State of the Art in Lighting Simulation for Building Science: A Literature Review

Carlos E. Ochoa[*], Myriam B.C. Aries and Jan L.M. Hensen

Eindhoven University of Technology, Department of Architecture, Building and Planning, P.O. Box 513, 5600 MB, Eindhoven, the Netherlands

This paper examines the current state of the art in lighting simulation related to building science research. Discussion on historical developments and main modelling approaches is followed by describing lighting simulation within the design process, where it is applied beyond presentation renderings. Works are grouped using the main aspects of a program (input, modelling, and output). Lighting simulation currently focuses on representing accurately a large number of common situations encountered by building designers and researchers. Existing models apply roughly the same theoretical algorithms and calculation aids, limiting representation of certain physical phenomena. Although some models can be used for element design, they are not practical enough to develop or prototype new, untested elements. Elaborate building components require separate analysis through complex simulation aids. Few tools support the early architectural design process. Simplification applies when integrating lighting simulation to whole-building simulation. Input quality affects accuracy, while output needs careful expert interpretation.

Keywords: daylighting; artificial lighting; algorithms; input and output; whole-building simulation; design tools

1. Introduction

Lighting simulation is challenging, due to the strict requirements to represent reality, but at the same time provide different degrees of complexity for diverse users within the same field. As part of its many benefits, it can provide researchers with faster and improved ways to compare more sophisticated results that would have taken long time spans to obtain. It also substitutes bulky energy-consuming equipment and rigid scale models. Designers are able to compare and change project options affected by artificial and natural lighting. Benefits of well-designed natural and artificial lighting are easier to visualize. Lighting simulation allows itself to integrate with the design process and with other types of building simulation.

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[*]Corresponding author. Email: C.E.Ochoa@tue.nl

Although widespread use of computer lighting simulation in building science is approaching its second decade, a comprehensive literature overview does not exist. Comparisons are often made between different models (computer and real-life) in order to verify side-by-side accuracy or features, but these evaluations become outdated as computer programs are modified or fall into disuse. A critical literature review, on the other hand, serves to map developments in the field and advance different aspects. This is important, since lighting simulation is increasingly becoming 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 who did not use any daylight prediction software had dropped to 21% (Reinhart and Fitz 2006). This percentage might reduce even further, as architectural and engineering students become familiar with computer modelling during their education (Pentilla 2003). Lighting simulation usage will also increase as result of newer, complex construction codes and certifications requiring sophisticated ways to demonstrate compliance (de Wilde and Prickett 2009, Ibarra and Reinhart 2009).

This paper examines current state of the art in lighting simulation related to building science research. A section is dedicated to its use in the architectural design process, since lighting simulation is widely applied beyond presentation renderings. Works are grouped using a scope related to the main aspects of a program (input, modelling, and output). Unified criteria such as algorithm or output type can be applied to evaluate many models, despite differences in intended usage or current capabilities. The approach is adapted and modified from business simulation tools studies (Bosilj-Vuksic *et al.* 2007). General evaluation criteria presented by these authors were used, but modified in order to highlight relevant features of lighting simulation. Although this review has a bias towards daylight analysis (due to the complexity in depicting it), models for artificial lighting design are also represented.

Literature sources come from searches of citation databases (such as Scopus, ISI Web of Knowledge or Google Scholar), and websites related to lighting simulation. Descriptions and verifications of lighting models were examined. Additionally, applications and comparison of those models under different research contexts were taken into account.

2. Lighting simulation
2.1 Historical Developments

Prediction of light behaviour is ideal for calculation with computers. Formulas stating it take considerable time to solve by hand. Complexity grows proportionally to that of the scene being computed. Certain repetitive applications, such as design of electric lighting installations in closed rectangular rooms, were among the first to take advantage of computer calculation. Some of the first programs for that purpose can be traced back to the 1970s (Hirata *et al.* 1999). Attempts were being made in that same decade to integrate daylight and artificial lighting calculations in fixed conditions using simplified formulas (Plant and Archer 1973). Output was primarily numerical in nature.

Around the same years, computer graphics experienced dramatic advances that would have remarkable outcomes during the 1980s. Researchers developed computer methods that improved calculation and representation of light falling on arbitrary volumes (Nakamae and Tadamura 1995). Being based on light transport and material properties, these calculations were not restricted to a single scenario. Results could be extracted as numerical data or as images with resemblance to reality. A separate computational field was developed: "physically based rendering" (Kniss *et al.* 2003). Some applications with direct benefits from these improvements are cinematography, architectural representation and lighting research. However, fully realistic, accurate calculations proved to be computer intensive, complex to define, and carry implicit limitations (Wilkie *et al.* 2009). This limited early lighting simulation programs to simple geometries, no daylight or energy evaluation, and inaccurate output of only a few parameters (Svendenius and Pertola 1995). Although these aspects are addressed by contemporary models, the formulation of calculation-efficient algorithms solving the "global illumination problem" continues to be a work in progress (Ulbricht *et al.* 2006).

Lighting simulation can still be divided into two main areas, even though they mutually benefit from developments in each of them. The first one is photorealistic rendering, involved with production of artistic images. The second field, and focus of this review, is physically based visualization (also known as predictive rendering). It deals with accurate representation and prediction of reality under given conditions and following physical laws (Ward and Shakespeare 1998, Moeck and Selkowitz 1996).

2.2 Modelling

2.2.1 Lighting Simulation Algorithms

Algorithms are a finite and precise sequence of instructions. They are applied in simulations to solve lighting distribution problems in order to combine effectively different physical formulas.

a) Algorithm Development

A detailed description of principles and developments of lighting simulation algorithms is given by Dutre *et al.* (2006). It forms the basis for this section, and is suggested for further reading. According to these authors, modern physical models explaining light transport in all types of media (such as quantum optics) are too complex for computer calculations and image generation. Instead, a simplified model of geometrical optics and energy conservation is used, from which physical formulas are known. This model can solve most illumination problems with different light sources and provide numeric results for the simulation space. However, difficulties are encountered when diffusing or refracting media are involved (such as advanced optical materials). It also assumes a steady-state light distribution. Differences between measurements and simulations in specific modelling contexts might be accounted due to these restrictions.

Implementation of the geometrical optics model to solve the global illumination problem was gradual. Hurdles were posed by calculating surface reflectivity according to material. They can be represented through different sub-models, which specify their bidirectional reflection distribution functions (BRDFs). First application steps were taken in computer graphics, but outcomes were limited to colour assignment (rasterization) and hard-shadow determination (Pineda 1988). Later the two most popular illumination algorithms in use today, raytracing and radiosity, were introduced.

b) Lighting simulation algorithms and calculation aids

An earlier account on daylighting simulation algorithms and resources was given by Carroll (1999), as an inventory of methods for complete analysis tools. At this moment, lighting simulation algorithms can be classified into three types. These are direct calculations, view-dependent algorithms, and scene-dependent algorithms. Contemporary models are able to use one or a combination of them. Although certain phenomena are difficult to compute by these

approaches alone (fog, special diffusing materials, etc), approximations to represent their effects exist (Kniss *et al.* 2003, Dutre *et al.* 2006).

•*Direct calculations* are used for lighting directly from light sources. These sources can be the sun, daylight openings (total of sun and sky contribution), or luminaires. The term is used mainly in the text to link models involving luminaire design and calculation. They involve specific physical formulas and simplifications. They are often delineated in different national standards and cover most usual situations. A well-known example is the lumen method.

•*View-dependant algorithms,* such as raytracing, are classified according to the direction from which rays are computed by the model in a scene. Rays are traced from the light source (forward tracing) or from the observer's eyes (backward tracing) or both ways (Lafortune and Willems 1993). This makes it an image-bound method. It provides a way to compute light phenomena from direct illumination, specular surfaces and reflections. However, limitations exist when computing multiple diffuse reflections or indirect lighting effects.

•*Scene-dependent algorithms* such as radiosity were adapted from heat transfer techniques into lighting simulation (Willmott and Heckbert 1997). They have the advantage of being a scene-based method. The scene can be divided into surface elements. Radiometric values are determined for each surface, independently of the view. One of its weaknesses is the inability to handle well specular reflections (*idem* 1997). Refinements to the model were introduced through surface meshes. In this way, umbras and penumbras can be calculated (Wang *et al.* 1992). Due to more complex calculation formulas, the method is used chiefly for lighting calculations than for image generation. New developments are underway to reduce load on hardware and make it more efficient (Wang *et al.* 2009).

Other scene-dependent algorithms are known as integrative approaches. They are considered among the most efficient and accurate to calculate the global illumination problem since they combine both raytracing and radiosity through different methods. The first integrative approach was first stated as an algorithm by Kajiya (1986). The Radiance model (Ward and Shakespeare 1998) uses a method combining backward raytracing and bidirectional distribution functions. A detailed description on the Radiance calculation method is found in (LBL, 2010d).

The photon map (Jensen 1996) is another integrative, scene-dependent model that uses multiple passes. In it, packets of energy (photons) are sent to surfaces involved. Results are stored per simulation scenario, while raytracing and surface radiance are also applied. The photon map is useful to calculate accurately caustics and occurrences related to light concentration.

• *Calculation Aids:* For practical implementation of these algorithms in modern computing systems, statistical sampling must be used in order to obtain values in an acceptable period. Deterministic methods exist for classical numerical approaches (Lafortune 1995). However, the most widely used techniques are known as Monte Carlo methods. They are popular since the approach assumes that the expected value of the sample is the correct value for that sample. Once estimates are found, an average of estimates can be performed to complete the problem. This can provide accurate results, but algorithms must run for enough time to take many samples. Some areas can be left without any values (referred as "noise") and correctors have to be introduced (Kniss *et al.* 2003). Monte Carlo techniques have accuracy limitations, but sometimes are the best way to solve certain physical problems (Dutre *et al.* 2006).

A summary on lighting simulation algorithms is given in Table 1. An illustration of the basic principles of three main algorithms is given on Figure 1.
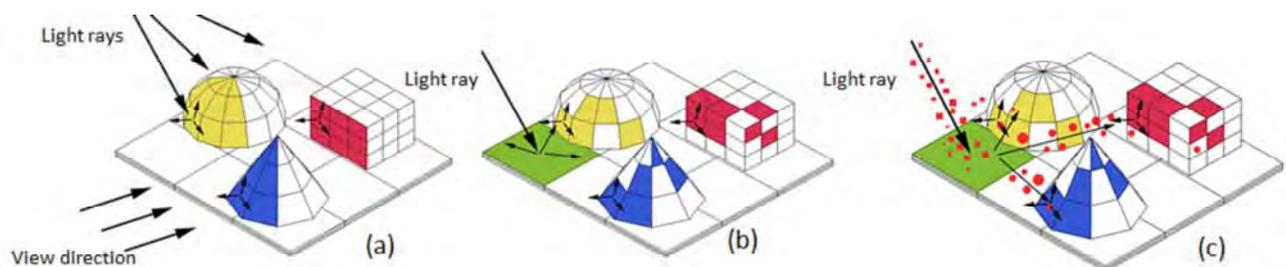

Figure 1. Schematic pinciples of three commonly used lighting simulation algorithms: (a) raytracing (b) radiosity (c) photon map

Algorithm	Value
View-dependent	-forward ray tracing -backward ray tracing -bi-directional ray tracing
Scene-dependent	-radiosity -photon map -Integrative approaches -Multi-pass approaches
Direct calculation	-for artificial lighting, follows national standards
Calculation aids	-deterministic methods (classical approaches) -statistical sampling methods (Monte Carlo)

Table 1. Lighting simulation algorithms currently available

2.2.2 Current lighting simulation tools

The United States Department of Energy (USDOE) maintains a list of simulation tools (USDOE, 2010a), which includes a short description of their capabilities, weaknesses and strengths. Some of these tools are dedicated to lighting, while others integrate it within whole-building calculations. The list is not exhaustive, but gives an overview of the variety available. A brief overview of current models in the context of usage in zero-energy building design, usage and limitations is provided by Guglielmetti et al. (2010).

This review will refer to current models mentioned in English-language literature only. This section in particular will be dedicated to models used primarily for lighting simulation in building science. It also does not pretend to be an exhaustive list of every model or their features. Whole-building simulation tools will be discussed in its respective section.

From the online list presented by USDOE, the most influential model among the lighting simulation research and computer graphics communities continues to be Radiance (Ward 1994, LBL 2010a). As a measure of its influence in the literature, conference proceedings by Ward (1994) have been cited 529 times according to Google Scholar. The book by Ward and Shakespeare (1998) has recorded 294 citations in the Scopus database. Radiance was among the first to generate calculation results for a fixed viewpoint, using as input data three-dimensional geometrical description of a scene and physical properties of its materials. It has also advanced some of the current calculation techniques available in most lighting simulation models (Ward *et al.* 1988)

Compared to similar software packages, Radiance has many "non-attractive" characteristics. For example, it lacks a user interface of its own and needs considerable expertise to manipulate its variables. Nevertheless, it continues to be favoured by the lighting research community (Reinhart and Fitz 2006). This can be partly explained by features such as: it is intended for building research (instead of imaging only), is flexible to solve a great majority of natural and electric lighting simulation problems, is freely available, and is distributed under an open source agreement (LBL 2010a). The open source nature allows contributions from researchers themselves and model continuity (Ward 2002). It is also one of the few models validated extensively (e.g. Grynberg 1989; Mardaljevic 1995, 2001 and 2004; Ng 2001; Reinhart and Herkel, 2000; Reinhart and Walkenhorst 2001; Reinhart and Andersen 2006). It has presented consistent results in terms of accuracy within acceptable limits, according to test situation. Radiance has been incorporated as a limited lighting simulation engine within other tools, such as ADELINE (FIBP 2002, unsupported), Desktop Radiance (LBL 2000, unsupported), Rayfront (Mischler 2003, unsupported), Daysim (NRC 2009) and RadianceIES (IESVE 2010). However, the use of programs known as virtual machines and in software programming as "porting", create self-contained and system-independent operating environments. They behave like an operating system within another operating system. This type of software allows programs written in one platform to be used in a different one. It has allowed users to run Radiance within its native UNIX environment with comparable results.

Apart from the continuity presented by Radiance, many tools emerged –and fell in disuse– during these last twenty years. Some others remained in test stages. Among the chief

products in use today, commercial software like AGi32 (Lighting Analysts 2010) is mentioned. Distributed mostly in North America, it can perform electric lighting and daylight performance analysis (Reinhart *et al.* 2006). For this purpose, it uses photometric data files and has many standard CIE sky models. Direct calculations are mainly used for lighting fixtures. Radiosity calculations are used for complex or daylit scenes. Limited raytracing analysis is used for daylight and small surfaces. The user can decide to use backward or forward raytracing at the same time. Raytracing is chiefly used in this model to generate renderings.

Similar in scope to the previous program is DIALux (DIAL GmbH 2010). It is widely used for calculation of indoor and outdoor electric lighting systems. It follows different national standard lighting calculations, and can import directly photometric databases from manufacturers. There are some daylight calculation capabilities, using German standard DIN 5043 and CIE Publication 110. Geometrical input is limited to certain shapes. Sky choices are somewhat limited but acceptable for diverse range of weather conditions. There is an external radiosity and raytracing model, POV-Ray (Persistence of Vision 2010). It is used to produce images from calculation results and for presentation renderings. DIALux is available free of charge but is not open source. Some noteworthy scientific studies that used DIALux include determining criteria for energy efficient lighting (Ryckaert *et al.* 2010) or simulating luminaire arrangements for a study of patients suffering dementia (van Hoof *et al.* 2009).

Relux (Relux Informatik 2010) is also used primarily for electric lighting design, and includes links to photometric databases from manufacturers. It is oriented to German-speaking and European markets. It calculates lighting arrays, daylighting, and some energy consumption data. Calculation for each aspect can be made separately, or in a combined mode. A radiosity and a modified Radiance raytracing algorithm are used, although the user can decide to incorporate them into calculations. The raytracing module is also used for rendering. Its accuracy has been validated by Maamari *et al.* (2006a). It has been used to evaluate comfort conditions of traditional architecture (Ruggiero *et al.* 2009), and to provide an electric lighting basecase for comparison with daylighting systems (Linhart and Scartezzini 2010). Relux is also free of charge, but not open source.

Another commercial model available is Inspirer (Integra, 2010). Distributed mainly in Japan, it is used for architectural and industrial design analysis. It employs bidirectional

raytracing. Limited validation has been performed on its accuracy (Drago and Myszkowski 2001; Khodulev and Kopylov 1996). These tests showed acceptable results. The program generates high quality images.

In 1997, Autodesk acquired Lightscape (a simulation tool based on radiosity) and used it in many rendering products. However, recent packages from this company currently incorporate the *mental ray* simulation engine (mental images GmbH, 2010). This engine can also be found in other industrial prototyping software. It uses the photon map algorithm together with calculation principles similar to radiosity and raytracing. It can interpret a wide range of CAD surfaces and shapes. Illuminance Engineering Society (IES) luminance data for luminaires are supported. This has allowed Autodesk products to include building analysis functionality in products such as 3D Studio Design (Autodesk, Inc 2010a). A comparison between the mental ray engine within 3D Studio and Radiance in its original raytracing and radiosity algorithm has been made (Reinhart and Breton, 2009) with good agreeable results between these two simulation models. A Radiance version exists which incorporates photon map algorithm functionality. This version, however, must be installed separately (Schregle 1998, 2004; Wienold 2008).

A recently available tool is the Velux Daylight Visualizer (Velux 2010). It has been developed and validated against CIE test cases (Labayrade *et al.* 2009). The tool incorporates Jensen's photon map model, as well as bidirectional ray tracing. As the tool name implies, it is dedicated to daylight analysis only. It admits to having many limitations such as geometry, but has an intuitive modelling approach. This is done by restricting the number of variables the user can modify. Once the tool is matured, most likely it can be anticipated for use in conceptual architectural design stages.

From the tools described above, it can be seen that Radiance remains the "general purpose" lighting simulation tool. Other packages implement similarly advanced algorithms, such as radiosity or the photon map. Tools dedicated to artificial lighting layouts use advanced algorithms only as supplement to direct calculations when diffuse daylight is involved. Direct calculations are needed to demonstrate compliance with local building codes, and daylight has limited scope within them.

A summary of characteristics discussed in this section is given in Table 2:

Tool	Algorithms used	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 principles -raytracing principles	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 Radiance follows forward raytracing and photon map models			

Table 2. Summary table of current lighting simulation tools. Note: this table does not pretend to be exhaustive.

2.2.3 Accuracy validations and model comparisons– an evolution

A natural outcome when many simulation models are available is to compare them. Evaluations presented in the literature 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 between results obtained through each method due to intrinsic methodological limitations, as will be discussed in section c).

a) Validations using built realities

Most comparisons under this category examine lighting simulation models for use by architects in the production and evaluation of designs.

Roy (2000) provided a classical, comprehensive study of programs available at that time. The author examined features, ease of use and applicability to design contexts against the "ideal rendering package" for architectural use. A similar study was conducted by (Christakou and Amorim 2005) for the Brazilian context.

Ubbelohde and Humann (1998) studied four programs for use in daylighting studies (Radiance and three programs now discontinued: Lumen Micro, Super Lite, and Lightscape). They found that results are affected by choice of sky model and input detail. They simulated two floors of an existing San Francisco building with an atrium. A physical model was an additional benchmark. However, their choice of simulated skies was deliberately simplified, differing from existing weather conditions at measurement time. Input was more detailed for Radiance and Ligthscape than for the other programs. Therefore, these two followed more closely real measurements.

Ashmore and Richens (2001) also studied four simulation programs (ADELINE-Radiance and three programs now unsupported: Lightscape, RadioRay, and Microstation 7). A scale model under two artificial overcast skies was used as benchmark. Programs had to replicate real-life measurements of a small room next to a very large courtyard, using reflectances from

the model. Simulation programs gave good results except close to the window. These authors acknowledged their scale model and choice of two artificial skies were error sources.

Ochoa and Capeluto (2006) replicated in Radiance a meeting room located in Israel, under summer conditions. Using published meteorological solar data for the location, they compared physical measurements against simulation results under three sky types: CIE clear, Perez All Weather Model (Perez et al, 1993) and CIE intermediate. It was found that for the specific geographic and weather conditions the best sky model was CIE intermediate sky, although atmospheric factors such as turbidity were unknown.

Ng (2001) found that choosing correct reflectances affect simulation results. Desktop Radiance and Lightscape were used to analyze heavily obstructed spaces in Hong Kong. Measurements were taken inside test spaces, and compared with computer models. Sky model was overcast, generated using local meteorological data. Large relative errors were reported. Mardaljevic (2004) explained these errors from reflectivity estimation of surrounding surfaces, which played a significant role. Ng *et al.* (2001) modelled an isolated Singapore museum under overcast conditions. In that case, simulation followed closely daylight measurements. According to Li *et al.* (2004), furniture reflectances in a Hong Kong classroom also affected accuracy results.

Drago and Myszkowski (2001) tested a rectangular atrium of complex detail located in Japan. They compared Inspirer with physical measurements. The highly glossy atrium surfaces required determination of BRDF functions for diverse materials. Good agreeable trends were obtained only for the atrium centre line but not for reflective surfaces. They found that observers favoured pictures generated with "artistic" settings in the program over those generated using realistic measurements. This finding agrees with (Apian-Bennewitz *et al.* 1998, Maunder *et al.* 2001).

Galasiu and Atif (2002) compared LBL programs Adeline, Radiance, and Superlite to assess the impact of daylighting in a real-life atrium of polygonal plan located in Canada. They found that, for certain cases, simulation models do not estimate well direct sunshine. They took measurements for clear and overcast conditions at three different levels. Localized disagreements were found between reality and modelling. In particular, there were overestimated values for

direct sunshine. Li and Tsang (2005) used Radiance to predict electric lighting savings on a corridor, based on estimated illuminances.

The above-mentioned examples of validations demonstrate how models were applied to different situations encountered by building designers and the type of data they work with. They also stress that models must respond to user requirements regarding program manageability while providing adequate representation of reality.

b) Validations under controlled laboratory settings

Comparisons under controlled settings were performed, in most cases, to demonstrate model accuracy in predicting illumination data.

Mardaljevic (1995) successfully validated Radiance for a set of clear and overcast sky measurements in a room with three fenestration systems. This work was extended to validate Radiance through the BRE dataset of test conditions (Mardaljevic 2001).

Khodulev and Kopylov (1996) compared Lightscape, Radiance, and Specter (from the developers of Inspirer) tools against theoretical results for a cube of known dimensions but rather simple properties. All models had close approximation to theory.

Fontoynont *et al.* (1999) performed the first standardized tests for simulation tools, under the framework of IEA-SHC Task 21. Tools were tested against an atrium with variable surface finishes. Benchmarks were scale models. It was found that quality of input data is influential. Careful manipulation of simulation parameters influenced accuracy. Models at that time were found to be time-static. The work of Task 21 was continued by Maamari and Fontoynont (2003), who developed a set of test scenarios. These would serve as the basis for the CIE test cases (Maamari *et al.* 2006a). They were demonstrated by comparing two light simulation tools, one for general rendering and another for electric lighting design.

Reinhart and Walkenhorst (2001) undertook Radiance validation of a very large number of sky conditions in order to develop a dynamic simulation method. This test was applied to a specific full scale model with external blinds. Reinhart validated Radiance and 3D Studio

(mental ray photon map) using a new dataset to test common devices such as lightshelves and curved blinds (Reinhart and Breton 2009).

Schregle and Wienold (2004) used an experimental test box for their validation studies. Photometric measurements were acquired, such as surface illuminances and BRDFs. The artificial light source had known properties. Its contents were photographed in high dynamic range format (HDR). Results were compared with simulations using Radiance and photon map algorithms. A high degree of accuracy was reported. The method was extended to two built cases (single window opening and lightshelf).

Validating models under controlled conditions serve developers to test algorithms under reduced uncertainty. They should be undertaken during preliminary phase before incorporating it to a full simulation model.

c) Standardized comparison methods

Comparing lighting simulation tools might seem a simple method to rank or choose among them. In practice, the outcome is affected by many factors. Maamari and Fontoynont (2003) mentioned that replicating built realities or scale models introduce uncertainties. These include measurements, geometry and photometric properties of materials (such as lamp depreciation and surface reflectivity). For daylighting simulations, hourly data of high quality are not available to most locations in the world (David *et al.* 2010). On the other hand, testing computer programs under pure laboratory conditions ignores normal building activity (Galasiu and Atif 2002).

In order to overcome the above difficulties, there have been propositions to standardize comparison methods. One first approach was the Cornell box (Goral *et al.* 1984), used to validate the earliest rendering algorithms. The method has the disadvantage of being primarily for visual comparison (Ulbricht *et al.* 2006). BRE proposed a dataset based mostly on daylight performance under specific situations (Mardaljevic 2001). CIBSE proposed a series of tests limited to artificial lighting (Slater and Graves 2002). The CIE proposed a series of test cases to be used as benchmarks (CIE 2006) based on work by (Maamari and Fontoynont 2003, 2006). These test cases try to include the widest range of possible variations simulation software might

encounter, yet keeping it simple and replicable. The cases include both artificial and natural light, and diverse types of surfaces.

d) Accuracy levels

Despite the push to test simulation models under standardized conditions, no definitive agreement exists on an "acceptable" degree of accuracy. Errors exist in physical measurements of artificial lighting (Moore 1980) and daylighting (Hayman 2003). Concerning lighting simulation, CIE estimated (Fisher 1992) 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. The value of 20% for use in real cases has been validated by Reinhart and Andersen (2006). This value has appeared in studies replicating built realities. Galasiu and Atif (2002) report up to 20% variation between simulated and measured indoor values but large differences for areas under direct sun. Milone *et al.* (2007) measured and predicted illuminance levels for different floors of a building in a compact urban setting. For lower floors, with less direct daylight, the difference was around 5%. For upper floors, with more daylight, this was around 20%. The main implication of over or underestimation, lies on calculating energy savings from electric lighting systems shutting off at certain illuminance levels.

The measured point value error range can be applied to individual element modelling. Dobrre and Achard (2005) simulated a light pipe using optical analysis software. Variation from measurements was about 7 to 15%, with largest errors close to the pipe emitter.

Validations under laboratory conditions do not consider uncertainties introduced by including users or surroundings. They should yield accurate results within single digit percentage. This is achieved by using dedicated equipment to control measurements, and careful manipulation of simulation parameters. For example, Schregle and Wienold (2004) report 7% and 2% differences between measurement and simulation results.

Table 3 summarizes validation methods presented, together with disadvantages and accuracies.

Criteria	Method	Value	Disadvantages	Reported Accuracy
Model verification	Replicate Built realities	-tests on buildings, live measurements	-hard to replicate elsewhere -hard to replicate geometry -hard to replicate sky conditions -hard to replicate reflectances	5-20%
	Laboratory tests	-controlled settings -CIE test cases -element testing	-detaches from model usability -can be done only with specialized equipment and data	2-7%

Table 3. Lighting simulation validation methods.

2.2.4 Approaches to Solve Different Lighting Simulation Problems

Assumptions of current lighting simulation algorithms regarding steady-state and geometrical distribution can affect how certain problems are solved. They include time-dependant simulations (to study user behaviour and responsive elements), modelling of new untested components, and multiple simulations for performance (prototyping). Time-span calculations must be divided into very small segments to replicate effects over a period. Therefore, a different approach is required.

a) Dynamic vs. static

As mentioned in section 2.2.1, simulation algorithms assume light distribution occurring in a steady-state. This can be a correct assumption for a large number of cases. For problems involving daylight, dynamic behaviour of light must be considered. Examples are yearly irradiation studies, occupant response to changes in light quality, and dynamic shade elements.

Irradiation studies: A common approach is to divide the time-span into small segments of available data. The model performs simulations on these segments, accumulating results. This is typically accomplished by using solar radiation data from weather files for a location (usually hourly averages). Interpolations predicting solar position and radiation have to be made for shorter time steps as allowed by the weather file (Walkenhorst *et al.* 2002). Examples of tools producing cumulative solar radiation maps using such principles are Radmap (Anselmo 2008) and GenCumulativeSky (Robinson and Stone 2004). Radmap is used within Radiance to calculate solar irradiation and illuminance maps, over imposed on a model view. It uses weather data files in EnergyPlus (USDOE 2010b) and SatelLight formats. These programs can help determine best orientations for photovoltaic panels, shading devices, etc (Compagnon, 2004).

Automated blinds and shades: Many studies have been done on simulating blind deployment triggered by external and user factors. Some examples studying activation due to weather factors are: Daysim tool for annual daylight availability and influence of automated lighting controls (Reinhart and Walkenhorst 2001); daylight responsive dimmer for electric lighting (Athienitis and Tzempelikos 2002); automated blind control for user comfort (Wienold 2007, 2009; Koo *et al.* 2010); energy consumption triggered by luminaire dimming and occupancy sensors (Roisin *et al.* 2008); considerations of multiple variables for adequate controller modes (Daum and Morel 2010).

Traditional shading studies are focused on response to solar penetration for specific times of the year. Mardaljevic (2003) proposed a method based on total yearly irradiances, using typical reference year (TRY) data. It is useful for analyzing multiple "on/off" openings. Variable angle blinds have been simulated by Mahdavi *et al.* (2005). Ecotect can use data from and to Radiance, which can then use it to produce shading masks and analyze facade cover (Marsh 2005). Daylight evaluations of different dynamic shading elements for a tall building have been performed by Tzempelikos *et al.* (2007).

User behaviour: Occupant activities and interaction within a building will affect total energy consumption, but few models consider how each parameter is affected by these activities (Hoes *et al.* 2009). Regarding lighting simulation, interaction studies are focused on shade activation and light switching. Algorithms based on real office studies were used to predict light switching, window opening and blind closing correlated to time of year, temperature and number

of occupants (Reinhart 2004, Herkel *et al.* 2008, Lindelof and Morel 2006, Bourgeois *et al.* 2006).

b) Design of new elements

Even though predictive rendering follows physical laws, not every physically possible element can be simulated with it. This is particularly true for elements using principles not covered by the geometrical optical model, such as light concentrators. In addition, calculation methods used by algorithms make it difficult to characterize certain components. Backward raytracing and geometrical factors using the original formulation of the Radiance model, for example, make it hard or even impossible to model complex curved and specular surfaces (Ward and Shakespeare 1998). Highly reflective objects such as thin light pipes and optic fibre are best modelled using the photon map approach (Farrel *et al.* 2004) even though large diameter light pipes are still handled well (Mohelnikova and Vajkay 2008). It is logic to think that new developments are under way, at the time of writing, to provide a reliable method of simulating these elements through improvements to the Radiance model.

For an adequate description of optical properties through the current geometrical optical model, certain elements require laboratory testing with goniophotometers. BRDF and BTDF functions are determined, as in translucent panels (Reinhart and Andersen 2006) and many complex fenestration systems (CFS). A specific discussion is given in section 3.1.3.

c) Element prototyping

In order to find optimal or near-optimal element sizing, certain parameters must be changed multiple times. To achieve this, many researchers had to perform trial-and-error simulations (e.g.: Joarder *et al.* 2009, Li and Tsang 2008, Reinhart 2005, Capeluto 2003).

Optimization software is the best approach to use when the number of test parameters becomes too large. However, considerations must be taken on type of optimization algorithm, connectivity with optimizer software and input accepted by the lighting simulation tool (LBL 2010b, Esteco 2010). Optimization studies have been applied to facades, due to their complexity and influence on energy and daylighting. They include smart facade optimization (Park *et al.* 2003), lighting controllers (Guillemin and Morel 2001), visual discomfort and solar penetration

(Torres and Sakamoto 2007), external horizontal shading devices and their angles (Manzan and Pinto, 2009), and "random" placement of windows for minimal energy use (Wright and Mourshed 2009).

Alternatives to optimization software are possible. Luminaire design software has been used to optimize length, width and geometry of a highly reflective light pipe (Dutton and Shao 2007) and a daylight collector (Wittkopf et al. 2010). Ray-by-ray analysis of luminaire design software offers possibility to analyze certain complex fenestration systems involving high reflectivity (Breault Research Organization Inc 2010, Optical Research Associates Inc 2010). External shade elements can be optimized through purely geometrical approach. Tools illustrating this purpose are Sunshades (Shaviv1984), which presents geometry according to number of fins, and Winshade (Kabre 1999). Another approach was enabled by performing rapid estimates of illumination levels (Lehar and Glicksman 2007). This allowed use in early design stages. A summary of how different lighting simulation problems are approached is found in Table 4.

Criteria	Classification	Value	Examples
Approach to solve diverse problems	Dynamic simulations	-division into small time steps	-irradiation maps -automated blinds/sensors -movable shading devices
	Simulation of new elements	-limits posed by optical model -laboratory tests to determine behaviour	-optic fibre simulation -light pipe simulation
	Element prototyping	-use external optimization program -use shadowing studies interactively	-luminaire design software -nomogram (sunshades)

Table 4. Resolution of diverse lighting simulation problems

3. Input and Output

3.1 Input
Within the context of this study, input will be understood 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 desired output quality.

3.1.1 Data entry methods and guidance for input
Frequently used methods include: text files, use of command prompt, translators from computer aided drafting (CAD) programs and graphical user interfaces with or without their own CAD system. Each input method has its advantages and disadvantages. Text files provide a method of sharing input data that can be edited easily and with few computer resources (Ward and Shakespeare 1998). They can be modular in nature, separating different aspects of the simulation scenario. However, many users have expressed that exclusive use of text files as input is tedious (Roy 2000), time consuming, and error-prone (Huang *et al.* 2008). This makes mistakes in simulation hard to trace, restricting their effective use to experts. Command prompt entry is used mostly to provide instructions to the simulation engine (Ward and Shakespeare 1998).

An alternative to composing text files or entering commands is given by graphical user interfaces (GUIs). They can be integrated within the simulation model itself, or be a "front" to other models. This provides improved control over them. Examples are "trad" shell (Ward and Ousterhout 1996) and RadianceIES (IESVE 2010). Interfaces offer different degrees of sophistication. The "trad" interface, for example, manages certain aspects of the simulation process but offers no geometrical composition. Other interfaces offer this management through complex sets of menus (Autodesk, Inc 2010a). Drag-and-drop elements and connection to manufacturer databases is becoming common to electric lighting design programs (Lighting Analysts 2010, DIAL GmbH 2010, Relux Informatik 2010).

A model that is to be implemented on modern interactive operating systems has to consider having a GUI for wide use. It was found by Reinhart and Fitz (2006) that researchers tend to learn models by themselves. This makes the use of GUIs appropriate for use according to degree of expertise. Another point in favour of GUIs is that they can provide guidance for input. Options on the screen can limit values to physically possible ones or those avoiding errors within

the program (Velux 2010). This gives less guesswork about "correct" numbers. Such guiding interfaces are usually destined for large, design-centred audiences. They are found within luminaire planning programs and some CAD translators.

Restrictive GUIs, on the other hand, tend to mask variables from the user. They can also limit definition of new but possible variables. One example is adding a new sky model. This could affect development of new solutions. The disadvantage to any GUI, as complete as it might seem, is that they must be kept up to date and with certain logic that can be followed by end users (Galitz 2007). Developing an interface can take time in itself and needs extensive testing.

Some lighting simulation models such as AGi32, Relux, Inspirer, and DIALux include their own CAD system to compose a scene for simulation. Material properties and translation of the geometry is done internally within that model. In many cases, they can import files from other CAD programs. Those are not the only ways to provide input to a model from a drafting source. Translators exist that prepare CAD files for use in other models. Ecotect (Autodesk, Inc 2010b) and RadianceIES prepare a scene for use under Radiance. They can also take DXF files as input. Variations of these translator programs are "plug-ins", extensions working within CAD programs. One current example is the "su2rad" plug-in (Bleicher 2009) for use in Google Sketchup, which also prepares a model for use under Radiance. This follows the now disused Desktop Radiance that could work within AutoCAD. A number of CAD translators are mentioned on the Radiance website (LBL 2010a). These also fell into disuse, partly due to changes in the structure and output of CAD programs.

3.1.2 Abstraction of reality for input

Even if different models attempt to be physically accurate, simplifications have to occur to keep calculation times reasonable. Complex curves and surfaces were represented first through interpolations, and later as polygon-based elements (Pauly *et al.* 2006). Using recent computer hardware, the number of arbitrary polygons and surfaces that can be entered in any given model is unrestricted or very large. However, the degree of simplification used for surface input can

affect simulation results of geometry-dependent devices (Greenup and Edmonds 2004, Ochoa and Capeluto 2006, Reinhart and Breton 2009, Freewan 2010).

Physical properties of isolated surfaces, such as reflectance, can be determined from accurate laboratory experiments. These results can be applied to indoor surfaces composing an interior space. On the other hand, determining reflectance of composite surfaces located outdoor of the simulation space presents a different problem. Influential items such as surrounding ground and facade reflectivity can at best be estimated. Weighted estimations introduce large result variations (Ng 2001, Mardaljevic 2004, Ibarra and Reinhart 2009).

Due to the changing nature of daylight, deliberate simplifications are made through sky luminance distribution models. This introduces in itself simulation errors. The amount of divergence can be determined using instantaneous measurements both in and outdoors (Mardaljevic 1995, 2001, 2004). However, measured data for validation might not be available to all researchers or model users (Mardaljevic 2004). Care must be taken with data accuracy, in particular under sunny conditions (Hayman 2003).

Problems are still encountered when producing data exchange from CAD models into separate lighting simulation models (Ward 1994, Roy 2000). They relate to conventions each program uses to export surfaces and how these are recognized in the target simulation model.

3.1.3 Direct input from reality

In recent years, two systems have been developed to couple direct input from reality into lighting simulation models. The first is use of photography to reconstruct a scene in a digital model, and the second use of HDR photography for scene analysis. These methods were proposed by Debevec *et al.* (1996, 1997). Regarding HDR input, hardware cost might still pose a problem for widespread use. For reliable results, a high-quality digital camera with options for multiple exposures needs to be calibrated in a specialized laboratory. Specific lenses and processing software are also needed. However, resulting images allow pixel-by-pixel study of different lighting metrics (Inanici 2003). Applications include analysis of different real life mock-ups and their digital counterparts (Inanici 2005).

Current simulation models provide specification methods for mainstream glazing and fenestration systems. Customized glazing combinations, based on manufacturers' databases, can be composed for lighting and whole building simulations using programs such as WINDOW 6, (LBL 2010f) or WIS (Windat, 2006). On the other hand, innovative materials and light redirection systems are harder to model. Complex fenestration systems (CFS) differ from conventional systems in their optical properties. These are determined using specialized equipment such as goniophotometers (Andersen *et al.* 2001). Properties sought are bidirectional transmittance distribution functions (BTDFs) and bidirectional reflection distribution functions (BRDFs) (Andersen and de Boer 2006). Laboratory measurements can then be translated as functions for use within lighting simulation models (de Boer 2006).

Elements characterized this way include curved reflective blinds (Andersen *et al.* 2005), translucent panels (Reinhart and Andersen 2006), prismatic and laser cut films (Thanachareonkit *et al.* 2006). Controlled tests and lighting simulation results have good agreement (Maamari *et al.* 2006b). Yet, limitations remain when determining BTDFs and applying them to lighting simulation. Physical modelling under real skies remains the most reliable source of experimentation with CFS (Thanachareonkit and Scartezzini 2010). It can also be assumed that parameter variations in a CFS would require separate laboratory tests. This limits the method to researchers with access to that equipment. An alternative is virtual goniophotometer software, but these types of simulation always need experimental validation (Mitanchey 2002, Krishnaswamy *et al.* 2002). Input features in lighting simulation models can be summarized according to the criteria presented in Table 5.

Criteria	Classification	Value
Data entry	Data entry method	-Text file -CAD input -CAD translator -GUI -Drag and drop
	Direct Data entry from reality	-HDR pictures -Translation from goniophotometers
Abstraction of reality	By model	-Surface simplification -Translation of surfaces from CAD input -Sky model simplifications
	By model user	-Reflectance estimation in complex settings
Description of lighting and daylighting system	Conventional system	-Methods within model available to specify them
	Non conventional system	-Laboratory tests to determine behaviour and produce a descriptive function (CFS)

Table 5. Evaluation criteria for input acquisition in lighting simulation models

3.2 Output

3.2.1 Types of output available

In this review, output will be defined as the ways through which model results are conveyed for human interpretation. Output can be divided into two large groups: text-only (quantitative output) and graphical representation (qualitative output), such as seen in Figure 2. Each lighting

simulation tools enables a certain way to prepare output. For example, by specifying format of either text or image output.

a) Quantitative output

Text-only files frequently contain photometric data from points of a previously defined calculation grid. They can be exported to spreadsheets or word processors. These external programs help process data (e.g. statistical analysis) or present it (e.g. 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 (Fontoynont *et al.* 1999).

Among the models examined, only Velux Daylight Visualizer could not produce text files. In the rest of them, it is frequent to obtain numerical outputs for illuminance, or daylight factor. AGi32, Relux, DIALux and Radiance also provide luminance values and glare ratings. Glare is usually calculated and identified in a scene as view directions having luminance values above a given threshold (Ward 1992).

b) Qualitative output

Qualitative output serves many purposes. Among many examples available: assessment of user preferences for luminaire arrangements in offices (Newsham *et al.* 2005), lighting preferences by users of different ages (Oi 2005), quality of lighting in architectural spaces (Eissa and Mahdavi 2001) and even as ways to simulate complex visual stimuli in medical patients (Ruppertsberg and Bloj 2006). Qualitative output can be divided in:

- Interactive renderings shown on screen. Depending on program capabilities, modelled space and calculations can be changed interactively and on real time (DIAL GmbH 2010, Autodesk, Inc 2010a). Graphical output data are usually overimposed on a chosen view. It may consist of isocontours or falsecolour images for luminance, illuminance, and glare. Point values can be displayed, by clicking on the image (Ward and Shakespeare 1998). Values can be overlaid on the image (Lighting Analysts 2010).

- Production of images for further analysis or processing. This is a very important type of output. In Radiance, the image itself is encoded with information computed from the

simulation (LBL 2010c). Radiance was among the first lighting simulation tools using HDR as image output to fulfil this purpose. HDR images offer the advantage of encoding colour gamut and luminance range information that is much closer to that of an original scene (Ward, 2005).

- Images presenting data interpretation, as in cumulative overlays of yearly temporal performance (Andersen *et al.* 2008, Glaser *et al.* 2004, Mardaljevic 2003).

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

3.2.2 Output interpretation

Lighting simulation tools are employed by users with different degrees of lighting and daylighting design expertise. One group consists of architects who are not lighting experts, but study influence of natural and artificial light in their designs. The other group consists of lighting/daylighting researchers and physicists, who are not full time designers but favour validation and verification (Reinhart and Fitz 2006, Hien *et al.* 2003 Attia *et al.* 2009). Although current tools offer a variety of output data, considerable expertise is needed to interpret and explain results (Hong *et al.* 2000). Few lighting simulation tools offer result interpretation or analysis (Reinhart and Fitz 2006). Output interpretation should be made fit to user type. Relux

offers modest graphical indications. Compliance of a lighting setup with DIN standard regarding energy consumption takes the form of a traffic light. Adequate data visualization and interpretation is necessary when large amounts of simulation results are involved (Glaser *et al.* 2004) and to plan specialized work (Nassar 2008). Table 6 explains schematically the current state of output.

Criteria	Classification	Means	Values	Examples
Type of output	Quantitative	-Text file	-Illuminance -Luminance -Glare -Daylight Factor	-tabular format (for use in post processing)
	Qualitative	-On screen rendering -Image file -HDR pictures	-image -falsecolour -isocontours	-luminaire assessment -user preferences -spatial lighting quality -medical uses
Output interpretation	By model	-Very few offer interpretation	-indicate code compliance	-"traffic light" by Relux
	By model user	-Lighting experts	-considerable expertise needed	-building physics researchers -physicists
		-Non-lighting experts	-interpretation on what results mean	-architects who dedicate primarily to design

Table 6. Output in lighting simulation

4. Applications of Lighting Simulation
4.1 Whole-building simulation

Lighting simulation is only part of the whole-building simulation problem (Citherlet *et al.* 2001). Tools exist for calculation of about every aspect influencing design and operation of a building. However, integrated tools at present face many shortcomings in terms of modelling, usage and application (Trcka *et al.* 2009). Four approaches exist for whole-building simulation (Citherlet and Hand, 2002):

- 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 (Capeluto *et al.* 2003, Gomez-Muñoz *et al.* 2010).
- Use of interoperable programs, results from one tool can be used directly by another. For example, results from Window 6 database (LBL 2010e) can be imported by EnergyPlus.
- Coupling separate simulation models at runtime, where one model controls the other (Janak 1997, 2009).
- Single simulation program where different sub-modules are integrated within a single calculation routine (Crawley *et al.* 1997, 2004).

The influence of solar radiation transmitted through windows and calculation of its components, has been incorporated since the earliest whole-building simulation models, such as DOE-2 (Reilly et al. 1995). According to Janak (1997), lighting aspects influencing energy consumption are the following: short step variance of daylight, details on building geometry, light transmission through fenestration systems and switch modes of artificial light. Despite the fact that advanced stand-alone lighting simulation programs can model these features with certain detail, simplification must be used when it comes to whole building simulation. Compromises such as simplified split-flux calculation, reduced reference points and interior reflections are needed to reduce execution time (Hitchcock 1995, Hitchcock and Carroll 2003).

Examples of simplification for whole-building simulation include converting building layout to thermal zones, or representing curved surfaces through polygons (ESRU 2010, USDOE 2010c, Autodesk, Inc 2010b). Other simplifications apply according to whole-building simulation tool, such as shading system representation (USDOE 2010b). A representative

example of simplification for whole-building simulation seen in a graphical way is given by Figure 3. Results provided by leading whole-building simulation tools need post-processing and careful human interpretation.
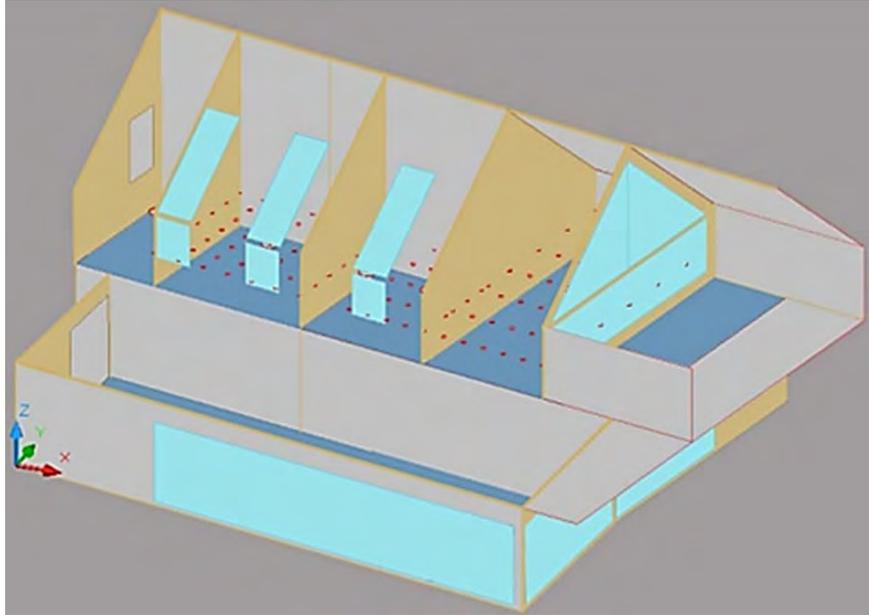

Figure 3. Geometrical simplifications required by whole-building simulation models

These facts aside, current whole-building simulation models are useful because of their simultaneous solution capabilities (Crawley *et al.* 2008). Although more detailed whole-building simulation tools provide more accurate results (Yezioro *et al.* 2008), their advantage resides not on accuracy of a single simulation run but on comparing different trends (Hong *et al.* 2000). They are capable of handling climate files containing yearly solar radiation data. This facilitates study impact of daylight on energy consumption (Wong *et al.* 2010, Hviid *et al.* 2008, Tzempelikos and Athienitis 2007, Ghisi and Tinker 2005); behaviour of fenestration systems (Jonsson and Roos 2010, Loutzenhiser *et al.* 2007, Li *et al.* 2006); as well as interaction of energy and visual comfort using advanced glazing materials (Lee and Tavil 2007).

Nevertheless, whole-building simulation tools integrating lighting simulation need further development. They must be more user-oriented (Attia *et al.* 2009), improve data exchange and input from other programs (Bleil de Souza 2009), as well as from users (Hand *et al.* 2008). They

should interpret output and guide users (Petersen and Svedsen 2010). Table 7 presents how whole building simulation is currently related with lighting simulation.

Criteria	Value	Examples
Approach to whole building simulation	-use stand alone tools separately -use interoperable tools -coupled models -single simulation engine with sub modules	-urban planning for solar insolation, shade and wind -Window 5 and EnergyPlus -ESP and Radiance (ESP-r) -EnergyPlus, TRNSYS
Integration of lighting simulation in whole building simulation	Lighting aspects influencing whole building simulation	-variance of daylight -building geometry detail -light transmission through fenestration -artificial light switching modes
Input and output	Input	-simplification of input -complexity to enter input in model
	Output	-mostly text based -careful human interpretation of results

Table 7. Lighting simulation within whole-building simulation

4.2 Applications of lighting simulation in the architectural design process

a) 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 (Aliakseyeu *et al.* 2006, Sarawgi 2004). Few provided analysis (Reinhart and Fitz 2006), or suggest solutions. They are single-output based (Hien, *et al.* 2003) and focused on being used by experts (Petersen and Svendsen 2010). Long computational times are a setback (Sarawgi 2004). During early design stages, architects need to compare interactively the outcome of their intentions.

- Lightsolve (Cutler *et al.* 2008, Andersen *et al.* 2008) was proposed for design exploration. It offers guidance on how some advanced fenestration systems affect a certain scenario. Their aim is to accomplish a goal-based design process (Lee *et al.* 2009).
- A virtual heliodon was proposed by Sheng *et al.* (2009) as a "sketcher" that corrects intensity with altitude, thus behaving similar to a real sun. In this way, realistic illuminance predictions were obtained. SPOT (Bund and Do 2005) was proposed as an immersive virtual reality environment. Users can observe how changes in building geometry affect sunlight.
- NewFacades (Ochoa and Capeluto 2009) suggested facade combinations and shows their impact on total building energy and visual comfort.
- The Virtual Lighting Simulator (LBL 2010e) and Daylight Variations Book (Diepens *et al.* 2000) provided online overview of how different lighting setups look under specific conditions.

Models exist that suggest volumetric solutions assuring solar access to neighbouring buildings. They can be used for early design stages and for urban planning. The "solar rights" and "solar envelopes" concepts (Knowles and Berry 1980) are calculated by tools such as Sustarc (Capeluto and Shaviv 2001), Helios (Seong *et al.* 2006), SunScapes (Ratti and Morello 2005) and through solar masks (Alzoubi and Alshboul 2010). 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.

Models can provide physical validation of architectural ideas. The tool by Ng (2005) indicates variety in maximum building height for high rises, ensuring daylight access for lower

floors. It does so by calculating vertical daylight factor. Based on their solar envelopes tool, Capeluto *et al.* (2005, 2006) recommend angled urban profiles that also provide high density while at the same time solar access to all levels. Shading (Yezioro *et al.* 2006), determines proportions of urban squares or atriums for adequate solar insolation and best positions for urban greenery.

b) Design development stages

Current lighting simulation models can be used after deciding on fundamental issues such as massing, building position, window size and orientation. A detailed overview on the considerations and steps for proper daylight simulation is given by (Reinhart 2011, in preparation). Exploration of artificial lighting layouts is facilitated by tools dedicated to that purpose. CAD programs such as AutoCAD and SketchUp provide quick solar shading studies. More refined daylight and electric lighting studies within CAD programs are provided by SketchUp plug-ins, such as *SunTools* (Capeluto 2010) or *LightUp* (LightUp Inc, 2010) respectively. Experts are needed for maximum performance of specific building components such as glazing and redirecting systems (Page *et al.* 2007), shades and blinds (Al-Shareef *et al.* 2001), and automated shading and lighting control modes (Kim and Park, 2009; Koo *et al.* 2010).

c) Compliance with building codes

When a building project is finalized and submitted for approval by corresponding authorities, lighting simulation can be used to confirm code compliance. Simulation will become important as performance codes eventually replace prescriptive ones (Hien *et al.* 2003). Solar rights models provide framework for volume concept approval. For compliance with interior daylight standards, Steward and Donn (2007) proposed a tool to examine if detailed simulations are needed or not. Window access to direct solar radiation can be examined through sky view factor and view solid angles (Capeluto 2003, Souza *et al.* 2003). These tools are more effective to check for compliance than classical 60 degrees obstruction rules.

d) Building commissioning and operation

Few lighting simulation programs tackle actual operation of a building. As mentioned, it is due to complexity in representing occupancy and user interaction with different control elements such as blinds, movable shades, sensors and switches (Lam *et al.* 2009, Clear *et al.* 2006, Inkarojrit 2007). A review and comparison of current simulation techniques for lighting control systems and daylight sensors is given by Doulos *et al.* (2005). They describe current switching modes, influence on energy consumption and assess different tools used for their simulation. One of these tools is Daysim (NRC 2009), which analyses different strategies using control elements. Radiance simulation of photosensors is proposed by Ehrlich *et al.* (2001) to predict their performance and take into account effects of location on walls or ceilings. Degelman (1999) suggested simulation of motion sensors using Monte Carlo probability to predict light switching. Whole-building simulation models incorporating artificial and natural lighting have means to represent occupancy, switches and sensors through different degrees of abstraction.

4.3 Education

The use of lighting simulation models as instructional tools is tied to improving their use within the architectural design process (Sarawgi 2006). Exposure of students to CAD programs makes them interested in digital media (Pentilla 2003). Setbacks mentioned by student users are complexity to learn programs, scarce beginners' help and overall detachment from mainstream CAD systems. This might detract students from using them in their professional life, even if they acknowledge daylighting benefits (Sarawgi 2006). Teaching simulation tools during the educational phase, on the other hand, provides a sense that modern building design is the result of collaborative efforts (Charles and Thomas, 2009).

Table 8 presents a summary of the use of lighting simulation in the design process and for educational purposes. Figure 4 presents a schematic overview of the relationship between lighting simulation tools and different steps of the design process.

Criteria	Requirements	Values and examples
Early Design Stage	-few detail on geometry and material properties - comparison between options -should suggest solutions	-goal based design (Lightsolve) -Virtual heliodon -immersive interactive virtual reality (SPOT) -design suggestions and impact on visual comfort and energy (NewFacades) -solar volumes tools -height impact tools (Ng, 2005) -shading tools (Yezioro, 2006)
Design Development Stage	- exploration behaviour of design under artificial lighting -exploration behaviour of design under daylighting, -exploration of functional properties -refinement of element behaviour	-simulation programs for artificial lighting -solar studies within CAD, SunTools -determination of properties for shades and blinds -determination of operational modes of automated shading or lighting redirecting systems
Code Compliance verification	-types of code: prescriptive or performance based	-use of solar volume tools -interior lighting (Steward and Donn) -determine window access to direct solar radiation (sky factors, solid angles)
Building operation and occupancy stage	-should represent complexity of user interaction and occupancy -should represent properly sensor	-Dynamic representation of blinds, sensors and switches (Daysim) -Photosensors and motion

	performance	sensors simulation (Ehrlich et al, Degelman)
Education	-tied to developments of lighting simulation models for use in architectural design process	- use as tools to teach correct design principles -easy to learn - provide sense of collaboration in the design of modern buildings

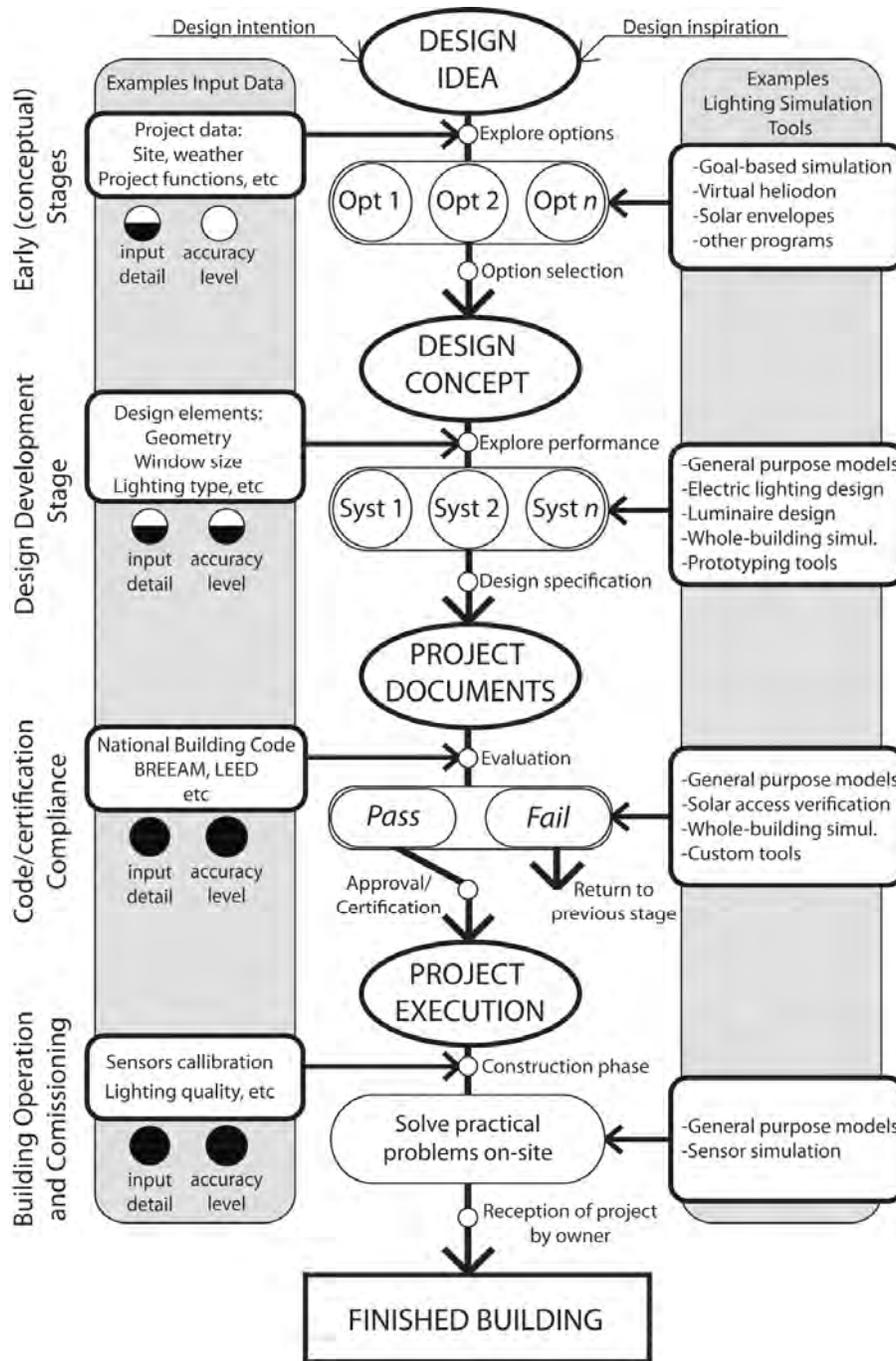Table 8. Use of lighting simulation within the design process and in education

Figure 4. Application of lighting simulation during different stages of the design process.

5. Discussion and Further Research

Our review has introduced multiple subjects for further research. The current state of the art in lighting simulation for building science is summarized schematically in figure 5.
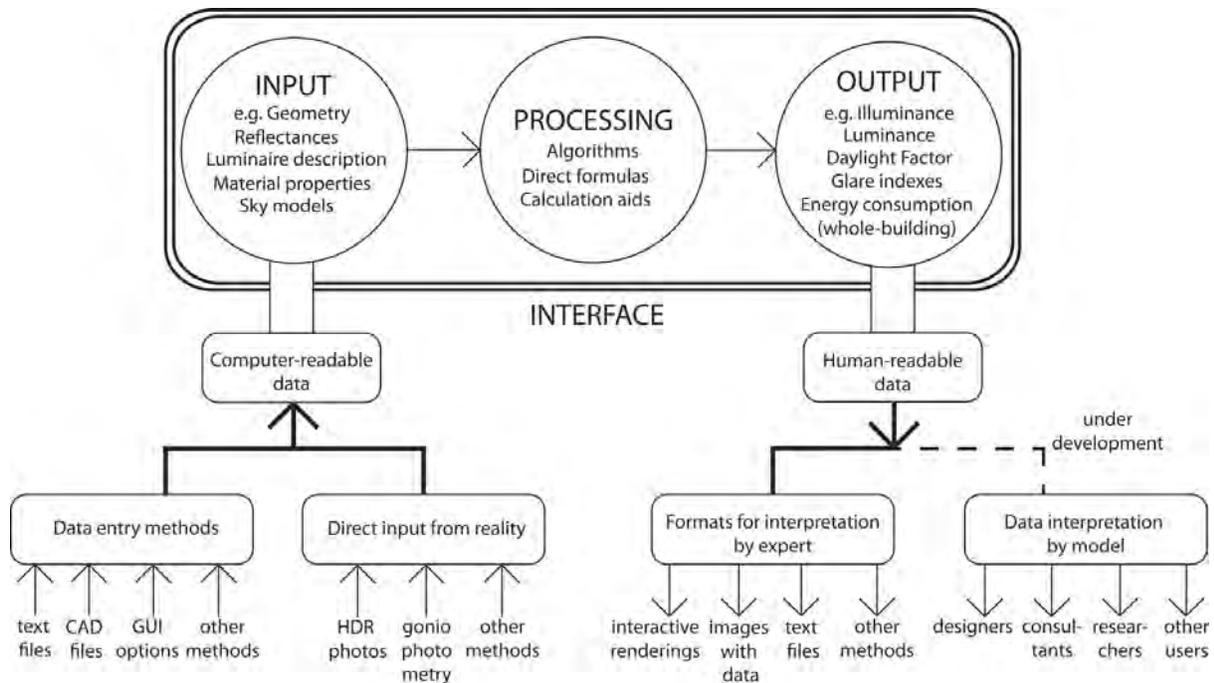
Figure 5. Current state of the art in lighting simulation for building science, analyzed using the approach presented in this paper.

Fundamental issues for further exploration include exploring the expression, through effective computational language, of modern light transport models. In this way, a wider array of physical phenomena could be simulated. Similarly, models should be developed based on human eye response to light and not only mimicking it.

It can be useful to improve calculation of dynamic problems encountered in lighting simulation, beyond subdivision into smaller time segments. It is needed also to study carefully how occupancy and quest for visual comfort are best represented. Lighting simulation packages should also consider their potential for prototype and optimization of lighting and daylighting elements proposed by users.

Regarding usage, some current lighting simulation models have been customized to specific needs. This is the case of electric lighting design tools. Their CAD interfaces and luminaire databases are intended to pass from design to specification. However, their capabilities for daylight interaction and fenestration analysis are limited for now.

Users requiring detailed exploration of daylight, lighting and energy have to adapt general simulation tools to their purposes. This group includes architects, energy consultants and building officials. They might encounter difficulties by the amount of detail required to specify a scenario, operate the tool and interpret results. Tool operation usually occurs by self-learning. It might pose additional problems and be time-consuming without a background in building physics. It is necessary that future tools should interact with different users and bridge the information gap needed to run a lighting simulation. Interpretation of user wishes and intentions should be advanced. Detailed studies on adaptable interfaces are needed.

Regarding input, models should be able to better translate geometry provided by CAD systems. Standard material libraries should be more easily available. Input can benefit greatly from exploring potential of using HDR imagery to characterize reflectivity and transmission functions of complex fenestration systems. This would replace complex laboratory equipment. Concerning output, it would be desirable to explore result interpretation and feedback within the simulation model. Suggestions include possibilities for custom output production using information visualization elements. In this way, new and unexpected trends can be identified.

Improved input and output methods are essential to advance explorations on lighting and daylighting in the architectural design process. Presently, detailed input information (material properties, geometry) is required to perform lighting simulations, independent of design process stage. Such accuracy is not known or required during conceptual design stages. In addition, there is little guidance on "correct" values. Output type provided by current models in many cases is not compatible to progress with the design process and does not provide advice. Output information is mainly for expert interpretation. Goal-based simulation is not available except in few experimental models.

Two areas should be surveyed. The first is to provide early design stage assistant tools for examination of alternatives with better use of daylight and artificial light according to the tasks that will be performed in the building. These assistants should provide a seamless pass between different steps in the design process, using a gradual exposure approach to variables. During early stages, tools should offer "educated assumptions" on input-related accuracy. During later stages, they can allow their complete specification. Output would have to take an integrative and

interpretative scope. This means that results would be presented according to user type, provide a guide for the next steps and be used by other tools.

The second area for further research is incorporating the level of detail achieved by lighting simulation into whole-building simulation. However, new computational developments such as parallel processing could be used to provide for both high accuracy and short execution times. Use of simplified tools to confirm building code or certification compliance should also be investigated.

It might be clear to many readers that for making reality the proposed advances in lighting simulation for building science, provisions of time, personnel and funding are needed. Securing investments for this area is more difficult than, for example, lighting simulation for cinematic purposes. Architects and building scientists concerned with realistic lighting modelling and research are still a small market niche, and the supply of lighting equipment for real-world experimentation is relatively large. Current models in use are product of government funding, pure volunteer work or the interest of private companies that designers use their products. This irregular situation makes that interesting initiatives, such as development of improved programmable interfaces, design-generating models or whole-building simulation, be subject to uncertainty in their continuation or completion if enough interest or funding are not generated.

6. Conclusions

Lighting simulation for building science has advanced rapidly within two decades. In 1995, there were still reports on shortcomings regarding accuracy, calculation of few parameters, long computational times, simple scenarios and disconnection from whole-building simulation. These aspects have been addressed in rather adequate ways by current lighting simulation models. One exception is input and output. This aspect has to be addressed, as the literature reports that number of users applying lighting simulation to building research has increased. This brings new challenges, as a variety of unforeseen situations is encountered and purposes for using lighting simulation widen.

From the models presented in our study, Radiance remains the general purpose simulation engine. Its influence on the literature is extensive, being taken by the lighting research

community as an industry standard throughout the last twenty years. Although continuity is a positive factor and Radiance is maintained by lighting simulation researchers, focusing on one model might hinder development of new ones. However, it was found that tools for specialized tasks exist, such as design of artificial lighting. They are supported by luminaire manufacturers. These specialized tools tackle interaction between electric and natural light but less comprehensively than Radiance. Predictive lighting analysis aspects, although still complex, have been incorporated in products used by a wider design public such as 3D Studio. This provides an interesting direction to integrate space modelling and lighting simulation.

Current geometrical optics algorithms were found present in all models examined. The most implemented were raytracing and radiosity, with photon map being used in fewer tools. Novel elements based on principles beyond the scope of these algorithms require physical experimentation. Problems that need dynamic approaches are solved through division into small dimension or time steps.

It has been seen from the literature that minimum accuracy between measurements and simulation of a built space remains around 20%. Acquiring reliable measurements of reflectivity from surroundings is very difficult. Replicating sky conditions is done by luminance distribution models. Manipulation of variables in lighting simulation models affect accuracy. The literature presents many examples of different comparisons between models, but the divergence between methods has prompted standardization of these tests.

Both input and output benefit from current and future computational hardware. Geometry limits and calculation times for output are less of concern today than twenty years ago. This will turn the focus on how users enter data and what kind of output they obtain. In order to achieve that, improved ways to obtain reflectivity and transmittance functions will be needed, as well as customizable output and data interpretation. It is also noteworthy that lighting simulation starts to take direct input from HDR images, even though not all models are able to handle it.

Integration of lighting simulation within whole-building simulation is still under development. Progress is needed for the complexity required in lighting simulation to be useful in energy calculations. Nevertheless, the two areas have benefited mutually from occupancy and automation studies. Time and personnel must be invested to develop reliable interaction of

lighting and energy models. Few lighting simulation models exist for proper support of the architectural design process. Those that do can be also used for urban planning and code compliance. More is needed to reach a stage where complete reliable solutions are really suggested by models following design logic and are integrated in the process of whole-building simulation.

Advancing the field of lighting simulation for building science requires investments in time, money, and human resources. The acknowledged benefits of this type of simulation should be translated into increased sponsorship from different stakeholders, in order to avoid research initiatives becoming stagnated.

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