

CURRENT PERSPECTIVES ON LIGHTING SIMULATION FOR BUILDING SCIENCE

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ABSTRACT

This paper presents developments in lighting simulation during the last twenty years, using a scope related to the main aspects of a program (input, modelling, and output). Existing models use very similar theoretical algorithms and calculation aids. This limits characterization of certain physical phenomena. Current focus is on accurately representing common situations encountered by building designers and researchers. New or untested elements are difficult to develop or prototype. Input quality affects accuracy, while output needs careful expert interpretation. Few tools exist to support the early architectural design process. Well-considered simplification is required when integrating lighting simulation to whole building simulation.

INTRODUCTION

Widespread use of computer lighting simulation in building science is approaching its second decade. Lighting simulation is increasingly used as substitute to traditional verification techniques. In 1994, almost 77% of participants in a survey used both computers and physical models for their professional practice. By 2004, participants not using any daylight prediction software had dropped to 21% [1]. It is becoming part of architectural and engineering education [2], as well as a method to verify code and certification compliance [3]. Comparisons are often made between real life and computer models to verify their accuracy or features, but these evaluations become outdated as computer programs are modified or fall into disuse.

For this paper, lighting simulation models were analyzed through a scope related to the main aspects of a program (input, modelling, and output). Although this overview has a bias towards daylight analysis (due to the complexity in depicting it), models used for artificial lighting design are also presented. Literature sources come from searches of citation databases and websites related to lighting simulation.

LIGHTING SIMULATION MODELS

Algorithms used in lighting simulation

Lighting simulation falls into two main areas that benefit mutually from developments in each of them. The first is “photorealistic rendering”. It deals primarily with artistic production of images. The second field and focus of this article, is “physically-based visualization” also referred to as “predictive rendering”. It deals with accurate representation and prediction of reality under given conditions and following physical laws [4].

An outline of lighting simulation algorithm development can be found in [5]. According to these authors, modern physical models (such as quantum optics) explaining light transport in all types of media are too complex for computer calculations and image generation. Instead, a model combining simplified geometrical optics and energy conservation is used. This model can solve most illumination problems with different light sources. However, difficulties are encountered when diffusing or refracting media are involved. Such media is found in advanced optical materials. It also assumes a steady-state light distribution.

Lighting simulation algorithms and their supporting calculation methods have different classifications. Each has specific applications and limitations (Figure 1):

- Direct calculations used for artificial lighting. These are specific physical formulas and simplifications, often delineated in national standards to cover most usual illumination situations.
- View-dependant algorithms. Classified according to direction from which tracing rays are computed: coming from the light source (forward tracing), from the observer’s eyes (backward tracing) or from light source and observer (bidirectional raytracing). Used for lighting calculations and renderings.

- Scene-dependent algorithms. One main example is radiosity, adapted from heat transfer into lighting simulation. A scene is divided into surface elements or meshes. Radiometric values are determined for each surface, independent of the view. Mainly used for calculations but not for rendering due to complex formulas.
- Integrative approaches. These are efficient and accurate by combining two or more algorithms. The Radiance model [4] uses backward raytracing to compute radiance values for a scene and radiosity to store scene values. The photon map [6] uses packets of energy (photons) to compute radiosity and raytracing values, making it useful for caustics and occurrences related to light concentration.
- Calculation aids for practical implementation. The most widely used techniques are Monte Carlo methods. They assume that the expected value of the sample is its correct value. An average of estimates completes the solution. Algorithms must run for enough time to take many samples. Monte Carlo techniques have accuracy limitations, but sometimes are the best way to solve certain physical problems [5].

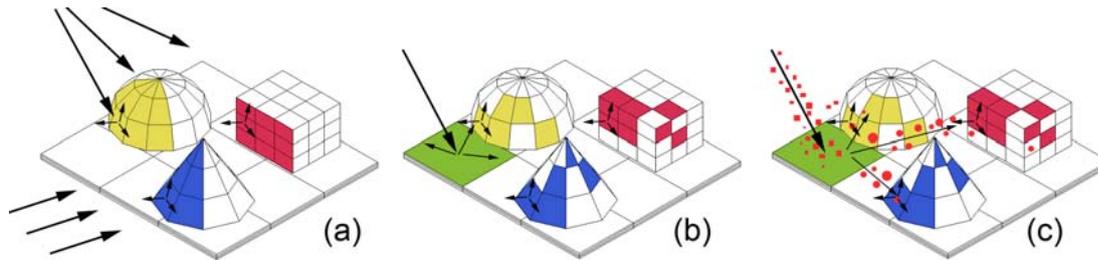


Figure 1 Three commonly used lighting simulation algorithms: (a) raytracing (b) radiosity (c) photon map

Examples of current lighting simulation tools

Many lighting simulation tools exist today. However, Radiance [4] continues to be the most influential of them. It has received an extensive number of literature citations and was among the first to employ integrative techniques. It lacks many user-friendly features such as an interface. As a general purpose tool, it solves a large number of lighting simulation problems. It has been validated extensively and incorporated into other tools.

Examples of current, widely used electric lighting design programs are AGi32 [7], DIALux [8], and Relux [9]. These programs combine raytracing and radiosity in diverse ways and for different purposes. Common features include defining geometry through their own CAD systems. Users can select luminaires from a manufacturers-maintained database. Some limited daylight integration is found in these models, such as sky type selection.

Architectural lighting analysis tools include: Inspirer [10], applying bidirectional raytracing; mental ray modelling engine [11], incorporating photon map model (found in many Autodesk products); and Velux Daylight Visualizer [12], an early stage design tool also using the photon map model. A tool summary is given in Table 1.

Table 1

Summary of current lighting simulation tools

TOOL NAME	ALGORITHMS	PURPOSE	AVAILABILITY
AGi32	-direct calculation -Radiosity -limited raytracing	Luminaire design daylight integration	-paid
DIALux	-direct calculation -daylight calculation -POV raytracer for images	Luminaire design, daylight integration	-free -proprietary software
Inspirer	-bidirectional raytracing	General purpose	-paid
mental ray	-photon map -radiosity -raytracing	General purpose	-found within paid modelling software
Radiance*	-backward raytracing -scene radiance	General purpose	-free -open source
Relux	-direct calculation -radiosity and modified Radiance raytracing	Luminaire design, daylight integration	-free -proprietary software
Velux Daylight Visualizer	Photon map -bidirectional raytracing -irradiance caching	Conceptual stages in daylight application	-free -proprietary software

*the photon map version of the program follows forward raytracing and photon map models

Lighting simulation validations

Evaluations of lighting simulation tools can be divided into two large groups: comparisons based on replicating a built reality, and comparisons in controlled laboratory settings. Each approach has advantages and disadvantages. It is difficult to compare results obtained through both methods due to methodological limitations within them.

Comparisons that replicated existing built environments demonstrated usage and accuracy of models under architectural contexts or for architectural design use [13]. Those studies found that accuracy is affected by sky model choice and estimation of reflectance from surrounding buildings.

Validations under controlled laboratory settings demonstrated the precision of a model in predicting illumination data. They serve developers to test algorithms under reduced uncertainty. One methodology is to simulate a set of standardized lighting and daylighting situations (datasets) [14]. Another method consists in replicating, within the simulation model, a close-to-ideal real life situation where lighting and material properties are known [15].

Accuracy in these kinds of validations is variable, and must take into account measurement errors. The International Commission on Illumination (CIE) estimated that an acceptable range would be 10% for average illuminance calculations, 20% for measured point values, but very difficult to reach 5% in complex situations [16]. The value of 20% for use in real cases has been validated in many studies replicating built realities. Validations under laboratory conditions yielded results within single digits [15]

Modelling specific simulation problems

Assumptions of current lighting simulation algorithms regarding steady-state and geometrical distribution can affect how certain problems are solved.

- Time-dependant simulations: Calculations must be divided into small segments to replicate effects over a period. The model performs simulations on these segments, accumulating results. Solar radiation data from weather files is used, usually consisting of hourly averages. Interpolations are made to predict solar position and radiated energy for shorter time steps. Examples where this approach is used include: solar irradiation studies [17], automated shading devices and user behaviour [18].
- Element prototyping: Extremely reflective elements (such as optic fibres or reflective tubes) are difficult to model using current raytracing approaches. The photon map can solve some of these hurdles [26]. Other problems include determining optimal or near-optimal dimensions of a certain configuration. These can be solved by trial and error, through coupling lighting simulation programs with optimization software, use of luminaire design software, or by geometrical approaches [19].

INPUT IN LIGHTING SIMULATION

Data entry methods and abstraction of reality

Input will be defined as the way in which data are taken from reality, and then abstracted for a simulation model to process it. Input methods can influence model behaviour and required output quality. Frequently used methods include: text files, use of command prompt, translators from computer aided drafting (CAD) programs, and graphical user interfaces (GUI) with or without their own CAD system. Each input method has its advantages and disadvantages. Text files use few computational resources, yet can be tedious or complex to understand. GUIs have different degrees of complexity, and need careful development. Software tools with their own CAD systems can take DXF files from other CAD systems. Variations to these GUIs are “plug-ins” for established computer drafting systems [20]. Input methods such as text files and command prompt allow direct manipulation of model variables, while other methods such as GUI input tend to assume variables for the user.

Input methods require abstraction or simplification of reality that can affect results. For example, curves are usually represented through a large number of polygons. Reflectance has to be estimated or weighted for outdoor elements surrounding a scene. Sky models are used to represent the changing nature of daylight, but errors can be introduced, in particular with sunny sky estimations [21].

Methods to produce input from reality

Developments in high dynamic range (HDR) digital photography allow HDR images to be used for scene analysis. Although specialized equipment and software is needed, resulting images allow pixel by pixel study of different lighting metrics [22]. Mainstream lighting, glazing and fenestration systems can be specified without much problem in current simulation models. Customized glazing combinations, based on manufacturers' databases, can be composed for lighting and whole building simulations using programs such as WINDOW 5

[23] or WIS [24]. Other types of systems, such as complex fenestration systems (CFS), require an adequate description of optical properties such as bidirectional transmittance distribution functions (BTDF) [25]. These are determined through laboratory testing with goniophotometers. Elements characterized this way include translucent panels [25], curved reflective blinds [26], prismatic and laser cut films [27]. Virtual goniophotometer software is available, but requires experimental verification [28].

OUTPUT IN LIGHTING SIMULATION

Output

Output will be understood as how model results are conveyed for human interpretation. Output can be divided into two large groups: text-only (quantitative output) and graphical representation (qualitative output). Each lighting simulation tool enables a way to prepare output, such as specifying format of either text or images.

Text-only files frequently contain photometric data from points of a previously defined calculation grid. Results can be exported to spreadsheets or word processors. These external programs manipulate data (e.g. for statistical analysis) or present it (e.g. through diagrams). Data content of text-only files is in most cases, purely numerical and in table format. Accuracy of numerical results can be affected by manipulation of simulation parameters.

Qualitative output is useful for many purposes. Some examples include: lighting preferences by users of different ages [29], assessment of user preferences for luminaire arrangements in offices [30], and simulation of complex visual stimuli for medical patients [31]. Qualitative output can be divided in interactive images, production of images for rendering and images with data interpretation (Figure 2).



Figure 2 Example of lighting simulation output: Images with data interpretation (illuminance contours)

Interpretation of output

Current tools offer a variety of output data, but considerable expertise is needed to interpret results [32]. Few lighting simulation tools offer result interpretation or analysis [1]. Output interpretation should be made fit to user type. These are of two main types: One group consists of architects who are not lighting experts, but study influence of natural and artificial light in their designs. The second group consists of lighting/daylighting researchers and physicists, who are not full time designers but favour validation and verification [33].

LIGHTING SIMULATION WITHIN WHOLE-BUILDING MODELLING

Tools exist for calculation of almost every aspect influencing the design and operation of a building. However, integrated tools currently face many shortcomings in terms of modelling, usage and application. Four approaches exist for whole building simulation [34]:

1. Use of stand-alone simulation tools separately. Results obtained from one tool are translated or applied to another. Used mainly at the urban planning level.
2. Use of interoperable programs, results from one tool can be used directly by another. For example, glazing properties defined by Window 5 database can be imported into EnergyPlus.
3. Coupling separate simulation models at runtime, one model controls the other. For example, Radiance being controlled by ESP-r.
4. Single simulation program, different sub-modules are integrated within a single calculation routine. Examples are TRNSYS and EnergyPlus.

According to [35], lighting aspects influencing energy consumption are: short step variance of daylight, details on building geometry, light transmission through fenestration systems and switch modes of artificial lighting.

Advanced stand-alone lighting simulation programs can model these features with certain detail. However, simplification must be used when it comes to whole building simulation. This is seen when converting building layout to thermal zones, or representing curved surfaces through polygons (Figure 3). Other simplifications apply according to each tool, such as how shading systems are represented [36]. Results provided by leading whole building simulation tools need post-processing and careful human interpretation.

Current whole building simulation models are useful since they can solve simultaneously different problems. More detailed whole building simulation tools provide more accurate results [37]. Their advantage resides not on accuracy of a single simulation run but on comparing different trends. These models can handle climate files containing yearly solar radiation data at different time steps. This facilitates studying an array of complex problems, such as the effect of daylight on energy consumption, behaviour of automated fenestration systems and the impact of energy and visual comfort with automated systems [38].

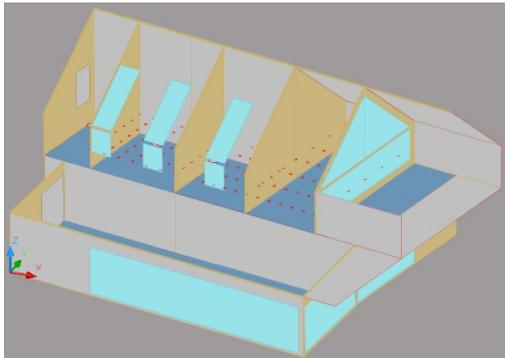


Figure 3 Geometrical simplifications required by whole-building simulation models

LIGHTING SIMULATION AND THE ARCHITECTURAL DESIGN PROCESS

Urban planning

Simulation models exist that suggest volumetric solutions assuring solar access to neighbouring buildings. They can be used for early building design stages and in urban planning. The “solar rights” and “solar envelopes” concepts are calculated by tools such as Sustarc [39], Helios [40], SunScapes [41] and through solar masks [42]. These tools were developed originally for highly luminous climates, where balance must be obtained between shade in summer and access to solar radiation in winter.

Applications include indicating height variety in high-rise complexes [43], which ensures daylight access for lower floors. Urban profiles for high density but with solar access are recommended by the tool proposed by [39]. Proportions of urban squares and urban planting positions can be studied employing the program developed by [44]. Such simulation models can additionally be used to verify construction code compliance.

Early design stages

The vast majority of current computer tools are not suitable for use during early architectural design stages. They require a level of accuracy and detail not known at that time [45]. Few provided analysis [1] or suggested solutions. Models usually produce a single output [46] and are usually meant to be used by lighting experts [47]. During early design phases, architects should compare interactively the outcome of their intentions. Some tools have been proposed for use during these stages, such as Lightsolve [48] and virtual heliodons [49].

Design

Current lighting simulation models can be used after deciding on fundamental issues such as massing, building position, window size and orientation. Examination of artificial lighting layouts is facilitated by tools dedicated to that purpose. Experts are needed to determine maximum performance of specific building components such as glazing and redirecting systems, shades and blinds, and control modes for automated shading and lighting.

SUBJECTS FOR FURTHER EXPLORATION

Input can benefit greatly from improving geometry translation from CAD systems. User interaction should be increased to interpret realistic input and user demands. One contributing element is careful study on user interfaces. HDR cameras could be used to characterize reflectivity and transmission functions of complex fenestration systems. This could replace complex laboratory equipment. Concerning output, it is desirable to

investigate further result interpretation and user feedback. Possibilities for custom output production should be researched, combined with elements known from information visualization.

Explorations in lighting using simulation tools should follow the architectural design process. Early design stage assistant tools can be developed for examination of alternatives improving use of daylight and artificial light. These assistants should help pass seamlessly between different stages of the design process. The level of detail achieved by lighting simulation should be incorporated into whole building simulation. Use of simplified tools to ensure code or certification compliance should be investigated.

Fundamental suggestions for further research include expression, through computational means, of modern light transport models to enable simulation of a wider variety of physical phenomena. Models should be based on human eye response to light and not only mimic it. Improvements are necessary for calculation of dynamic problems in lighting simulation, by means of enhanced representation of occupancy and visual comfort.

CONCLUSION

Rapid advances have been observed in twenty years on lighting simulation for building science. Aspects that have experienced development were: accuracy, number of parameters to calculate, computational times, scenario complexity and connection to whole building simulation. An exception occurs with input and output, where the quality of output is still sensibly affected by manipulation of input parameters.

Radiance remains a widely accepted general purpose simulation engine. Its influence on the literature is extensive, being considered an industry standard. However, care must be taken that focusing on one model does not hinder development of new ones. Specialized tools exist such as those used for artificial lighting design, which are supported by luminaire manufacturers. They tackle interaction between electric and natural light, but less comprehensively than Radiance. Predictive lighting analysis has been incorporated in products such as 3D Studio, although its application is still complex for use by the general design public. Nevertheless, this fact foresees the integration of spatial modelling and comprehensive lighting simulation.

The most implemented geometrical optics algorithms are raytracing and radiosity, with photon map being used in fewer tools. Physical experimentation is required when verifying new elements using principles beyond the capacities of those algorithms. Dynamic behaviour is solved by dividing a time lapse into smaller steps.

Minimum accuracy between measurements and simulation of a built space remains around 20%. Estimating reflectivity from surroundings is difficult and can affect results. Luminance distribution models are used to represent sky conditions, but their features are very abstract. Standardized tests are proposed to validate different models.

Input and output benefit from computational hardware developments. This is true by lowering geometry limits and calculation times. This has turned the focus on improving data entry methods, output customization and result interpretation. Lighting simulation starts to take direct input from HDR images, but at the moment not all models are able to handle it. Better methods are needed to obtain reflectivity and transmittance functions.

Research is needed to increase reliable interaction between lighting and energy models. Complexity handled by lighting simulation should be incorporated in whole building simulation. Nevertheless, their present combination is beneficial for use in multi-variable research such as occupancy and automation studies. A small number of lighting simulation models exists to support the architectural design process. Some of those tools can be applied for urban planning and code compliance. Lighting simulation models require further development in order to truly suggest complete reliable solutions.

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