Discussing Photon-Mapping and Radiosity-Based Rendering Algorithms to Evaluate Qualitative Lighting Design in Contemporary Architecture

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Abstract: This paper attempts to determine the impact of different light propagation algorithm on visual perception of qualitative lighting design in contemporary architecture. Radiosity-based and photon-mapping-based light simulation software is used in this empirical study as a “switch” to isolate the occurrence of the specific lighting phenomenon. Images generated by the two rendering software are graded using a subjective lighting metric. The results show varying visual response. This finding informs architects that general radiosity-based renderer might not be adequate to portray accurate computational representation of translucency, directional diffused reflection and caustics; lighting phenomena observed in contemporary architecture.

1 INTRODUCTION

Light has always been crucial to architects. It illuminates the physical environment and enables people to formulate visual perception of an architectural space. It reveals the scale and texture of building materials. It informs users of the design intentions. Light may only be one of the many aspects of architecture. But light reveals the building, its intentions, its place, its form, its space, and its meaning. Light reveals architecture and, in the best instances, architecture reveals light1.

Recent contemporary design trend places an emphasis on interaction of materials with light. “Interactive” materials like glass, water and metal as illustrated by the Art Museum in Bregenz by Peter Zumthor or the Health Future in Hanover by Toyo Ito, have been exemplary in highlighting the importance of the play of light within architecture.

Richard Kelly was one of the pioneers in establishing such qualitative lighting

design in the 1950s. Arising from his experience with stage lighting, he recognized that various forms of light can be used as mediums for imparting information and mood and he identified the three forms; namely ambient light, focal glow and the play of brilliance\(^1\). Effects of translucency, directional diffused reflection and caustics, such as interaction of light with glass, water and metal, contribute largely to the play of brilliance; and hence to the aesthetical performance of light in instilling the mood of festive or prestige to architectural spaces.

Despite establishing the significance of such synergy between light and materials to architecture, not all aspects of light are taken into consideration during the architectural design stage, perhaps due to the difficulty in replicating the entire spectrum of lighting phenomena with traditional visualisation tools. Without the use of appropriate form of visualisation, design process can be highly impaired such that even the best conceptual ideas will appear diluted.

2 PRIOR RESEARCH

Communication of design intentions from the architects to the users has to be truthful and clear. An erroneous artist’s impression will convey inaccurate information and is thus highly misleading, proving frustration to both designers and users. Prior research on computationally rendered architectural spaces as means of lighting design evaluation revealed that a high degree of agreement exists between the lighting quality evaluations, based on the observation of real spaces as compared with the observation of scientific renderings of such spaces\(^2\).

Visualisation and prediction of lighting qualities and atmosphere in contemporary architectural spaces has become popular with the widespread of commercially affordable lighting simulation software\(^3\). The common digital light propagation software used in the architectural profession is a typical combination of radiosity and ray tracing-based algorithms. Viability of such software had been demonstrated in the prior research paper that actual architectural lighting design could be replicated fairly accurately by digital representation. However, this general radiosity-based light propagation algorithm tends to simplify the interaction of light and materials (ideal diffuse reflection) to a grade that translucency (diffuse transmission), directional diffuse reflection and specular-to-diffuse illumination (caustics) cannot be taken into account\(^4\).

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3 FORMULATION OF HYPOTHESIS

The hypothesis of this research paper was that the general radiosity-based renderer was inadequate to portray translucency, directional diffuse reflection (dd-reflection) and caustics in contemporary architecture. Advance computational visualisation software based on photon-mapping was used as a comparison to highlight the visual effects of these three lighting phenomena in architecture, against those simplified by the radiosity algorithm.

The test was established with the understanding that both rendering algorithms would produce differing images despite being rendered with comparable lighting parameters. The visual differences generated by the two rendering algorithms of the same scenes would likely produce varying response in visual perception in users. The following lighting set up would be conducted to evaluate three selected architectural spaces based on the above three lighting phenomena:

1) Indirect (global) illumination using a common used radiosity-based algorithm with Ray tracing (Lightscape 3.2)
2) Indirect (global and caustics) illumination using photon-mapping-based algorithm with Ray tracing (Mental Ray 2.1.45.1)

4 EXPERIMENT STUDY

4.1 Overview

- Based on the previous research paper, a proven series of 10 selected semantic differential rating scales was adopted into this empirical study to capture the subjective lighting quality dimensions.
- Three architectural lighting scenes were selected which involved one of the three to-be-evaluated lighting phenomena in each of these architectural spaces. The selection required that these spaces must have an international reputation for excellent lighting design.
- High-quality computationally rendered images of the three selected architectural lighting scenes were generated using general radiosity-based renderer and photon-mapping-based advanced visualisation software. The rendered images satisfied both the visual resemblance condition (sufficiently comparable depiction of the architectural lighting schemes) and photometric reliability (sufficiently accurate replication of photometric measurements in terms of means of luminosity of the rendered images).
- Computationally rendered images generated from both rendering algorithms on the selected three lighting scenes were evaluated by a group of 50 test participants using the subjective lighting metric.
Digital Design

- The visualisations of the three architectural lighting scenes generated by radiosity-based renderer were compared with those of photon-mapping to determine if and to what extent; the radiosity-based renderer could reproduce true lighting propagation, which could be accurately rendered by advanced computational tool based on photon-mapping.

4.2 Radiosity-Based and Photon-Mapping Algorithms

Radiosity with ray tracing RAD provides global illumination by computing the illumination of each surface from both the light shining from a source directly toward the surface and the indirect light reaching the surface after being reflected (one or more times) from other surfaces in the environment (lambertian ideal diffuse reflection).

Photon-mapping with ray tracing PM is a physically correct lighting solution that is able to simulate all true light propagation (as compared to the simplified Radiosity-based algorithm) in computational simulation. Photon-mapping generates global illumination by emitting photons in a manner that closely abide the scientifically accepted photon theory and hence is known to be highly accurate in depicting light interaction with materials.

4.3 A Subjective Lighting Metric

<table>
<thead>
<tr>
<th>Table 1 The 10 Selected Semantic Differential Rating Scales</th>
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<tbody>
<tr>
<td><strong>Category</strong></td>
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<tr>
<td>1. Evaluative (Psychological Impression)</td>
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<td>2.</td>
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A series of 10 selected semantic differentiate scale was adopted based on previous proven attempt to ascribe qualitative lighting characteristics into relative magnitudes for ease of comparisons. Non-parametric statistical test such as the 7-point bipolar scales was be used in the 10 selected semantic differential rating scales for evaluating the architectural lighting scene.

![Figure 1 Example of a scale (dim/ bright) of the derived metric (semantic differential).](image)

### 4.4 Selection of Architectural Lighting Models

Three award-winning contemporary architectural lighting scenes were selected because of the occurrence of one of the three evaluated lighting phenomena in each of the architectural space.

1) Byzantine Fresco Chapel Museum (BFCM) could exhibit both renderers’ ability to express true translucency in the form of a series of frosted glass panels. Diffuse transmission of light upon entering a fine-grained medium will create the “glowing” effect as visually expected of translucent frosted glass.

2) The CAAS washroom was an interior design proposal that employs brushed metal surfaces as one of central material finishes within the room. Intense spotlights projected onto the textured surfaces were expected to cast directional diffused reflections to the immediately surrounding, highlighting the use of cool materials within the sanitized space.

3) Thermal Bath Vals (TBV) utilised streams of daylight from fine slits between the roof slabs as the primary light source. The presence of water, dimly-lit interior with intense sunlight was likely to generate specular-to-diffuse illumination (caustics) onto the adjacent masonry walls. This lighting scene could evaluate the effects of caustics as a therapeutical element enabled only by photon-mapping.

### 4.5 Rendered Images

The selected three architectural lighting scenes were rendered using RAD and PM. The brightness information was derived from the means of luminosity histograms read off image-editing software as a common form of measurement of lighting levels between the two renderers to ensure both images are rendered comparably.
Figure 2 BFCM renderings generated by RAD (left) and PM (right).

Figure 3 CAAS renderings generated by RAD (left) and PM (right).

Figure 4 TBV renderings generated by RAD (left) and PM (right).

4.6 Evaluating the Rendered Images

As this paper was designed in the interest of the architectural profession, the participants were equipped with adequate knowledge in the design field and were mostly architecture students. A group of 50 people participated in the subjective evaluation. To ensure consistency, the following measures were observed:
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- The test participants observed images of the architectural spaces from same predefined angles of view (Figure 2, 3 and 4).
- The images were presented to test participants in high-quality printed photo paper to convey minimum loss of image detail due to media.
- Half of the 50 sets were conducted such that images presented were in reverse order of the other 25 sets to counterbalance any order effect.

4.7 Results

Table 2 Descriptive statistics in terms of means and standard deviation (in parenthesis) of evaluations of renderings in terms of translucency, directional diffuse (dd) reflection and caustics generated by RAD and PM.

<table>
<thead>
<tr>
<th>Lighting phenomenon</th>
<th>Translucency</th>
<th>DD-Reflection</th>
<th>Caustics</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Architectural model</td>
<td>BFCM</td>
<td>PM</td>
</tr>
<tr>
<td>1. Dim - Bright</td>
<td>PM</td>
<td>4.38 (1.35)</td>
<td>4.80 (1.37)</td>
</tr>
<tr>
<td>2. Non-uniform – unif.</td>
<td>PM</td>
<td>4.58 (1.33)</td>
<td>4.36 (1.22)</td>
</tr>
<tr>
<td>3. Boring – Interesting</td>
<td>PM</td>
<td>4.48 (1.07)</td>
<td>3.28 (1.38)</td>
</tr>
<tr>
<td>4. Private – Public</td>
<td>PM</td>
<td>4.36 (1.07)</td>
<td>4.10 (1.68)</td>
</tr>
<tr>
<td>5. Simple – Complex</td>
<td>PM</td>
<td>4.98 (1.08)</td>
<td>3.82 (1.30)</td>
</tr>
<tr>
<td>6. Dull - Shiny</td>
<td>PM</td>
<td>4.52 (1.07)</td>
<td>3.66 (1.23)</td>
</tr>
<tr>
<td>7. Small – Large</td>
<td>PM</td>
<td>4.30 (1.34)</td>
<td>4.18 (1.59)</td>
</tr>
<tr>
<td>8. Unpleasant - Pleasant</td>
<td>PM</td>
<td>4.14 (1.25)</td>
<td>4.02 (1.3)</td>
</tr>
<tr>
<td>9. Cool – Warm</td>
<td>PM</td>
<td>5.00 (1.09)</td>
<td>3.32 (1.22)</td>
</tr>
<tr>
<td>10. Somber - Cheerful</td>
<td>PM</td>
<td>4.34 (1.29)</td>
<td>3.80 (1.23)</td>
</tr>
</tbody>
</table>
Figure 5 Evaluation Mean BFCM

Figure 6 Evaluation Mean CAAS

Figure 7 Evaluation Mean TBV
5 DISCUSSION

From Figures 5-7, it was indicative, through the survey evaluation, that differences in rendering algorithms do affect individual perception of translucency (BFCM) and caustics (TBV) in the rendered architectural spaces. However, the visual effects of directional diffused reflection (CAAS) from both digital visualisation tools, created similar impact on the visual perception of the test participants.

The third, fifth and ninth semantic differential tests in BFCM (Figure 5) suggest that translucency rendering produced by photon-mapping (PM) were more interesting, complex and warm as compared to the general radiosity-based algorithm. The difference in evaluation points was probably attributed to the gradation in light intensity and colour of the frosted glass panels rendered by photon-mapping, in contrast to the highly homogenous diffused appearance by radiosity.

In CAAS (Figure 6), the evaluation scores for both images were comparable with only the exception of photon-mapping generating a slightly more pleasant lighting scene. It was likely due to the diffused reflections cast on the ceiling and floor as shown in the first semantic differential test.

The expression of caustics was the most significant evidence that radiosity is inadequate to exhibit the focused light pattern reflecting off water surface in TBV in (Figure 7). Most of the evaluation results for the image generated by photon-mapping were significantly different and scored exceptionally high in terms of pleasantness, interesting, shiny, bright and complex.

A scatter plot of evaluation mean of TBV lighting scene by radiosity and photon-mapping was highly dispersed and hinted of a weak correlation between images generated by both rendering algorithms. However, the sampling points were limited and hence more lighting scenarios would be required before there could be a conclusive validity of the research hypothesis.

6 CONCLUSION

The objective of this research paper was to empirically establish if and to what extent, the general radiosity-based renderer could portray the play of brilliance as important part of qualitative lighting design. Translucency, directional diffused reflection and caustics have been discussed as “interactive” materials that cause play of brilliance. The initial results suggested that there was strong evidence to indicate that radiosity-based algorithm could be inadequate to exhibit translucency and caustics in the expression of glass and water in contemporary architecture. The evaluation results were however, insufficient to substantiate the need for advance computational visualisation tool for the visual effects of directional diffused reflection caused by brushed metal surfaces.

In this study, certain assumptions and conditions must be made, for example, a) the advanced visualisation tool based on photon-mapping renders digital light
propagation accurately in comparison to the simplified radiosity algorithm, b) consistency in 3D CAD model construction in terms of geometry, and c) there must be comparable input of parameters in terms of geometry, material properties and lighting parameters despite the use of different digital platforms.

This paper was to highlight the awareness of inadequacy of the general radiosity-based algorithm to accentuate the interaction of light with specific materials. Future research should attempt to further explore the correlation between computational visualisation and a) different typologies of architecture in investigating the entire spectrum of light, and b) more extensive range of materials with various surface treatments in greater and direct relevance to the architectural industry.

REFERENCES


