EXPERIENCES WITH AND INTERPRETATION OF STANDARD TEST METHODS OF BUILDING ENERGY ANALYSIS TOOLS

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ABSTRACT

The authors separately apply ANSI/ASHRAE Standard 140-2001 to the simulation program TRNSYS, comparing not only their results but the differences in their simulation assumptions and in their interpretations of the Standard's test cases. Results of the application are presented for all three authors, showing that there is a significant amount of leeway within a complex simulation tool such as TRNSYS for users of different backgrounds to apply their own common simulating practices and still fall comfortably within the range of acceptability specified by such Standards. Included in the application results are results of sensitivity tests that demonstrate the relative importance of assumption differences.

INTRODUCTION

Increasingly, obtainment of energy efficiency certification requires the use of simulation packages and standardized energy codes to insure that a proposed building will meet a minimum energy performance guideline. A number of standards and guidelines have been developed in an effort to assist end users in choosing an appropriate tool. ANSI/ASHRAE Standard 140-2001 [1] and BESTEST [2], to name two, have the dual purpose of aiding simulators in assessing tool capabilities and aiding software developers in verifying their work and in steering package development. These goals are achieved through a series of specific and increasingly complex test cases that are entered into the software package under evaluation. Ideally, a software package would generate a given answer for a given test case and in fact "official" answers are printed in the standard for eight well regarded packages. However, simulation by its very nature is something of an art form and often there is more than one method for modeling a given situation. For example, a simulator may choose to use a window model that is integrated with the building model or may choose to use an explicit, detailed window model that is external to the building model. The simulator's personal experience, standard working methods, and interpretation of the test case parameters also necessarily affect the final results.

In this project, three people with differing simulation backgrounds (a user, a user/developer, and a developer) applied the ASHRAE Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs to the software package TRNSYS (version 15.3) [3]. TRNSYS v.15 was developed by the Solar Energy Laboratory, University of Wisconsin – Madison, in conjunction with the Centre Scientifique et Technique du Bâtiment in Nice, France and Transsolar Energietechnik, GmBH in Stuttgart, Germany.

Commercially available since 1975, TRNSYS was originally developed for the simulation of solar thermal processes. Over its lifetime, TRNSYS has been expanded into a full fledged building energy modeling package. The current version (15.3) was released in June 2002. TRNSYS v. 13 was one of the software packages included in the original development of the BESTEST standard on which ASHRAE Standard 140 is based.

It is anticipated that in applying ASHRAE Standard 140 to TRNSYS, the three users will make different simulation assumptions and will end up with different results. The main goal of this project was to determine whether these differences in results would lead to similar or different conclusions about the strengths and weaknesses of the TRNSYS package.

METHODOLOGY

The authors of this paper represent a range of TRNSYS users and developers. Authors A and C have spent time both working for the TRNSYS Development Group and as TRNSYS users in consulting practices. Author B has not worked directly on TRNSYS development but has used the program extensively for research and consulting.

ASHRAE Standard 140 is divided into five series of test cases. These are 600-650, 900-960, 195-320, 395-440, and 800-810. Each series begins with a base case (600, 900, 220, 400, and 800 respectively) on which subsequent cases are built. This paper deals primarily with the results from the 600 series of cases (low mass building) and the 900 series of cases (high mass building). Each case in a given series tests the software's ability to model a specific change in building configuration (addition of a night setback thermostat, addition of south shading, modification of window orientation, etc.). Each series of cases seeks to apply the same set of changes to fundamentally different buildings (low mass and high mass). The 220, 400 and 800 series cases seek to isolate the effect of or sensitivity to one particular variable or algorithm in the software. In many cases, it is not the absolute results that matter as much as the difference between case results. In other words one examines a particular effect by subtracting the result of one case from its corresponding base case. ASHRAE Standard 140 uses four major figures of merit in assessing tool capability: annual heating load, annual cooling load, peak heating load and peak cooling load. Individual cases often have specific output reporting requirements. For example in the free float cases (heating and cooling system removed from the building), the user is asked to report the minimum, maximum and average annual temperature that occurs within the zone. While all cases specified in ASHRAE Standard 140 were run as part of this project, the results focus on the first two series of cases, namely 600-650 and 900-960.

The building at the heart of all case series is a 6m x 8m x 2.7m box as shown in Figure 1. The box is modified in various cases by shifting windows, by adding overhangs and wing walls, by adjusting heating and cooling set points, by adding night time ventilation and by making similar, targeted modifications. The most complex modification involves the addition of an unconditioned second "sunspace" zone to the south side of the building.

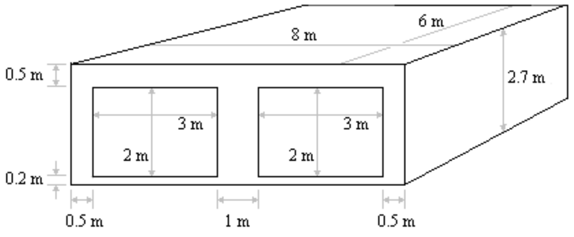

Figure 1: Basic ASHRAE Standard 140 Building Configuration

It was the original intent for each of the three authors to apply ASHRAE Standard 140 individually and without intercommunication in order to examine differences in results uninfluenced by someone else's interpretation of the Standard's text. However, it soon became apparent that without collaborating on the early interpretation of at least the 600 series, it would in fact be difficult to draw meaningful conclusions through result comparison of later cases. That is to say that even at the most basic case level, it is probable that simulation program users will interpret the Standard differently, hiding differences that might arise in results based on habits and assumptions. Consequently, authors B and C worked together to come up with a common interpretation of Case 600 before entering that and subsequent cases into the software individually. One such source of collaboration was that TRNSYS relies on an external piece of software to generate its detailed window descriptions. TRNSYS's built in window descriptions did not correspond well to the window description in the Standard. Author C created the window specified in Standard using Window 5.2 [4] and gave the resulting data file to author B, again in an attempt to provide a better basis for result comparison.

Author A worked entirely independently from authors B and C in order to determine whether differences at the base case level would be significant. In all cases, a Standard user has access to a range of acceptable results as these are published in the Standard's documentation.

SIMULATION ASSUMPTIONS

In comparing results after applying Standard 140, it became apparent that the authors had made differing assumptions even with collaboration in a number of areas and at a very basic level.

Diffuse Sky Models

The first area was in the choice of a diffuse sky model. In TRNSYS, the user is allowed the choice between four correlations for estimating the amount of diffuse solar radiation incident on a surface of given orientation (slope and azimuth). The user may choose to assume that the sky is isotropic in nature; that is that apart from the location of the sun itself, the sky is uniformly bright. The user may alternatively use the Hay and Davies correlation, which accounts not only for isotropic diffuse radiation but also for the brighter area of sky surrounding the sun location (circumsolar diffuse). The third and fourth options are to use either the Reindl or the Perez correlation, which both account for isotropic diffuse, circumsolar diffuse and horizon brightening [5]. The TRNSYS documentation suggests that the Hay and Davies, Perez, and Reindl correlations are largely comparable but that Perez is more computationally complex. Through conversations with the correlation developers, however, author A was told that the Reindl model had been optimized for solar thermal applications (non vertical, south facing, tilted surfaces) and that the Perez model had been optimized over the entire range of possible surface orientations. Examination of the TRNSYS 13 input files provided with the Standard indicate that the Hay and Davies correlation was used in the original work. Author B chose to accept the computational complexity and use the TRNSYS sky diffuse correlation optimized over a large range of surface orientations (Perez model) while Authors A and C used the Reindl correlation.

Interior and Exterior Convection Coefficients

The second area of difference was in the treatment of combined convection/radiation coefficients provided for interior and exterior surfaces in the Standard. The TRNSYS building model separates convection and radiation, asking the user to input convection coefficients but calculating the radiation portion internally. The user is unable to affect the radiation coefficient. ASHRAE Standard 140 provides combined coefficients in the main body of the standard and provides split convection and radiation coefficients in an Informative Annex. According to the Standard, the radiative portion of a combined film coefficient is based on a linearized gray-body radiation equation [6].

$$h_i = 4\varepsilon\sigma T^3$$

The TRNSYS building model developer, however, recommends that the average radiative coefficient for surface temperatures between 0 and 100 ºC be taken as 5 W/m2.K and that the convective portion of the combined coefficient be calculated as the difference between the values reported in the Standard and the average radiative coefficient value. As a third option, TRNSYS is equipped with a detailed external model that calculates convection coefficients for interior vertical or horizontal surfaces. The model estimates the effect of a temperature difference between a plate and surrounding fluid (air) on the natural convection heat transfer coefficient between the air and wall. The convection coefficients for these surfaces can therefore be dependent upon the surface/air temperature difference instead of being set to the constants given in the Standard. Author A made use of the detailed, external model for calculating inside convection coefficients. For exterior surfaces, Author A employed equations that compute convection coefficients as a function of wind speed for exterior surfaces. These equations are provided in an informational Annex to the ASHRAE Standard as background material explaining the calculation technique used to compute the constant (average) values provided in the body of the Standard. Author B used constant convective heat transfer coefficients from the ASHRAE Standard 140 Annex for both interior and exterior surfaces. Author C used constant coefficients based on the building model developers recommendations.

Shading

A third difference came in the treatment of shading. The TRNSYS building model is not a geometrical model, meaning that there is no information entered about the positioning of walls with respect to one another. Consequently, shading is most often handled by an external model that calculates the net effect of wing walls and overhangs on an aperture. In Case 610, a 1m wide overhang is applied along the roofline of the entire south façade of the building. In Case 630, the south facing windows have been moved to the east and west façades and each window is outfitted with an overhang and wing walls on either side. When faced with such shading configurations, it is not uncommon to assume that the effect of shading on the opaque portions of the façade (the walls) is negligible in comparison to the effect of shading on the windows themselves. Authors A and B accounted for shading on walls as well as on windows. Author C made the simplifying assumption that the opaque walls would be dominated by conduction and so defined shading devices only for the windows, allowing opaque surfaces to use unshaded radiation values.

Ground Coupling

Another source of interpretation difference came in the treatment of ground coupling. Standard 140 states that “to reduce uncertainty regarding testing the other [non ground coupling] aspects of simulating the building envelope, the floor insulation has been made very thick to effectively decouple the floor thermally from the ground.” It is possible in TRNSYS to completely decouple the ground and building not by inserting large amounts of insulation but to specify that the temperature at the slab/soil interface is the identical to the zone temperature and that therefore, the slab is adiabatic but still contributes to the capacitance of the building. In their initial meeting, authors B and C decided to interpret Standard 140 to mean that complete decoupling of the building and ground was intended where possible. Consequently, both made the adiabatic slab assumption when applying the Standard in TRNSYS. Author A, however, followed the suggestion in the Standard that “for software that requires input of ground properties … the ground in the vicinity of the building is dry packed soil with the following characteristics: deep ground temperature = 10 ºC”

Time Step

TRNSYS uses a constant, user defined time step throughout a given simulation. The authors independently chose different time steps for their work. Author A used a time step of 1 hour for all cases except 640 and 940. In those two cases, he used a time step of 0.1 hour. Cases 640 and 940 involve a thermostat night set back in which the heating set point in the building jumps from 10 ºC to 20 ºC each morning at 7AM. In order to model such a step change, TRNSYS would have to allow for there to be two, simultaneous set point temperatures (10 ºC for the time step ending at 7AM and 20 ºC for the time step beginning at 7 AM. Since this is not possible in TRNSYS, the software in fact does not register that the set point temperature has changed until one time step later. When using a one hour time step, this delay causes significantly low peak heating loads; more time step precision was required in order to alleviate the problem. Authors B and C used a 0.25 hour time step throughout their simulations.

Minor interpretational differences bear some passing mention as well. In the TRNSYS building model, it is always possible to define a given aspect of the model (thermostat setting for example) as an internal schedule or as an external input. When set to be an internal schedule, the user is required to create a 24-hour repeating schedule for the variable at hand. When set to be an external input, the user must make use of an external component in the TRNSYS simulation to generate the required value. While author B chose to define thermostat setbacks and night ventilation schedules as external inputs, authors A and C chose to make use of internal scheduling. It is difficult to imagine how this difference might have a bearing on results as they are completely equivalent.

TRNSYS 15 does not directly read the TMY format weather data file provided with ASHRAE Standard 140. Consequently, some manipulation of the weather file was necessary. Authors B and C manually modified the weather file using Microsoft Excel to strip out unused data and create a columnar data file readily readable by TRNSYS. Author A used a freely downloadable program that automatically converts TMY data files to EnergyPlus [7] format, which TRNSYS can read directly. The only difference in data used by the authors came in the cloudiness factor. Author A made use of a sky temperature model (for radiation calculations) that reads the cloud cover from the weather data file while authors B and C used a sky temperature model that computes cloud cover internally.

Examination of the TRNSYS 13 input files used in generating the original BESTEST results sheds light on other areas in which differing simulation assumptions could have been made although all three authors independently came to the same assumption.

The method for defining windows in TRNSYS has changed, allowing a user the potential for treating them differently. Again all three authors treated windows in the same manner, generating a data file from the Window 5.2 software. Authors B and C used exactly the same data file (created by author C) while author A created the file independently. Both authors A and C found it difficult to exactly recreate the parameters of the window specified in the ASHRAE Standard using Window 5.2. Examination of the window data files created by the two authors show only negligible differences, however. An alternate method for treating windows was used in the original TRNSYS work. At that time a detailed window model was not incorporated into the building model. Instead, a user defined windows in an external model and added the solar and thermal gains computed by that model to the zone. This method may still be used in TRNSYS although it is widely thought to be less accurate than using the detailed, building incorporated model in part because it neglects radiation exchange between the surface temperature of the window and the temperatures of other zone surfaces.

Table 1 summarizes the assumption differences between the three authors.

Table 1: Simulation Assumption Differences

Major Interpretational Differences				
Author	**Diffuse Sky Model**	**Ground Coupling**	**Convective Heat Transfer Coefficient**	**Shading on Walls**
A	Reindl	Decoupled from constant ground temperature	Variable value	Shading effects on walls
B	Perez	Adiabatic slab	Constant value, split recommended in Standard 140	Shading effects on walls
C	Reindl	Adiabatic slab	Constant value, split recommended by model developer	No shading effects on walls
Minor Interpretational Differences				
Author	**Schedules**	**Time step**	**Weather Data**	**Windows**
A	Internal schedule	1 hr, 0.1 hr where needed	Preprocessed to EnergyPlus format	Created using Window 5.2
B	External input	0.25 hr throughout	Manually modified file	Created using Window 5.2
C	Internal schedule	0.25 hr throughout	Manually modified file	Created using Window 5.2

RESULTS AND ANALYSIS

The intent of this paper is not to present the complete results of applying ASHRAE Standard 140 to TRNSYS 15.3. Rather it is to show the effects of differences in simulation technique and interpretation of the Standard.

ASHRAE Standard 140 relies on two types of results, absolute values and deltas (differences in results between cases). Running each case results in absolute values of annual heating load, annual cooling load, peak heating load, and peak cooling load. These results are checked to make sure that the program being tested falls within the predefined range of acceptable answers. Given that different base case assumptions were made, it was expected that there would be differences in results throughout each given series. Figure 2 and Figure 3 show the four figures of merit for the two series base cases, 600 and 900.

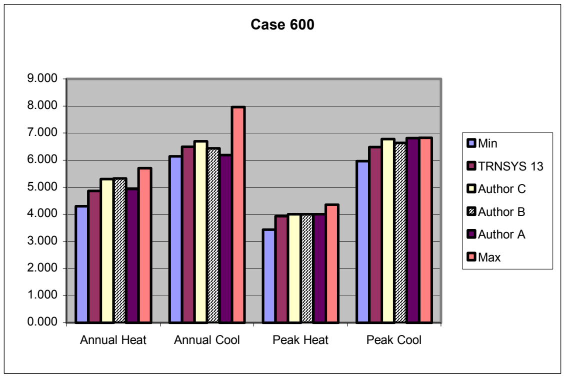

Figure 2: Case 600 Results

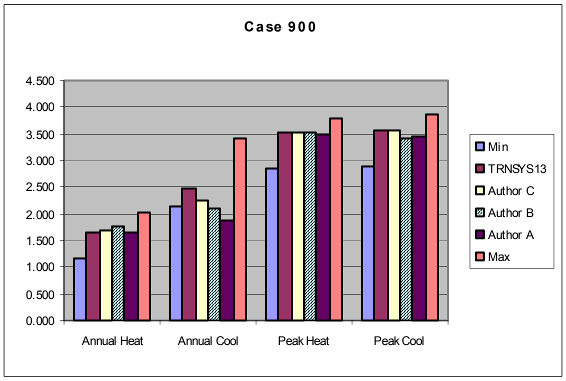

Figure 3: Case 900 Results

It is evident that the base assumption differences are fairly insignificant for the Case 600 annual heating between authors B and C while author A's annual heating results are lower. Turning to Case 900, differences between annual heating results are somewhat magnified; more separation between author results can be noted. Case 900 is simply a high mass version of Case 600; walls and floor materials are replaced with heavier weight construction materials. Annual cooling loads in both Cases 600 and 900 show more dramatic differences with author C consistently predicting the highest cooling loads, author A predicting the lowest cooling loads and author B predicting in between. These annual value trends continue throughout all cases in the 600 and 900 series. Author A is consistently lower on both heating and cooling while authors B and C are essentially equal on heating but author C is higher on cooling. The root causes for Author A's lower annual heating results were clarified as the results of the Standard's sensitivity tests were analyzed.

The above mentioned trends continue throughout both the 600 and 900 series with the exception of Cases 630 and 930, in which the windows have been moved from the south façade to the east and west façades, and have been outfitted with both overhangs and wing walls.

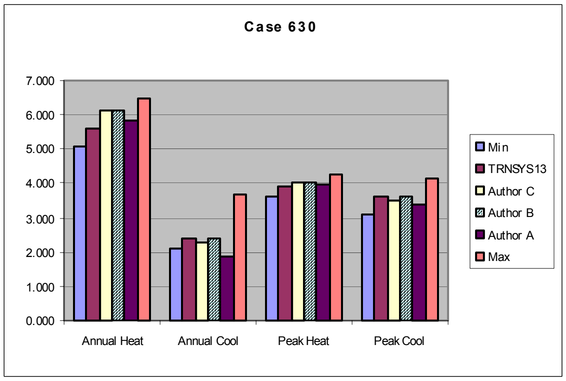

Figure 4: East / West Shaded Window Orientations

Here again authors B and C match on annual heating load while author A's results are lower. However, authors B and C have reversed trends on annual cooling with author B predicting a higher value. Author A remains the lowest of the three. One would think that because authors A and B made nearly the same shading assumptions, their results for Case 630 would be similar. Once all cases in the Standard have been run, it becomes possible to examine the sensitivity of the software to a given change in building configuration by subtracting the results of one case from the results of the base case for that series. In looking at the result differences (or deltas) between Case 630 and the Case 620 (unshaded east and west windows) one sees in Figure 5 that authors A and C show a greater sensitivity (a larger decrease in annual cooling load and a larger increase in annual heating load) to shading the east and west windows. Referring once again to Table 1, authors A and C used the same sky diffuse model but different shading assumptions. The fact that their Case 630-620 delatas are similar would suggest that the choice of sky diffuse model (especially when combined with shading effects) is important.

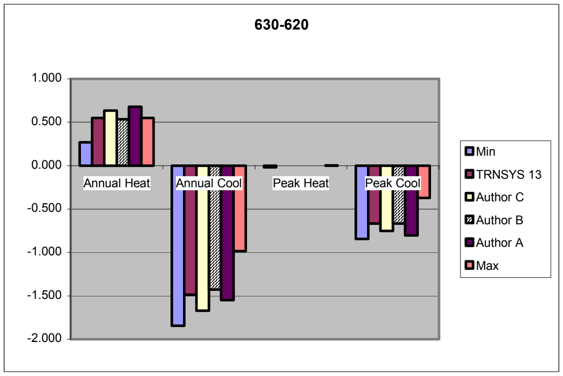

Figure 5: Case 630 Sensitivity

In both the 600 and 900 cases it is interesting to note that authors B and C predict larger heating loads and smaller cooling loads with TRNSYS 15 than had been predicted using TRNSYS 13. This trend carries through all cases in the 600 and 900 series. No investigation into the root cause of differences between TRNSYS 13 and 15 was carried out.

In order to determine the root cause of the result differences obtained by author A and by authors B and C, the 900 case was rerun, modifying author A's assumptions in a manner that isolates the effects of each assumption and brings them closer to those of authors B and C. In Figure 6, the average of author B and C's results is shown in the first column of each series. The second column shows author A's results based on his assumptions. The column labeled A0 shows author A's results having replaced time dependent convection coefficients with constant values; all other assumptions remain unchanged. As can be seen from the figure, this replacement resulted in higher annual heating and cooling loads. Replacement of only author A's decoupled ground assumption with an adiabatic slab assumption (column A1) drove annual cooling load higher and annual heating load lower, suggesting that the use of thick insulation under the slab and a constant deep earth ground temperature does not completely decouple the ground from the building. In Case A1, Author A's original time dependent convection coefficient assumption was used so as to isolate the effects of the slab assumption. The final column in each series shows the result of changing both the convective heat transfer coefficient assumption and the ground coupling assumption. It is notable that both annual cooling and annual heating match the average of author B and C's results.

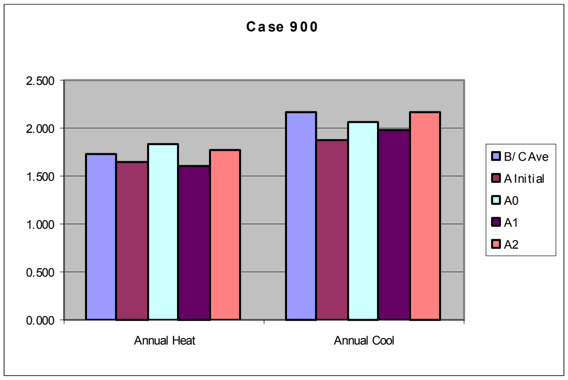

Figure 6: Case 900 Result Sensitivity to Base Level Assumptions

Tests were also carried out the other assumption differences as well: time step choice, different window data files, and cloud cover assumptions. Changes in annual results due to these assumptions were comparatively minor.

A somewhat limited number of conclusions can be drawn from simply looking at the absolute values of the four figures of merit. Of perhaps more interest are the differences (or deltas) between cases. Given the comparatively minor differences between absolute value results, it was expected that the base case level assumptions would be seen to be of less importance and that one would notice similar deltas between authors. In other words, that the base case assumptions would have little effect on the overall sensitivity of TRNSYS to variation of other parameters. Certain cases did exhibit such behavior as can be seen between authors B and C in Figure 7 where case 600 results were subtracted from case 900 results.

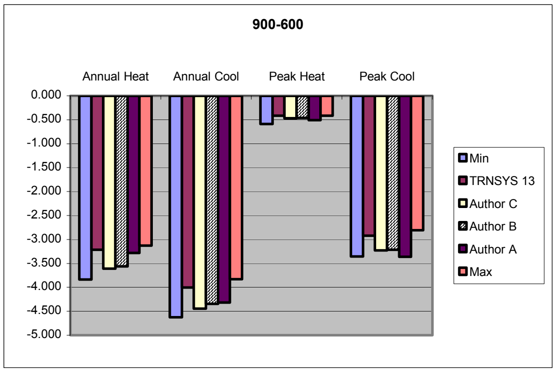

Figure 7: Difference in Results Between Cases 900 and 600

The fact that the delta results for authors B and C are nearly identical in all four categories indicate that for the change between the Case 600 and 900 buildings the loads are either insensitive to their base case assumption differences or that TRNSYS is equally sensitive to the different assumptions. The change from case 600 to case 900 involves the replacement of low mass walls and floor with high mass walls and floor. Equal deltas could suggest that the diffuse sky model (and thus the amount of diffuse solar radiation incident on the building) is of little importance in the annual energy calculation (low sensitivity). It may equally well suggest that some other factor was significantly more important (accounting entirely for the difference) and that in essence TRNSYS was equally sensitive to the Perez sky model as it was to the Reindl model.

A difference in annual heating load and in peak cooling load is seen between the results obtained by authors B and C and the results obtained by author A. Since no shading is included in either case and since authors B and C obtained nearly identical results using different sky diffuse models, the sensitivity difference can likely be attributed to ground coupling and convective coefficient assumptions. The result suggests that annual heating load is less sensitive and peak cooling load is more sensitive to building mass changes when one allows for time dependent convection coefficients and heat transfer to the ground. Further investigation showed that changing from an “effectively decoupled” ground model to a completely decoupled ground model (adiabatic slab) drives annual cooling load up and annual heating load down, suggesting that the “effectively decoupled” slab still transfers energy between the zone and the ground (complete decoupling is not achieved). Since modification of author A’s ground temperature assumption from complete decoupling to effective decoupling would therefore further decrease his annual heating load, this modification would not bring the authors’ results closer. It is therefore more likely that the variable heat transfer coefficients are the root cause of author A’s consistently lower annual heating results.

There are few trends visible in the author’s delta results. One pattern that exhibits itself is in cases where shading effects are examined. In Cases 610 and 910, a 1m wide overhang is added along the length of the building’s south façade. In Cases 630 and 930, overhangs and wing walls are added to east and west facing windows.

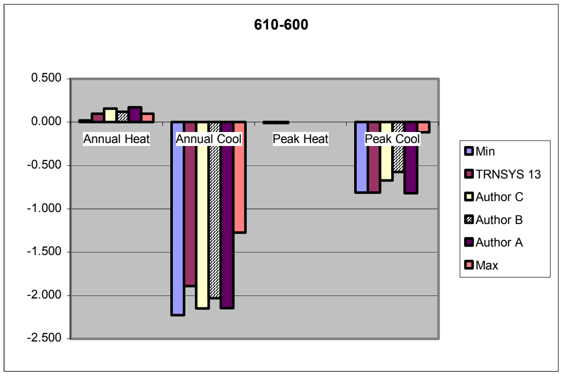

Figure 8: Sensitivity to South Overhang Shading

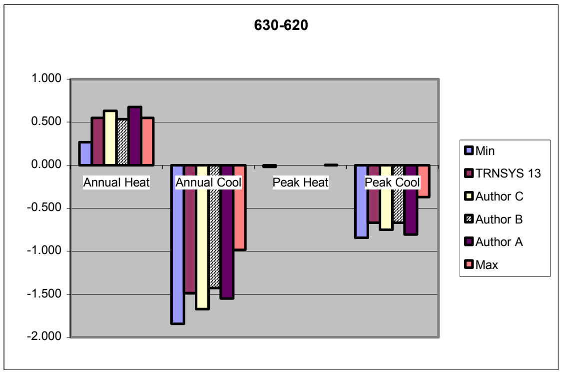

Figure 9: Sensitivity to East / West Overhang and Wing Wall Shading

Since A and C obtained similar delta results, one can conclude that TRNSYS is no more sensitive to one shading assumption as opposed to another. A and C differ in their assumptions about ground coupling, constant versus varying convective heat transfer coefficients, and the necessity of accounting for shading on opaque surfaces. Author B’s delta results are lower indicating that TRNSYS is less sensitive to shading given one of Author B’s assumptions. The only assumption where B differs from both A and C is in his choice of diffuse sky model; author B chose the Perez correlation while authors A and C used Rinedl.

CONCLUSIONS

A number of conclusions can be drawn from the work done in applying ASHRAE Standard 140-2001 to TRNSYS. First and foremost, it is clear that there is a great deal of leeway within a given software package to make widely varying assumptions and yet still fall well within the range of acceptability. It is equally notable, however, that the differences obtained by the authors were relatively small as compared to the size of the range of acceptability. This grouping would suggest that even though there is such great assumption leeway within the program, a user can have confidence that their results will not show wild variation.

Of the main assumption and interpretation differences made by the authors, it was found that a dramatic decrease in annual heating and cooling loads comes from allowing the interior and exterior convection coefficients to change with ambient conditions. Different methods of splitting radiative and convective parts from a combined coefficient have little effect. The second major difference came in ground coupling. Authors interpreted the standard differently, some assuming that the intent was to completely decouple the ground from the building and others using the Standard's suggested method for decoupling the two. Switching from a decoupled assumption to an adiabatic slab assumption resulted in higher annual heating loads and lower annual cooling loads, indicating that the suggested decoupling still allows for a measurable energy transfer between the slab and ground. Treatment of shading on not only transparent but also on opaque surfaces was also found to be important. However, TRNSYS appears to be quite sensitive to choice of sky diffuse model as well to the actual treatment of shaded radiation.

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