Lighting Simulation in Architectural Design

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Abstract

This paper outlines the use of computational lighting simulation software as a design support tool for a proposed prototypical energy efficient collaborative R&D laboratory building at Carnegie Mellon University. The study investigates the challenges of effectively applying simulations in the design decision-making process and establishes a framework which designers may apply to conduct relevant and reasonably accurate lighting performance analysis.

Introduction

Advances in computational technology have produced increasingly affordable applications that can reasonably predict the performance of lighting in terms of time and cost, two important factors affecting the pervasive use of such technology in the context of architectural design practice. Evaluations of the use of such software to predict illumination levels in building designs have shown much potential for architects. (Ubbelohde and Humann, 1998; Lau and Mistrick, 2002) The reality however is that the use of lighting simulation tools is not common in architectural practice, especially by architects in the design process as contrasted to being post design verification tools by other experts such as lighting or electrical engineers. (AIA, 2000; Wong and Lam, 1999)

The focus of this paper is to attempt via an actual case of using lighting simulation in supporting architectural design to experience and discuss the difficulty of employing simulations under such circumstances. The objective is to better define the current obstacles and help guide the development of lighting simulation software that can play a larger role in architectural design.

A description of the design objective is first defined, followed by the formulation of specific informational needs leading to the specification of the simulation task. The role of simulations in supporting rational design decision making has been justified by the need for quantitative results that involve intensive computation. However, the formulation of such supposed well defined quantitative questions is argued to be but only part of the requirements in making simulations useful or even applicable. Following this discussion, an appropriate simulation software is chosen for this exercise to conduct simulations and the difficulties that the architect may face is documented.

The Design Task – BAPP

The Building as Power Plant (BAPP) is a proposed 6 storey, 64175 square feet prototypical collaborative R&D laboratory building at Carnegie Mellon University. This building is to integrate advanced energy efficient building technologies with innovative distributed energy generation systems such that it all consumes a fraction of typical building energy requirements and most if not all of energy requirements are generated on site. Given that lighting contributes 26% to 30% of building energy use (Roth et. al.: 2002), the design seeks to maximize the use of daylighting by designing efficient lightshelves, light reflectors or other cost effective architectural elements that would bring more daylight indoors while serving other functions such as balconies or supports for photovoltaic collectors.

The design objective, given the proposed building form and glazing type, is to increase daylight availability and uniformity of distribution. Glare is another important criterion to be addressed. This is actually a problem with 2 quantifiers for evaluation: the predicted change in indoor illuminance which the device would cause, and a more subjective evaluation of trade-off between cost or functional effectiveness of the proposed device.

While simulations may well be suited to answer queries on how a particular design would perform, it is difficult to apply when the informational need is ambiguous. Typical design questions, such as “what is the best solution” rather than “which is the best solution amongst defined alternatives” demonstrates this fundamental difficulty. While not suggesting that simulation tools should take over the creative process by “automating” design, a higher level of design support is still desired.

Simulations typically generate large amounts of data that are often difficult to understand cognitively and seldom suggest suitable courses of action. A more concise specification of the simulation task following the clearer definition of the informational need could include the purpose, context and history. For example, considering the design objective to maximize daylight performance given a base design, what is the performance of this case with respect to the last and what else is possible? The resulting information should be succinct and able to directly support design decisions such as the formulation of a design alternative.

In the case of conducting lighting simulation for the BAPP, the design objective is to identify the “best” design that maximizes daylight availability and performance given the locality and façade design of the building. This translates to an informational need in terms of quantitatively describing illuminance and uniformity. This will enable the specification of effective and relevant simulation tasks as well as guide the development of software functionalities that would allow simulations to play a larger role in architectural design.

Choosing the Tool

While the quantitative accuracy of a simulation is usually the most important factor from a scientific point of view, the criteria are somewhat different in architectural practice, given the constraints of resources, education, time and nature of design problem at hand. In this context, Lightscape is selected based on the considerations of appropriateness, ease of use and accuracy, with particular emphasis on ease of use (Ubbelohde and Humann, 1998).

Appropriateness

The appropriateness of software is examined according to the available functionalities and potential to perform the desired analysis, deliver data in appropriate metrics and address the informational need as defined by the design objective. Most lighting simulation software can predict the effects of daylighting, and present illuminance data at various spatial points, and calculate the average illuminance on a defined work plane. However, there is generally a lack of sophisticated post processing capabilities. Large amounts of data are presented either numerically or graphically to represent the predicted quantities, but do not directly address the informational needs that would present possible design solutions. While the graphical representations allow interpretation of distributions, it is difficult to cognitively compare and assess the relevant performance of each design.

While it is unreasonable to expect simulation software to have functionalities that address context specific and unique informational demands, the general categorization and development of new metrics of quantifying performance (Mahdavi and Pal, 1999; Ries et. al., 2001) begin to suggest how corresponding functionalities can be developed within simulation software.

Ease of Use

There are many practical resource constraints during the architectural design process, including time, cost and effort. It is usually impractical to spend weeks preparing and conducting simulations. Most architectural firms prepare their design electronically with an increasing number of firms preparing digital 3-D models and even adopting object orientated data structures for such models (AIA, 2000). An important factor in the choice of a simulation software is compatibility and interoperability with existing CAD platforms so that the building geometry can be directly imported and used. As most of the time in preparing for a simulation is usually spent on the geometric model (Bazjanac, 2001), such compatibility would greatly enhance the ease of use of the simulation software. The software should have modeling functionalities that support fast updates and modifications to the geometry as most simulations are concerned with parametric evaluations. Further more, the software should be computationally feasible and fast on resources typically found in architectural firms, such as desktop personal computers.

Learning how to conduct simulations is currently not an essential part of most architectural education curricula. Hence many architects are unfamiliar with the concepts and use of simulation software. Poor formulation of problem statements and experiment setup can increase time and effort while not getting relevant results. Well designed documentation, intuitive software user interface as well as technical support can greatly improve the situation. Software that builds upon established semantics as found in prevalent computational platforms and applications (e.g. the multitude of hierarchies and descriptors employed in CAD) are generally easier to learn and use.

Accuracy

While research (Kopylov et. al.,1998) asserts that Lightscape achieves accuracy faster, it has an error of 2.8% which is higher than other software. Our testing on the same experimental setup but using more detailed parameters achieved significantly better results. With the improvement of processing power and speed in desktop personal computers recently, it is reasonable to assume that the typical architectural practice will have the resources to conduct the simulation to a higher resolution. Other research (Shalaby and King, 2002) have also suggested that a linear correction coefficient can be applied to greatly improve the accuracy of Lightscape.

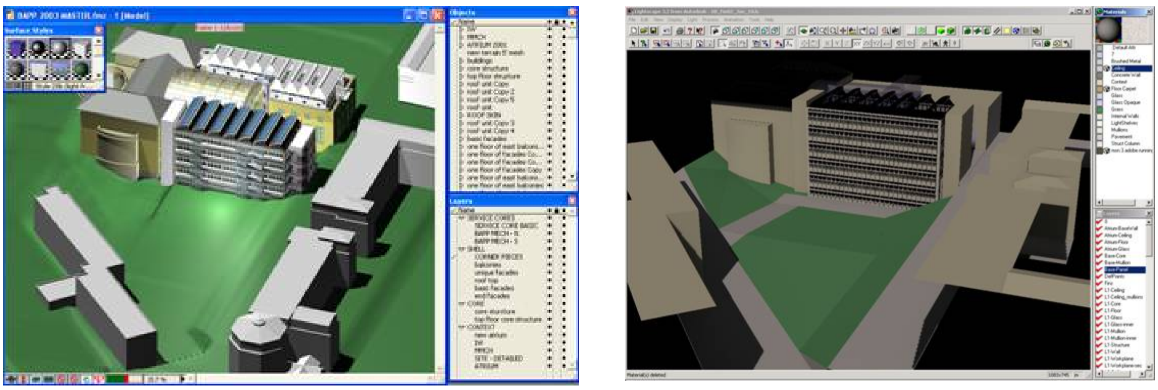
Given that the simulation task is comparative in nature, the accuracy of the algorithmic representations of the behavior of light is more important than how precise the actual quantities are. Since the basic formulation of the algorithms in Lightscape has been demonstrated to be satisfactory for detailed comparative studies, the dominant issue in choosing to use this software was the ease-of-use.

Simulation

Conducting a lighting simulation task can be described as consisting of 3 distinct parts. Pre-processing deals with the preparation of the scene to be simulated, including the preparation of the geometric model, material properties, context description and simulation parameters. The processing stage is the actual computation of the scene by the software and post-processing involves the manipulation and presentation of the data as responses to the overall informational demand.

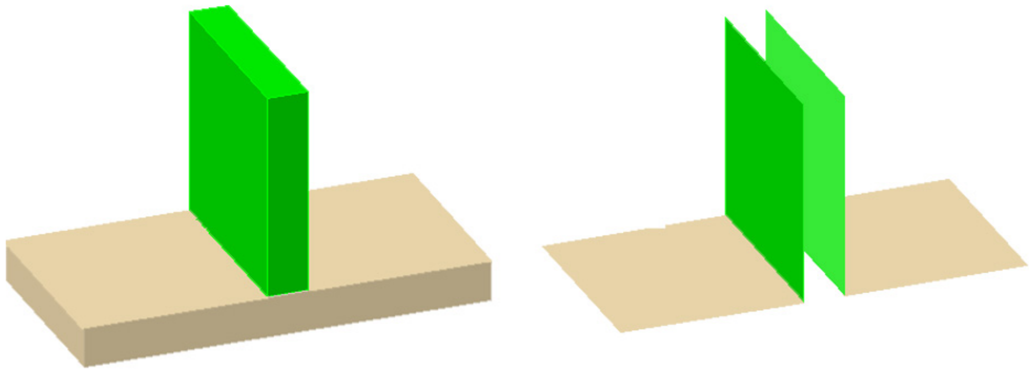
Geometric Model

Figure 1. Translation of design CAD model (left) into a model for lighting simulation (right)



In this experiment that represents typical design situations, the building geometry has already been prepared in a CAD format. However, even though Lightscape presents the "ideal" situation where the entire model can be imported, the geometry is not completely ready for lighting simulation. The semantics and methods of geometric description for design communication and presentation is markedly different from that required for simulations. In design, objects are usually defined to describe a spatial configuration or construction, but in simulation, the objects are grouped according to the zones that they describe; a single architectural object such as a floor subdivided by a wall may be 2 separate objects when described in simulations.

Figure 2. Difference in geometry description of floor and wall construction between design (left) and simulation (right)



In the same manner of semantic differences, there is little concern on the surface normals in CAD models for design but this is crucial for lighting simulation in order to relate the surfaces topologically to a space. There is thus a need for the user to check the normals after import and this can take significant time and effort depending on the situation. Similarly, layering and coloring conventions used in managing a CAD model is different between design and simulation conditions. There is again considerable time and effort required to update the imported geometry.

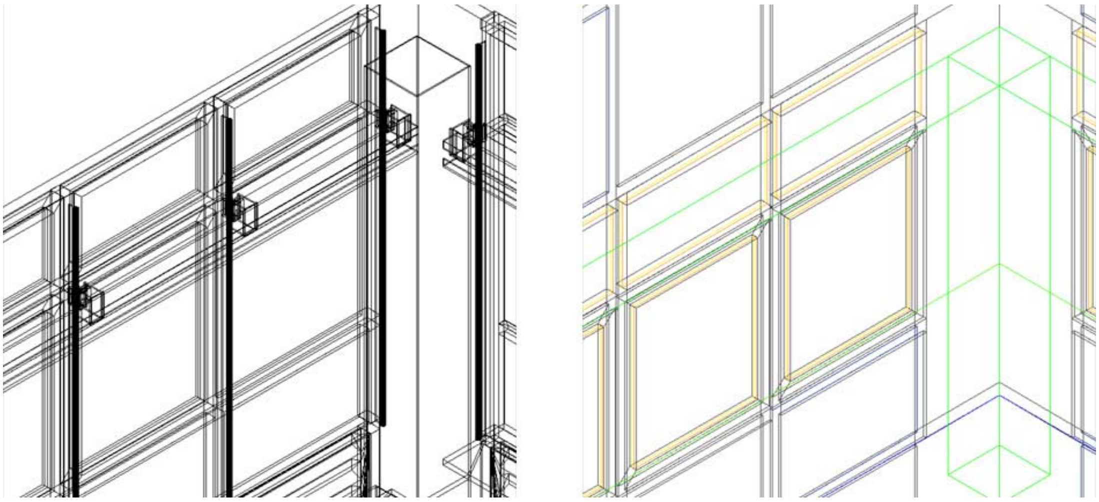
With developments in unified protocols for geometric description, there can be a data structure that sufficiently describes a building object such that it can be readily represented in both semantic contexts. The challenge is not to over burden the designer at the stage of object creation during design, but still to be able to provide the necessary information at the simulation stage. A possible way to achieve this is to design a data structure that can readily be analyzed by an algorithm to determine the characteristic of the object and represent the model in the alternative semantic. There have been some developments toward this direction. (IAI, 2003; NUS, 2002)

This idea applies to the similar problem of material definitions. Different software tends to focus on different attributes of material properties and even use proprietary scales and definitions. While architects are familiar with the general attributes of different building materials, the diverse informational demand from different domains without a common standard makes its difficult and even confusing and unrealistic. For example, the reflectance and color bleed scales within Lightscape are not the standardized scales used in describing material properties.

The different agendas of geometric representation between design and simulation also result in accuracy problems. Since the design model's main function is to communicate design concepts and ideas, there are often approximations or deviations that would reinforce the expression of such concepts, but inadvertently become problematic in simulations. This is especially true of the description of the physical context of a building, where maintaining geometric precision which is usually considered "as unimportant".

Another obstacle is that the information contained in CAD models is often excessive for an efficient simulation. Simulation speeds are dependent upon the number and complexity of objects within a scene and given that not all objects contribute significantly to the illuminance, the simulation will be slowed down by the extra elements such as the bottom surface of doors or fine details such as curved architraves or inner surfaces on curved doorknobs. There is thus a need to spend intensive time on abstracting the CAD model into one that is succinct for a reasonably accurate simulation.

Figure 3. Abstraction of wall, mullion and window details (Original on left, final on right)



The abstraction of models is a particularly perplexing problem that exists on 2 levels. The first deals with insignificant objects and the second, the amalgamation of objects. In the first case, the problem that confronts the user is in determining which objects are insignificant. For example, in typical suspended ceilings with aluminum frames holding matt white ceiling panels, the frames would have a higher reflectance than the panels. It is obvious that the additional surfaces of the frames would increase the simulation time, but given their relatively small surface area, the effect on the overall illumination could be insignificant. One might consider removing such insignificant details but without the simulation, it would be difficult to determine if the frames are indeed insignificant.

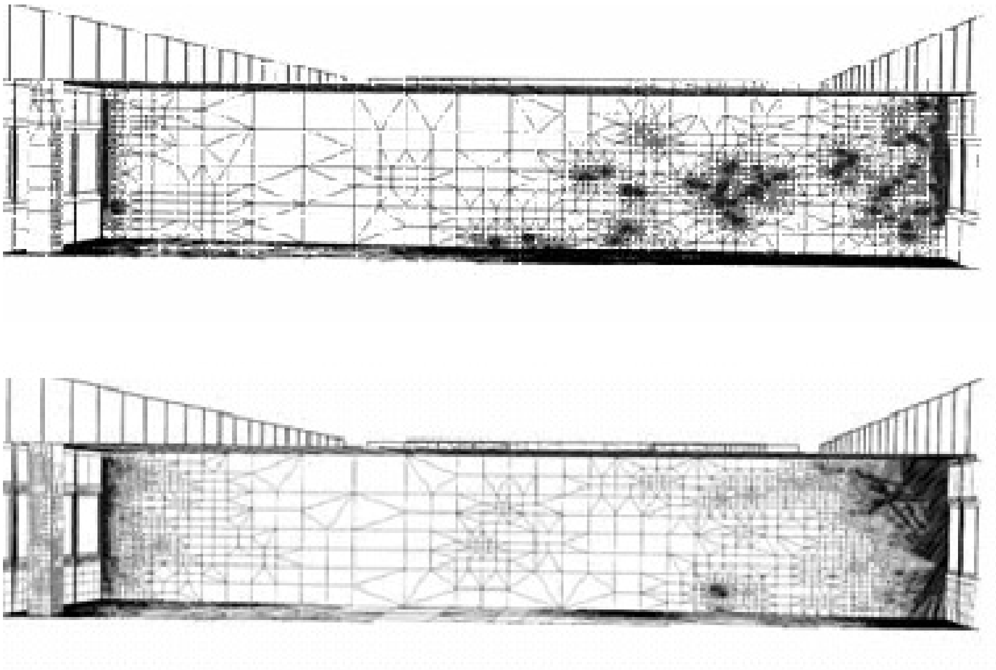
In the second case, when adjacent objects of the same material property would “behave” identically as one larger object while the latter results in faster computations, then it may be worthwhile spending significant time to modify the model. Similarly, when material properties (e.g. reflectivity) of adjacent objects are only slightly different, it might be worthwhile to amalgamate these objects as a single entity. To derive a suitable description for this amalgamated object can be difficult or even beyond the knowledge of the user.

It is apparent that this process of abstraction is particular to the nature of the larger informational task. Averaging slight reflectivity differences might be an acceptable trade-off for faster computation in our task of comparative performance in indoor illuminance distribution, but it is clearly unsuitable for a scenario that would be considering specular reflectances or glare.

Considering the situations where abstraction is desirable with negligible impact on the results, there can be a more efficient method of implementing both types of abstraction where an automated processor would be able to determine the geometric manipulations required given the parameters of acceptable trade-off. As a simple example, it would be useful if the façade mullion surfaces facing the same direction within a single zone can be identified and amalgamate as illustrated in Figure 2.

A particular problem identified in preparing the model is the tacit knowledge and experience that is required. This is especially the case when defining simulation parameters specific to the software such as the meshing options and process parameters. Experience in using computational simulations that employ meshing and some understanding of the methods employed by the software to “solve” the scene is required to prepare a suitable and efficient model for processing. One can only venture to postulate that with the increasing awareness of a performance based approach to building design, simulations will become an important part of the design process and that architectural education or training will equip architects to deal with this requirement in education and training.

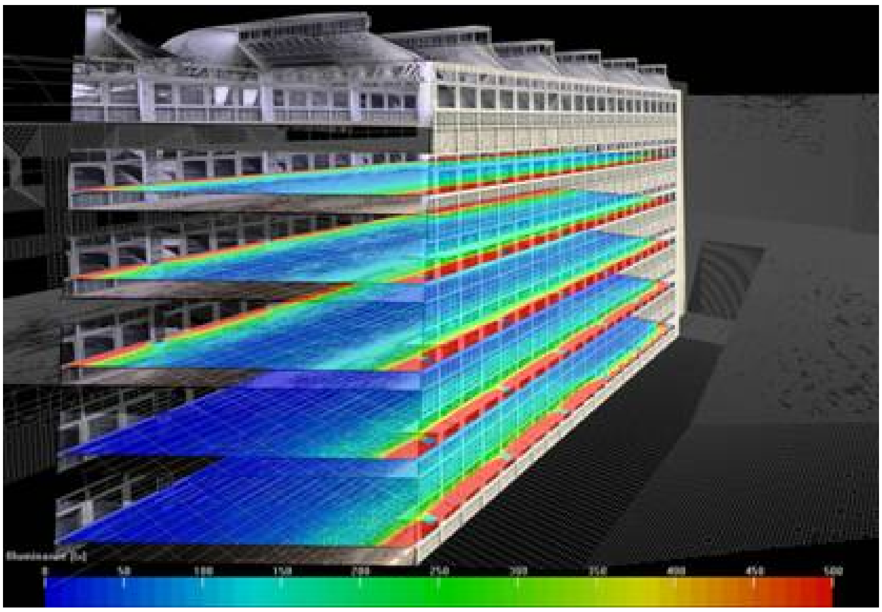
Figure 4. Effects on accuracy by slight changes in meshing and process parameters



Data Analysis

As discussed earlier, most lighting simulations do not have the functionality to consider a clearer definition of design purpose, context and history. Consequently, simulations can only report large amounts of data that attempt a quantitative description of the design but not directly addressing the informational demands of the design problem. Similarly, Lightscape gives us large amounts of data (e.g. illuminance values on all defined work planes at regular spacing at the specified time and day of a year). Ideally one could simulate the BAPP for all day-lit hours in the entire year at small time-steps, but due to the time and resource constraints, 2 representative days in a year on an hourly time-step were selected.

Figure 5. Post-processing functionalities

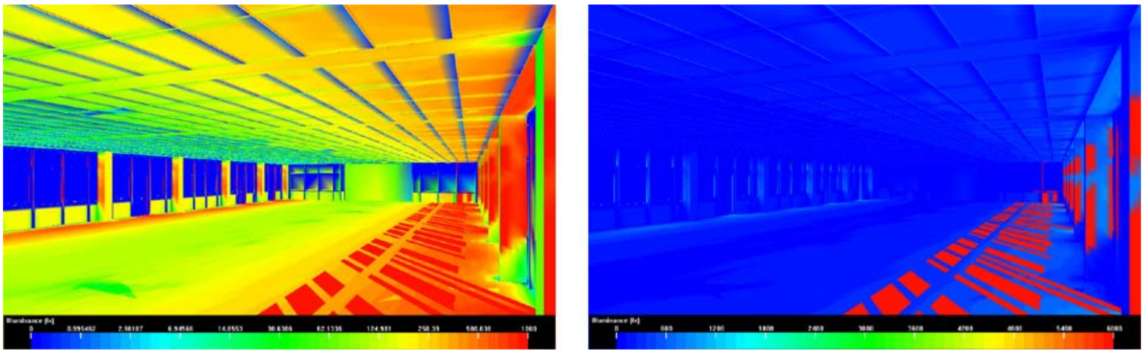


Most lighting simulation software include only a limited palette of post-processing functionalities, such as false color graphs, perspective renderings or animations. Even if all the functionalities are used, it is difficult to achieve a representation that would allow an efficient analysis in response to the informational need. In Figure 5 above, an animation was generating by compositing 12 sets of 3 different types of renderings. Yet the representation only begins to help in understanding the resulting lighting performance of the particular design. It is still difficult to assess and compare illumination distributions between different designs or even attempt to answer the initial question: “considering the design objective to maximize daylight performance given a base design, what is the performance of this case with respect to the last and what else is possible?”

The earlier suggestion to develop new functionalities utilizing new metrics of quantifying performance also extends to post-processing. There needs to be new methods of data transformation, reduction and translation that would express the data more effectively and new methods of representation that would communicate the information accurately and cognitively.

The challenge of accuracy in communication is best exemplified by the attempted to represent the illuminance distribution on a single work plane. While a false color representation greatly simplifies the need to present a large number of numerical values at regular grid points, it is difficult to select a scale that describes the data accurately. The extremities of the data are too far apart and results in a range that is too large. Selection of a logarithmic scale might alleviate this problem but the cognitive recognition might be affected. A limited and fixed linear scale used on all charts would ensure consistency when making comparisons, but the fixed limits do not communicate the condition of the extremities.

Figure 6. Challenges in cognitive representation, linear scale (left) logarithmic scale (right)



Conclusion

While Lightscape was adopted for this study, the observations may be generalized and applicable to the larger consideration of employing lighting simulations for architectural design. Simulation software have improved much in terms of accuracy and general ease of use, but there are still areas that need improvement for them to be feasible design support tools.

Contemporary simulation tools are focused on providing quantitative evaluations without the capability to consider more concise problem definitions that include design purpose, context and history. This is considered central to the issue of effectively and efficiently addressing the informational demands of real world design problems. Corresponding developments in post-processing and representations are likewise necessary before simulations can effectively integrated as part of the design process.

It is noted that the semantics in geometry description is quite different between the design and simulation contexts. There are also differences in proprietary definitions of material properties in various sofware. A possible solution is to implement standardization, both in terms of quantitative units as well as a standardized data structure that would facilitate the ease of translation and interoperability.

There can be further developments to reduce the efforts required to optimize a model for simulation through geometric and material property abstractions. Other difficulties such as the level of accuracy of modeling during design and the tacit knowledge and experience required to efficiently run a simulation might not yield as easily to technological solutions. Education and training might be more appropriate. There should be some form of education or training that prepares the architect to deal with issues such as the benefits of performance based architecture, purpose and limits of simulations as design support tools, metrics of performance, formulation and quantification of design problems, data analysis and visualizations.

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