2 sealed box located in Austin. The addition of windows to this sealed box in the second set of simulations (Sim-2 step1) showed up to 29% increase in cooling energy and up to 3.4% decrease in heating energy in DOE-2 and EPlus. The addition of a conditioned upper story decreased the heating loads up to 74% and cooling loads up to 41% in EPlus and DOE-2. The building obtained at the end of Sim-2 simulations was used as the base case for the third set of simulations (Sim-3). Sim-3 simulations showed that incremental increase in number of people and wattage of lights/equipment increased the cooling load and decreased the heating load linearly by similar percentages in EPlus and DOE-2 up to 16% with respect to the base case building. After the introduction of infiltration, cooling load was 16-17% higher than the base case building in DOE-2 and EPlus. EPlus results showed the highest divergence from those of DOE-2 in terms of the heating load calculated for the same infiltration condition. For the same infiltration, EPlus calculated 40.4% higher heating load, whereas DOE-2 calculated 10.6% higher heating load when compared to the base case building.

This study revealed that, when there is no infiltration, for a 400 m^2 house in Austin with 25% window-to-wall ratio, EPlus calculated 16-17% lower total building load than calculated by DOE-2 as incremental loads were added (Figure 7). With the introduction of infiltration, the difference between DOE-2 and EPlus decreased by 27%, and EPlus calculated 11% lower total building load compared to DOE-2 for the same building. Further studies are necessary on the simulation of infiltration in EPlus and DOE-2 in order to identify the reasons for the differences between the programs.

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