ADVANCED LIGHTING SIMULATION
IN ARCHITECTURAL DESIGN IN THE TROPICS

EDWARD YAN-YUNG NG, LAM KHEE POH, WU WEI,
and TAKEHIKO NAGAKURA*

School of Architecture, National University of Singapore, Singapore
*School of Architecture and Planning, Massachusetts Institute of Technology,
U.S.A

Abstract. This paper outlines a two years research program that the team attempted to apply one of the most powerful computational lighting simulation software RADIANCE to assist in daylighting design of an actual building in the tropics. The validation studies, which were carried out in the Asian Civilisation Museum (ACM) in Singapore, show that Radiance can be used to predict the internal illuminance with a high degree of accuracy under overcast sky conditions without external obstruction. The experimental application of Radiance to daylighting investigation of the ACM further supports its capabilities as well as its accuracy. Using Radiance to study two daylighting control options (curtains and louvers), it can be found that louvers are more effective than curtains as daylighting control devices, and that the angle of the louvers has more effect than their reflectance on daylight penetration and distribution.

1. Introduction

The use of Computer Aided Design Techniques for lighting design attracts great interest from architects and lighting designers. Radiance is a mature ray tracing software that enables accurate and physically valid lighting and daylighting design. It has been applied successfully to aid the design of many buildings, but notably and mainly new and unrealized designs with little existing contextual restraints.

For this research, Radiance, an established computer aided design software, is applied to aid the design of an actual building - the Asian Civilisation Museum (ACM) in Singapore. ACM is located at the Empress Place which is a famous historic building and an important national monument in Singapore. The signification of this research is the testing of the usefulness of a piece of software under controlled and idealized situation and subjecting it to a real design problem. Apart from the need to overcome technical problems, the need to work under the auspicious of the conservation and preservation of a national monument poises another level of sophistication. The research represents an attempt to break the barrier between research and practice.
The paper outlines a two years research project of the National University of Singapore where the team attempted to aid the designers in their design decision making process by making available important simulation data on the behaviour of daylighting environment of the interior spaces through a number of lighting control devices and options. The above work flow diagram summaries the research.

2. Advanced Lighting Simulation

Advanced Lighting Simulation (ALS) is an attempt to provide an accurate simulation of a design, so that it is perceptually, mathematically and logically correct. A great number of ALS software and tools have been developed in the last ten years. However, only a few ALS software are available to designers at present.

The ALS software used in this research project is the Radiance lighting simulation system. Radiance is a collection of programs for the graphical simulation and analysis of lighting. It uses the technique of backwards ray-tracing to calculate scene illuminance and has the ability to account accurately for both diffuse and specular inter-reflection in complex spaces. Radiance is available from the Lawrence Berkeley laboratory, Berkeley, USA.

Radiance was chosen for this research for the following major reasons: (1) Radiance has been validated and is suitable for illuminance calculation, and to predict internal illuminance to a high degree of accuracy for a range of sky conditions. (2) Radiance is equipped with some unique daylight simulation capabilities, such as the ability to model multiple specular reflectors, complex fenestration and using sophisticated sky model (CIE standard sky). A major consideration of this research is daylighting distribution in the interior and Radiance has been experimented in its capability to simulate the complex lighting environment, complicated geometry. On the whole, Radiance is one of the most powerful lighting simulation systems. It is a well established software in the research community and has already been used in many design projects.
3. Experimental verification of Radiance Simulation in the Tropics

Experimental verification of Radiance has never been done in a tropical climatic condition. It is a lengthy but necessary pre-requisite to its successful application. Two experiments were conducted to investigate the validity of Radiance. A summary of the experiments is provided in Table 1.

TABLE 1. A summary of the two experiments to validate Radiance

<table>
<thead>
<tr>
<th>Experiment I</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective</td>
<td>To validate Radiance under overcast sky of a particular time of a day.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>12 measure points, Salon Room, Empress Place Building, Singapore</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measurement Time</td>
<td>12pm Noon</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equipment</td>
<td>MAVOLUX Digital-readout &amp; Datalogger/Photocell recorder system.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Experiment II</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective</td>
<td>To validate Radiance under overcast sky of a particular time of a day.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>12 measure point, Salon Room, Empress Place Building, Singapore</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measurement Time</td>
<td>Hourly intervals between 9:00am to 4:00pm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equipment</td>
<td>MAVOLUX Digital-readout &amp; Datalogger/Photocell recorder system.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.1 THE EMPRESS PLACE BUILDING AND THE SALON ROOM

The proposed Asian Civilisation Museum in Singapore is located at the Empress Place Building (Figure 1) and is targeted for completion in year 2000. The building is mainly of three-story high. The major exhibition areas are located on the second floor, which is more than 3700 m² in floor area. The building is around 130m long, 57m wide and 22m in height.

The Salon room (Figure 2) is part of the main gallery area on the second floor of which is about 5.5 m above from the ground. It is the only room in the Empress Place Building where most of the windows are not blocked up. Thus, it was selected to be the test room. The Salon room is 12m long, 9m wide and 9m in height. The interior walls and ceilings are flat and white painted. However, the conditions of the internal and external obstruction were rather complicated. For example, curtain blocked part of the window and some trees surrounded the room.
outside of the Salon room. Although the windows of the Salon room have conventional single glazing, it is pretty dirty since the room has not been used for quite a long time.

3.2 THE MEASUREMENTS

Indoor and outdoor measurements are collected for each of the three experiments. A total of 12 points inside the building and one outside the building were used. The illuminance of all the points was recorded on an hourly basis using the handheld Mavolux Digital. The measure probe of the Mavolux Digital was placed horizontally on the floor, and the sensors of Datalogger/Photocell system which were used in the Salon room were mounted horizontally on the floor. The Datalogger/Photocell system was programmed to record measurement once every 30 seconds; every 5 minutes the arithmetic mean of the ten most recent readings was stored in a hard disk file. All the measurements were conducted under overcast sky conditions unless otherwise noted. External illuminance data were taken hourly at the roof top of the Empress Place Building using Mavolux Digital.

3.3 THE RESULTS OF MEASUREMENT

The illuminance levels in the Salon room at noon were recorded using Mavolux Digital in Experiment I (Figure 3). In general, except two measure points, the measured results were quite consistent. The upper and lower quartiles of the mean is about 20% of the mean.

For the measure results of experiment II, the data is relatively consistent except the same two measure points. A good correspondence can be found between measurements taken by the two instruments--Datalogger/Photocell system and Mavolux Digital. A relative differences (Figure 4) of less than 15% has been noted for most of the points. None of the points has a difference greater than 20%. The differences can be due to errors in measurement. As Love has
pointed out, a slight difference in the recording time for the two different instruments can result in considerable differences in readings even under heavily overcast sky conditions. Where the relative difference RDE (%) is defined as:

\[ \text{RDE (Relative Difference)} = \left( \frac{M_D - M_M}{M_D} \right) \times 100\% \]

\(M_D\): The average measure result by using Datalogger/Photocell reading.

\(M_M\): The average measure result by using MAVOLUX reading.

Figure 3. Max., Min. and mean illuminance values at noon during the eight measuring day using the Mavolux Digital.

Figure 4. Difference of the mean illuminance during the three measuring days in the Salon room.

3.4 RADIANCE SIMULATION

Microstation 95, Autocad release 13 (with TORAD) and Radiance 3.1.5 were used in the simulation study. Computer 3D model was built up in Microstation 95. Since one of available Radiance translation programs “TORAD” can only be used in Autocad 13 only, Microstation files have to export to Autocad Release 13. From Autocad 13, the 3D geometric data is translated into Radiance files using “TORAD”.

Similar to the real building, the computer model was built in two storeys, and illuminance distributions were calculated in the second storey only. Geometrically, the model space generated for the simulations was a very close representation of the test space. The dimensions of the Salon room were measured to an accuracy of ±1cm and the room is described in the model as a collection of rectangular polygons. A rectangular ground plan of 85m (w) by 105m (h), with reflectivity set at 0.55 and centred on the building, was the only non-luminous external object. For saving computational time, the computer model was built as simple as possible and all the unnecessary non-light contributing polygons were neglected. The reflections of surface materials used in the simulation program were the average of the values measured on site. The sky condition is CIE standard overcast sky. A high-quality with mid-resolution setting is employed. Corresponding to the two measurement experiments, the computer simulation studies were conducted with similar conditions.

Since Radiance could not simulate external obstruction properly, and the internal and external conditions of the actual building are rather complicated, all the glazing in the computer model were simulated as opening. To correct the
results, correction multipliers were used. This will be discussed later. The inability to simulate external obstructions is an important shortcoming of Radiance.

3.5 COMPARISON OF SIMULATION RESULT WITH THE ON-SITE MEASUREMENTS

Measured results were compared to the simulated results. For the comparison between Experiment I and Simulation set I, it is noted that there are large discrepancies between the two data (Figure 5). Figure 7-18 summarises results obtained in Experiment II and Simulation set II.

![Figure 5](image)

**Figure 5.** Measured, simulated and corrected results at noon on measure point 21 to 32.

![Figure 6](image)

**Figure 6.** RE of measure point 21 to 32 between the measured results of experiment I and the corrected simulation results.

![Figure 7](image)

**Figure 7.** Measured, simulated and corrected results at point 21 between 9am to 4pm.

![Figure 8](image)

**Figure 8.** Measured, simulated and corrected results at point 22 between 9am to 4pm.

![Figure 9](image)

**Figure 9.** Measured, simulated and corrected results at point 23 between 9am to 4pm.

![Figure 10](image)

**Figure 10.** Measured, simulated and corrected results at point 24 between 9am to 4pm.

The error in the comparison of experiment I and simulation I is actually expected and anticipated for the following reasons. Firstly, The different conditions between the real building and the model used in the Radiance. As has been previously explained, some of the openings in the Salon Room are obstructed by internal and external objects. These were not incorporated into the Radiance simulation as Radiance is not capable of accounting for external obstruction easily. In addition, the complicated internal conditions in the Salon room are not simulated in the Radiance. Secondly, The site measurements which
were taken under the overcast sky may not be accurate because of the difficulty in controlling the level of the overcast sky in the on-site measurement under the real sky conditions.

3.6 CORRECTION COEFFICIENTS

To account for the external obstruction and other measurement and simulation errors, correction factors were computed and applied to the simulation results. To obtain the correction coefficient of each of the measure points, the pairing data of Experiment I and II are used. There are 9 pairing data for each of the measure points. The compute $C$ of each of the points, the following objective function is minimised:

\[
\min C
\]

Figure 11. Measured, simulated and corrected results at point 25 between 9am to 4pm.

Figure 12. Measured, simulated and corrected results at point 26 between 9am to 4pm.

Figure 13. Measured, simulated and corrected results at point 27 between 9am to 4pm.

Figure 14. Measured, simulated and corrected results at point 28 between 9am to 4pm.

Figure 15. Measured, simulated and corrected results at point 29 between 9am to 4pm.

Figure 16. Measured, simulated and corrected results at point 30 between 9am to 4pm.

Figure 17. Measured, simulated and corrected results at point 31 between 9am to 4pm.

Figure 18. Measured, simulated and corrected results at point 32 between 9am to 4pm.
C = \min \sum_{i=1}^{n} |M_i - CS_i|

Where \( M_i \) is the mean of the measurement results. \( S_i \) is the mean of the simulation results. \( C \) is the correction coefficient.

Figure 5 shows the mean illuminances of the measurements, the simulation and the correction simulation at the different measurement points for experiment I. The relative errors are illustrated in Figure 6. Generally, good correspondence was found to exist in between the measured results of experiment I and its correction simulated results. For all the measuring points, the relative errors are less than 15% except one measure point with a relative error of less than 18%. To further validate the use of the correction coefficients, they are applied to the results of experiment II. From Figure 7 to Figure 18, it is noted that correlation between the simulation results and the measurements can be found during different times in an entire day. For all the measuring points, the measured results and corrected simulation results show good correspondences. From the summary of the RE (relative error) as shown in Figure 19, it is noted that the relative errors for all the measure points are less than 20%. This indicates a good fit between the corrected simulation results and the measured results, and the validity of the correction coefficients. The relative error "RE" is defined as:

\[
RE = 100 \frac{I_{\text{measured}} - I_{\text{simulation}}}{I_{\text{measured}}}
\]

Where \( I_{\text{measured}} \) is the mean values of the measured illuminance. \( I_{\text{simulation}} \) is the mean values of the simulated illuminance.

3.7 DISCUSSION

The results demonstrated that Radiance is reasonably accurate in simulating the lighting environment under overcast sky conditions in the tropics. In situation where no external and internal obstruction is experienced, the results are particularly encouraging. However, care should be taken to conduct studies of these natures. Because of the following factors: 1) Radiance simulation results
under standard CIE luminance distributions may show notable differences from real sky conditions, especially in the case that the exterior environment has great variations in weather. 2) The larger discrepancy may occurs under some particular sky conditions since the CIE standard equation does not take the variation in atmospheric turbidity into account. 3) The key limitation of Radiance is highlighted in this study, namely its inability to take into account external obstructions. Although it has been demonstrated that correction coefficients could be applied to approximate the simulated results with the measured results, their use is highly undesirable in design.

4. Applying Radiance to the Daylighting Investigation of the Asian Civilisation Museum

Recent trend in museum design placed great emphasis on utilising daylight to create small but subtle variations in lighting intensity, to achieve better colour rendition of objects, and to provide visual relief and orientation to the visitors. It is in this light that the curator of the Asian Civilisation Museum has been so keen on introducing daylight into his new galleries at the Empress Place Building.

Allowing daylight into an art gallery is a tempting but difficult proposition. The great difficulty in planning accurately for daylight illuminance of exhibition areas is in estimating in advance what the interior illumination is likely to be at various times of the day and the year. Recently, advanced lighting simulation have been made to provide accurate daylighting performance tools for museum lighting design. Some previous studies carried out overseas have shown that Radiance can accurately simulate the daylit museum interior. Experimental results above have demonstrated that, with care, Radiance could be used to predict internal illuminance to a good degree of accuracy under overcast sky in the tropics.

There are a number of constraints need to be considered when using daylight in ACM. Firstly, illuminance levels has to be carefully controlled. This could be achieved by adding sun and daylight shielding devices to the openings to limit and control the admission of light into the building. Secondly, as the Empress Place Building is a historical monument, care should be taken not to disturb its architectural qualities. Therefore any daylight limiting or enhancing devices have to be carefully designed. Particularly, conservation and preservation issues, and the integrity of the existing building, have to be balanced with daylighting provisions. One of the most difficult tasks in this study is to model and validate some of the existing daylighting control devices that are part of the feature of the building. It is also important that new devices have to be architecturally consistent with the building.
4.1 DESIGN STUDIES

The elevations of the Empress Place Building are endowed with large patio windows at the bottom and small square-shaped ones on top, and dealing with opening on the sides is a well-known design problem for museum designers. Since the ACM is a historical building, the side windows cannot simply be eliminated for architectural reasons, and most design strategies for daylighting of museums cannot be used here. Working with the design team, two simple and efficient lighting controlling devices are studied. They are venetian blinds (louvers) and curtains. The simulation studies are divided into three parts (Table 2).

**Table 2.** A summary of the three design studies of the ACM using Radiance

<table>
<thead>
<tr>
<th>Part A - Present illuminance distribution</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Study A-1 With all the windows opened</td>
<td>The purpose of this investigation is to study the daylighting possibility in the ACM without any daylighting control options and under the existing lighting conditions. It also could provide necessary information for comparing other simulation results.</td>
</tr>
<tr>
<td>Study A-2 With high-level windows blocked</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Part B – Options using curtain</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Study B-1 Curtain with 35% transmittance (28.35% diffuse and 3.5% specular)</td>
<td>The effects of different transmittance of the curtain on lighting distribution in the Salon room are investigated. Designer has expressed to the research team that low transmittance glass would be used in the ACM. As the curtain was modelled as a cloth membrane, a translucent materials in Radiance, the results could also be used to approximate glass of 35% and 60% light transmittance.</td>
</tr>
<tr>
<td>Study B-2 Curtain with 35% transmittance (28.35% diffuse and 3.5% specular)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Part C – Options using louvers</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Study C-1 Horizontal louvers with 20% reflectance.</td>
<td>The part C is to study the effects of reflectance and angles of varies louvers system to the daylighting levels and distribution in the Salon Room. Two different angles were used: horizontal and 45-degree titled louvers. The louver surfaces were simulated as smooth plastic material in Radiance with 20%, 50% and 80% reflectance respectively. The width of each louver slat is 50mm and the distance between the each louver slat is also 50mm.</td>
</tr>
<tr>
<td>Study C-2 Horizontal louvers with 50% reflectance</td>
<td></td>
</tr>
<tr>
<td>Study C-3 Horizontal louvers with 80% reflectance</td>
<td></td>
</tr>
<tr>
<td>Study C-4 45-degree slant louvers with 20% reflectance</td>
<td></td>
</tr>
<tr>
<td>Study C-5 45-degree slant louvers with 50% reflectance</td>
<td></td>
</tr>
<tr>
<td>Study C-6 45-degree slant louvers with 80% reflectance</td>
<td></td>
</tr>
</tbody>
</table>
For the purpose of analysing illuminance distribution on the horizontal as well as vertical surfaces, objects mimicking the exhibits are placed in the Salon room. One of the measuring days for the experiments conducted earlier is selected as an input to Radiance. Simulations were conducted at noon using the CIE standard overcast sky. All external obstructions were excluded since the curator of the ACM stated that all the existing trees could be removed. As the main concern of this study is daylighting illuminance distribution, thus it is assumed that UV radiation in daylighting has been eliminated through the use of protective glazing.

4.2 RESULTS AND DISCUSSION

For studying the daylighting distribution of each of the design option, a plan, a perspective, a fish eye and a section view of the Salon room were simulated. Twelve images of each of the studies were rendered. In total, 120 images were rendered and the computational time is approximately 4000 hours using a SGI Onyx Super Computer. All images were rendered using high-quality with mid-resolution setting.

The simulation results of study A-1 show that the illuminance distributions are quite uniform and the illuminance levels of around 1000Lux could be recorded in an uncontrolled space even under an overcast sky. It is noted that the illuminances in the room were much higher than the limits set in the CIBSE guide when all the windows are opened. Therefore, it is not feasible to use daylighting in ACM without any daylighting control systems.

When the high-level side windows are blocked (Study A-2), it is noted that the Salon room looks very dull. This dullness has been observed in the actual room under similar lighting conditions. However, the interior illuminance distribution is not even. These simulation results could conclude that blocking the high-level windows does not help redistributing the daylighting though this could reduce the illuminance level in the room. Illuminance levels are more uneven when this option is used.

Simulation results of study B-1 and B-2 indicate that curtain is a useful daylighting control device as it can be used to reduce the overall illuminance in the room. When the transmittance of the cloth membrane were increased from 35% to 60%, illuminance values increased two-fold. However, it is also noted that the uses of curtain have little effects in re-distribution daylight. It can be concluded that careful consideration, selection and usage of curtain (or low transmittance glass) could reduce the interior daylighting level. From the design point of view, using low transmittance glass may have the effect of the window openings appearing too dark when viewed outside. Using low transmittance curtain may alleviate this side-effect.

The results of Part C show that the venetian blind (louver) devices are effective daylighting control options. When horizontal louvers are used (Study
C-1 to Study C-3), daylighting levels could be reduced by approximately 55% when the reflectance of the louvers is set at 20%. Values of the daylighting levels are directly proportional to the reflectance of louvers. However, illuminance of 550lux can be recorded at the centre of the room even when the reflectance of the louvers were set at 20%. This indicated the need for other forms of lighting control devices to supplement the louvers. When 45 degree slant louvers with different reflectance are used (Study C-4 to Study C-6), the simulation images show that the illuminances level can significantly reduce. Average illuminance is in the region of 300Lux using louvers with an 80% reflectance. Slant louvers also improve the uniformity of the daylight and reduce the differences of illumination between the back of the room and the most brightly lit area near the window openings.

The simulation results of Part-C lead to these conclusions: 1) The use of venetian blind (louver) devices are more effective daylighting control options. 2) The angles of the louvers have more significant influence than the reflectance of the louvers in shaping daylight levels and their redistribution. 3) The uses of louvers are more effective than the use of low transmittance glass or curtains. Uniformity of illuminance levels in the room is improved.

The simulations show when the 45 degree slant louvers with 50% reflectance is used, the illuminance levels achieved satisfy the basic requirements of the CIBSE Lighting Guide. Some sensitive class II exhibit could be placed in the gallery space when this type of louvers is used. However, when making the observation, it should be noted that the simulations were conducted only under overcast sky conditions. Further studies using other sky conditions may be needed.

5. Conclusion

The Empress Place Building represents a challenge to the apply of advanced lighting simulation (ALS) technology to building design. In this case ALS technology is used to study lighting design of an existing historical building. The validation studies demonstrated that Radiance is reasonably accurate in simulating the light environment in the tropics under overcast sky without any external obstruction. When Radiance was applied to assist in daylighting design of ACM, this software further indicated that it is an effective lighting design tool. The research results showed that ALS technology is particular useful when a large number of options have to be considered during the scheme design stage of the design process.

Acknowledgements:

The authors would like to thank the National University of Singapore for
funding the project; Dr Kenson Kwok of Asian Civilisation Museum, Mr. Cheah Kok Ming of Public Works Department, Singapore and Mr. Grey Ward and Mr. Charles Ehrlich of Lawrence Berkeley laboratory, USA for their kind contributing to the research.

References