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TEACHING DAYLIGHT SIMULATIONS – IMPROVING MODELING WORKFLOWS FOR SIMULATION NOVICES

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ABSTRACT

This paper is a follow up study on previously published research that focused on improving the quality and accuracy of simulations conducted by daylight simulation novices. The previous work identified common mistakes that simulation beginners make and proposed a set of simulation guidelines meant to guide users on how to avoid making these mistakes. Based on these earlier findings this paper proposes a set of simulation exercises to teach daylight modeling to simulation novices. Exercises in this teaching toolkit range from simple static metrics such as daylight factor or daylight illuminance, to more advanced dynamic metrics such as daylight autonomy.

The proposed teaching toolkit was tested in a semester-long class on daylighting with an enrollment of 17 students during Spring 2012 at the Massachusetts Institute of Technology. The paper evaluates the quality and accuracy of the resulting student models. The study also analyzes whether the remaining errors are reasonable and what impact they have on different daylighting metrics. The latter point should help to clarify whether simulation novices are capable of accurately modeling advanced, dynamic metrics such as daylight autonomy or useful daylight index. Dynamic daylight metrics, although commonly acknowledged to be superior to static metrics, are frequently perceived to be ‘too complicated’ for non-experts to model. Such perceptions typically support the use of static metrics over dynamic metrics in green building rating systems.

INTRODUCTION

The increasing use of daylight simulations to evaluate daylight quality and quantity in buildings design has been documented by several studies (Reinhart and Fitz 2006) (Galasiu and Reinhart 2008). In North America, the growing use of and interest in daylight simulation tools has been aided by several professional organizations. The American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE) through their 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. The US Green Building Council (USGBC) through their widely used LEED Green Building Rating System promotes daylight simulations as one of the compliance paths to earn its daylighting credit (LEED BD+C 2009, USGBC 2011). Similarly, Standard 189.1-2009, a joint effort by ANSI/ASHRAE/USGBC/IES requires daylight simulations to demonstrate usable illuminance levels in office spaces and classrooms (ASHRAE 189.1-2009).

Additionally, institutions are also currently moving from static daylight metrics to more complex performance metrics. The Illuminating Engineering Society of North America (IESNA) is recently promoting dynamic metrics such as spatial daylight autonomy as one of the future daylight performance metrics. At the same time, the new upcoming version of LEED v4, to be out for final ballot on March 2013, will include two modeling compliance paths for Indoor Environmental Quality (IEQ) credit 7, the new daylight credit. The green building standard will not only keep the point-in-time simulation option (with minor alterations) as one compliance option, but also will add a second compliance option using spatial daylight autonomy.

Finally, the American Institute of Architects (AIA) has recently released document named *An Architect’s Guide to integrating Energy Modeling in the Design Process (AIA 2012)*, which suggests that architects lead the way by carrying out daylight simulations early in the design process to evaluate daylight performance throughout the design process.

The context can be summarized by a growing demand for daylight modeling and a strong push for this modeling to be carried out by architects. This results in an increasing need for teaching daylight modeling to a large number of individuals and assuring that they are adequately trained. Having all simulation newcomers obtain accurate simulation results in this fast-paced environment will be challenging.

Several validation studies have confirmed that today simulation tools can provide accurate simulation results. However, a recent study published by the authors (Ibarra and Reinhart 2009) explored the importance of users in the accuracy of simulation results and how large of an error margin might be introduced by typical simulation newcomers. The study compared daylight factor simulation results from a Best Practice model of an L-shaped perimeter classroom to 69 novice models of the same space generated by architectural students. The work concluded that user modeling errors resulted in overwhelming inaccuracies and that teaching daylight simulation to novices is not a trivial endeavor and it needs to be addressed in small steps. However, the study also concluded that simulation tips or guidelines have the potential to importantly reduce user errors and improve model quality.

This work is a follow up study to test a proposed teaching toolkit that addresses the modeling process in smaller steps. An intrinsic part of this work is testing the effectiveness of platform-independent modeling guidelines aimed to improve simulation novices' model quality and reduce modeling errors. The study also explores whether the modeling error remains constant throughout different daylight metrics.

This work wants to contribute to a necessary field of study, education in building performance simulations. Assessing novice's user errors and proposing enhanced teaching methods will become critical to effectively implement daylight simulations in practice with meaningful results.

METHODOLOGY

Teaching Toolkit

This work proposed and tested a teaching framework or toolkit that consisted of a series of assignments aimed at effectively teaching daylight simulation to novice modelers. The toolkit starts by the selection of an existing space and then continues with a series of exercises of increasing complexity to analyze daylight quality and quantity using different daylight metrics. Overall the approach allows novices to first familiarize themselves with simple daylight metrics that they can observe and experience, to then move to more abstract dynamic performance metrics.

Exercise Description

The starting point for this approach is the selection of an appropriate reference space. It is recommended that the instructor selects a reasonably sized partially-daylit space. Space geometry and overall dimensions need to convey enough detail to allow the discussion of *how detailed the model needs to be?* but not so extensive that the expected daylit area becomes a small fraction of the total area and not really affected by space geometry. A reasonably sized space will also allow students to effectively assess and measure the space to create their 3D models.

Daylight Area Study and 3D model

The first exercise requires students to visit the selected space, assess and map the perceived daylight area and build a first 3D model. Participants are also required to carry out indoor illuminance measurements at a set of equally spaced points at a specific time of day and measure surfaces' reflectance and transmittance.

Revisiting the 3D Model and Comparison of Measured and Simulated Illuminance

The second exercise comprises an "upgrade" of the 3D model and running a point-in-time illuminance simulation to validate their models against their previously measured data. By revisiting their 3D models and using the daylight modeling guidelines (Appendix A) provided in this second assignment, students are able to better understand the criteria behind an appropriately created 3D model for daylight simulations.

Simulation of Different Daylight Metrics

This third exercise requires students to carry out three simulations of increasing complexity: daylight factor, point-in-time illuminance and daylight autonomy. Novices are requested to report both overall performance metrics as well as values for each of the sensor points used in exercise 1. This intent is to help users better understand the conceptualization of each metric and better relate the overall space metric to a daylight penetration profile.

Comparison of Initial Daylit Area Assessment and Annual Performance Metrics

The final exercise involves going back to the selected space and comparing the daylight area profiles of the different simulated metrics to their original daylight area assessment.

Implementation of the Teaching Toolkit

In Spring of 2011, the authors implemented the proposed teaching toolkit as part of a semester-long elective course at MIT, 4.430 Daylighting Buildings.

Figure 1: *Location on campus, exterior view and floor plan of room 10-485*

The course was offered as part of the Building Technology Program of the School of Architecture. A total of 19 architecture and building technology students from different graduate programs at the Massachusetts Institute of Technology (MIT) and Harvard University were enrolled in the course.

Students all classified themselves as either exposed for the first time to daylight simulations or as simulation novice with less than 6 months of exposure to daylight simulation. Most students were familiar with CAD tools, except for a few students for which the class constituted their first encounter with CAD tools.

Simulation Setting

The modeled space (MIT room 10.488-10.489) was located on the fourth floor of MIT's Building 10, just under MIT's famous Great Dome in Cambridge, USA (Latitude: 42°21′34"N, Longitude: 71°05′31"W). The space is daylit through three windows, has 0.25 m thick walls and a 6.55 m high ceiling. The floor area is about 82 m^2 and the room dimensions in the widest sections are 12.26 m along the east-west axis and 6.63 m wide along the north-south axis. As seen in Figure 1, the space is effectively divided in two rooms by a set of sliding doors. The room further from the window has a recessed ceiling at 3.92 m high.

All 3D models were created in Rhinoceros and simulations were carried-out using a combination of RADIANCE and DAYSIM program [Ward and Shakespeare 1998; Reinhart and Walkenhorst 2001] using DIVA-for-Rhino Version 2.0 as the simulation interface [Solemma 2012].

Daylight Area Assessment and 3D model

Illuminance measurements were taken on February 21st between 8:30am and 9:30am at a total of 12 points at regular 1m intervals at 0.85m height along the central axis of the space. Measurements were produced using T10A handheld Konica Minolta illuminance meters. Each student using a reflectance sample card from CIBSE Lighting Guide 11 assessed the optical characteristics of all walls (Loe, 2001). Surface reflectances were then combined with RGB color definitions to produce accurate RADIANCE material definitions.

Comparison of Measured and Simulated Illuminance

After receiving the daylight modeling guidelines students revisited their 3D models and reported their updates. For the point-in-time illuminance comparison of this east facing space it was important for students to simulate the sky conditions at the exact time of their measurements. Direct Horizontal Radiation [W/m^2] and Diffuse Radiation [W/m^2] values were provided for every 5-minute interval for February 21st between 8.30 and 9.30am. Users used the Perez Sky model and the custom sky feature built within DIVA v.2 for their simulations.

Simulation of Different Daylight Metrics

Three simulations were conducted: daylight factor, point-in-time illuminance per LEED daylight credit (IEQc8.1) and daylight autonomy. Daylight factor was used since it is one of the oldest indicators of daylight performance and it is very easy for novices to conceptualize. Daylight factor is defined as the ratio of illuminance E(x) at a point x divided by the illuminance of an unshaded upward facing point under a CIE overcast sky. The widely used LEED 2009 daylighting credit approach was selected for the point-in-time illuminance calculations. LEED IEQc8.1 (without addenda) calculations involved running two point-in-time illuminance simulations using CIE clear sky with sun model at 9am and 3pm on an equinox day and then reporting the percentage area that lies between 25 footcandles and 500 footcandles (269 lux and 5,381 lux) at both simulation times. Finally, daylight autonomy simulations included mean daylight autonomy and spatial daylight autonomy. Mean daylight autonomy with target illuminance of 300 lux ($DA_{MEAN300}$), reports the mean percentage of the occupied time that the target illuminance threshold of 300 lux is met. Spatial Daylight Autonomy ($SDA_{300/50}$) reports the percentage of the space area that meets the target illuminance of 300 lux at least 50% of the occupied time. Simulations considered a 9am to 6pm occupancy schedule and no blind controls.

Students were required to submit their Rhino files, material definitions, and a written report explaining their findings.

Model Analysis

This work presents the analysis of the outcome of three of the teaching toolkit exercises. First the authors created a benchmark model to be used as a reference case for the study. Subsequently, the analysis of the model sample was carried out in two phases. First the authors compared the measured and simulated point-in-time illuminance reported by the students in exercise two. This was followed by a comparison of each one of the four daylight metrics reported for exercise three: DF_{MEAN}, LEED IEQcr8.1, $DA_{MEAN-300}$ and $DA_{300/50}$).

Best Practice Model

A reference model of the space was created by the authors using Rhino R4.0 (figure 2). As previously mentioned, the model then served as a benchmark case against which all other models were compared for the simulated metrics. The model was created following the same methodology described in the exercises. Interior surfaces were modeled according to Table 1. Figure 2 shows a Rhino visualization of the benchmark model. A 32x40 horizontal grid with a total of 802 upward facing sensors was set at a height of 0.85 m above the floor. A Mean Bias Error (MBE) of 0.1 was defined as sufficient accuracy expected for the reference model. The MBE was given by:

$$MBE = \frac{1}{N}\sum_{i=1}^{N}\frac{(E_S - E_M)}{E_M} \qquad (Equation\ 1)$$

Where N is the number of sensors, E_S is the simulated illuminance and E_M is the measured illuminance at each sensor point.

Table 1 *Optical surface properties*

Glazing	Single glazing, 82% transmittance
Black mullions	Lambertian diffuser, 11% reflectance
Interior Walls – white paint	Lambertian diffuser, 72% reflectance
Interior Walls - white texture	Lambertian diffuser, 62% reflectance
Ceiling	Lambertian diffuser, 80% reflectance
Floor 10.488	Lambertian diffuser, 11% reflectance
Floor 10.489	Lambertian diffuser, 36% reflectance
Metallic Bridge	Lambertian diffuser, 55% reflectance
External Ground	Lambertian diffuser, 20% reflectance
Exterior Walls	Lambertian diffuser, 35% reflectance

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 'medium complexity' as defined in the Daysim Manual (Reinhart 2006).

Table 2*. RADIANCE simulation parameters*

ab	ad	as	aa	ar
4	1500	20	0.1	100

Comparison of Measured and Simulated Illuminance

A first comparison of the students reported measured and simulated illuminance at each sensor point was performed to analyze the accuracy of the student models. The statistical indicator use for this analysis was the relative error given by:

$$RE = \frac{(E_S - E_M)}{E_M} \qquad (Equation\ 2)$$

Where E_S is the simulated illuminance and E_M is the measured illuminance at each sensor point.

Subsequently, a comparison of absolute predicted illuminance was carried out to understand the impact of user error in the extent of the daylit area of the space. Due to the fact that students' measurements occurred during a small but dynamic window of time (early morning for this east facing space) models had to be resimulated at a single time step to perform this comparison.

A relative error band of 20% was assumed for the Radiance-based simulations. Work plane illuminance can typically be modeled with an accuracy of about 20%, which can be considered to be "sufficient for most design purposes" (Reinhart and Breton 2009).

Comparison of Daylight Factor, Point-in-time Illuminance and Daylight Autonomy

The statistical indicator used for this analysis was the relative error of the given metric reported by the student, as function of the benchmark value provided by the reference model.

A second step compares the values reported at each one of the 12 sensor points for all daylight metrics to explore the variance in the daylight profile of the space for all student models.

RESULTS

Comparison of Measured and Simulated Illuminance

Figure 3 shows the relative error of the measured and simulated illuminance reported by each student. The figure shows a 20% error band is along with the benchmark model. Result show that 8 out of the 17 student models are having problems accurately tracking horizontal illuminance throughout the space. The figure also shows the robustness of the reference model, which lies between the error band thought the whole space.

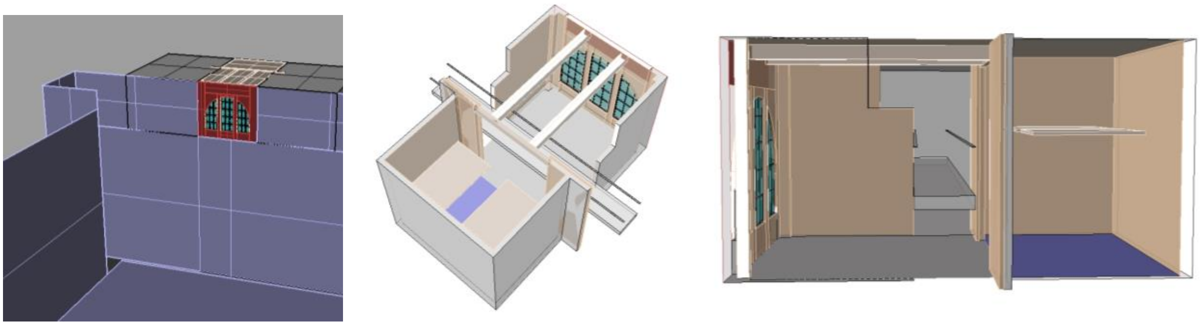

Figure 2: *Best Practice model of room 10.488 and 10.489 created in Rhinoceros R4.*

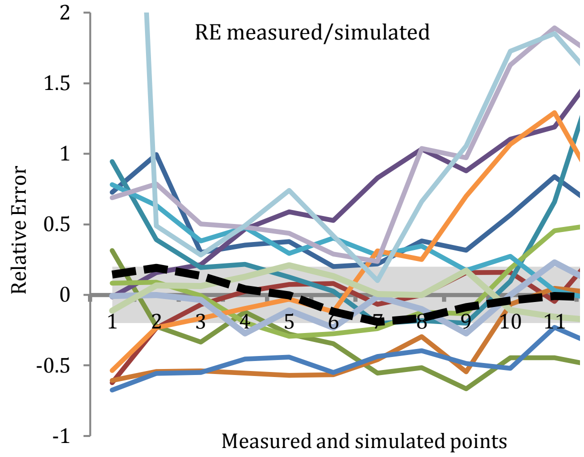

Figure 3. Comparison of simulated illuminance for all student models on February 21st, 8:50am.

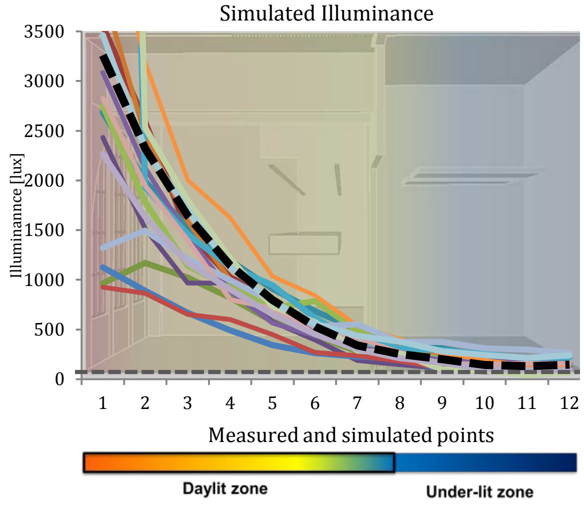

Figure 4 Comparison of relative error of simulated and measured Illuminance for all student models

To better understand how this large relative error affects the daylit area predictions within the space all models were resimulated at the same point in time. Figure 4 shows the comparison of simulated illuminance at 8:50am for February 21st for all 17 student models. The benchmark model is displayed as a dotted black line for reference. The chart overlays the illuminance measured along the twelve sensor points, spaced 1m apart, and the room section to better visualize the magnitude of the resulting illuminance profile of the space. A grey horizontal dotted line marks the 300lux threshold.

The figure shows that student models are predicting illuminance at the back of the room somewhat accurately but are having problems at the front part of the room. All models would predict the daylit are starting between sensor 7 and 9.

Comparison of Daylight Factor, Point-in-time sIlluminance and Daylight Autonomy

Figure 5 shows the comparison of all simulated daylight metrics for all 17 student models plus the benchmark model. Results show mean daylight factor, point-in-time illuminance per LEED daylight credit requirements, mean daylight autonomy and spatial daylight autonomy. Relative error for each model is graph on a second axis for all metrics The benchmark model results are shown as model #1 and are black coded. For the DFmean results, models are sorted from lowest to highest. The resulting model number is kept for consistency throughout the rest of the charts.

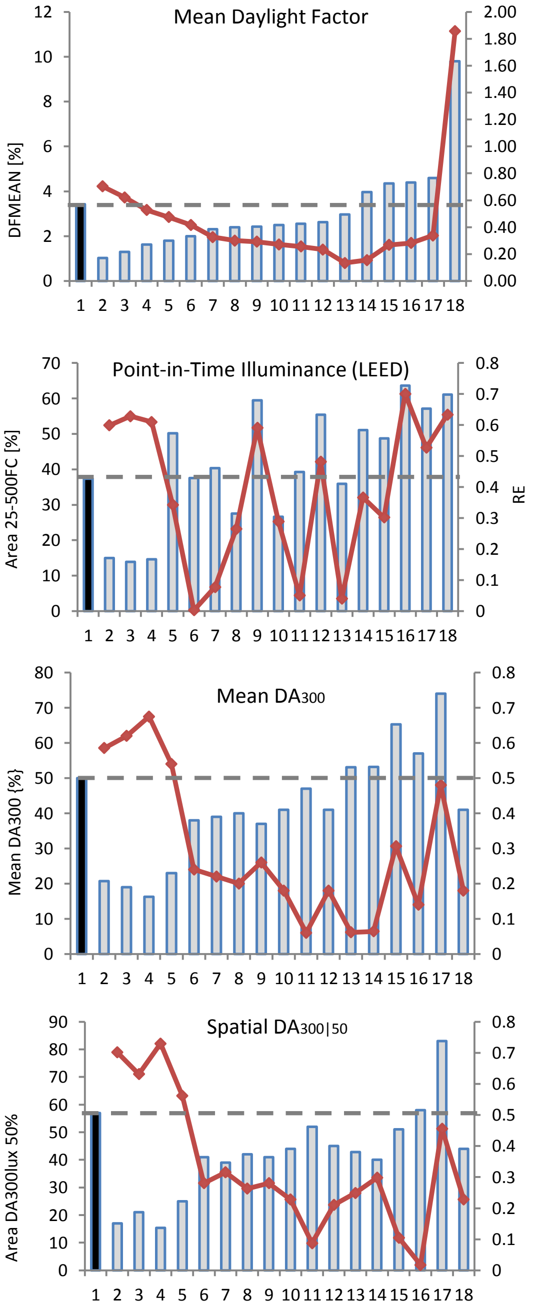

Figure 5 Comparison of all daylight metrics

Results show that when one model is analyzed across metrics, point-in-time illuminance show discrepancies compared to other metrics for the same models. One can conclude that for this studied case some user errors affect point-in-time illuminance simulations more dramatically than any other metric.

To identify the causes of these unique discrepancies Figure 6 shows the point-in-time simulation results for all 12-sensor points of the reference model at both 9:00am and 3:00pm. Figure 7 shows the resulting illuminance map with the LEED daylight compliant area.

When analyzing these simulations in detailed one can see that that accurately predicting the direct sun light during morning hours is critical. Only 3 out of the 17 students (18%) accurately predicted the high illuminance levels at 1m from the façade. Additionally, 8 of the 17 students (47%) were not able to predict the lower threshold of the daylight compliant area within a 1m discrepancy.

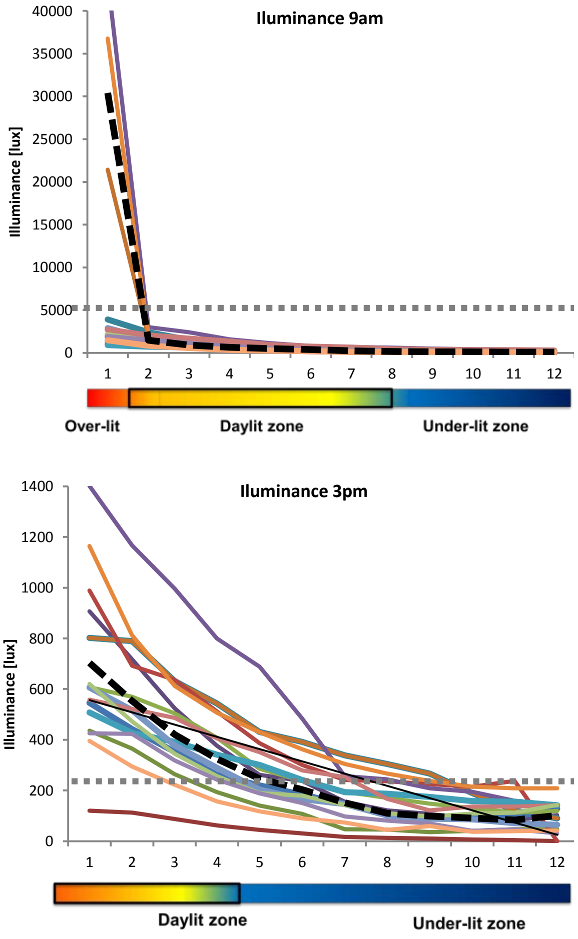

Figure 6 *Point-in-time illuminance simulation per LEED IEQc8.1 daylight credit*

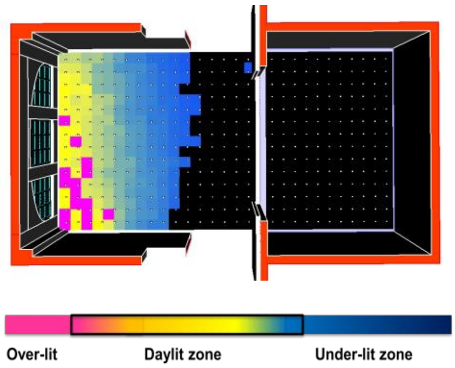

Figure 7 *Compliant daylight area per LEED IEQc8.1 daylight credit*

Finally, Figure 8 shows simulations results for all student models across all daylight metrics. Daylight factor simulations show a mean relative error (RE_{MEAN}) of 0.30 and an interquartile range (IQR) of 0.21. LEED point-in-time simulations show a RE_{MEAN} of 0.37 and an IQR of 0.33, compared to DA_{300} and $SDA_{300|50}$ that show a RE_{MEAN} of 0.22 and 028 and a IQR of 0.30 and 0.22 respectively.

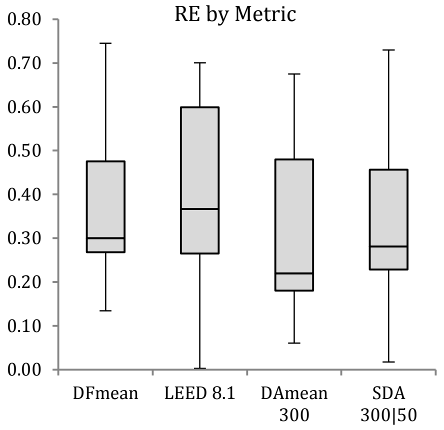

Figure 8 *Comparison of relative errors by daylight metric*

DISCUSSION

Validation of a preliminary model by novices

Establishing a good correlation between the simulated and measured illuminance proved to be a difficult task for simulation novices. Illuminance profiles at the back of room were less problematic than profiles in areas with direct sunlight. Small variations in sun position (i.e. as small as 10 minute discrepancies or single digit errors in room orientation) resulted to be critical for this east facing space during early morning. Other user errors that affected direct sunlight contributions were sky conditions settings and not using the suggested radiance parameters.

Nonetheless, this step proved to be very valuable for students as it provided the opportunity to revisit their models after carrying out a first comparison. The main changes/upgrades to the preliminary 3D models were space orientation, adding a ground plane and surrounding buildings, setting windows as single surface, and grouping surfaces in layers for ease of assigning material properties.

Teaching Approach and Modeling Guidelines

Novices' results for all daylight metrics are very encouraging. When compared to student results from 2005 and 2006 from the authors' previous study the findings are apparent. Teaching daylight simulations in smaller incremental steps and providing students with modeling guidelines resulted in 24% of students with a relative error of less than 0.25 compared to 0% in 2005 and 14% in 2006. More importantly, 88% of the students had a RE of less 0.5 compared to a 5% in and a 22% in 2005 and 2006 respectively.

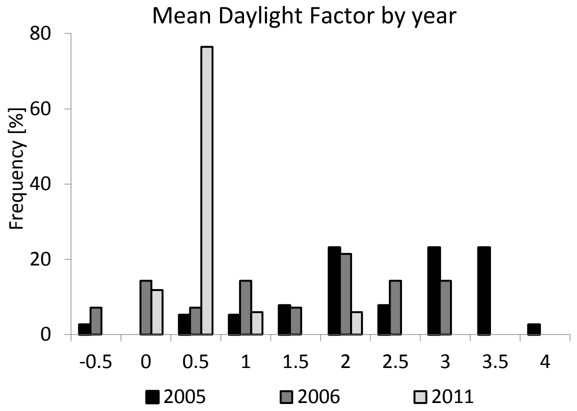

Figure 9 *Comparison of Daylight factor simulations by year*

Comparison of Daylight Metrics

Key characteristics for a strong daylight metric are meaningfulness, comprehensiveness and robustness. Authors will avoid pursuing the evident argument of how meaningful it is to use a metric that only considers a best/worst case scenario for just 2 hours of the year, and instead will focus on the issues of comprehensiveness and robustness.

Authors' experience suggests that perhaps the most important of the three characteristics for novices to succeed in daylight modeling is how easy is for them to understand the pursuit metric. With all the potential mistakes that can be made along the simulation process, it is critical that beginners understand and can relate to the metric being reported. If this is not the case, modelers making multiple errors and grossly over-predicting or under-predicting the daylight quality in the space will still report whatever values the engines conveys.

In this study it was evident that students had trouble understanding the calculation approach required to comply with the LEED point-in-time illuminance calculation. Only 29% of the students were able to correctly explain its conceptual calculation approach when presenting their results for this metric.

In terms of the robustness, most user modeling errors resulted in consistent inaccuracies within all reported metrics, with exception to point-in-time illuminance simulations. All errors that affected the RE of daylight factor results also affected mean daylight autonomy and spatial daylight autonomy. On the other hand, only important modeling mistakes that affected direct sunlight affected considerably more mean DA than DF_{MEAN} and SDA. This seems reasonable since SDA would only be affected if the sensor points do not meet the 300 lux threshold and will not be affected by how far the threshold is surpassed. Also, we must consider that DF is a metric that considers and overcast sky, thus it is independent of orientation.

In contrast, even very small modeling errors (i.e. 6 degrees of error in orientation) can result in dramatically relative error for the point-in-time illuminance. This speaks to the lack of robustness of such type of metrics and it is worrisome considering that this type of metrics are still widely used by institutions world-wide

In this space an 8 min difference resulted in direct sunlight hitting the first sensor point and jumping from about 3,000 lux to above 20,000 lux.

Additionally, the point-in-time metric reported that only 37.4% of the space area is classified as daylit space in contrast to a 57% of the space area when using SDA300|50. Even when eliminating the over lit area requirement for the point-in-time illuminance (it is a known shortcoming of SDA that it has no upper illuminance threshold), the point-in-time illuminance still reported only a 38.8% of compliant area, that is still a 46% less area than SDA300|50.

Authors conclude that point-in-time illuminance should be categorized as a weak and unstable metric and should not be used to evaluate the daylight performance of a space. This is especially true in the design of new spaces were many variables are still unknowns and might cause important miscalculations.

Although spatial daylight autonomy is a bidimentional metric that combines time and space, it seemed to be the metric that was better understood by the students. As seen in figure 8, the metric presented the second lowest mean relative error (RE_{MEAN} 0.28) for the sample and the lowest interquartile range (IQR 0.22). Authors do suggest the metric be calculated considering automated shading devices (blinds) or complex fenestration systems to accurately account for potential overlit areas.

Remaining User Errors

An interesting finding was the amount of time that most students dedicated this time around to model every geometric detail of the space, as compared to 2005 and 2006 (in this previous work geometric inaccuracy was surprisingly high). Most interesting is the fact that the most detailed models were not the ones that resulted in more accurate results. In fact, models #2, #3 and #4 which presented the highest under-prediction of spatial daylight autonomy had very detailed geometries but presented errors such as, glazing with double surfaces or sensor grids which extended beyond the illuminated room. On the other extreme, the model that presented the highest over prediction of spatial daylight autonomy (model #17), was the one with the most geometric over-simplification, by for example having a rectangular window head-height, and not considering the catwalk and nor the door head between the two room (figure 9). This reinstates the value of the proposed modeling guidelines; students who paid attention to all steps equally obtained more accurate results than those that only were diligent with space geometries.

In terms of radiance parameters, a parametric sensitivity analysis showed that at least an ambient bounce (ab) of 4 should be used as higher values present no significant improvement for the analyzed scene. And tent to duplicate simulation time. On the other hand, a value of 1000 ambient division (ad) proved to be sufficient when calculating mean illuminance or SDA. However, values as high as 2000 were required in some cases if the objective was to calibrate to measured horizontal illuminance in sensor points close to the façade.

Rules of Thumb Comparison for Model Validation

The teaching approach used for this course started by asking students to compare their simulated results with their measurements of the same space. This approach might present obvious limitations for daylight modeling in new constructions where no physical space can be measure during design phase.

Figure 5 shows the strong correlation in the models along the different daylight metrics. Results show a very high correlation of 0.93 between the daylight factor sample and mean daylight autonomy. This validates the step 5 of the proposed modeling guidelines, which recommends performing simple rule of thumb calculations and compare results against a simple daylight factor calculation to confirm the validity of your model.

The authors would encourage modelers in that situation to perform simple rules of thumb calculations to be used to validate their models. The effectiveness of the Modified Lynes formula (Lynes 1979; Reinhart and LoVerso 2010) to quickly predict daylight factor calculations in a space was reinstated when revisiting the precedent study. When using the Modified Lynes formula to predict the daylight factor for room 10.488 and 10.489 the resulting value is 2.43% DFmean. This results on a RE-DFmean of 0.29, which is almost identical to the mean relative error of all students for daylight factor simulations. This step proves to have sufficient accuracy to allow novices to validate their models before performing more complex or weather dependent metrics. Thus the authors have included it as a fundamental step for any daylight modeling exercise.

$$DF = \frac{A_{glazing}\, T_{vis}\, \theta}{A_{total}\, 2(1 - R^2_{mean})}$$

(Equation 3)

Where:
DF = mean daylight factor
Aglazing = total glazing area (m2)
Atotal = total area of all interior surfaces including windows (m2)
Rmean = area weighted mean surface reflectances of all interior surfaces (0... 1)
Tvis = visual transmittance of the glazing (0… 1)
θ = unobstructed sky angle (in degrees)

CONCLUSION

The implementation of a proposed teaching toolkit that addressed daylight modeling in smaller incremental steps was highly successful. The teaching approach with its proposed modeling guidelines resulted in important improvements in simulation novices' accuracy. When compared with previous studies, 24% percent of 2011 novices were able to predict daylight factors within a relative error of 0.25 compared to 0% in 2005 and 14% in 2006. More importantly, 88% of 2011 students had a RE of less 0.5 compared to only a 5% and a 22% in 2005 and 2006 respectively.

The detail analysis of user errors along different daylight metrics concluded that point-in-time illuminance are most brittle and are highly affected by small simulation mistakes and modelers should move to more robust annual metrics. The analysis also proved that comparing simple daylight factor simulations results to simple rules-of-thumb calculations is highly recommendable for novices to check the validity of their models. For the studied space, rules of thumb calculations resulted in roughly the same relative error than daylight factor simulations when compared to the reference case (RE 0.29 and 0.30 respectively).

Finally, the study concluded that most diligent students who spent exponentially more effort in creating the 3D model of the space did not result in most accurate results. Those students that paid attention to the whole simulation process where the ones with higher simulation accuracies. This reinstates the value of proving modeling novices with a daylight simulation checklist that guides them throughout the process.

ACKNOWLEDGEMENT

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APPENDIX A

See next page.

Appendix A. Daylight Modeling Checklist *(Ibarra and Reinhart)*

Before you start	Did you decide which daylighting performance metrics to simulate and how to interpret the results?	☐
	Do you have a general idea of what the results should look like? e.g. a mean daylight factor in a standard sidelit space should typically lie between 2% and 5%; interior illuminance typically lie between 100 lux and 3000 lux and daylight autonomies typically range from 30% to 90% throughout the space.	☐
	Have you verified that the simulation program that you intend to use has been validated for the purpose that you intend to use it for? i.e. that the simulation engine produces reliable results *and* that the program supports the sky models related to your performance metric of choice. (An example would be the old CIE overcast sky for daylight factor calculations.)	☐
	Have you secured credible climate data for your building site? (This is only required for climate-based daylighting performance metrics.)	☐
	Have you performed rules-of-thumb calculations of simple daylight metrics to later validate the integrity of your simulation model? i.e. Before you run complex daylight metrics, such as daylight autonomy, consider comparing simulated average daylight factor to the average daylight factor calculated using the modified Lynes Formula (Reinhart and LoVerso 2010).	☐
Preparing the scene	Did you model all significant neighboring obstructions such as adjacent buildings and trees?	☐
	Did you model the ground plane?	☐
	Did you model wall thicknesses, interior partitions, hanging ceilings and larger pieces of furniture? Try to model overall space dimensions at least within a 10cm tolerance. Façade details part of window assemblies should be modeled with a 2cm tolerance. Special attention should be set on modeling window geometries and window-head-heights.	☐
	Did you consider window frames and mullions by either modeling them geometrically or by using reduced visual transmittances for windows and skylights?	☐
	Window glazings: - Did you check that all window glazings only consist of one surface? Several CAD tools model double/triple glazings as two/three closely spaced parallel surfaces whereas daylight simulation programs tend to assign the optical properties of multiple glazing to a single surface.	☐
	- Did you check that all windows are ’inserted’ into the wall planes and not "overlaid" on the wall surfaces? Several CAD tools suggest that you can create and visualize a window in many different ways, one simply being the placement of a window surface on top of a wall surface which case end up with two coplanar surfaces. As a result the simulation program will either ignore the window or somehow ‘guess’ which surface to consider.	☐
	Did you assign meaningful material properties to all scene components? Typical surface values might range from: interior walls 50-60%, ceilings 50-80%, shiny floors 50-70, carpet 4-15, exterior ground 20% and exterior facades of surrounding buildings 20-40%.	☐
	Did you model any movable shading devices such as venetian blinds? If yes, do the results make sense? Do any of the model assumptions need to revisited?	☐
Setting up the simulation	Make sure that you set up your project files correctly. This may involve: - Checking that your project directory and file names do not contain any blanks (“ ”). - Verifying that all sensors have the correct orientation, i.e. work plane sensors are facing up and ceiling sensors are facing down. - Setting the resolution of the work plane to 0.5m x 0.5m or 1ft x 1ft and placing it around 0.85m above the floor. - Selecting the correct sky model (CIE, Perez, etc.). - Selecting simulation parameters that correspond to the ‘scene complexity’. To do so you should consult the technical manual of your simulation program. - Comparing initial simulation results of simple daylight metrics against hand-calculations to check the integrity of the model before analyzing the daylight performance of different design variants.	☐
* For a scene of low complexity (typical sidelit space with a standard window and no complex shading devices) use the following recommended Radiance simulation parameters: ab= 4; ad =1500; ar=100, as=20; aa = 0.1; av=0 0 0. Sensitivity analyses have demosntrated that higher radiance parameters for this type of scene will considerably increase run-time without relevant benefits in simulation accuracy.		