DAYLIGHT FACTOR SIMULATIONS – HOW CLOSE DO SIMULATION BEGINNERS 'REALLY' GET?

Diego I. Ibarra, Christoph F. Reinhart
Graduate School of Design, Harvard University
Cambridge MA, USA
dibarra@gsd.harvard.edu, reinhart@gsd.harvard.edu

ABSTRACT

The daylight factor is usually one of the first daylight performance measures that simulation newcomers calculate. Apart from the intrinsic limitations of the daylight factor as a meaningful daylighting performance metric, little work has been done in the past as to how accurate one can actually expect simulation novices to simulate the daylight factor compared to an expert modeler. This paper presents the comparison of daylight factor predictions from a 'best practice' model of an L-shaped perimeter classroom to a total of 69 novice/student models. In all cases the models were prepared in ECOTECT and simulated in RADIANCE. The paper discusses common mistakes that simulation beginners make when carrying out a daylight simulation, how close their simulation results were compared to the best practice model, and how software developers and educators could potentially guide users to avoid making these mistakes. In addition, a comparison of simulation results obtained with ECOTECT's build-in split flux method as opposed to RADIANCE is carried out for the 69 models in order to quantify in how far using a less reliable simulation engine compromises the accuracy of a simulation.

Keywords:

Daylight simulation, simulation errors

INTRODUCTION

Introducing effective daylight strategies has become an essential goal for any sustainable building. However, since it is difficult to evaluate its quality and quantity in non-standard spaces through simple rules of thumb, the use of daylight simulations has considerably increased as a necessary step to accurately evaluate daylight in buildings. This has been a conclusion of two recent surveys: the first survey focused on simulation experts and their specific use of daylight simulations (Reinhart and Fitz 2008), the second survey addressed more globally how green building design teams are currently implementing daylighting in their projects. Both groups reported that they routinely use simulations especially at the design development stage (Galasiu and Reinhart 2008). The simulation experts mostly modeled work plane illuminances and daylight factor (DF) whereas the green building community was also concerned with the overall energy implications of daylighting and solar gains.

In North America, the growing use of and interest in daylight simulations tools can be attributed to building standard and green building rating systems alike. E.g. ASHRAE's Standard 90.1-2007 (ASHRAE 2007), which serves as a building energy code requirement in several US states, now stipulates the use of daylight simulation in order to determine the energy saving potential of photocell controlled diming systems in a particular space. At the same time, the US Green Building Council's widely used LEED Green Building Rating System promotes daylight simulations as one of the compliance paths to earn daylighting credit 8.1 (USGBC 2006).

The rising interest in daylight simulations has largely happened in parallel with a rising interest in building energy modeling. But, one important difference between the two types of simulation programs is that while there already exists an ASHRAE/ANSI standard that 'specifies test procedures for evaluating the technical capabilities [...] of computer programs that calculate the thermal performance of buildings'(ASHRAE 2007), there is no such standardized testing procedure in place for daylighting software. This caveat notwithstanding, a number of validation studies using measured indoor illuminance have been completed over the past 15 years. Especially the RADIANCE backward ray-tracer (Ward and Rubinstein 1988) has been studied systematically over the last decade (Mardaljevic 1995, Reinhart and Walkenhorst 2001, Reinhart and Andersen 2006). These validation studies have shown that RADIANCE can be combined with a daylight coefficient approach to reliably model the changing levels of daylight in a building over the course of a year. Work plane illuminances can be typically modeled with an accuracy of about 20% which can be considered as sufficient for most design purposes given that the human eyes itself is a logarithmic sensor. A very recent validation study suggests that the Mental Ray raytracer under 3ds Max Design 2009 can also model indoor illuminances with an accuracy comparable to Daysim/Radiance (Reinhart and Breton 2009).

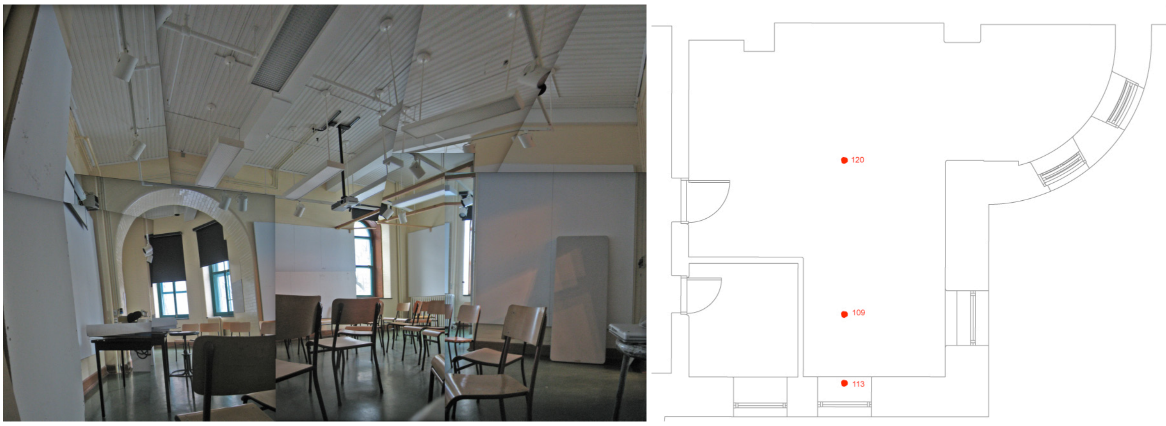

Figure 1: Left – view of the room; left - floor plan of the room.

One could in principle conclude from these studies that validated daylight simulation programs can now be recommended to design teams interested in implementing daylighting into their projects *and* that the use of these programs will yield reliable results if the investigated buildings are of comparable complexity to the ones investigated in the validation studies. But, given that previous validation studies were carried out by a handful of simulation experts one might actually wonder how accurate one can expect the results of simulation novices to be?

Few studies have focused on the impact of the user in the accuracy of simulation results by analyzing the output of multiple users modeling the same simulation case. Kummert (Bradley, Kummert and McDowell 2004) compared the difference in simulation results when three expert users applied ANSI/ASHRAE Std 140-2001 to the TRNSYS simulation program (TRNSYS 2009). The users where categorized as a developer, a user/developer, and an expert user. The study concluded that there is a great leeway within a given software package to make widely varying assumptions and yet still fall well within the range of acceptably accurate results. The study concluded that despite this modeling latitude, knowledgeable users can still be confident that their results will not dramatically vary from those of other expert users (Kummert et al. 2004). This conclusion might be reasonable for expert users who understand the underlying assumptions and limitations of a simulation program. But, are these conclusions also valid for novice users? How large is the error margin introduced by typical simulation newcomers? Can common mistakes be identified and potentially be avoided in the future?

To answer these questions this paper compares daylight factor simulation results for a ‘best practice’ model of an L-shaped perimeter classroom to a total of 69 novice/student models. The objectives of this work are to indentify common mistakes that simulation beginners make and to develop guidance for software developers of how they could help users to avoid making these mistakes.

In addition, a comparison of simulation results obtained with ECOTECT’s build-in split flux method as opposed to RADIANCE is carried out for the 69 models in order to quantify in how far using a less reliable simulation engine compromises the accuracy of a simulation

METHODOLOGY

During the Fall 2005 and 2006 Terms the second author asked a total of 87 students at the McGill School of Architecture to model the daylight factor distribution in one of the school’s “L” shaped crit rooms (Figure 1). The task was assigned as part of the deliverables for an introductory course in lighting and daylighting for 3rd year Bachelor of Architecture students. The room is located on the ground floor of the Macdonald-Harrington Building in Montreal, Canada (Latitude: 45°50′N, Longitude: 73°70′W). The building was designed by Sir Andrew Taylor and built between 1896 and 1897. The room is daylit through four windows and is characterized through over 800mm thick walls and a 4350mm high ceiling. The floor area is about 64 m^2 and the room dimensions in the widest sections are 11.95m along the east-west axis and 8.17m wide along the north-south axis. The optical characteristics of all walls and windows were measured using a reference white surface and a Hagner luminance meter[1]. The resulting material properties are listed in Table 1.

Table 1. Building material optical properties

Ceiling	Diffuse reflectance 80%
Wall	Diffuse reflectance 80%
Floor	Diffuse reflectance 8%
Windows	Visual transmittance 65%

The students were requested to model the space in ECOTECT and report the daylight factor at selected positions within the space. The students were not given any floor plans or sections of the space and accordingly had to measure all dimensions themselves, build a model in ECOTECT, assign

[1] http://www.hagnerlightmeters.com/products.htm

adequate material properties and run a daylight factor simulation. In class they had previously learnt how to do a daylight factor calculation using either the build-in split-flux method in ECOTECT or the export function to Radiance. For the assignment they were given the choice to use either program. It is interesting to highlight that *none* of the students carried out the simulation using RADIANCE. One may infer from this information that most simulation newcomers, whether students or practitioners, would probably make the same choice given that the limitations of the split-flux method are not widely known. For this reason and in order to quantify the difference in simulation results that one gets from using either ECOTECT (v5.6) split-flux or RADIANCE, all models were run using both programs with RADIANCE (v3.8) acting as the benchmark case for ECOTECT.

Another motivation for running the simulations in RADIANCE was that the authors hope that the use of the split-flux method in ECOTECT will ultimately be phased out so that users have to use RADIANCE or another validated engine, by default. The main focus of this study is to understand what type of modeling mistakes simulation newcomers make and - while a simulation program such as ECOTECT can easily be changed to another engine - it will always be up to the user to enter building geometry data correctly and to assign meaningful material properties.

Model Analysis

The model sample was narrowed down as follows: Out of the 87 students who were enrolled in the fall 2005 and 2006 terms 9 did not submit their ECOTECT files leaving 78 ECOTECT models for the authors to review. In addition, even thought the assignment had to be submitted individually, students ended up working in groups. To accurately account for the modeling mistakes done by each individual user or user group, the model sample was narrowed down to consider only one model per group. A total of 9 models were discarded during this process leaving 69 'independent' models. It is worthwhile mentioning that it is unclear at this point whether students who submitted the same ECOTECT model had actually worked in a group or whether a student had simply copied and submitted a peer's file without actually working on it.

Best Practice Model

A "best practice" model was created by the authors using ECOTECT. Additional elements, such as a 2D floor plan and trees, were created in a separate CAD tool and imported individually in .3ds format into the ECOTECT model. Interior surfaces were modeled according to Table 1. The ground albedo was set to 20% and the outside trees were modeled as transparent surfaces assuming a visual transmittance of 30%. The diffuse reflectance of all neighboring buildings was set to 50% and all window shades were assumed to be fully opened. Figure 2 shows an ECOTECT visualization of the 'best practice model'. A 32x40 horizontal grid with a total of 802 upward facing sensors was set at a height of 800mm above the floor, which corresponds to the height at which the students were supposed to model the sensor grid.

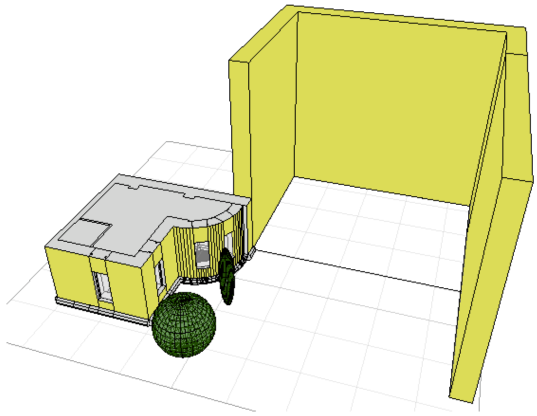

Figure 2. Best practice model

As explained above, the practice model as well as all student models were simulated using both the ECOTECT's built in split-flux method as well as RADIANCE. For the best practice model the ECOTECT simulations were run using the 'Full Precision' setting in ECOTECT. For the student models the ECOTECT simulations were rerun using the lighting analysis setting that the students had originally chosen. Table 2 lists the RADIANCE simulation parameters that were used for all simulations, ambient bounces (ab), ambient divisions (ad), ambient sampling (as), ambient accuracy (aa) and ambient resolution (ar). These simulation parameters were chosen based on recommended values from earlier Daysim validation studies and correspond to a scene of 'high complexity' as defined in the Daysim tutorial (Reinhart 2006).

Table 2. RADIANCE simulation parameters

ab	ad	as	aa	ar
6	1500	100	0.05	300

Since RADIANCE simulations using the best practice model served as the benchmark case against which the student models were analyzed, a relative error band of 10% was assumed for the RADIANCE daylight factor simulations of the best practice model. The 10% error band was derived from Reinhart and Andersen (2006).

Analysis of the Model Sample

The analysis of the student models was carried out in two steps. Initially, a qualitative overview of the 69 models was performed during which the authors manually went through all of the models and identified the most common simulation mistakes that were done by the students. Based on this initial screening the authors selected fifteen independent model inputs that could be quantified for all models (Table 3). These fifteen model inputs were grouped

Table 3. List of model inputs that were used to characterize the 69 student models.

Category	Question	Possible Answers	Error Frequency
General	Q1: In which semester was the model built?	Fall 05 / Fall 06	2005 - 2006
Geometry	Q2: Was the model built within ECOTECT? Imported from a third party unsuccessfully (i.e. not exploded or incomplete envelope)? Or Imported successfully (i.e. with glazing or added in ECOTECT)?	0= Imported unsuccessfully | 1= Built within ECOTECT | 2= Imported Successfully	26
	Q3: Are interior room dimensions modeled accurately?	0=Yes | 1=wrong depth | 3=wrong height | 4=wrong depth and height	44
	Q4: Are the window dimensions (size and position of window openings) modeled accurately?	0= Yes 1= No	30
	Q5: At what thickness are the walls modeled?	Thickness in mm [target value 980mm]	13
	Q6: Are neighboring buildings modeled?	0= Yes | 1= No	16
	Q7: Are adjacent trees modeled?	0= Yes | 1= No	24
Materials	Q8: Did the model use the customized NRC material library (as opposed to the ECOTECT default library; Fall 06 only)?	0= Yes | 1= No	67
	Q9: What was the modeled glazing transmittance?	visual transmittance in % [target value 65%]	69
	Q10: What was the modeled ceiling reflectance?	reflectance in % [target value 80%]	55
	Q11: What was the modeled wall reflectance?	reflectance in % [target value 80%]	69
	Q12: What was the modeled floor reflectance?	reflectance in % [target value 8%]	69
Simulation Settings	Q13: Were the sensor positions correctly (correct sensor height)?	grid height in mm.[target 800mm]	18
	Q14: Were the sensor modeled correctly (grid sufficiently fine and inside envelope boundary)?	0= Yes | 1= No	14
	Q15: What was the selected simulation precision in ECOTECT:	1= lo | 2= medium | 3= high | 4=very high | 5=full	

into four categories: General, geometry, materials and simulation settings.

The first category (Q1) differentiated between the school year in which a model was build. A difference in the accuracy of simulation results between 2005 and 2006 was expected because for the fall 2006 term the instructor provided (a) a few modeling tips for the students such as “remember that ‘real’ walls have a thickness” and “consider surrounding objects (buildings, trees, etc.)”[2] and (b) encouraged students to work with a customized material database for ECOTECT[3], which provided more realistic material descriptions for lighting than the original ECOTECT material library.

The second category was concerned with model geometry. The initial screening revealed dramatic geometry errors in nearly all of the models. These errors were the results of several modeling shortcoming. The building geometry editor in ECOTECT actually builds all walls and ceiling as single surfaces, i.e. with zero thickness. As a result typical models build in ECOTECT tend to substantially overestimate indoor daylight factor levels especially in spaces such as the investigated classroom room that had a wall thickness of 980 mm (Q5). Another, more surprising, common error was that many students modeled the window head of all classroom windows as a straight line and not rounded (Q4). A large number of students were unsatisfied with the limited three-dimensional modeling capabilities of ECOTECT and instead used another CAD tool and imported their scene geometry into ECOTECT for further analysis (Q2). While this is might - in principle - have been a good idea it often resulted in grossly erroneous models with typical importing errors being that the whole scene was imported in a single group with a fixed material property, planes that were imported only as construction lines resulting in missing walls and ceilings, no planes in fenestrations, and out of scale models. Two other frequent model shortcomings were that external trees and neighboring buildings were not included in the model. The thresholds for identifying accurate space dimensions (Q3) were established based on a study on error impact over simulation results carried out by Thanachareonkit (2008). Thanachareonkit’s study, concluded that for a sidelit space simulated under a CIE overcast sky, a variation of over 5cm on a sensor point will result in a 10% illuminance variation for sensors located at 0,2, 3.2 and 6.2m from the window, compared to real measurements. Assuming that a modeling error of more than 5cm in window dimensions under a CIE Overcast Sky will equally result in more than a 10% error in simulation accuracy, a maximum of 10% error on the space dimensions was allowed. In conjunction with a 20x24 sensor grid (301 sensor points for the space geometry) this corresponds to a maximum of 5cm sensor displacement along the X and Y axes. The threshold for accurate window dimensions (Q4) was equally set to a 5cm from the target level. The wall thickness was verified in absolute values in relation to the 980 mm target value (Q5). Considering the surrounding buildings and

[2] Wording taken form original assignment.

[3] http://irc.nrc-cnrc.gc.ca/ie/lighting/daylight/daysim/docs/NRC_LightingLibrarySetup.exe (last accessed February 2009)

trees (Q6 and Q7) were evaluated on a yes or no basis.

For the material category the fact whether a student had used the customized NRC material database for ECOTECT (Q8) as well as the assigned surface reflectances and transmittances (Q9 to Q12) were verified. The simulation settings verified whether the sensor grid was set to the correct height above the floor (Q13) as well as whether all sensor grids were properly positioned within the room (Q14). As explained above the simulation precision (Q15) was only used for the ECOTECT split-flux simulations.

RESULTS

In this section the simulation results of the best practice model as well as the 69 student models are compared between ECOTECT split-flux and RADIANCE. Afterwards the RADIANCE simulations of the 69 student models are compared to the best case results. Through the results section the mean daylight factor (DF_{mean}) and the percentage of sensor above a 2% DF ($Area_{>2\%}$) are used as daylighting metrics for the models.

Comparison of ECOTECT and RADIANCE

The DF_{mean} and $Area_{>2\%}$ for the best practice model simulated in ECOTECT and RADIANCE were 0.55% and 0% for ECOTECT compared to 2.59% and 41.65% for RADIANCE. Figures 4 and 5 visualize these drastic discrepancies between the two programs. The differences can be attributed to the fact that the ECOTECT split-flux method does not take multiple lighting reflectances into account which leads to a gross under-prediction of interior lighting levels in the presence of thick walls, light-shelves, overhangs or other elements that are commonly found in daylit spaces.

Table 3. Comparison of RADIANCE and ECOTECT simulation results for Best Practice Model

	Average DF	Area Above 2% DF
ECOTECT	1.53	6.89
RADIANCE	2.59	41.65

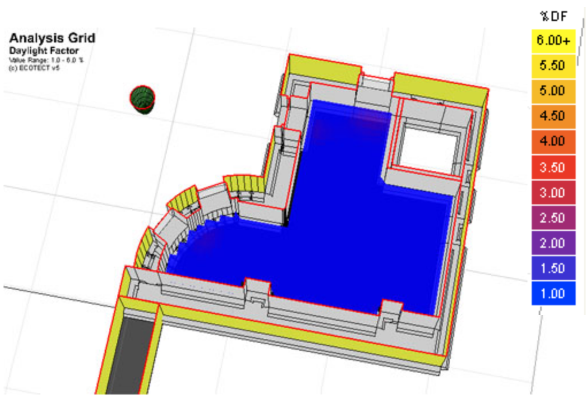

Figure 4. ECOTECT Daylight Factor Simulation

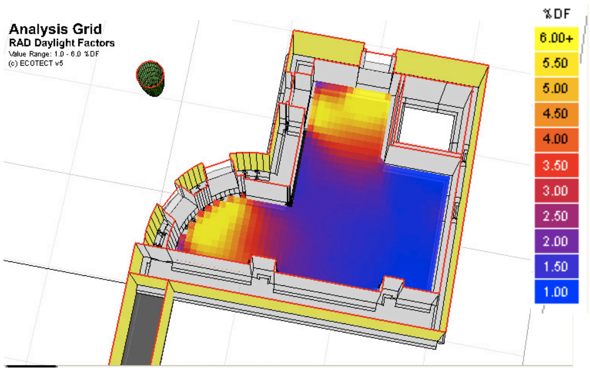

Figure 5. RADIANCE Daylight Factor Simulation

Figure 6 shows ECOTECT and RADIANCE simulations of DF_{mean} for the 69 student models. The benchmark simulation result of the Radiance best practice model is shown was will with an error band of 10%. Comparing the ECOTECT and Radiance results for each student model individually, one finds for 60 out of the 69 student models RADIANCE predicts higher daylight factors than ECOTECT: In 2005 the DF_{mean} was 5.9% for the ECOTECT simulations compared to 8.3% for RADIANCE. In 2006 the numbers were 4.5% and 8.2%, respectively.

When analyzed by year, the 2005 ECOTECT student models tend to their repsective RADIANCE models than in 2006. The reason for this is that in 2005 only 5 out of 39 students considered modeling wall thicknesses whereas all 30 student models in 2006 had non-zero wall thickness[4]. When wall thicknesses are modeled, daylight penetration resulting from reflected light is much more relevant than direct sky contributions which means that ECOTECT tends to predicts lower levels than RADIANCE. The only excetion to this rule occurs if a student used low simulation precision settings. In that case ECOTECT might accidentally predict higher levels than RADIANCE.

The fact that the ECOTECT simulations are sometimes higher and sometimes lower than Radiance underlines that that using the ECOTECT split-flux method cannot even be interpreted as a 'worst case scenario' for a space but that it may both grossly over *and* under predict real daylight factor levels in a space. The authors therefore believe that this simulation engine should not be used *at all*. This topic is revisited below.

Comparison of Student Models and Best Practice Results

A comparison of the RADIANCE simulations in Figure 6 shows that in both years the results from the student models were significantly higher than for the best practice model. In 2006, two models (17 and 25)

[4] A direct consequence of the modeling tips given by the instructor.

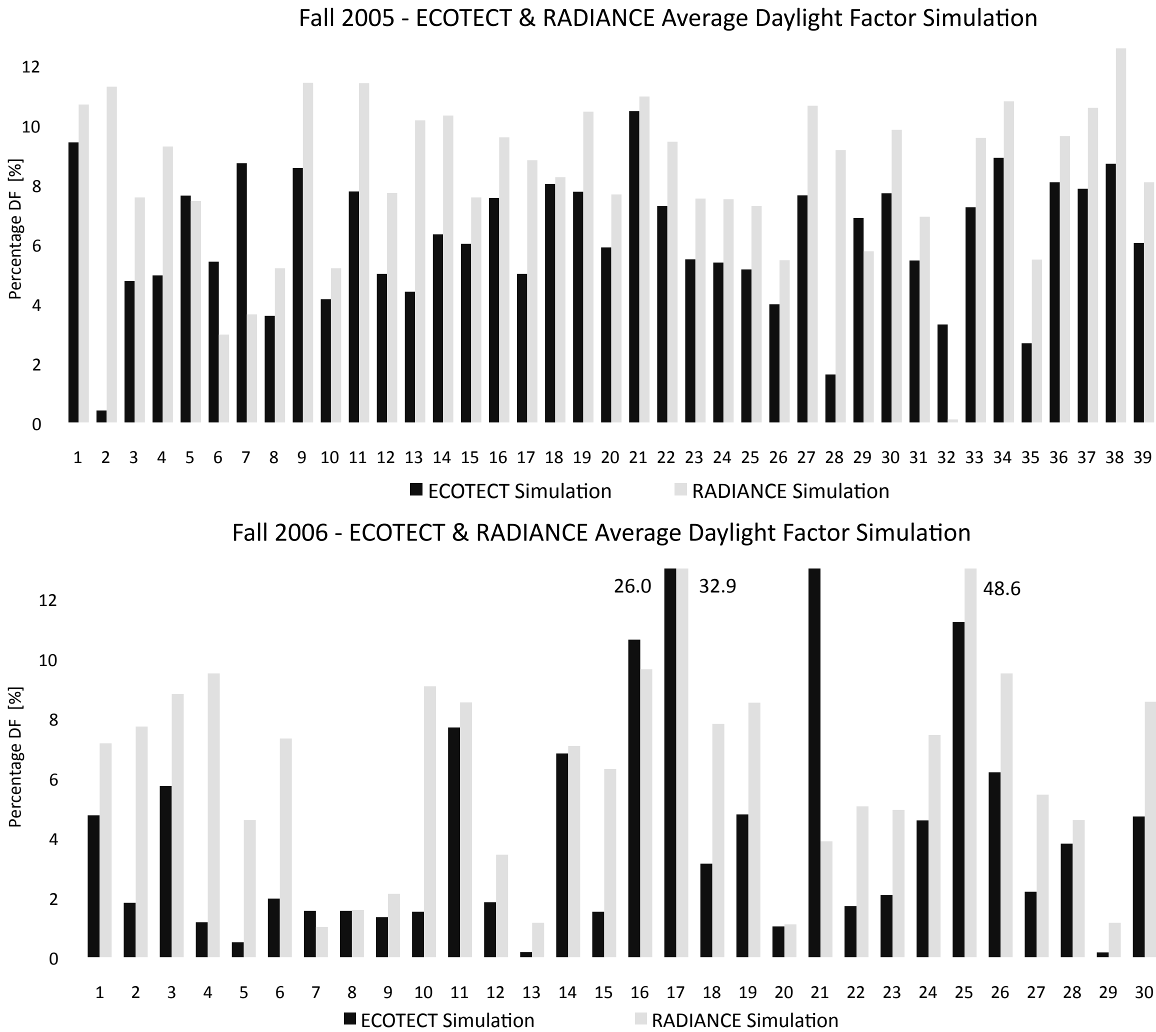

Figure 6. Comparison of ECOTECT and RADIANCE average daylight factor results for the 2005and 2006 models. The simulation results are compared to the best practice RADIANCE model for which a 10% error band is plotted as well.

show extreme values of 32.92% and 48.60%. In both cases these high results stem from and unsuccessful import of the scene geometry from another CAD tools into ECOTECT: In model number 17 the ceiling plane was imported as construction lines only. Similarly, in model 25 most of the perimeter walls were imported as construction lines.

Figure 7 shows a frequency distribution of the RADIANCE results from Figure 6 binned into 1% slots for 2005 and 2006. Contrary to what one would expect, the two distributions do not approximate a normal distribution but the results lie by around 200% to 300% to the 400% over the best practice model results. In fact in 2005 only one models was in either the 2% or 3% bins that can be interpreted as the 'acceptable result' range. In 2006 the number of acceptable models grew to six that still only corresponds to 16% of the submitted student models. As will be shown in the following the reason for the different types of models submitted in 2006 can be largely attributed to the 'simulation tips' provided by the instructor in the second year.

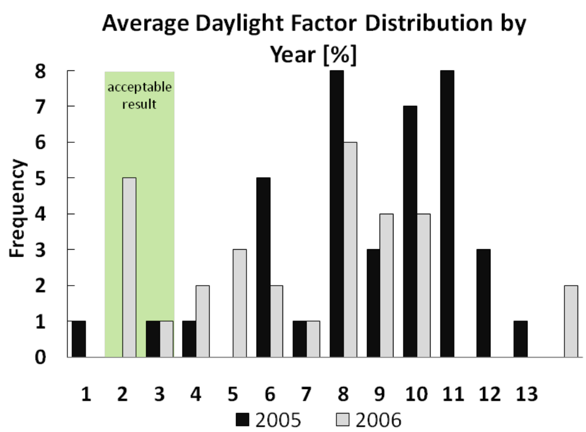

Figure 7. Frequency distribution of RADIANCE student models for 2005 and 2006.

Figure 8 shows the frequency distribution of the relative error of DF_{mean} grouped by how the scene geometry was build (Q2). Each scene was either built within ECOTECT or imported into ECOTECT from another CAD tool. As explained above, in many instances this import leads to corrupted models which is why the imported models are divided into 'Model imported OK' and 'Model imported wrong'.

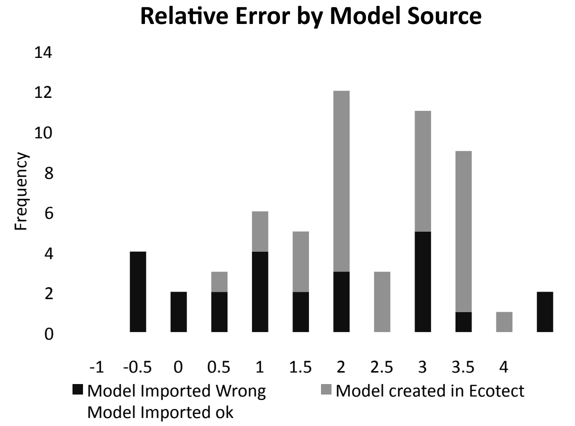

Figure 8. Frequency distribution of the relative error of DF_{mean} by model source.

One could expect that the models that have been imported correctly would generated the most reliable results since they take wall thickness into account and generally model the room dimensions in greater accuracy than ECOTECT models due to the limited 3D modeling capabilities in ECOTECT. Surprisingly, this is not the case since the models that were imported correctly do seem to be systematically better than the other models. The reason for this finding is that *all* students' models were somehow seriously flawed. Even if they properly imported the model geometry students forgot to explode the imported scene and assign meaningful material properties and in many instance window glazings were somehow forgotten. In some instance scene elements were simply imported as construction lines[5].

Figure 9 shows a frequency distribution of the models that were built in ECOTECT only separated by year. While the 2005 models area scattered across a large range the 2006 model are actually much closer together. The reason for this is that in 2006 all ECOTECT models had non-vanishing wall thicknesses. Despite of the general improvements of the models build in ECOTECT in 2006 over 2005 all models still experiences some shortcoming which is why they still lay a factor of 2 over the best practice model.

[5] In this context it is important to note that the ECOTECT 5.6 import function – while greatly improved over previous version- is still rather prone to errors. In Some instances the ECOTECT models with missing planes but when exported to RADINCE the planes were included in the RADIANCE model.

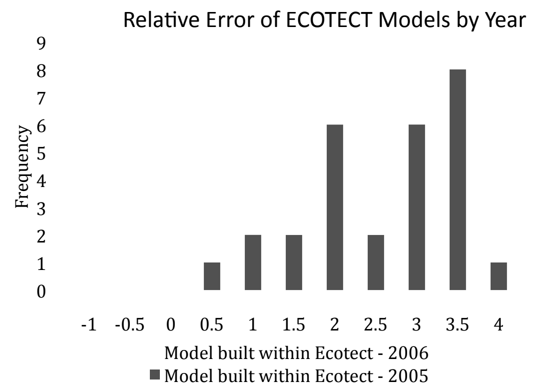

Figure 9. Frequency distribution of ECOTECT models only by year.

DISCUSSION

The previous section presented the simulation results for all 69 models and compared them to a best practice model results. The sobering results of the student's models reveal that even simple mature workflows have to be taught in greater detail for novices to obtain accurate simulation results. Part of the problem can be attributed to the limited 3D modeling capabilities of the ECOTECT GUI. Modeling three-dimensional spaces using zero thickness walls does not lead to acceptable results. One may question if the test space was unrepresentatively difficult for ECOTECT to model due to the uncommonly high wall thicknesses of 980 mm. The authors believe not because while modern buildings tend to have thinner walls they come with advanced façade features (overhangs, shading devices etc.) which also have to be geometrically modeled.

At the same time, import workflows from other programs have to be further streamlined and properly explained to software users; as many as 72% of the users who tried importing geometry were unsuccessful. Material properties, on the other hand, had a relatively minor effect on the model quality in this study mainly because the scene geometries were modeled inadequately.

Users were surprisingly careless when modeling space geometries, something unexpected from architecture students. The study demonstrates that students pay attention to simulation tips, which is a real opportunity for instructors and a good sign for the adoption of modeling guidelines.

There is currently a push toward moving away from the daylight factor as a performance metric for daylighting and using climate-based metrics instead (Reinhart, Rogers and Mardaljevic 2006). While this study used the daylight factor to determine the quality of a simulation one should assume that the results would have been largely the same if a climate based metric such as daylight autonomy or useful daylight illuminance had been used instead. The nature of the simulation errors lay in basic model properties, such as scene geometry and material properties, which are of equal importance for static and dynamic daylighting metrics.

CONCLUSION

When comparing the simulation results reported by ECOTECT's built-in engine and RADIANCE for the best practice model, ECOTECT reported a dramatic 79% lower daylight factor and a reduction in the Area above>2% DF from 41% to a 0%. For the 69 student models, ECOTECT simulations reported on average a 36% lower result and a 72% lower MBE than the same simulations run in RADIANCE. Furthermore individual ECOTECT models both grossly over- and under predicted daylight factor levels according to RADIANCE. This finding suggests that ECOTECT-based daylight factor predictions cannot be considered to be worst case assumptions and that RADIANCE should always be used instead of the build-in ECOTECT daylighting engine.

Comparing the quality of the student models submitted in 2005 and 2006 suggests that if the instructor provides simulation tips they are being followed. This finding puts an additional emphasis on the importance of high quality teaching material to complement simulation workflows: Offering simple simulation tips in the 2006 version of the class considerably improved the accuracy of the simulation results. Conversely, when no explicit modeling guidelines were provided in 2005, students tend to make dramatic errors, especially in relation to geometry input. If only a few parameters are addressed, users tended to overlook the impact of other variables, and continued to obtain inaccurate simulation results.

The authors conclude that even a simple set of modeling guidelines is generally required to complement any simulation workflow, however simple it may be, in order to ensure that simulation novices can follow it accurately.

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