A New Tool and Calculation Methodology for BIM-integrated Rapid Daylight Simulation *(Preliminary Draft for ASHRAE Energy Modeling Conference)*

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1.0 Executive Summary

In light of integrating building information modeling (BIM) with daylight simulation, the industry needs validation studies to help determine the accuracy of the newer, faster calculation engines developed for this type of application. Additionally, this new field of simulation tools need workflow studies to analyze the tradeoff between simplifying simulation inputs and quality control, and the difference between traditional and BIM-oriented geometry modeling tendencies. This research focuses on the new Lighting Analysis for Revit (LAR) daylight simulation tool and conducts validation tests using the National Resource Council (NRC) of Canada's Daylighting Laboratory empirical dataset. The methodology follows the Reinhart and Breton 2009 study on validating the 3ds Max daylighting engine against Daysim 3.0 in conjunction with the measured NRC dataset. Mean Bias Error (MBE) and Root Mean Squared Error (RMSE) were used as the two main metrics of validation. Given the lack of agreed upon MBE or RMSE values that constitute a "validated" software, the literature review found that targets +/-10% MBE and below 32% RMSE were generally deemed acceptable by the simulation community.

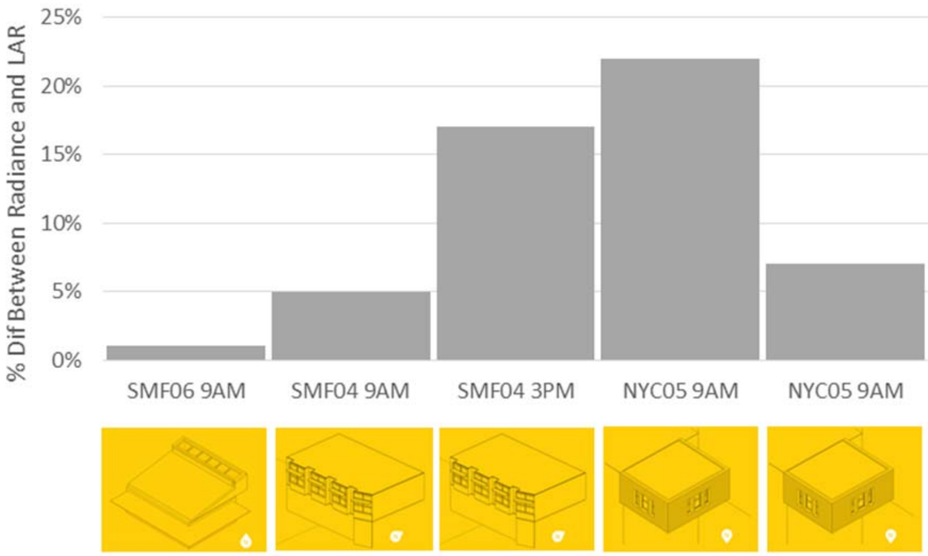
Simulations were conducted and compared against the NRC dataset for a simple, clear glazing condition over a period of 12 days at 5 minute timesteps. Looking at an average of front and back sensors of the NRC Daylighting Laboratory space, LAR's MBE totaled 11% for the front sensor average and -9% for the back sensor average (in comparison to -9% and -4% for Daysim, respectively). These numbers fall right around the MBE threshold for "validation." For the RMSE statistical analysis, the LAR simulations produced a 29% RMSE value for the back sensor average, and 47% for the front sensor average. The back sensors landed within the 32% RMSE, but the front sensors are a bit out of range. This may be due to the slight timeshifts when sensors are in direct sunlight between the measured and simulated data. This type of effect will create a high RMSE, but is inconsequential when determining the daylight quantity in a space. RMSE values were clipped to 100% to make the analysis less sensitive to this effect, but it may still be influencing the high RMSE value for the front sensors. See Table 1 below for a summary of the validation stats, which generally meet validation criteria for this particular NRC test case.

Table 1 - MBE and RMSE Results for LAR and Daysim (Compared Against Measured NRC Data)

Sensor Location	LAR		Daysim (Reinhart and Breton 2009)		3ds Max (Reinhart and Breton 2009)	
	MBE	RMSE	MBE	RMSE	MBE	RMSE
Front	11%	47%	-11%	31%	11%	28%
Back	-9%	29%	-4%	24%	6%	29%

For the workflow studies, this research analyzed the effect of window and wall detail, interior surface reflectance combinations, and exterior context detail on the amount of daylight in various spaces. The study also analyzed three different models that represented actual spaces from the California Energy Commission Public Interest Energy Research (PIER) program to understand how the software performed in more complex spatial configurations. The models range from single to triple sided glazing, spaces with skylights, windows with deep overhangs, etc. Both Radiance and LAR simulations were run in parallel, and the percent of area above 500 lux was used as the main comparison metric. This type of metric reflects more how practitioners would use the tool to determine if a space was adequately daylit or not. Figure 1 shows that between the three models and 5 different conditions (some were ran for two different timeframes), the percent difference between the two programs were relatively small (<10). However, the two conditions that produced the slightly larger differences do not have any direct sun inside the space. Either way, the values are still generally acceptable for most conditions.

Figure 1 - Real World Model Comparisons (Radiance vs. LAR)



Finally, the workflow studies found that modeling complexity from BIM workflows can have large effects on daylighting. For instance, depending on window and wall thickness modeling detail, area thresholds above 500 lux ranged from 48% to 93% for non-direct sun conditions, and from 74% to 83% for direct sun conditions with the LAR software. This type of finding suggests that careful consideration should be taken when determining the level of detail for facades, and how this compares to more typical "eggshell" modeling of envelopes for typical 3rd party daylighting analysis program workflows. Generally, the parallel Radiance and LAR simulations showed good agreement and similar ranges of sensitivity for the three workflow studies conducted in this research.

2.0 Introduction

Moving away from providing daylight simulation as a specialty service and into ubiquitous usage requires careful synergy between workflow and tool functionality. Innovation begins with a transition from the traditional simulation process of parallel geometry modeling to BIM-integrated simulation. Such tools must be fast, easy to use, and flexible to handle early conceptual modeling with limited inputs to more detailed analysis in highly developed building information models.

This paper summarizes a new tool developed and validated for rapid daylight simulation directly within the Revit environment known as Lighting Analysis for Revit (LAR). LAR's simulation engine uses a new calculation method called Multidimensional Lightcuts, based on initial research by the Cornell Lighting Lab, which significantly reduces the time and complexity needed to accomplish scalable and consistent illuminance calculations. The engine gets its speed from discretizing the integrals used in previous optimization methods such as supersampling, and instead adaptively approximates the sum of gather and light pair interactions with implicit hierarchies. Given this speed of calculation, the determination of accuracy is paramount to establishing confidence in the tool for practitioners. Thus, the paper documents a validation methodology based on a previous study by Reinhart and Breton on validating the 3ds Max daylighting engine against both Radiance and measured data from the National Research Council of Canada. Statistical metrics such as Mean Biased Error (MBE) and Root Squared Mean Error (RSME) are calculated for LAR over a period of months across a variety of window conditions. The study then compares these values to the Radiance and 3ds Max results to understand LAR's relative performance against its peers.

In addition to the analytical validation, workflow validation was also a critical component of this research. While the integration of analysis into the BIM environment solves a host of logistical problems, this environment introduces additional complexity into the simulation process that can be difficult to manage. Workflow validation efforts involved identifying these conflicts and quantifying their effect with a series of sensitivity studies that ranged from varying levels of envelope detail, the effect of external context, and surface reflectance combinations.

3.0 Literature Review

Unlike energy modeling, daylight simulation does not have one validation standard that has achieved widespread acceptance amongst the simulation community. For instance, LEED has a list of approved energy modeling software for credit compliance, but does not provide a similar list of approved daylight simulation software for complying with its daylighting credit. For energy and daylight simulation, there are methods to validate software based on idealized (calculated) and/or realistic (empirical measured) conditions. The former being more widely used as a standard of accuracy and confidence for energy modeling, while the latter has been more widely used for daylight simulation validation. Validation for idealized conditions for energy modeling references the ASHRAE Standard 140 and BESTEST (building energy simulation test) analysis cases. The reference provides a blueprint to create a model according to BESTEST protocols, and simulation results are then compared to known numerical solutions (Reeves and Olbina 2012).

A similar standard is gaining momentum in the daylight simulation community, CIE 171:2006, although it has not gained widespread acceptance and integration into certification standards like ASHRAE 140 and BESTEST. Historically, comparing lighting simulation results to published measured data has been the primary method of validation. A discussion of what these data sets are and the studies that followed are included later in this literature review. The alternative to using empirical data sets for daylight validation is to develop a series of test cases with known analytic solutions, such as with the BESTEST model for energy simulation. CIE 171 is such suite of sample lighting scenes with calculated numerical solutions based on radiative flux transfer theory. Simulated results are compared with the accepted solutions and if the values fall within an “acceptable” upper and lower error limit, the results are considered “validated.” These values differ depending on the test case, and can range between 6.7% AND 17.2% for each sensor (DDCI 2007). The ultimate designation of “validation” is still a judgement call, however, and there are no clear “pass/fail” guidelines per case or how many cases a software needs to “pass” to be considered “validated.”.

The CIE 171 standard has been met with some trepidation by the simulation community. Its approach of testing the different aspects of light propagation separately is useful in determining optimized rendering parameters for radiosity-based approaches, given that its test were mostly derived from radiative flux transfer theory. However, it may not be as useful in determining accuracy under more realistic test conditions and for software that uses ray tracing as its primary engine. Additionally, the AGI32 software published a full validation study using the CIE 171:2006 standard, and found issues that would suggest that some of the tests were incorrect and based on invalid assumptions (DDCI 2007).

The other method of daylight simulation validation has been to compare simulated outputs to a variety of available empirical datasets collected by various research institutions. This method has been used more often historically, and continues to be a primary method despite the release of CIE 171:2006. Despite the availability of such data sets, there still does not exist a standard or common reference that dictates how high or low accuracy metrics such as relative mean bias error (MBE) and relative root mean square error (RMSE) should be to determine a software “validated.” These two metrics represent the most consistent metrics used to determine “accuracy” and represent statistics that characterize similarities and differences between two data sets. The relative MBE shows how much larger or smaller one data series is in relationship to another, but negative vs positive errors can offset one another. Meanwhile, RMSE describes how far one data series fluctuates around the other and takes into account penalties from offsetting errors by squaring values. The error values and ranges found throughout the studies explored in this literature review will help inform the error targets of this research paper.

The BRE-IDMP dataset was created when the Commission International de l’Esclairage (CIE) organized the International Daylight Measurement Programme (IDMP). The program collected a wide series of daylight data for a range of daylight parameters including “research class” measurements of actual sky brightness distributions together with integrated quantities (Mardaljevic 2000). These data, combined with measured daylight values from over 15 monitoring stations and test sites all over the world, can be used to test simulation programs outputs against actual data. The Building Research Establishments (BRE) in Garston, UK, is among the most widely used datasets by a variety of different researchers. Among them including John Mardalijevic, who published a series of important papers on Radiance validation between 1995 and 2000 that used this dataset for their validation studies. One such study found an MBE range of -3%-12% for a range of clear glazing studies, with an RMSE between 11%-20% (Mardaljevic 1997).

Another more recent dataset exists for lighting simulation validation from the National Resource Council of Canada (NRC). The NRC published data collected from its Daylighting Laboratory in Ottawa Canada, which consists of measured indoor and outdoor illuminances as well as direct and diffuse outdoor irradiances for a variety of daylight test cases in a small office room setup. These cases cover five different window and blinds configurations, including a translucent window test case (Reinhart and Breton 2008). Christoph Reinhart and Pierre Felix Breton used this data set to validate the 3ds Max daylight simulation engine against Daysim and the measured data. The team found a range of MBEs for Daysim that ranged mostly between -11% to 12%, with one value hitting -31% error for internal blinds near the window. The 3ds Max engine performed similarly with MBE ranges between -12% to 11%, with large error ranges of up to 28% for external blind and translucent panel cases. RMSE values for Daysim were 34% and below, while the 3ds Max engine's values ranged from 49% and below for higher complexity cases and below 31% for lower complexity cases including the translucent panel.

A 2006 study on validating a translucent panel material for Radiance specifically also used the NRC dataset. Looking at 2 of the 16 potential sensors from the Daylighting Laboratory test room, the study found a MBE of 3.5% for the workplane sensor and 8.9% for a ceiling sensor. RMSE values were also low at 14.3% for the workplane sensor and 18.6% for the ceiling sensor. The same study looked at 5 different indoor illuminance sensors and found that errors ranged from 0-9% MBE and 14-19% RMSE (Reinhart and Anderson 2006).

The wide range of validation studies provide a spectrum of judgement calls that attempt to define what the "acceptable" range of MBE and RMSE values should be. For the purpose of this study, MBEs of less than 10% are ideal, but a range of up to 20% will still be deemed "valid." On the RMSE side, error values up to 25% will be the target, but ranges up to 32% are still acceptable, especially for ceiling-based sensor which tend to have a higher error margin (Reinhart and Anderson 2006).

4.0 Engine Validation

4.1 Description of LAR Simulation Engine

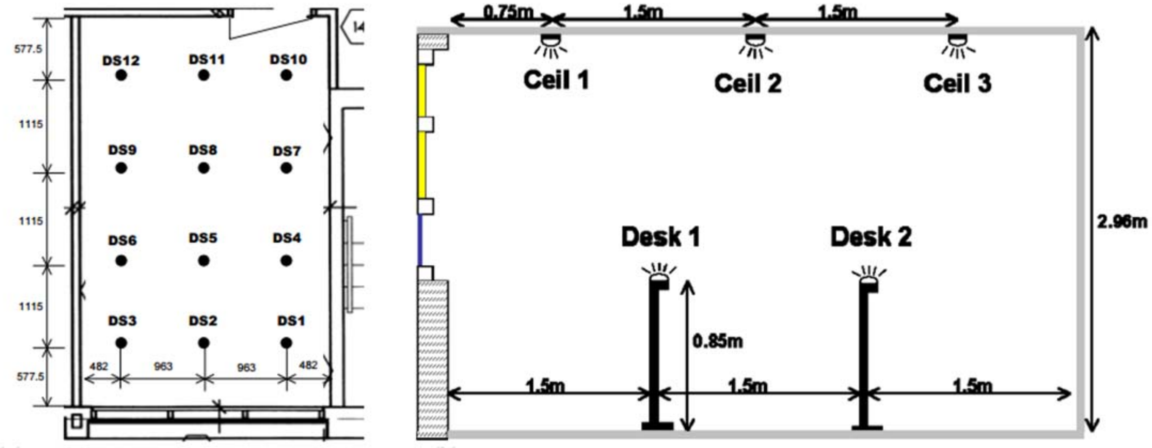
The LAR simulation engine that is the subject of this paper uses a method called Multidimensional Lightcuts based on initial research by the Cornell Program of Computer Graphics. The advances in the algorithm is responsible for the speed at which daylight analysis can be done in Revit, which is a key innovation that allows BIM-integrated simulation. The algorithm significantly reduces the time and complexity needed to accomplish scalable, consistent physically accurate rendering of illuminance data in an analysis domain. The method is particularly well-suited for use in a tool like Revit where easy, reliable results are preferred over manual calibration of the engine. The Lightcuts based engine can automatically produce consistent results and quality on even large, real-world models.

Multidimensional Lightcuts discretizes the integrals required to compute the illuminance by evaluating many point samples in the domain. Though all physical rendering simulations use some discretization, MDLC is different because it does some of its discretization as a fixed preprocess. This makes many of its points samples are static so it can build data structures that accelerate computation. In particular it uses error bounding trees to identify the small set of points samples required to accurately calculate the illuminance at each sensor. Compared to the random selection of points samples in other state of the art simulation tools, this can provide an order of magnitude speedup with the same levels of error. The error bounded nature of the algorithm also ensures that the process adapts automatically to the users model; increasing accuracy automatically in large and difficult-to-compute cases. This ensures consistency and accuracy across the wide range of scales and model conditions submitted by users.

4.2 Validation Methodology

This study choose to utilize the NRC data set and follow the Christoph and Breton methodology from their 2009 study on validating 3ds Max to determine how LAR compares to both Daysim 3.0 and the measured NRC dataset. The NRC's test case measurements came from the east room of the NRC Daylighting Laboratory, a roughly 9' wide, 15' deep room with a window to wall area ratio of 58%. Figure 2 shows a layout of the Licor illuminance sensors placed throughout the space. The NRC data set contains a host of information for 5 different window configurations of increasing complexity. The first test case (TC1) is a clear glazing condition, while TC2 utilizes a diffuse lightshelf, TC3 is all diffuse glazing, TC4 uses external blinds, and finally TC5 uses internal venetian blinds. This paper replicates the study for LAR using only TC1; future papers will include TC2-5. For more information on the NRC space, refer to the Christoph and Breton report, which is freely available online (http://download.autodesk.com/us/3dsmaxdesign/B3241.MentalRayValidation_v3.pdf).

Figure 2 - NRC Daylighting Loaboratory Layout and Sensor Locations



4.3 Simulation Inputs

Simulation efforts focused on trying to replicate the NRC physical space as closely as possible while ensuring material specifications matched the Reinhart and Breton paper's assumptions. An existing 3ds Max model of the laboratory space was imported into Revit as a .dxf skeleton and remodeled. Next, material parameters were applied following the specifications in Appendix Item A. Appendix Item B serves as a quality control checklist that lists material specification surface-by-surface within the model between the Radiance and LAR inputs.

4.4 Process

The NRC dataset contains simulation data from 5/12 to 5/24 on five minute timesteps. To replicate this data in LAR, the Diffuse Horizontal Irradiance (DHI) and Direct Normal Irradiance (DNI) values were extracted from the measured NRC data. Dyanmo was used to automate the simulation of the 3500+ timesteps, given that running LAR directly within Revit can only simulate two timesteps per run. The coordinated DNI and DHI pairs were fed into the Dynamo/LAR simulation using LAR's Perez sky model, which matched the sky model for the Daysim and 3ds Max simulations.

4.5 Results

The following MBE and RMSE tables describe the performance of Daysim, 3ds Max, and LAR against the measured NRC data set. The Daysim and 3ds Max values were taken directly from the Reinhart and Breton paper, and much care was taken to filter the data in similar ways to ensure proper comparison. For instance, to keep consistent with the earlier paper's methodology, measurements were only considered for the error analysis if the measured façade illuminance was above 5000 lux. This value removes the known issues with the Perez sky model surrounding its sensitivity to measurement uncertainties of direct irradiance during low sun angles around sunrise and sunset (Reinhart and Breton

2009). Additionally, due to the large RMSE errors that result from small shifts in time as sensors move in and out of direct sunlight at slightly different times, error values were "clipped" at 100% to replicate the Reinhart and Breton methodology.

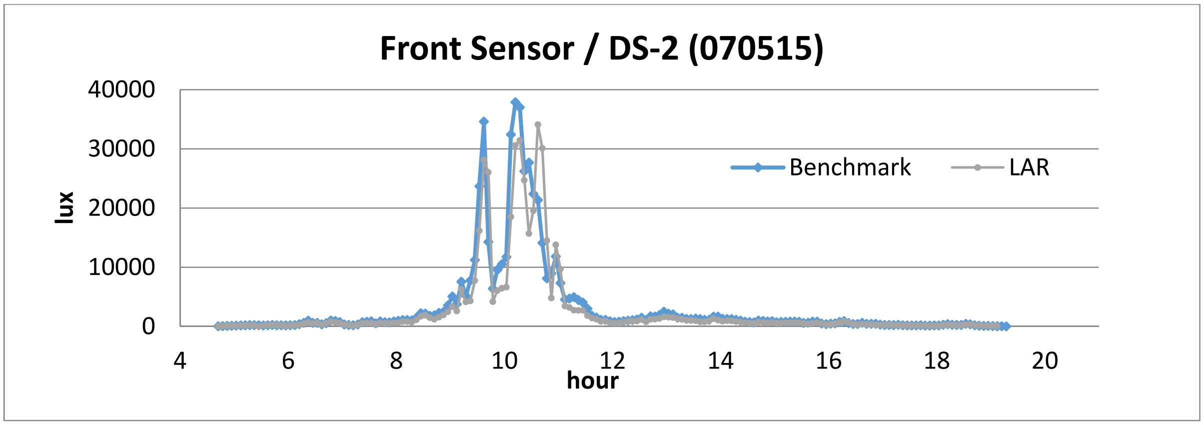
Table 2 shows that the MBE values for the front sensors totaled 11.4%, with the back sensor values landing at -9%. For reference, the "front" sensors represent the average of the front three sensors, labeled DS1-3 in Figure 2. Likewise, the "back" sensors represent the average of sensors DS10-12. These values are very close to the ideal 10% MBE error target discussed in the literature review section of this paper, and are well within the 20% upper threshold. The RMSE results for the back sensors fall within the 32% limit, but the front sensors lie slightly outside the threshold at 47%. Overall, the values come close to the Radiance values, respectively, with the RMSE for the front sensors being the only "out of bounds" value based on previous validation studies. Future studies will also look at MBE and RMSE metrics for outside sensor values and ceiling sensor averages.

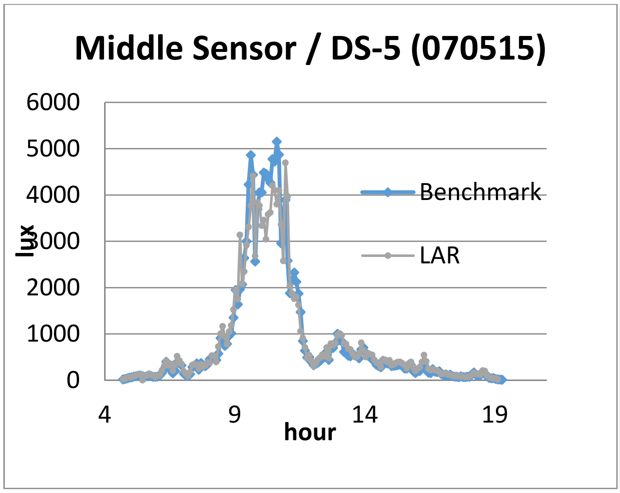
Table 2 - MBE and RMSE Results for LAR, Daysim and 3ds Max (Compared Against Measured NRC Data)

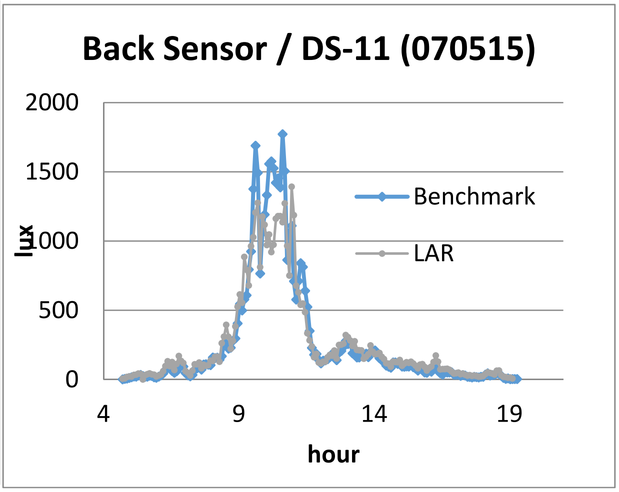
Sensor Location	LAR		Daysim (Reinhart and Breton 2009)		3ds Max (Reinhart and Breton 2009)	
	MBE	RMSE	MBE	RMSE	MBE	RMSE
Front	11%	47%	-11%	31%	11%	28%
Back	-9%	29%	-4%	24%	6%	29%

Figure 3 shows some daily illuminance plots for both the measured data (Benchmark) and LAR results for a random sunny day within the simulated data set. The three graphs represent the center sensor in the front row, the front middle row, and the back row of the space. The graphs show there is generally good agreement between the measured and LAR data, although the small differences get slightly larger as you move farther back in the space. Additionally, the front sensor shows a slight shift in direct sun spikes, which might account for some of the high RMSE errors, even though they are clipped to a maximum 100% error.

Figure 3 - LAR Daily Illuminance Plots - 3 Sensors







4.6 Conclusion

LAR performs well under 3 of the 4 statistical analysis used for this validation research. LAR's MBE analysis hits the accuracy targets discussed in the literature review section of this paper for both the front and back sensors. Its MBE values of 11% for the front sensor and -9% for the back sensors are very close to the ideal 10% MBE target, noting that acceptable upper values of 15 and 20% were observed in other research. The 11% MBE for the front sensor matches the magnitude error of Radiance, although it is a positive versus Radiance's negative 11% error. While the back sensor average is -9% versus Radiances -4%, both programs show an under-prediction for this part of the space.

LAR's back sensor performs just under the RMSE 32% target established by Reinhart and Breton's 3ds Max paper with an RMSE of 29%. The front sensor falls out of range at 47%, but this could be due to the over-sensitivity of the front sensors to slight time shifts of direct sun. The 100% clipped RMSE upper threshold helps to solve this issue, but still penalizes the analysis according to this effect. Further analysis is needed to identify the root cause of the time shift errors, or to determine a better way to handle the error statistically. As practitioners, error due to minute time shifts is not a large issue, but the problem exacerbates validation metrics like RMSE.

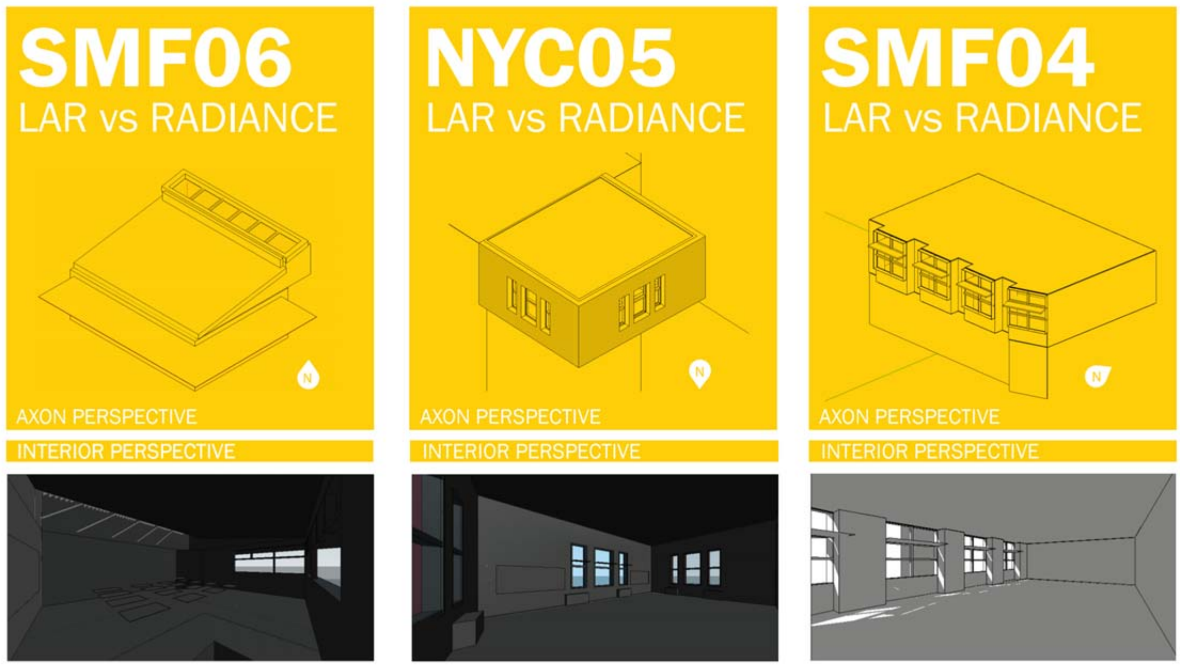
5.0 Workflow Validation

Integrating simulation into building information modeling solves a lot of logistical challenges associated with traditional energy and daylight analysis, primarily the need for separate geometry modeling in a 3rd party program with a broken feedback loop. However, as tools aim to reduce the complexity and number of inputs to achieve robust simulation, the ability to get a wrong answer quicker also becomes a new problem to solve. Additionally, building a daylight or energy model from scratch within a 3rd party analysis program provides a clear chance to simplify geometry. This is in stark contrast to dealing with the complexity of pursuing simulation studies within a fully-developed BIM model. Given these challenges, another goal of this research included using LAR to analyze daylight conditions of "real world" spaces, and to determine variability associated with common BIM-oriented modeling workflows. LAR simulations were run in parallel with Radiance and percent differences were reported for studies that focused on varying levels of interior reflectance, level of glazing detail and thickness, and the effect of exterior context.

5.1 Real World Models

A lot of validation lab models utilize simple spaces that are easy to control, model, and replicate in simulation studies. Part of this research aimed to use LAR on more detailed and varied spatial conditions that are more typical in practice. Additionally, floorplan percentage above 30 or 50 footcandles was used as the main metric to understand differences between LAR and Radiance. Scatter plots and distributions are also included to visualize grid and cross sectional illuminance data. The hope is that these types of comparisons are more aligned to what practitioners would look at to determine if a space is "well daylit." This type of metric can be more useful in cultivating confidence from practitioners than the more statistics-oriented MBE and RMSE analyses. Figure 4 shows snapshots of models that were provided by TLC Energy Services (former Heschong Mahone Group Inc.) and were part of the California Energy Commission Public Interest Energy Research (PIER) program. TLC provided Ecotect models that were created based upon the actual space, which were then translated into Revit models with the same material reflectance and glazing parameters.

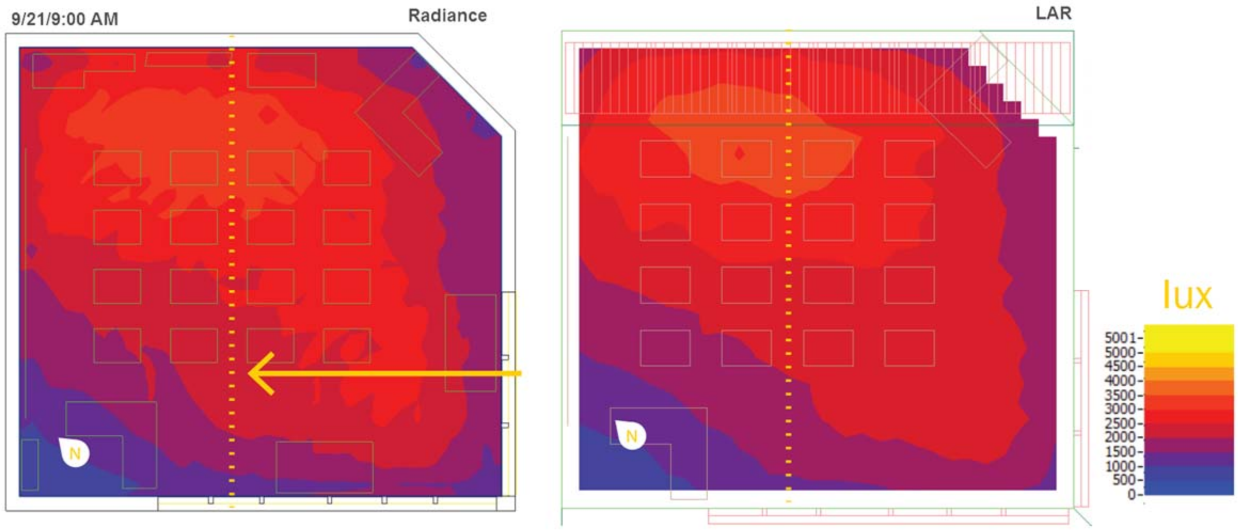
Figure 4 - "Real World" Models from PIER Dataset



5.2 Model SMF06 Results

Model "SMF06" represents a classroom condition with two-sided corner glazing, a clear skylight along the back wall, and a deep shading overhang. Figure 5 below shows the Radiance simulation results (left) and LAR results (right) as an illuminance contour map. For September 21st at 9:00 AM, the percentage of the floorplan that is above 1500 lux totals 89% for Radiance and 90% for LAR. This represents a 1.2% difference in values, and a 1% absolute difference. It is important to note that a 1500 lux threshold was selected to ensure that comparisons found an actual threshold to compare. For instance, if 300 lux was selected as the threshold, calculations would show that both spaces were 100% above 300 lux. Refer to Appendix item D for all of the metrics for SMF06, including a cross section illuminance plot, whisker plot distributions of each data set, and a scatter plot of each sensor value.

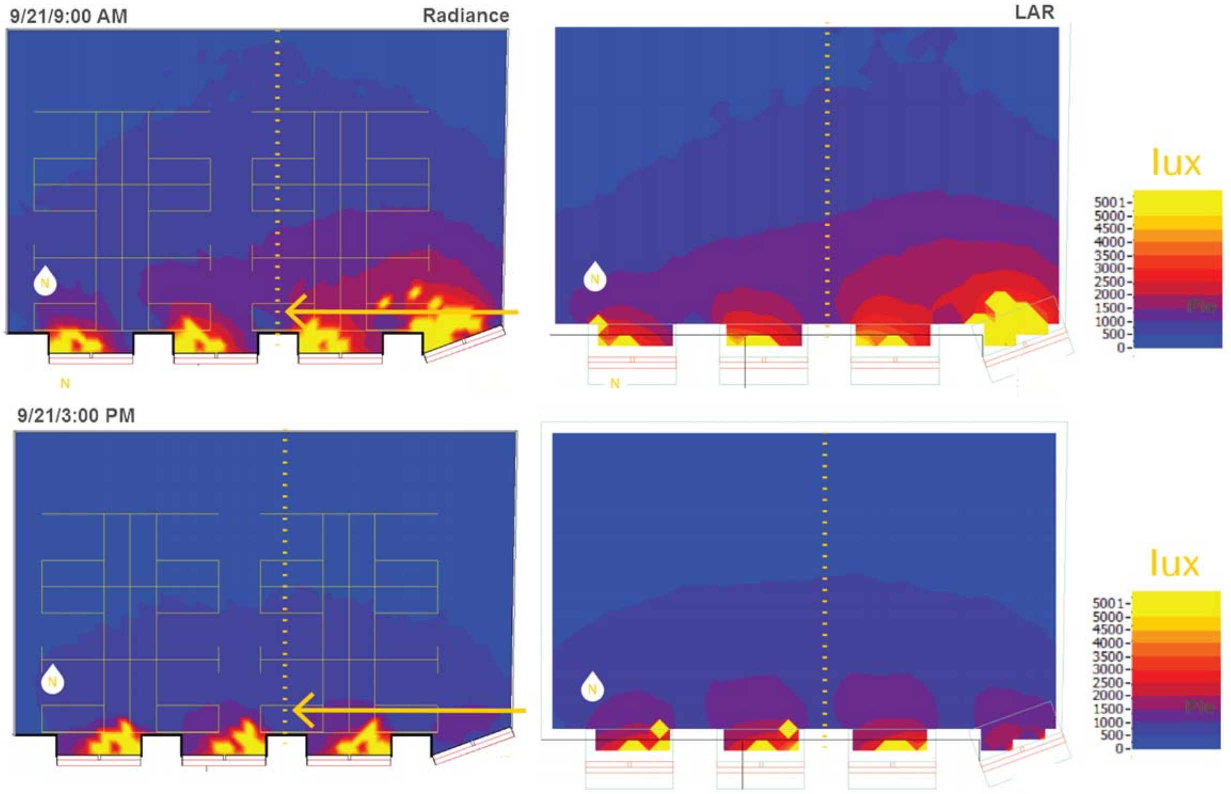
Figure 5 - SMF06 Illuminance Grids



5.3 Model SMF04 Results

Model SMF04 represents an open office condition with single-sided side lighting and a light shelf that extends into a shallow exterior shading device. The shading device divides the glazing into distinct view and daylight sections, with a glass plane that lies fairly deep in a thick wall section. Figure 6 shows the illuminance plots for both Radiance and LAR for the two different timeframes. For September 21st at 9:00 AM, the percentage of the floorplan that is above 500 lux totals 69% for Radiance and 72% for LAR. This represents a 5% difference in values, or a 3% absolute difference (69% - 72% = 3%). For practitioners this amount of error seems more than acceptable. The comparison values for 300 lux, a common LEED determination of daylit vs. non-daylit, are even closer together given the high percentage of daylight in the space. The SMF04 test model was also run for a 3:00 PM case, which represented a condition where the space did not receive direct sunlight. The percentage above 500 lux in this condition drops to 46% for Radiance and 38% for LAR. This represents a 17% difference, or an absolute 8% difference between the two programs. This would suggest that LAR is slightly less accurate for the 500 footcandle thresholds in conditions with only indirect lighting when compared to Radiance, although the overall difference is still fairly low. Refer to Appendix item D for all of the metrics, including a cross section of illuminance data, whisker plots of each data set, and a scatter plot of each sensor value.

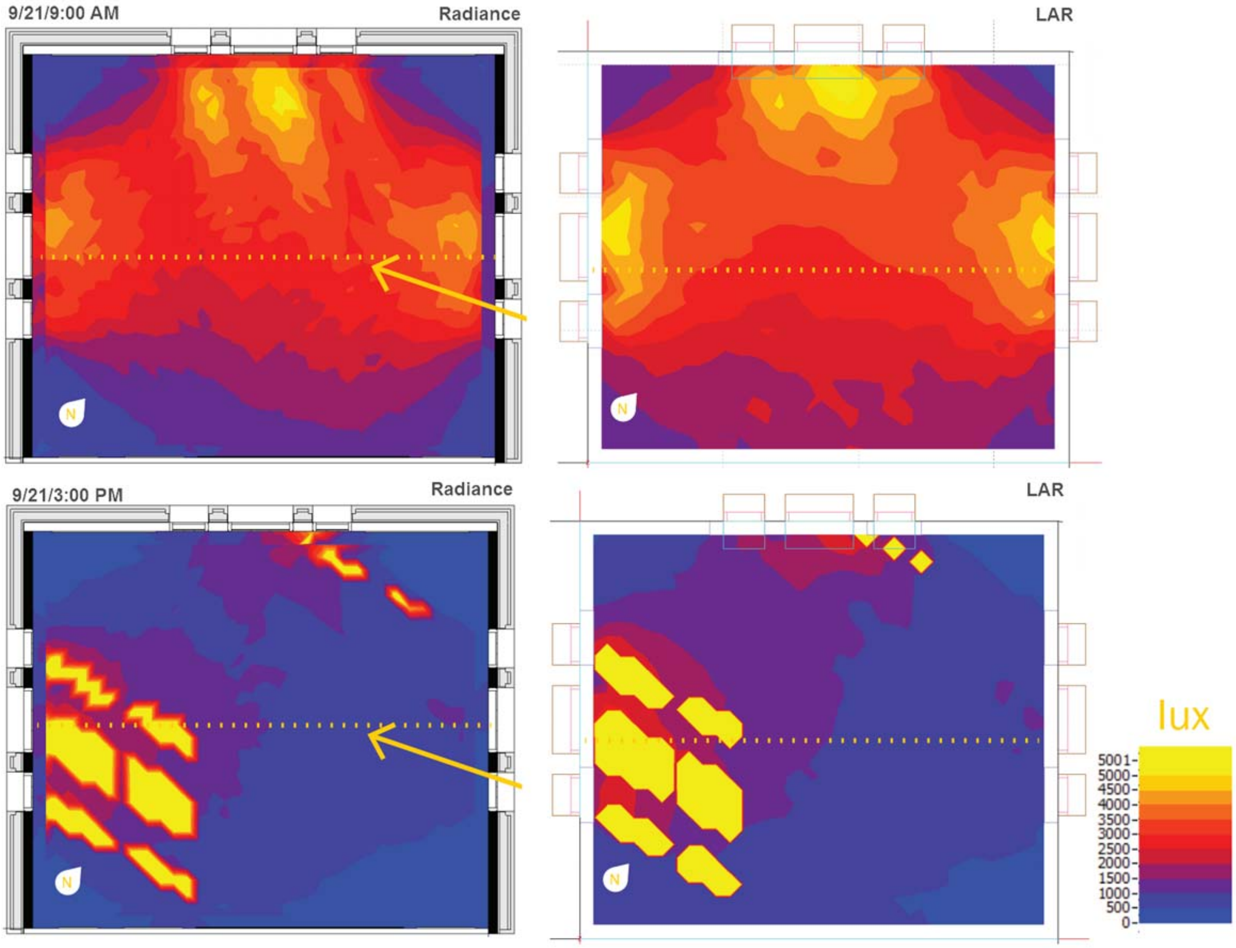
Figure 6 - SMF04 Illuminance Plots



5.4 Model NYC05 Results

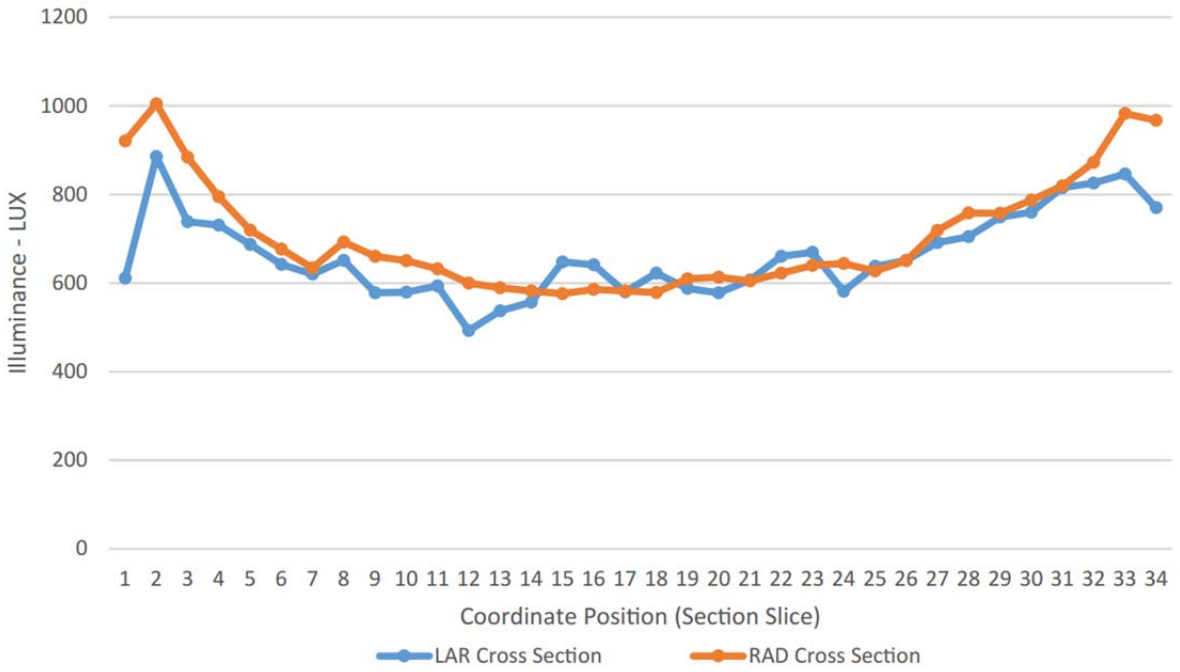
Model "NYC05" represents a small office condition with windows on three different sides set into 2' thick masonry walls. The glazing is clear and does not utilize any type of interior or exterior shading. This model also utilized two different timeframes, 9:00 AM and 3:00 PM, to analyze direct sun and no direct sun conditions. The 9:00 AM condition without any direct sun produces a floorplan whose percent area above 300 lux is 92% with Radiance and 72% with LAR, a difference of 22% or an absolute difference of 20%. On the other hand, at 3:00 PM with direct sun, the percent area above 300 lux totals 93% for Radiance and 87% for LAR, a much closer comparison with a 7% overall difference. Figure 7, below, shows the illuminance plots for these two time frames.

Figure 7- NYC05 Illuminance Plots



The discrepancy would suggest that the combination of deep walls (2' thick) and indirect lighting without direct sun would lead to slightly less accurate predictions when compared to Radiance. This insight is further reinforced by Figure 8, which plots the illuminance data from sensors that represent a cross section of the space runs roughly east to west in the plan, demarcated by the orange dotted line in Figure 7. The graph shows that the edges of the space have the highest error, while throughout the middle of the space the LAR and Radiance values are similar. This effect led the research team to develop a "sensitivity" study that explores the influence of the depth and detail of the façade on accuracy and is covered in the next section of this report. For all the metrics of model NYC05, refer to Appendix Item E for all of the metrics, including a cross section, whisker plots of each data set, and a scatter plot of each sensor value.

Figure 8 - NYC05 Cross Section Illuminance Plot



6.0 Workflow Studies

6.1 Surface Reflectance Workflow Study

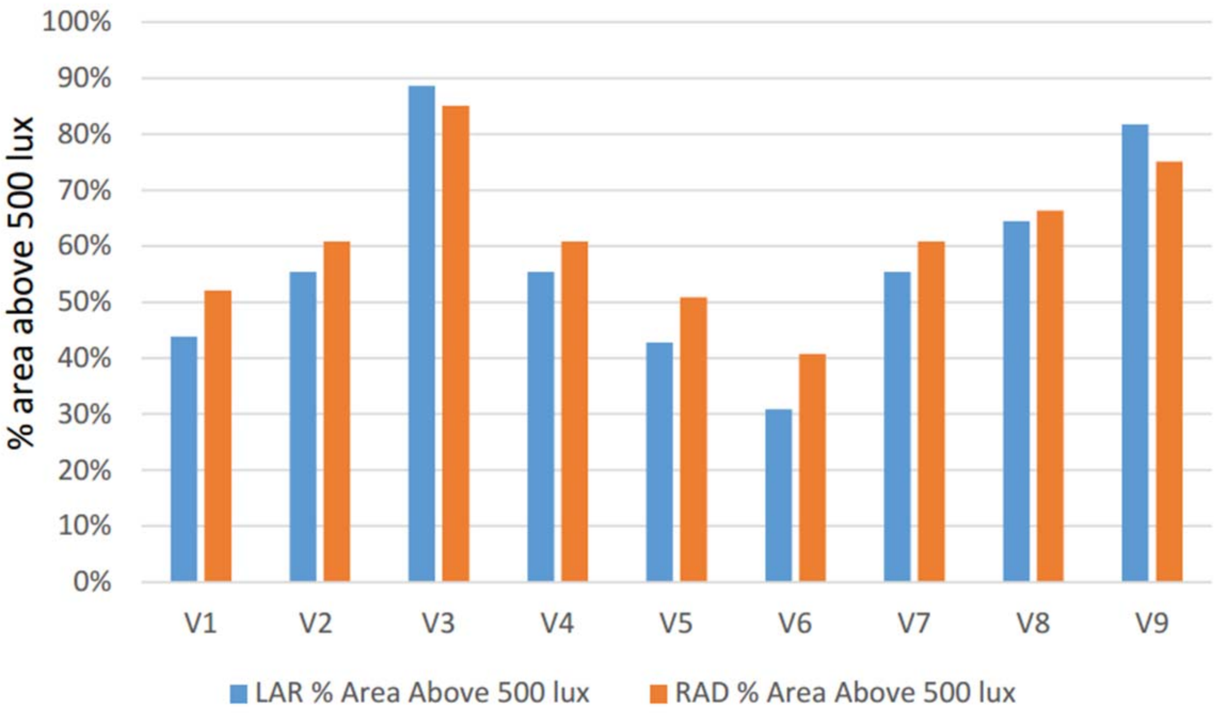
Model SMF04 was utilized to explore the effect of different combinations of wall, roof, and floor reflectance material specification and how it affected daylighting levels between Radiance and LAR. The study helped provide insight into both the difference between the two programs, but also looked at a key workflow aspect of BIM-integrated simulation. Consistent surface reflection specification is harder to control in the BIM environment, especially if walls are complex and multiple wall types exist in a large project. Given that LAR's surface reflectance input is tied to the RGB values of the "Appearance" material property, most materials will have a value associated with it even if the material is not "specified" for the daylight simulation. Further still, this specification may not align with the typical 80% reflectance for roofs, 60% for walls, 30% for floors, etc. This makes QAQC for material input critical in ensuring accuracy. This workflow study looks at a variety of combinations of different roof, wall, and floor reflectances to understand the magnitude of impact within and between reflectance specifications and between LAR and Radiance simulation software. Table 3 below shows the nine different simulation runs and highlights which component's parameter was changed.

Table 3 - Simulation Key for Surface Reflectance Study on Model SMF04

	V1	V2	V3	V4	V5	V6	V7	V8	V9
Wall Refl.	0.4	0.6	0.8	0.6	0.6	0.6	0.6	0.6	0.6
Ceiling Refl.	0.8	0.8	0.8	0.8	0.6	0.4	0.8	0.8	0.8
Floor Refl.	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.5

Figure 8 below shows the Radiance vs. LAR percent area thresholds over 500 lux for the space, and can lead to different insights about accuracy and sensitivity. For instance, looking at the overall change for LAR between V1 and V2 speaks to the magnitude of difference that a 20% change in surface reflectance specification can have (about 8% overall). Comparisons between LAR and Radiance are all fairly close, with all but one case having a total difference of 15% and below. Case “V6” has a variance of 24% and also represents the case with the lowest amount of daylight overall due to the low ceiling reflectance. Looking at cases V4-6, it looks like the percent difference gets larger as the ceiling reflectance gets lower.

Table 4 - Surface Reflectance Study Results (% Area Above 500 lux)



6.2 Wall and Window Detail Workflow Study

Next, model NYC05 was utilized to explore the level of glazing detail and its effect on comparisons between LAR and Radiance. Figure 9 below shows the seven different façade versions that were simulated with a combination of two variables: wall complexity and window complexity. V3 serves as a baseline of sorts, and represents the typical “eggshell” envelope condition that daylight simulations typically use, i.e. a plane for the wall and a plane for the window. In other iterations the thickness of the wall increases to 8”, and then to 2’ to represent the actual condition of model NYC05. For each of the two wall conditions, three different levels of window detail are tested: a plane, a double-hung window with frame/sash, and a curtain wall with mullions that match the thickness of the 8” wall.

Figure 9- Simulation Key for Window/Wall Detail Level Workflow Study for Model NYC05

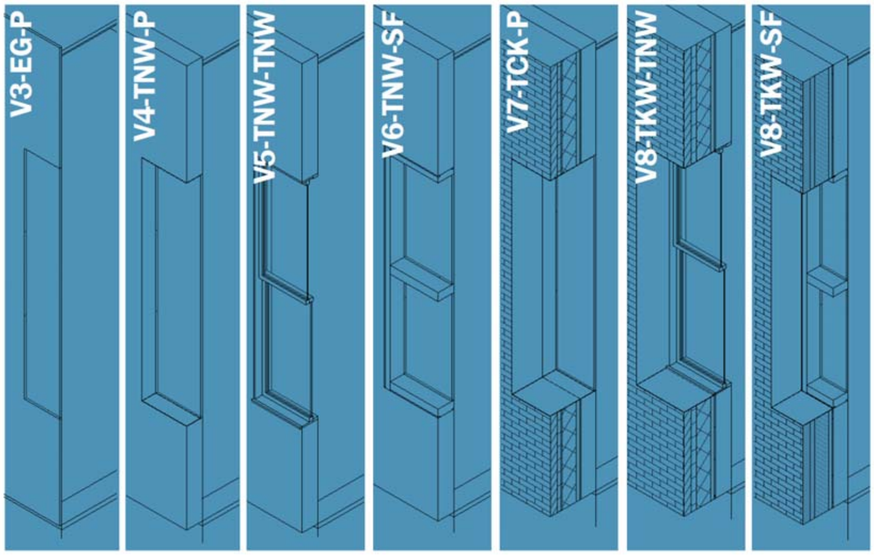
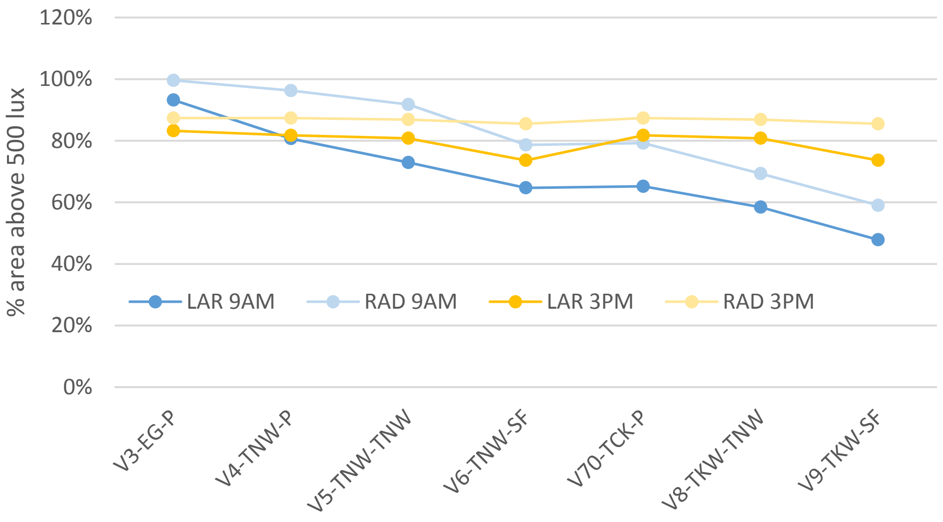


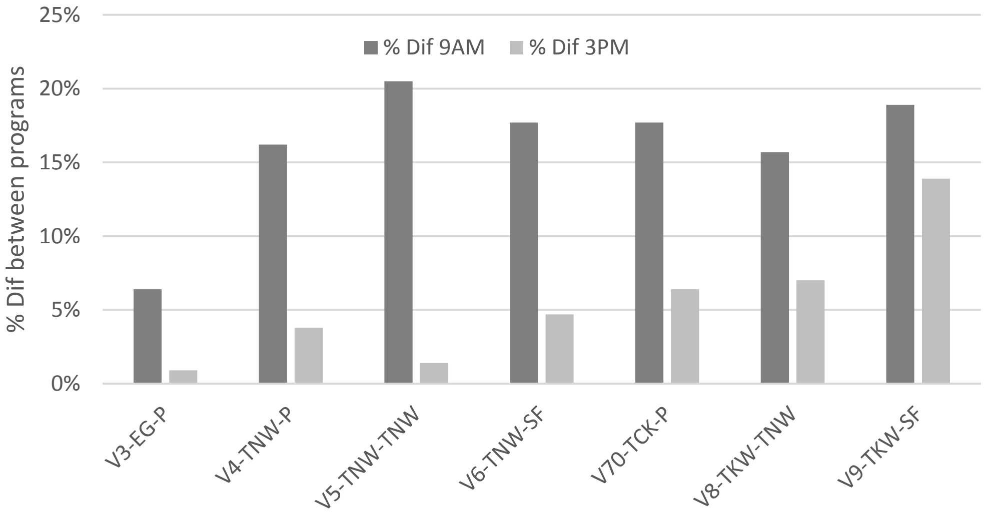
Figure 10 below shows the area percent thresholds above 500 lux for both the 9:00 AM (no direct sun) and 3:00pm (direct sun) condition between the Radiance and LAR programs. One thing to note from the graph is the difference between V3 and V9 within the same program. The 9:00 AM condition shows large variation for both programs: 93% to 48% area above 500 lux for LAR, and from 100% to 60% difference in Radiance. This large difference suggests that the level of detail of the façade make a substantial difference in the metric for the 500 lux range in a no-direct sun condition. The 3:00 PM condition shows this same effect, but not nearly to the degree as the 9:00 AM condition. Given the additional complexity of facades inherent in the BIM environment, this effect should be considered depending on the model and analysis context.

Figure 10 - Window/Wall Detail Workflow Results (% Area Above 500 Lux)



Instead of showing the floor area percent thresholds above 500 footcandles, Figure 11 below graphs the overall percent difference between the Radiance and LAR runs for the 9:00 AM and 3:00 PM condition. Both time conditions show good agreement between the two programs for the baseline eggshell condition. The 3:00 PM case shows low percentage differences overall, but does show a trend of slightly larger differences between the two programs with increasing wall complexity, and likewise for window complexity. The 9:00 AM condition shows differences hovering between 15% and 20%, with no clear trend relating to complexity.

Figure 11 - Results for Window/Wall Detail Workflow Results (% Difference Between Radiance and Lar)



6.3 Exterior Site and Building Context

Finally, model SMF04 was also used to determine the effect of exterior context's level of detail its overall percent of area daylit. BIM models often have more, and more developed, context by default than the typical radiance or Ecotect model. Thus, this study aimed to understand how varying levels of context detail influence the daylight availability in a space. More specifically, the study looks at varying levels of complexity for two conditions. First, the model varies the surface reflectance of the exterior site and ends with the inclusion an actual street with a different surface reflectance than the rest of the ground plane. The second study varies surface reflectances of a neighborhing building's walls, ending with the addition of actual windows, a common condition in some BIM context models. Figure 12 below shows the fully developed version of both studies; notice the orientation of the sites was changed to facilitate the sun shining directly on the exterior building, or to bounce off the exterior ground and into the space. These configurations were chosen to analyze conditions where the exterior context might have the most influence.

Figure 12 - Reference for Exterior Context Workflow Study

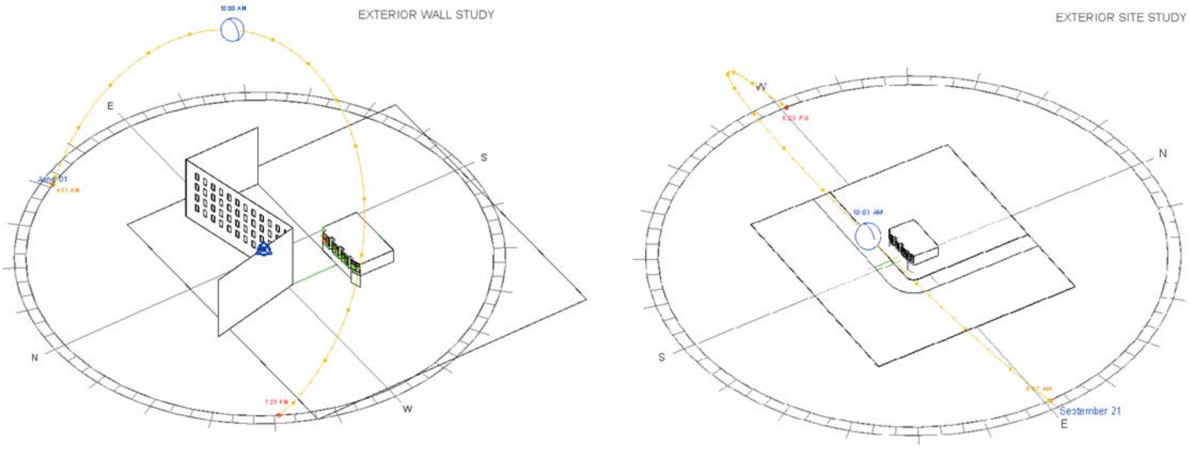


Figure 13 below shows the results from the site context study’s four different iterations and how the Radiance and LAR runs differ from one another. The first three versions represent a flat ground plane around the space with varying surface reflectance values. The Radiance model shows a higher variance between the 10% and 40% surface reflectance condition (a 20% change in % area above 500 lux), while the LAR simulations are less sensitive (only about a 10% change). It is also important to note that the two programs differ from each other more strongly with the low surface reflectance conditions, and agree more with the higher surface reflectance of the ground. The programs agree almost perfectly for the detailed condition (street = 15%, context 25%). However, the addition of the road drops the amount of area above 500 lux from 82% to 70% with the LAR program. This could be significant for projects and thus road context should be carefully considered when determining the appropriate level of detail for exterior site context.

Figure 13 - Exterior Site Detail Level Workflow Study (% Area Above 500 Lux)

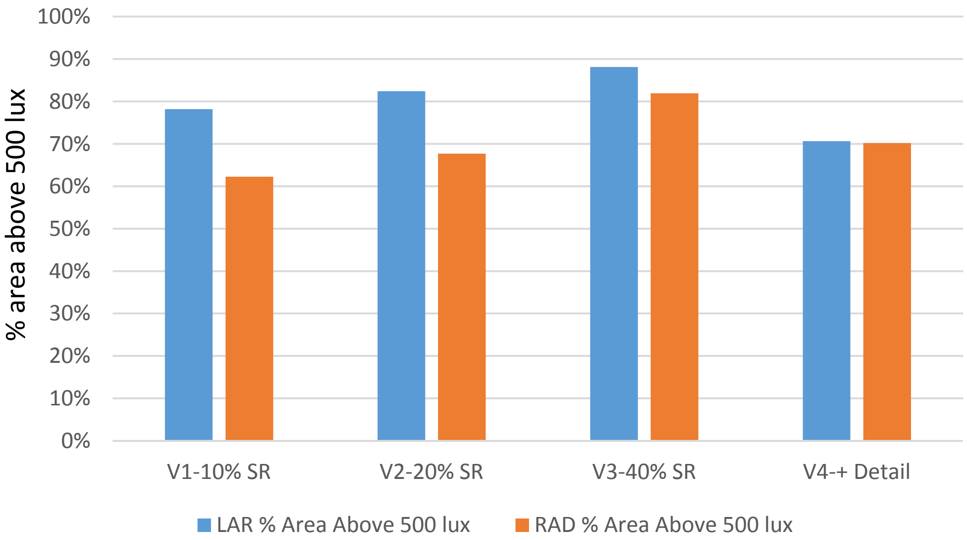
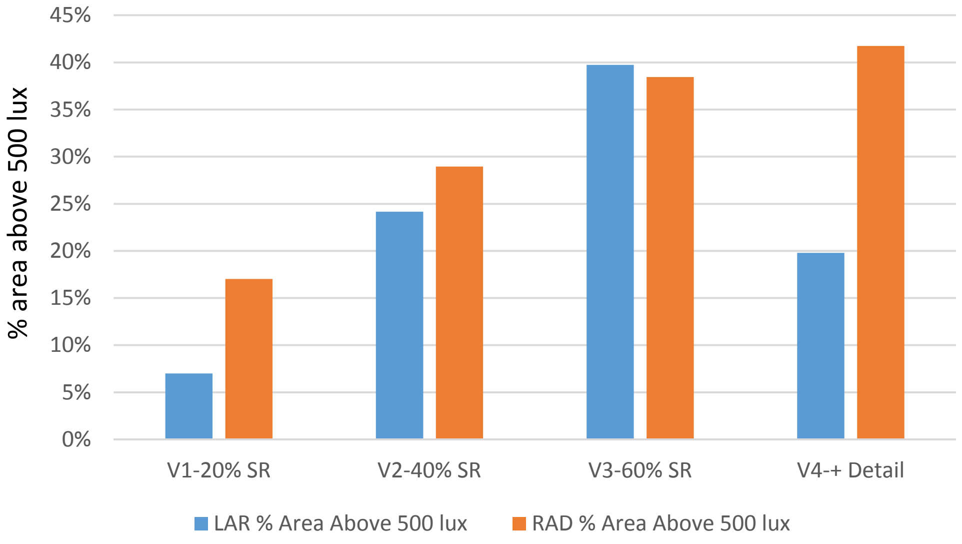


Figure 14 below shows the results from the context study's four different iterations of how a neighboring building might be specified and detailed. The first three runs vary the surface reflectance of the building's walls, while the last iteration adds window components to a façade with 40% surface reflectivity. The results show the same trend as the previous site context study, where the two programs agree more closely as the level of reflectance increases. The added windows iteration shows a large discrepancy between how the two programs handle reflected light by window materials (note: V4 should be compared to V2). Adding windows drops the percent of area above 500 lux by about 24%, but the Radiance runs show the opposite – a large increase in daylight, from 29% to 42%, perhaps due to more accurately modeling specular reflections. Additionally, the large spread of daylight values between both programs suggest that external context should be modeled consistently in all simulation environments and that windows should be modeled as opaque materials in LAR for the time being.

Figure 14 - Exterior Building Detail Level Workflow Study (% Area Above 500 Lux)



6.4 Discussion for Workflow Studies

Comparing the LAR results against Radiance for the three "real world" models shows generally good agreement for 3 out of 5 of the simulation conditions. The comparisons produced overall differences between the two programs for calculating area thresholds above 500 lux of 1%, 5%, and 7%, respectively. The NYC05 and SMF04 model conditions with zero direct sun did produce a 22% and 17% overall difference, however, and suggests that indirect lighting with deep walls lots of surface reflection near the window could be slightly improved. Additionally, the workflow studies provided some interesting insights, including:

- Generally good agreement (<20% overall difference) between the two programs for most cases
- Percent difference between the two programs increased for spaces with lower surface reflectance specifications
- Substantial influence of modeling complexity on daylight availability for spaces. Depending on window and wall modeling detail, area thresholds above 500 lux ranged from 48% to 93% for non-direct sun conditions, and from 74% to 83% for direct sun conditions with the LAR software.

- Model context detail, something more prevalent in BIM-integrated simulation workflows, can also have a substantial impact. Increases in external context wall reflectance of 20% produces roughly a 15% change in the % of floor area above 500 lux. Additionally, adding windows in either Radiance or LAR will have large effects on overall daylight values.

This research provides a mechanism for practitioners to determine the value and accuracy of LAR by looking at two things. First, the validation of the LAR calculation engine by using previously defined validation methodologies. Second, this research analyzed running a variety of simpler analyses on more detailed models while designing workflow studies to determine the differences between BIM modeling processes and traditional analysis modeling tendencies. Future studies aim to add more NRC window test cases to the validation study and to include translucent materials in the tests. Given the speed and ease of analysis that BIM-integrated tools provide, this type of research is critical to build confidence in the tool for practitioners concerning both accuracy and quality control. While integrating simulation into the BIM environment is still relatively new, this research shows that it represents a promising step in the evolution of performance based design.

7.0 References

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Reinhart, Christoph; Anderson, Marilyne (2006). “Development and validation of a Radiance Model for a Translucent Panel.” Energy and Buildings, v. 38, no. 7, July 2006, pp. 890-904 doi:10.1016/j.enbuild.2006.03.006

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8.0 Appendix

Appendix Item A – Material specifications for NRC Daylighting Laboratory, Daysim input, and 3ds Max inputs from Reinhart and Breton 2009 study.

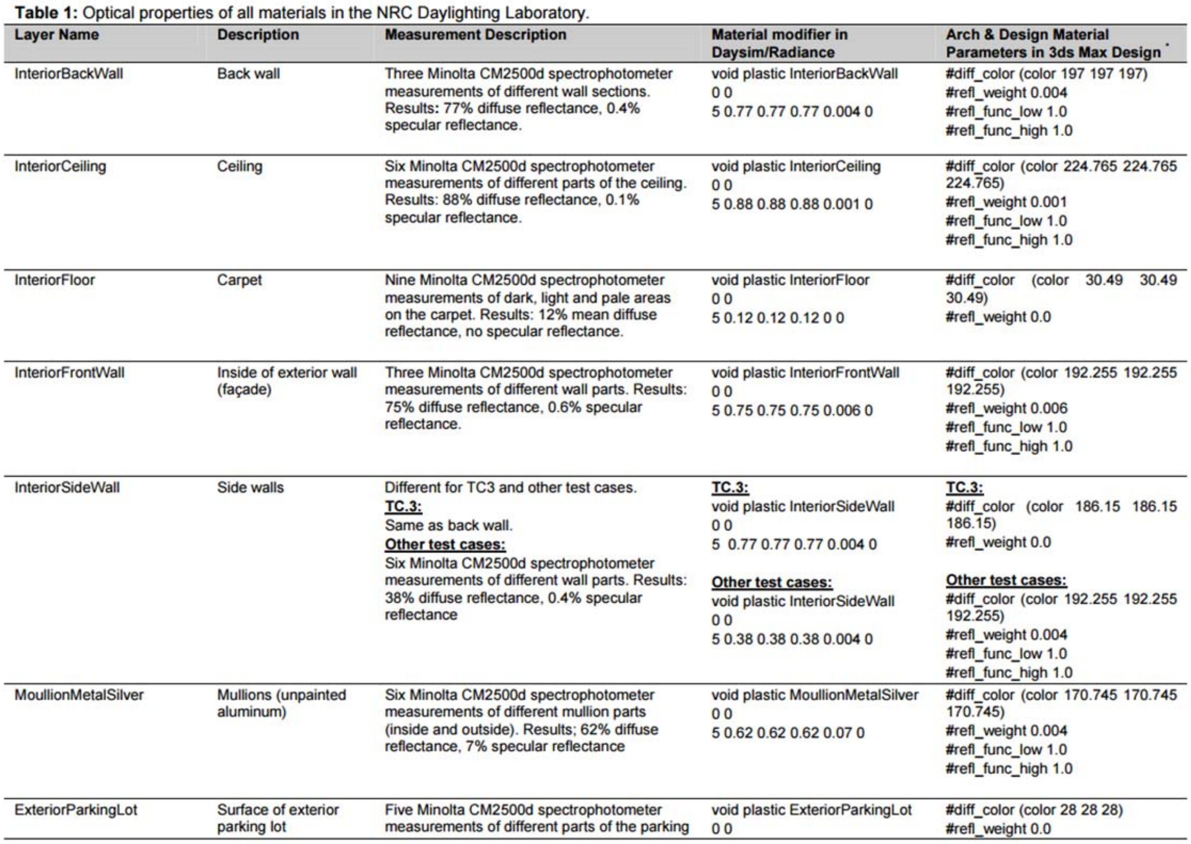
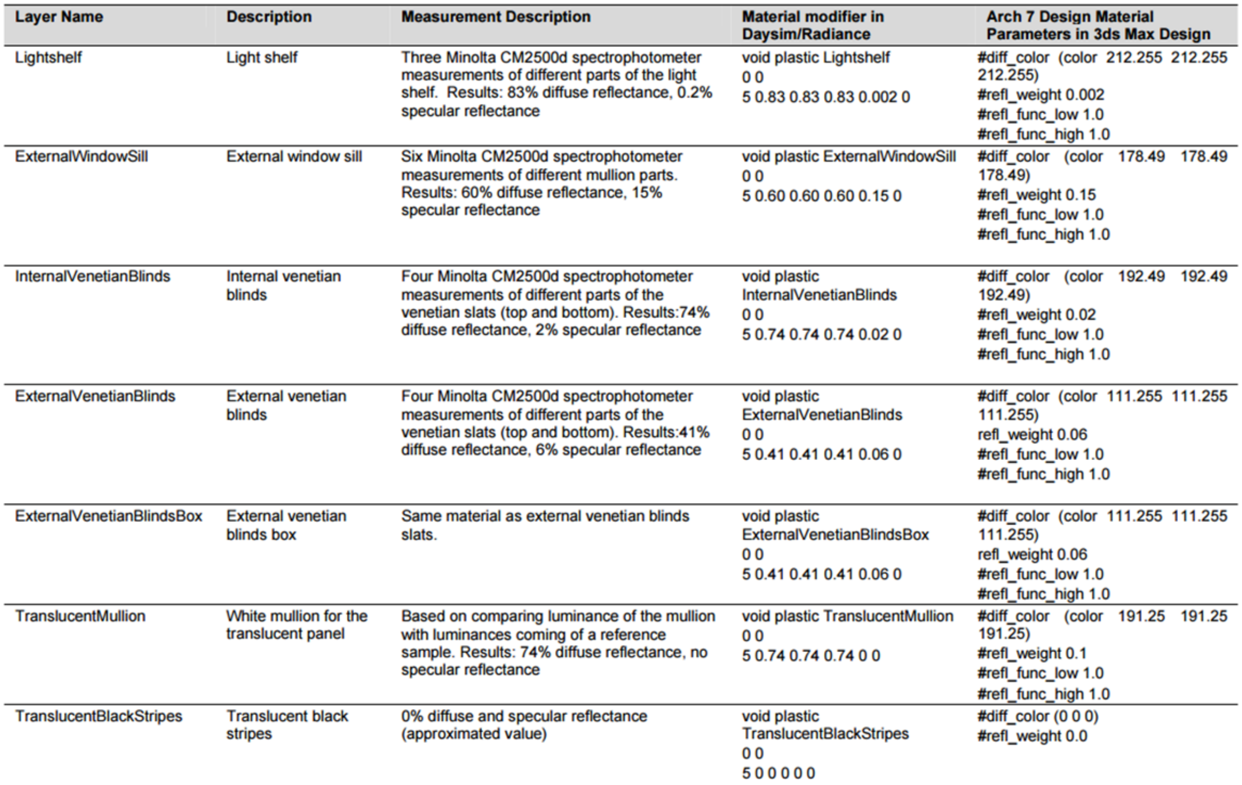


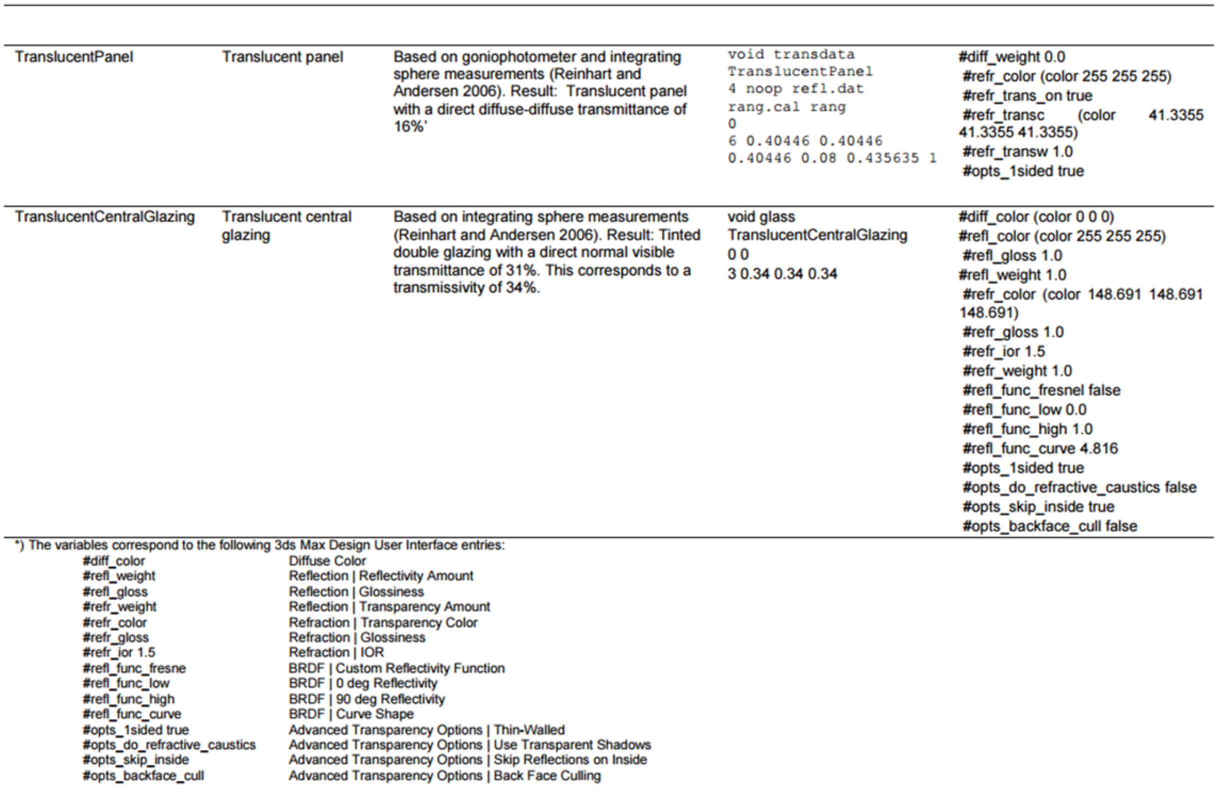
Table 1: Optical properties of all materials in the NRC Daylighting Laboratory.

Layer Name	Description	Measurement Description	Material modifier in Daysim/Radiance	Arch & Design Material Parameters in 3ds Max Design
InteriorBackWall	Back wall	Three Minolta CM2500d spectrophotometer measurements of different wall sections. Results: 77% diffuse reflectance, 0.4% specular reflectance.	void plastic InteriorBackWall 0 0 5 0.77 0.77 0.77 0.004 0	#diff_color (color 197 197 197) #refl_weight 0.004 #refl_func_low 1.0 #refl_func_high 1.0
InteriorCeiling	Ceiling	Six Minolta CM2500d spectrophotometer measurements of different parts of the ceiling. Results: 88% diffuse reflectance, 0.1% specular reflectance.	void plastic InteriorCeiling 0 0 5 0.88 0.88 0.88 0.001 0	#diff_color (color 224.765 224.765 224.765) #refl_weight 0.001 #refl_func_low 1.0 #refl_func_high 1.0
InteriorFloor	Carpet	Nine Minolta CM2500d spectrophotometer measurements of dark, light and pale areas on the carpet. Results: 12% mean diffuse reflectance, no specular reflectance.	void plastic InteriorFloor 0 0 5 0.12 0.12 0.12 0 0	#diff_color (color 30.49 30.49 30.49) #refl_weight 0.0
InteriorFrontWall	Inside of exterior wall (façade)	Three Minolta CM2500d spectrophotometer measurements of different wall parts. Results: 75% diffuse reflectance, 0.6% specular reflectance.	void plastic InteriorFrontWall 0 0 5 0.75 0.75 0.75 0.006 0	#diff_color (color 192.255 192.255 192.255) #refl_weight 0.006 #refl_func_low 1.0 #refl_func_high 1.0
InteriorSideWall	Side walls	Different for TC3 and other test cases. **TC.3:** Same as back wall. **Other test cases:** Six Minolta CM2500d spectrophotometer measurements of different wall parts. Results: 38% diffuse reflectance, 0.4% specular reflectance	**TC.3:** void plastic InteriorSideWall 0 0 5 0.77 0.77 0.77 0.004 0 **Other test cases:** void plastic InteriorSideWall 0 0 5 0.38 0.38 0.38 0.004 0	**TC.3:** #diff_color (color 186.15 186.15 186.15) #refl_weight 0.0 **Other test cases:** #diff_color (color 192.255 192.255 192.255) #refl_weight 0.004 #refl_func_low 1.0 #refl_func_high 1.0
MoullionMetalSilver	Mullions (unpainted aluminum)	Six Minolta CM2500d spectrophotometer measurements of different mullion parts (inside and outside). Results; 62% diffuse reflectance, 7% specular reflectance	void plastic MoullionMetalSilver 0 0 5 0.62 0.62 0.62 0.07 0	#diff_color (color 170.745 170.745 170.745) #refl_weight 0.004 #refl_func_low 1.0 #refl_func_high 1.0
ExteriorParkingLot	Surface of exterior parking lot	Five Minolta CM2500d spectrophotometer measurements of different parts of the parking	void plastic ExteriorParkingLot 0 0	#diff_color (color 28 28 28) #refl_weight 0.0

Layer Name	Description	Measurement Description	Material modifier in Daysim/Radiance	Arch 7 Design Material Parameters in 3ds Max Design
		lot. Results: 11% diffuse reflectance, no specular reflectance	5 0.11 0.11 0.11 0 0	
ExteriorGravelNearFacade	Exterior ground between façade and hedge	Different for TC3 and other test cases. For TC.3 the gravel was exposed whereas it was covered with black cloth for the other test cases. **TC.3:** 22% diffuse reflectance. **Other test cases:** 0% diffuse and specular reflectance (approximated value)	**TC.3:** void plastic ExteriorGravelNearFacade 0 0 5 0.22 0.22 0.22 0 0 **Other test cases:** void plastic ExteriorGravelNearFacade 0 0 5 0 0 0 0 0	**TC.3:** #diff_color (color 51 51 51) #refl_weight 0.0 **Other test cases:** #diff_color (color 0 0 0) #refl_weight 0.006
ExteriorWall	Exterior wall	Three Minolta CM2500d spectrophotometer measurements of different wall parts. Results: 58% diffuse reflectance, 0.1% specular reflectance	void plastic ExteriorWall 0 0 5 0.58 0.58 0.58 0 0	#diff_color (color 192.255 192.255 192.255) #refl_weight 0.006 #refl_func_low 1.0 #refl_func_high 1.0
ExteriorBlackCloth	Black cloth covering the hedge	0% diffuse and specular reflectance (approximated value)	void plastic ExteriorBlackCloth 0 0 5 0 0 0 0 0	#diff_color (color 0 0 0) #refl_weight 0.006
DoubleClearGalzing	Clear double glazing	Clear double glazing with a direct normal visual transmittance of 66.1%. This corresponds to a transmissivity of 72.0%. Measurement: With lamp QI105, at 6.5A (or 260.032mV across R) and LiCor LI250 with Photometric sensor LI210SA Ph5520, lined up on the rail perpendicular to the light path. Took a measurement with Licor: 1065.7 Lux Moved the window in the light path, flush against the light box (so perpendicular to the light path) and took another measurement: 703.9 Lux.	void glass DoubleClearGalzing 0 0 3 0.72 0.72 0.72	#diff_color (color 0 0 0) #refl_color (color 255 255 255) #refl_gloss 1.0 #refl_weight 1.0 #refr_color (color 207 207 207) #refr_gloss 1.0 #refr_ior 1.5 #refr_weight 1.0 #refl_func_fresnel false #refl_func_low 0.0 #refl_func_high 1.0 #refl_func_curve 4.816 #opts_1sided true #opts_do_refractive_caustics false #opts_skip_inside true #opts_backface_cull false



Layer Name	Description	Measurement Description	Material modifier in Daysim/Radiance	Arch 7 Design Material Parameters in 3ds Max Design
Lightshelf	Light shelf	Three Minolta CM2500d spectrophotometer measurements of different parts of the light shelf. Results: 83% diffuse reflectance, 0.2% specular reflectance	void plastic Lightshelf 0 0 5 0.83 0.83 0.83 0.002 0	#diff_color (color 212.255 212.255 212.255) #refl_weight 0.002 #refl_func_low 1.0 #refl_func_high 1.0
ExternalWindowSill	External window sill	Six Minolta CM2500d spectrophotometer measurements of different mullion parts. Results: 60% diffuse reflectance, 15% specular reflectance	void plastic ExternalWindowSill 0 0 5 0.60 0.60 0.60 0.15 0	#diff_color (color 178.49 178.49 178.49) #refl_weight 0.15 #refl_func_low 1.0 #refl_func_high 1.0
InternalVenetianBlinds	Internal venetian blinds	Four Minolta CM2500d spectrophotometer measurements of different parts of the venetian slats (top and bottom). Results:74% diffuse reflectance, 2% specular reflectance	void plastic InternalVenetianBlinds 0 0 5 0.74 0.74 0.74 0.02 0	#diff_color (color 192.49 192.49 192.49) #refl_weight 0.02 #refl_func_low 1.0 #refl_func_high 1.0
ExternalVenetianBlinds	External venetian blinds	Four Minolta CM2500d spectrophotometer measurements of different parts of the venetian slats (top and bottom). Results:41% diffuse reflectance, 6% specular reflectance	void plastic ExternalVenetianBlinds 0 0 5 0.41 0.41 0.41 0.06 0	#diff_color (color 111.255 111.255 111.255) refl_weight 0.06 #refl_func_low 1.0 #refl_func_high 1.0
ExternalVenetianBlindsBox	External venetian blinds box	Same material as external venetian blinds slats.	void plastic ExternalVenetianBlindsBox 0 0 5 0.41 0.41 0.41 0.06 0	#diff_color (color 111.255 111.255 111.255) refl_weight 0.06 #refl_func_low 1.0 #refl_func_high 1.0
TranslucentMullion	White mullion for the translucent panel	Based on comparing luminance of the mullion with luminances coming of a reference sample. Results: 74% diffuse reflectance, no specular reflectance	void plastic TranslucentMullion 0 0 5 0.74 0.74 0.74 0 0	#diff_color (color 191.25 191.25 191.25) #refl_weight 0.1 #refl_func_low 1.0 #refl_func_high 1.0
TranslucentBlackStripes	Translucent black stripes	0% diffuse and specular reflectance (approximated value)	void plastic TranslucentBlackStripes 0 0 5 0 0 0 0 0	#diff_color (0 0 0) #refl_weight 0.0



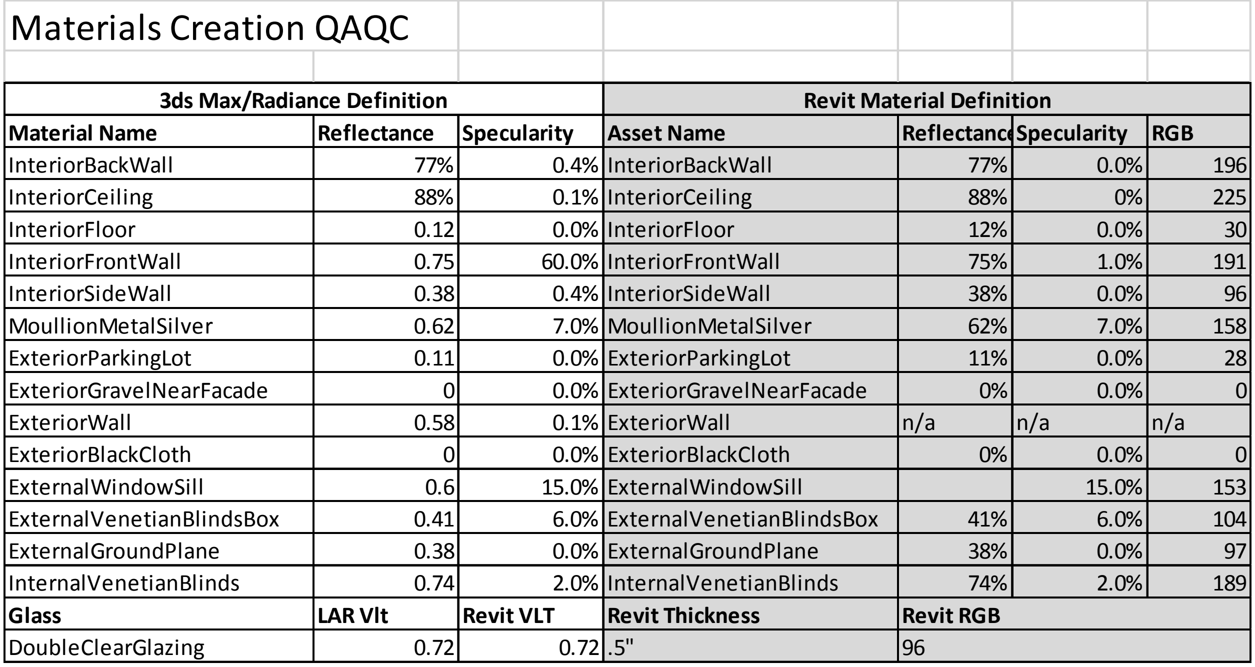
TranslucentPanel	Translucent panel	Based on goniophotometer and integrating sphere measurements (Reinhart and Andersen 2006). Result: Translucent panel with a direct diffuse-diffuse transmittance of 16%'	`void transdata`
			`TranslucentPanel`
			`4 noop refl.dat`
			`rang.cal rang`
			`0`
			`6 0.40446 0.40446`
			`0.40446 0.08 0.435635 1`
				#diff_weight 0.0
				#refr_color (color 255 255 255)
				#refr_trans_on true
				#refr_transc (color 41.3355 41.3355 41.3355)
				#refr_transw 1.0
				#opts_1sided true

TranslucentCentralGlazing	Translucent central glazing	Based on integrating sphere measurements (Reinhart and Andersen 2006). Result: Tinted double glazing with a direct normal visible transmittance of 31%. This corresponds to a transmissivity of 34%.	void glass TranslucentCentralGlazing 0 0 3 0.34 0.34 0.34	#diff_color (color 0 0 0) #refl_color (color 255 255 255) #refl_gloss 1.0 #refl_weight 1.0 #refr_color (color 148.691 148.691 148.691) #refr_gloss 1.0 #refr_ior 1.5 #refr_weight 1.0 #refl_func_fresnel false #refl_func_low 0.0 #refl_func_high 1.0 #refl_func_curve 4.816 #opts_1sided true #opts_do_refractive_caustics false #opts_skip_inside true #opts_backface_cull false

*) The variables correspond to the following 3ds Max Design User Interface entries:

#diff_color	Diffuse Color
#refl_weight	Reflection | Reflectivity Amount
#refl_gloss	Reflection | Glossiness
#refr_weight	Reflection | Transparency Amount
#refr_color	Refraction | Transparency Color
#refr_gloss	Refraction | Glossiness
#refr_ior 1.5	Refraction | IOR
#refl_func_fresne	BRDF | Custom Reflectivity Function
#refl_func_low	BRDF | 0 deg Reflectivity
#refl_func_high	BRDF | 90 deg Reflectivity
#refl_func_curve	BRDF | Curve Shape
#opts_1sided true	Advanced Transparency Options | Thin-Walled
#opts_do_refractive_caustics	Advanced Transparency Options | Use Transparent Shadows
#opts_skip_inside	Advanced Transparency Options | Skip Reflections on Inside
#opts_backface_cull	Advanced Transparency Options | Back Face Culling

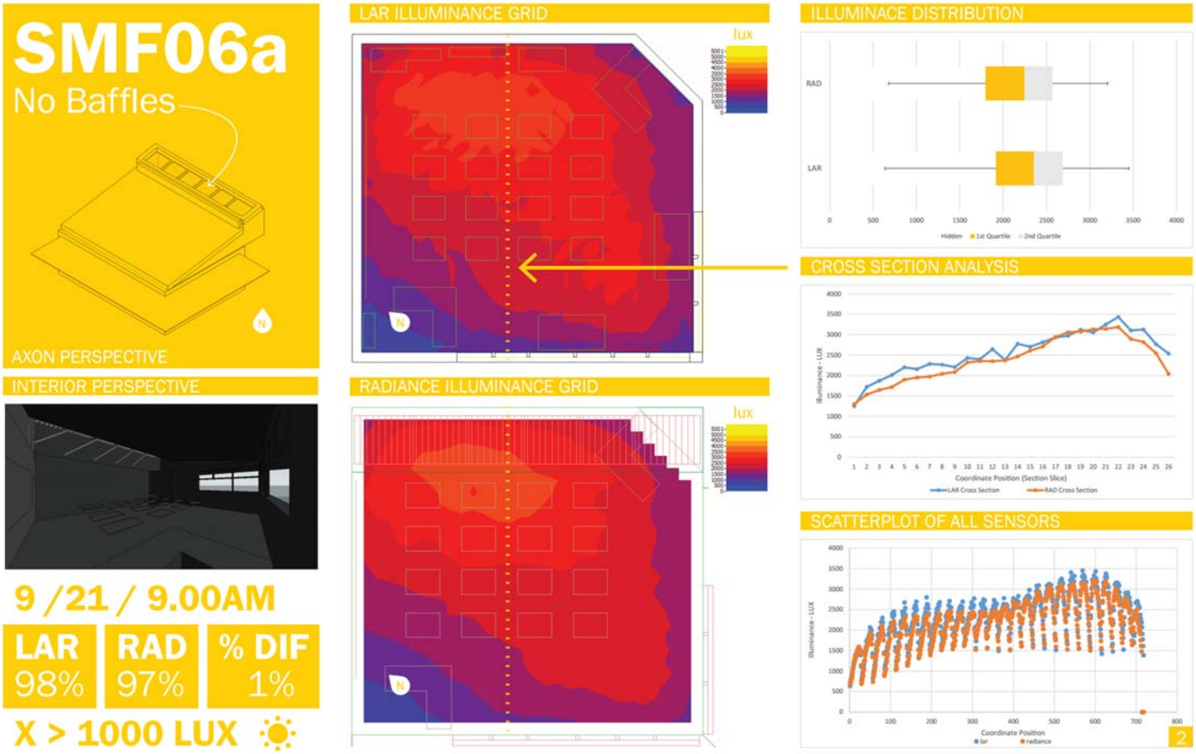
Appendix Item B – QAQC Table that shows the 3ds Max and Radiance material definition from the Reinhart and Breton 2009 study and the corresponding LAR inputs



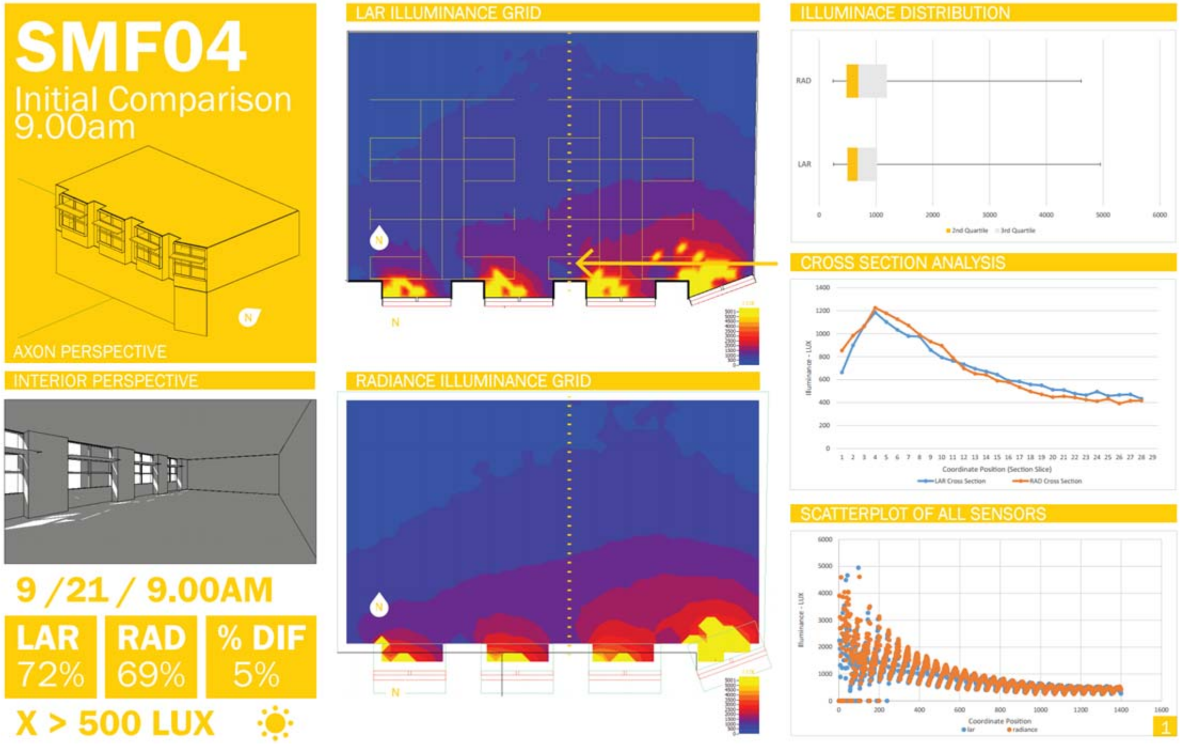
Materials Creation QAQC

3ds Max/Radiance Definition			**Revit Material Definition**			
Material Name	**Reflectance**	**Specularity**	**Asset Name**	**Reflectanc**	**Specularity**	**RGB**
InteriorBackWall	77%	0.4%	InteriorBackWall	77%	0.0%	196
InteriorCeiling	88%	0.1%	InteriorCeiling	88%	0%	225
InteriorFloor	0.12	0.0%	InteriorFloor	12%	0.0%	30
InteriorFrontWall	0.75	60.0%	InteriorFrontWall	75%	1.0%	191
InteriorSideWall	0.38	0.4%	InteriorSideWall	38%	0.0%	96
MoullionMetalSilver	0.62	7.0%	MoullionMetalSilver	62%	7.0%	158
ExteriorParkingLot	0.11	0.0%	ExteriorParkingLot	11%	0.0%	28
ExteriorGravelNearFacade	0	0.0%	ExteriorGravelNearFacade	0%	0.0%	0
ExteriorWall	0.58	0.1%	ExteriorWall	n/a	n/a	n/a
ExteriorBlackCloth	0	0.0%	ExteriorBlackCloth	0%	0.0%	0
ExternalWindowSill	0.6	15.0%	ExternalWindowSill		15.0%	153
ExternalVenetianBlindsBox	0.41	6.0%	ExternalVenetianBlindsBox	41%	6.0%	104
ExternalGroundPlane	0.38	0.0%	ExternalGroundPlane	38%	0.0%	97
InternalVenetianBlinds	0.74	2.0%	InternalVenetianBlinds	74%	2.0%	189
Glass	**LAR Vlt**	**Revit VLT**	**Revit Thickness**	**Revit RGB**		
DoubleClearGlazing	0.72	0.72	.5"	96		

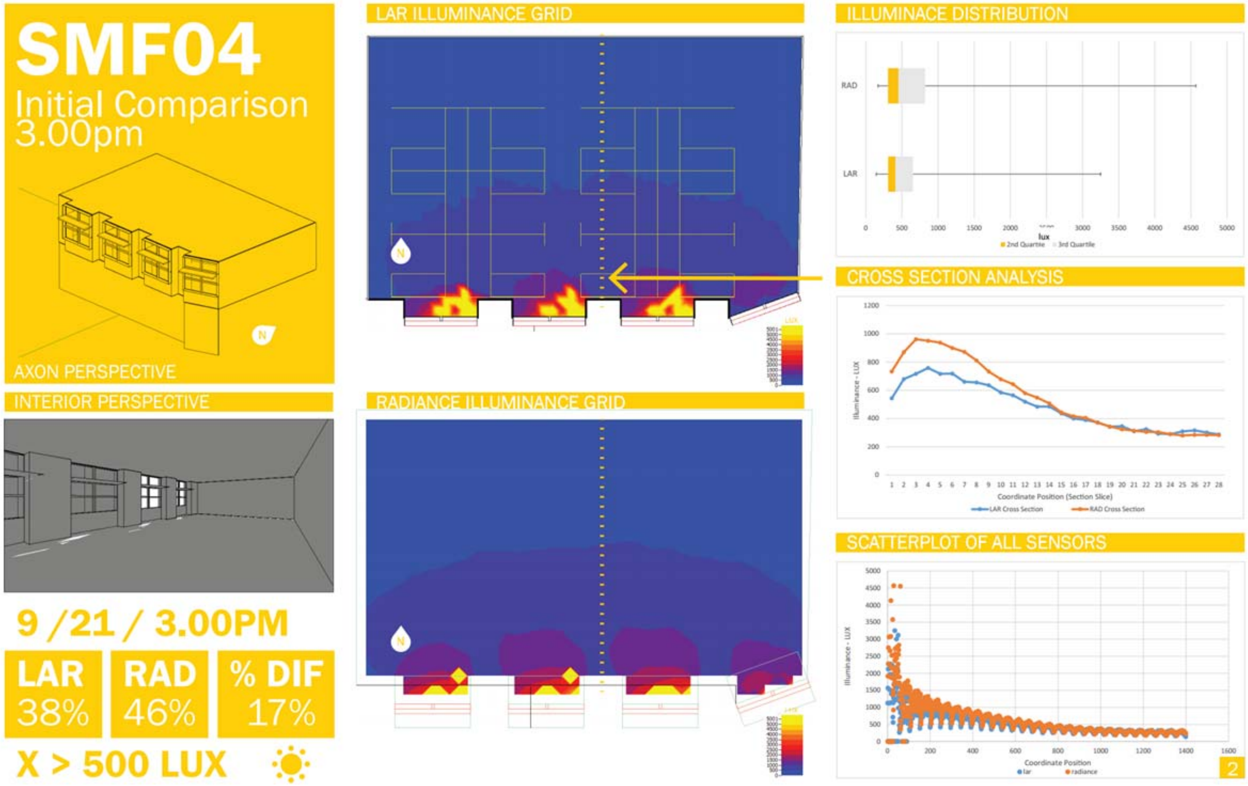
Appendix Item C – SMF06 Full Comparison Metrics



Appendix Item D – SMF04 Full Comparison Metrics



Appendix Item E – NYC05 Full Comparison Metrics



SMF04

Initial Comparison
3.00pm

AXON PERSPECTIVE

INTERIOR PERSPECTIVE

9 /21 / 3.00PM

LAR	RAD	% DIF
38%	46%	17%

X > 500 LUX

LAR ILLUMINANCE GRID

RADIANCE ILLUMINANCE GRID

ILLUMINACE DISTRIBUTION

CROSS SECTION ANALYSIS

SCATTERPLOT OF ALL SENSORS

2