Lighting Simulation
for a more value-driven building design process

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ABSTRACT

Concerns about global warming are increasing, hence, the urgency to cut carbon emissions. Reducing energy consumption, including lighting energy, is seen as the primary solution. Yet, solving the environmental factor should not come at the cost of other pillars of sustainable development. Rather, maximizing the total value of the building should be the focus. Maximizing value in the context of lighting entails improving the quality of the lighting. This study has investigated how lighting simulation could help in achieving better lighting quality. The aim of the thesis was defined as to understand the underlying architecture of lighting simulation and obtain an overview of its characteristics and applications as well as to study the use of current simulation tools.

The theoretical background of lighting simulation (in the domain of Systems Engineering) was reviewed from the literature. This revealed the missing and imperfect links in the solution-to-value chain. The thesis suggests the use of a new base metric, Retinal Illuminance Map, as a solution, which in combination with black box simulation of a visual system can help repair this incomplete chain.

The study of the current lighting simulation tools (Paper 1) revealed that illuminance-based metrics, luminance-based metrics, daylight availability metrics, and glare indexes are the most available performance metrics in existing lighting simulation tools. Based on usability, acceptability, availability, and previous references in the literature six software programs (Radiance, DAYSIM, Evalglare, DIALux, VELUX, and VISSLA) were selected and compared. It was found that no single tool could meet all the needs of a designer, hence, simulation tool(s) should be selected (or combined) according to the requirements of project goals and the stage of design.

Building on these studies, applications of lighting simulation were identified and compiled in relation to different aspects, including performance metrics, stages of design, optimization, model integration, BIM, and parametric modeling.

To obtain first-hand information about lighting designers' experience, an online survey was conducted in Sweden (Paper 2). The results showed that lighting simulation programs were widely (90%) used in Sweden for analysis and/or rendering purposes. The majority of lighting designers considered both daylight and artificial light in their design. Factors such as ease-of-use, simulation time and training had more weight than accuracy and the diversity of metrics in practitioner's eyes. Surrogate modeling was identified as a solution for speeding up simulation time, which would also enable exploration of design solution space especially in the early design stage.

Keywords: lighting simulation, lighting design, lighting quality, energy efficiency, perception,

This thesis is dedicated to my dear parents, Tahmaseb and Parvin,

for their endless love, supports and encouragement.

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P.S.
Thank you for reading :)

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LIST OF PUBLICATIONS

Paper I

Davoodi Anahita, Johansson Peter, Enger Johanna, *"Comparison of lighting simulation tools with focus on lighting quality"* Improving Energy Efficiency in Commercial Building Conference (IEECB'14), Frankfurt 01-03 April 2014

Paper II

Davoodi Anahita., Johansson Peter, Laike Thorbjörn, *"Current use of lighting simulation tools for lighting design in Sweden"* The Nordic Journal of Architectural Research (Submitted)

Paper III

Davoodi Anahita, Johansson Peter, Enger Johanna, " نرم افزارهای شبیه سازی نور، چالش ها و فرصت های پیش رو" or "*Lighting simulation tools, the challenges and opportunities*", Iran Lightning Design Conference (ILDC), Tehran, Iran, 19-21 November 2014, Armanshahr Journal,Specialized of Architecture & Urbanism (Accepted)

Paper IV

Enger Johanna, Davoodi Anahita, *"Visual Perception and Criteria for Good Lighting"*, 3AIC 2015 / MCS 2015 @ Tokyo

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List of Abbreviations

AEC	Architecture, Engineering and Construction
ASE	Annual Sunlight Exposure
BGI	British Glare Index
BIM	Building Information Modeling
BPO	Building Performance Optimization
BPS	Building Performance Simulation
CAD	Computer Aided Design
CBDM	Climate-Based Daylight Modeling
cDA	continuous Daylight Autonomy
CGI	CIE Glare Index
CIE	Commission Internationale de Eclairage
DA	Daylight Autonomy
DF	Daylight Factor
DGP	Daylight Glare Probability
DGPs	simplified DGP
DGR	Discomfort Glare Rating
EBD	Evidence-Based Design
HDR	high dynamic range
HVAC	Heating Ventilation and Air Conditioning
IFC	Industry Foundation Classes
LPS	Lighting Performance Simulation
MCDM	Multi-Criteria Decision Making
MOO	Multi-Objective Optimization
MRSE	Mean Room Surface Exitance
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
PPE	Predicted Percentage of Elevated
RGB	Red Green Blue
RIM	Retinal Illuminance Map
sDA	spatial Daylight Autonomy
SEA	Systems Engineering Analysis
UDI	Useful Daylight Illuminance
UGR	Unified Glare Rating
VCP	Visual Comfort Probability
VDD	Value-Driven Design
VDS	Virtual Design Studio

1 Introduction

Concerns about global warming are increasing and with them the urgency to cut carbon emissions. Reducing energy consumption, including lighting energy, is seen as the primary solution. Yet, solving the environmental factor should not come at the cost of other pillars of sustainable development. The energy-reduction view should change in favor of a value-driven view in which the value of energy reduction is weighed against other values and constraints to maximize the total value of the building [Green 2012; Seppänen 2006]. Different design philosophies support this ideal, of which value-driven design (VDD) and performance-driven architecture were of interest throughout this research. VDD is a systems engineering strategy that enables multidisciplinary design optimization [Sturges 2006]. According to Shi and Yang, the emphasis in performance-driven architecture is on “integrated and comprehensive optimization of various quantifiable performances of buildings” [Shi and Yang 2013].

Lighting can play an important role in increasing a building’s total value due to its impact on comfort, productivity, and health, to the extent that it is considered on par with energy efficiency [Dehoff 2012; Dehoff 2014]. Optimization of light in the design process is intertwined with other values such as thermal comfort and the view outside, which makes the optimization process complicated.

Before computers became widespread, design decisions were based on physical models, design tables, or rule of thumb methods and, in some cases, based purely on a designer’s subjective intuition. The performance metrics and design criteria matched the tools available for designers. Today, architects and lighting designers are increasingly using computer simulation software to back up their design decisions with objective performance indicators [Ibarra and Reinhart 2009; Reinhart and Fitz 2006]. This has created an expectation of being able to enhance performance metrics and the criteria on standards bodies by introducing metrics that are more capable of and better correlated to lighting quality. Such metrics, though, are more expensive in terms of computation, which can be addressed by the new tool—building simulation.

The emergence of simulation tools has started a new trend in architecture, namely, performance-driven or performance-based architecture [Negendahl 2015; Shi and Yang 2013] argue that:

> “Compared with the conventional architectural design methodology, which focuses on space and form, performance-driven design takes a holistic view towards ecological and environmental performances of buildings while ensuring that the functions and esthetics of the design are not overlooked.”

The concept of “form that follows performance” has been implemented in various degrees, ranging from inspirational influence to strict form generation from performance evaluations [Negendahl 2015]. Kalay defines the term “performance” as a measure of the desirability of the predicted behavior of a design solution, which covers non-conventional performance, such as fulfilling social sustainability criteria, in addition to conventional quantity-based performance [Kalay 1999]. Based on this definition, simulation tools can help in evaluating a large part of the performance of a design solution. This holistic view of performance is critical in our quest for improving lighting quality.

To gain a deeper insight into lighting simulation, we need to understand computer simulation as a general problem-solving method in analysis and design to a greater depth. It is important to identify systemic gaps between the outputs of these tools and the final (building) values that are intended to be optimized. For example, illuminance-based metrics are the most widely used metrics calculated in lighting design but they do not directly correlate with subjective visual performance [Cuttle 2004; Cuttle 2015; Van Den Wymelenberg 2013; Veitch and Newsham 1996].

What has been discussed so far concerned the final "user/occupant experience' or the "end". However, the "means" to reach the end is also important, that is the "designer experience". Although, simulation tools has been around for more than a decade, architects and lighting designers travel an uneven road in their design process, which in many occasions, are drawn to use the old rule of thumb methods or, at best, some basic software in their design process [Galasiu and Reinhart 2008; Reinhart and Wienold 2011]. The introduction of BIM as a new design platform has disrupted the designer's toolkit landscape. At the time of this study, BIM still remains undeveloped and fragmented from different aspects including design experience. Issues regarding the designer experience were also investigated throughout the research.

Metrics and criteria for good lighting design evolve with advancement in lighting design, computation technology, simulation techniques, and building design platforms as well as in related science and engineering fields. To move forward in this evolutionary process, a project has been initiated at Civil Engineering and Lighting Science Department of Jönköping University and being conducted in cooperation with Architecture and Built Environment Department of Lund University. The project is comprised of two sub-projects. The first one is titled "criteria for good lighting quality," which focuses on the interactions between human, light, color and space and how these interactions could be used in the design process to achieve user-centric lighting systems. The second project, which has been the main focus of this research, aimed to study lighting simulation tools and investigate how they can be employed in the design of buildings with good lighting quality.

1.1 Aim

The aim of this thesis was to understand the underlying architecture of lighting simulation and obtain an overview of its characteristics and applications as well as to study the use of current simulation tools. The findings were used to identify potential for improving lighting quality using simulation tools.

1.2 Research Questions

To fulfill the aim of this thesis the following questions were framed and the research effort was directed toward finding answers for them.

1. What are the characteristics of lighting simulation tools and their capabilities for the analysis of lighting quality of indoor spaces?
2. What are the applications of lighting simulation and which tools are currently used in practice?
3. How can lighting simulation tools be improved to provide better lighting quality?

1.3 **Research Methods**

This dissertation presents multiple studies some of which have been published as papers over the past two years. Because topics such as simulation software tools are within the engineering realm, a quantitative approach was mainly used, implying that the research approach is based on positivism. A qualitative method was also applied to the study by using context analysis.

Data collection and research methods of each study were chosen independently which include a combination of literature review and survey.

To answer the first research question *"What are the characteristics of lighting simulation tools and their capabilities for the analysis of lighting quality of indoor spaces?"* two different approaches were used. In the first study (presented in Paper 1) the focus was on understanding the current situation and characteristics of software available in general and to identify the strengths and shortcomings of the selected tools. [Easterbrook and others 2008] categorized this type of question as "exploratory"; it involves the use of existence questions (e.g., What are the existing simulation tools? What are the existing metrics?). It can also involve the use of "descriptive-comparative" questions (e.g., How does tool x differ from y?) for comparing these tools. The answers yielded insight on the current situation.

Using the answers, a systemic analysis was done to get a deeper understanding of the underlying architecture of lighting simulation tools (Chapter 2). This helped in identifying systemic gaps between simulation outputs and the values of interest (i.e., good lighting quality). Literature review was the main method used for data collection in both studies.

The second question, *"What are the applications of lighting simulation tools and which tools are currently used in practice?"*, is also categorized as "exploratory". Two study was conducted to answer this question. In the first one, current usage of lighting simulation tools was investigated (presented in Paper 2). Data collection was mainly done via an online survey, which was complemented with a literature review to gather information from previous works. In the second study, the applications of simulation tools were studied from literature in a wider scale (Chapter 3).

The findings from the first and second research questions provided a picture of the current state of the lighting simulation tools in terms of software characteristics, application, usage, gaps and shortcomings. The findings also provided a picture of designers' needs and the issues they are facing in their practices.

The above questions are all classified as "knowledge" questions focused on the understanding of the phenomena. The focus of the third question *"How can lighting simulation be improved in providing better lighting quality?"* required using questions concerned with designing better ways to do software engineering [Simon 1969a]. The design questions (e.g., What's an effective way to achieve X? where X refers to a better lighting quality analysis using simulation software). This type of questions is necessary when the goal is to design better procedures and tools for carrying out simulation [Wieringa and Heerkens 2006]. To answer the third question, the potentials for improving lighting quality using simulation tools were investigated using the findings from literature reviews and the first and second studies. The results are summarized in Chapter 5.

1.3.1 Methods for data collection

1.3.1.1 **Literature review**

The purpose of exploring the existing literature was to become familiar with what is already known about the research area. A systematic literature review was done for all the studies. The literature was obtained from secondary sources and documents.

1.3.1.2 **Peer reviewed journal and conference articles**

Scopus.com, scholar.google.se, and sciencedirect.com were the main bibliographic databases for collecting reliable articles.

1.3.1.3 **Books, licentiate and doctoral theses**

Some hard copies or electronic books as well as licentiate and doctoral theses relevant to the purpose of the study were reviewed for the data collection.

1.3.1.4 Documents and reports from websites

Relevant documents such as software manuals, online forums and communities related to the tools, reports, websites, and media were also used as sources of information.

1.3.1.5 Survey (online)

Online-survey was conducted to investigate the current use of lighting simulation tools in Sweden.
The online questionnaire was comprised of four types of questions: multiple choice multiple select (checkbox), multiple choice single select (radio button), prioritizable selection list (Drag & Drop Ranking question), and free text. The data analysis was performed using Microsoft Excel. In addition, a qualitative analysis was applied on the textual answers.

For a more detailed description of the methods, see Chapter 4: Appended papers.

1.4 Research Limitation

1. The scope of this research is limited to the visual aspects of lighting quality.
2. The current state of lighting simulation is limited in taking the quantitative aspects of lighting into account. Therefore, most of the investigation was done on the quantitative aspects. However, the potential of simulation techniques in enabling assessment of qualitative aspects was briefly discussed.
3. The focus of this study is on indoor lighting, particularly for office environment.
4. The study of lighting quality was done from an average person's point of view. Generalization to other groups such as elderly or people with disabilities should be avoided.
5. The study of software tools usage was limited to Sweden.
6. The literature review was the main data collection method used in gathering information for studying available software. Only literature in English was reviewed.

1.5 Thesis Structure

The simulation tools were reviewed from multiple perspective to provide a picture of the current state of the lighting simulation tools in terms of main characteristics, application, and usage. Then the findings were applied to identify potential improvements. The outline of the dissertation is illustrated in Figure 1.

The theoretical background of computer simulations is presented in Chapter 2. Then, the applications of the current simulation tools investigated are presented in Chapter 3. The author's previous studies are presented in the form of papers summarized in Chapter 4. The potential for software development is discussed in Chapter 5. The final chapter unifies the findings from all studies and lays the foundation for future work.

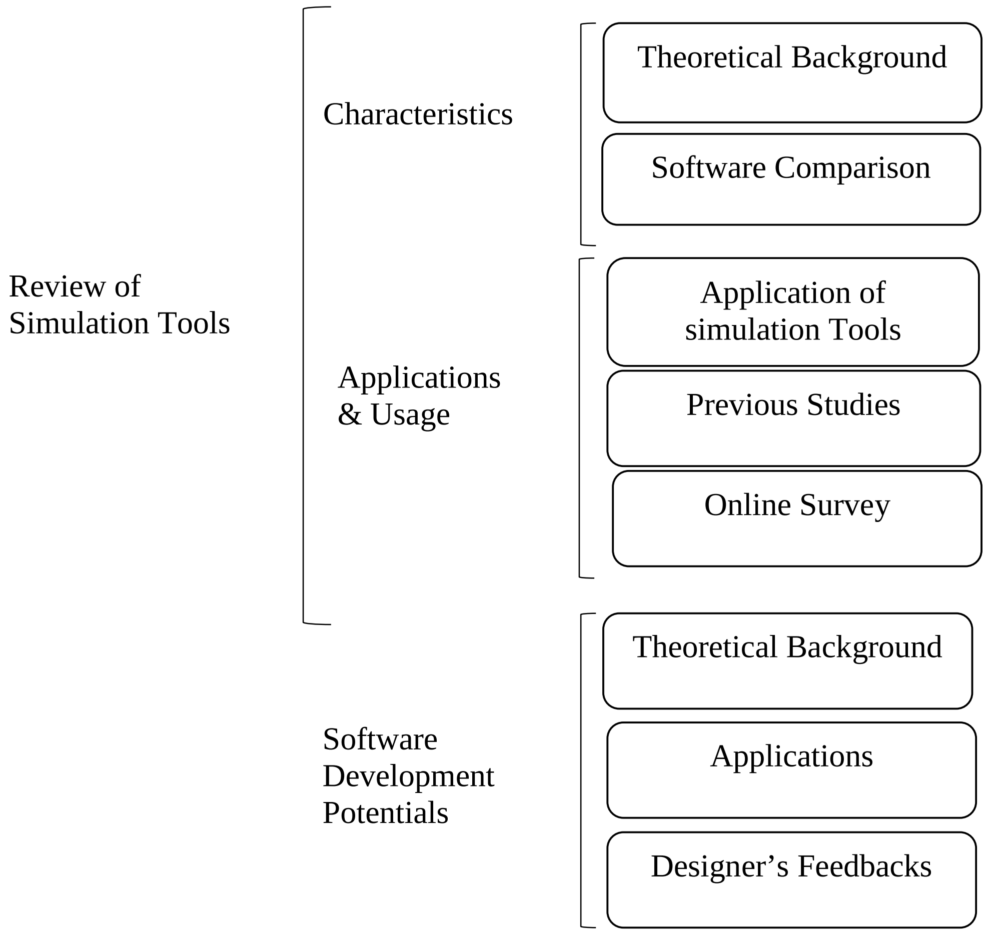

Figure 1. Outline of the dissertation

2 Theoretical Background: Systems, Modeling and Simulation

This chapter is dedicated to fundamentals of simulation in general and lighting simulation in particular. The fundamentals help identify systemic gaps between simulation outputs and the target values that designers seek to provide through their designs. This chapter also introduces some of the terminology used throughout this dissertation.

Theories of modeling and simulation are based on systems engineering [Gianni and others 2014] and their computer-based implementations are based on various IT fields. First, this chapter provides general information regarding systems, modeling and simulation. Then, this information is applied to lighting analysis. Systems thinking was also suitable for structuring this chapter and the following is the scheme followed for modeling and simulation [Velten 2009]:

1. Problem and system definitions:
   - Definition of a problem that is to be solved
   - Definition of a system, that is, a part of reality that concern the problem
2. Systems analysis: Identification of parts of the system that are relevant for the problem
3. Modeling: Development of a model of the system based on the results of the systems analysis step
4. Simulation:
   - Application of the model to the problem
   - Derivation of a strategy to solve the problem
5. Validation: Does the strategy derived in the simulation step solve the problem for the real system?

2.1 Problem and System Definitions

2.1.1 Problem definition[1]

The goal of value-driven building design is to produce a blueprint that maximizes the total value of a building within the constraints imposed by different project stakeholders. The generation of values in a building system occurs through complex interwoven processes consisting of numerous subsystems such as lighting, heating, air conditioning, and so on. Typically, each of these subsystems is designed to provide multiple primary values (e.g., lighting system to provide visibility, visual comfort). In doing so, they affect other systems' primary purposes (e.g., daylight can increase visibility as well as heat, which is the primary variable in heating systems). These effects are not always positive; for example, increasing daylight has a negative effect on cooling systems, hence, negotiation of variables are unavoidable through a design process. Due to the limits of human knowledge, the effects of these systems' variables on their target values and their lateral effects on other systems are not fully understood. If we try to illustrate the value stream of a design solution, the result would be a complex network of interwoven nodes. A simplified subgraph of this network that includes only the main nodes pertaining to lighting is illustrated in Figure 2**.**, which only partially captures some of the intricacies discussed so far.

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[1] It should be clear that this problem definition is specific to lighting simulation as a study subject and not the whole research.

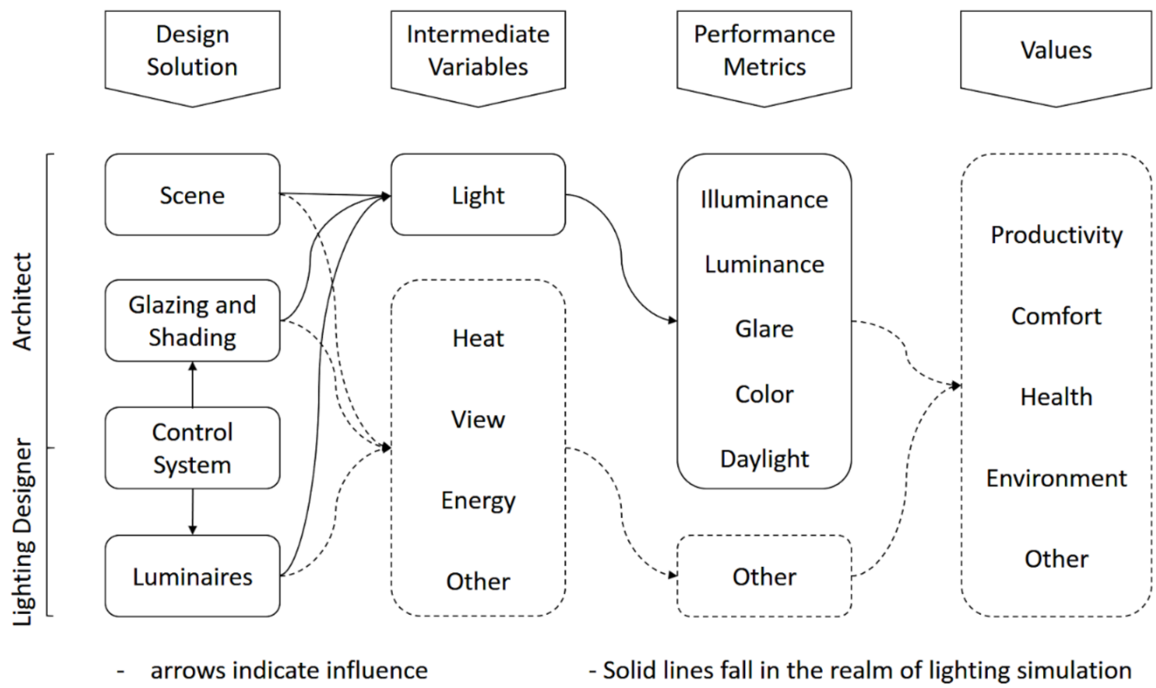


Figure 2. Value-generation network in building design

In human-centered systems like lighting, value should be assessed relative to the needs of the user, making its quantification complicated. For example, people have different needs and preferences for light levels, distribution, color, and so on. These differences are conventionally dealt with statistical techniques by various standards organizations that set the criteria for good lighting design practices.

To maximize a building's value, we need to understand the processes that generate value and quantify the variables in this value-generation network. From a quantifiability perspective, values can be classified into four categories: financial, quantifiable, measurable, and observable [Ward and others 2007]. The best category in terms of decision making is, undoubtedly, financial since it can directly be compared against the cost of a design solution. However, in practice, only a fraction of these values can be expressed in financial terms with an acceptable degree of accuracy. Even quantifying the cost of a design solution with high accuracy is next to impossible due to the overwhelming number of uncertainties in the procurement, construction, operations, and maintenance processes. Today, architects and lighting designers are increasingly using simulation software tools to assess and optimize their design solutions. However, a large portion of their design decisions are still based on best practices or intuition rather than on the specificities and dynamics of the project at hand [Galasiu and Veitch 2006; Reinhart and Wienold 2011]. Lighting simulation tools can be used to calculate the various categories of performance metrics (see Figure 2) of a design solution; however, these metrics do not easily and transparently translate into values. This is a systemic gap in evaluating the value-generating network.

2.1.2 System definition

A system is defined as "a collection of entities, for example, people or machines, that act and interact together toward the accomplishment of some logical end" [Kelton and Law 2000]. Another author, [Fritzson 2010], defines system as "an object or a collection of objects whose properties we want to study."

To study a system, it is necessary to define a boundary that separates it from its environment [Velten 2009]. Depending on what aspect of lighting is being studied, different boundaries can be drawn. For example, if the effect of lighting on skin-related health is being studied, the system boundary could be defined at occupant’s skin level on the output end. This, though, is rarely the case in the context of lighting design. Most lighting analysis problems concern the visual effects of light. Elements of a lighting system may include the sky and light fixtures, the interior scene as well as the exterior scene that blocks or guides light toward interior scene (e.g., neighboring buildings, ground.), the visual system (every organ related to visual perception) in which light is given as the input to the system and perception of the objects can be the final output. Light generation inside light sources such as the sun and luminaires always fall outside the system boundary. Figure 3 illustrates the lighting system with three different boundaries drawn in accordance with three example problems.

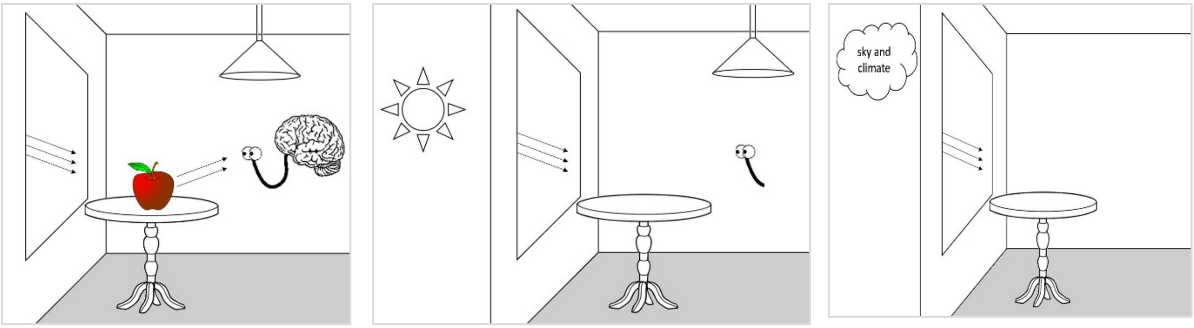


Figure 3. System boundary defined according to the example problems a) visibility b) dazzling glare c) energy efficiency

2.2 Systems Analysis

In lighting, the system can be broken down into two subsystems: physical (i.e., sky, scene) and human (visual system). The physical system pertains to the objective phenomena while the human system concerns the subjective experience of the system user.

Having the problem domain limited to the visual effects of light, the next step is to draw a boundary for the system. The fact is, though, that calculating visual effects of light is still a broad view of the problem and should further be broken down. As an example on the input side of the boundary, when artificial light is being designed, the light contribution from direct sunlight and diffuse daylight are omitted to ensure the availability of required light during dark periods. Hence, the sky and exterior scene fall outside the system boundary. On the output side of the boundary, visual comfort is a good example to study. A main factor in visual comfort is avoiding glare. Glare has many types including disability, discomfort, and dazzling glare [Hirning 2014] and each requires the boundary to be drawn at different points in the visual system (e.g., iris, retina, associative visual cortex).

Although most problems in lighting design concern the visual effects of light, recently, there has been a growing number of studies on the non-visual effects of light (e.g., circadian effect) [Inanici and others 2015; Mardaljevic and others 2013].

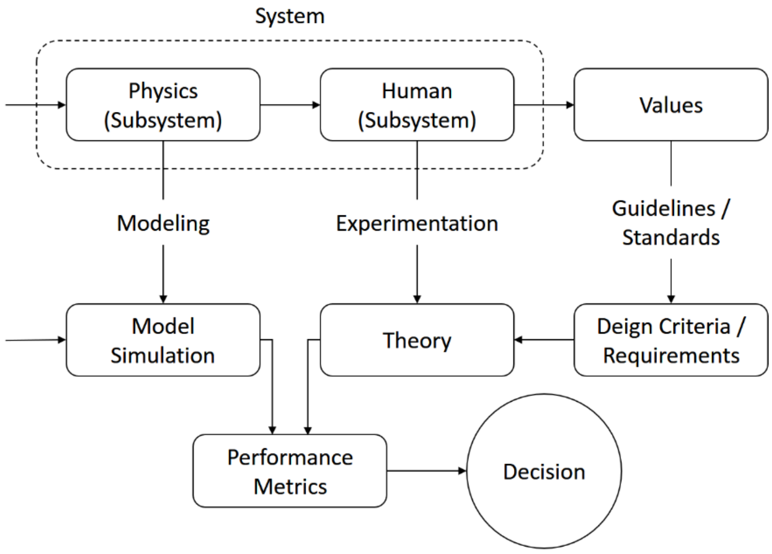


Figure 4. Analysis of systems in lighting

The nature of light (which is a constituent of the physical system) is understood relatively well, which makes it possible to express it in mathematical terms. The visual system, however, is too complex to be expressed yet mathematically. Instead, experiments are the primary means for understanding light perception. The results of these experiments are presented in simple spreadsheets and/or charts that map light settings (as input) to visual performances (as output). For example, illuminance levels are mapped to task visibility. Figure 4 depicts systems involved in lighting and how they are analyzed in lighting design processes.

2.3 Modeling

Before computer simulations became widely available, architects used physical/scale models to establish basic architectural forms for daylight analysis. Although, these models are effective in assessing the effects of fenestration and/or shading techniques on daylight distribution and intensities, the time required for even a quick assessment compared to that for a computer simulation means it is not feasible to use such models. Moreover, physical models are limited in assessing electric lighting and its interaction with daylighting [Steffy 2008]. Ultimately, physical models tend to limit the design process because of their focus on the finite analysis [Viola and Roudsari 2013]. Today, computer modeling and simulation have largely replaced their physical counterparts.

“A computer model represents the key characteristics or behaviors/functions of the selected physical or abstract system or process. Model is different from simulation in that the model represents the system itself, whereas the simulation represents the operation (behavior) of the system over time” [Kosky and others 2015; Steffy 2008].

The advantages of using computer models for obtaining information about behavior of a system are numerous: there is no need to experiment with the original system; there is no threat to the system; results can be obtained quickly; the investigations can cover a much broader range than would be possible with the real system; alternative development paths can be studied and compared; and the costs of the investigations are significantly smaller. The modeling approach also has its disadvantages. Because the model is not the original system, there is always uncertainty about whether it describes the system behavior correctly in all its aspects. However, validation of the model can remove much of this uncertainty as is described later [Bossel 2007].

As [Cellier and Kofman 2006] put it, “modeling and simulation is always purpose-driven, that is, we should know the purpose of our potential model before we sit down to create it.” In that sense a model is defined as “to an observer B, an object A' is a model of an object A to the extent that B can use A' to answer questions that interest him about A” [Velten 2009].

An important aspect of the above definition is that it includes the purpose of a model, meaning that the model helps us to answer questions and to solve problems. This is important because beginners in the field of modeling tend to believe that a good model is one that mimics the aspect of reality that it pertains to as closely as possible. Rather, the “best model” is the simplest model that still serves its purpose, meaning that it is still complex enough to help us understand a system and to solve problems [Velten 2009].

One of the simplifications in lighting modeling is applied on the light spectrum. When we are studying visual aspect of light, we are only interested in a narrow spectrum of light wavelength that affects human vision, hence, visual simulation is based on photometry rather than radiometry. The computation of light at each wavelength throughout the visible spectrum is prohibitively time consuming. Since humans have a trichromatic visual system, lighting is commonly simulated through tristimulus color space such that spectral information for lights and materials is defined and computed with the RGB data [Inanici and others 2015]. This simplification might seem natural and appealing; however, in the physical world, the interaction between the lights and materials occurs in full spectrum. Inanici et al. argued “The discrepancies may hinder the accurate computation of color dependent lighting metrics, especially the ones that are not dependent on the Commission Internationale de Eclairage (CIE) photopic spectral sensitivity curves (V(λ)), such as the circadian light” [Inanici and others 2015].

In this regard, modeling has taken two different paths in the building industry. Commonly, modeling is used for representation or information exchange, which is referred to as geometrical models. However, according to the aforementioned definition of the “best model”, geometrical models are often not useful for simulation without preprocessing. A hypothetical example is illustrated in Figure 5 in which a building design is modeled with fewer details in a simulation tool than in a design tool [Negendahl 2015]. In a geometric model of an opaque object only its outer surfaces are needed for lighting simulation. Other properties of interest are surface roughness, specularity, color, etc. A model created for the purpose of simulation is referred to as analytical model or calculation model.

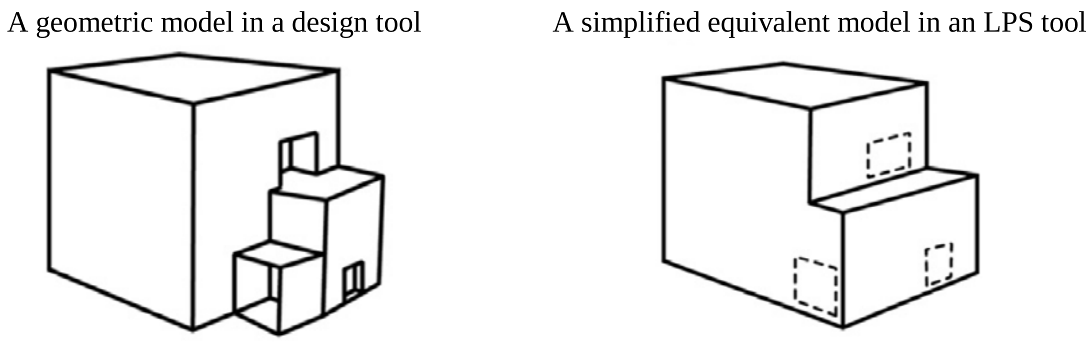


Figure 5. Models for simulation are simplified depending on the problem

Geometrical models are typically created by architects in the design tools while analytical models are usually created or manipulated by lighting designers in lighting performance simulation (LPS) tools [Negendahl 2015]. Figure 6 shows the relation between the user, program environment, and the model type.

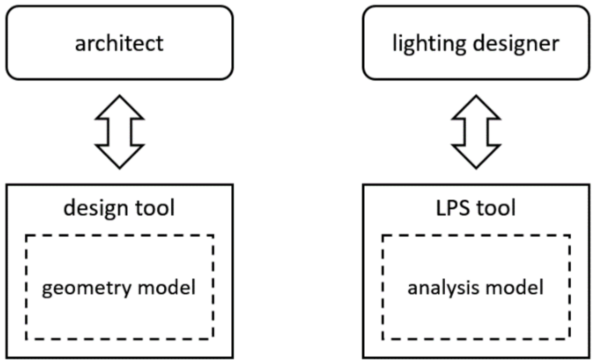


Figure 6. Geometrical and analytical models in the context. Modified from [Negendahl 2015]

Processing a geometric model from design software to a LPS environment has often been associated with tedious tasks such as manual export/import, model cleanup, modifications, adjustments, and so on. [Kota and others 2014]. These two different types of models can be integrated; building information modeling and parametric modeling are all closely related to each other and further investigated in Chapter 3.

2.4 **Simulation**

Simulations are "software systems we construct, execute, and experiment with to understand the behavior of systems. This often includes a process of generating certain natural phenomena through computation" [Chen 2003].

The advantages of computer simulation include the following: use of a common methodology independently of the type of system considered; lower marginal cost of model construction and simulation; ability to shorten or lengthen the time course of dynamic behavior; and dynamics that are not wanted in the real system do not impact the computer model [Bossel 2007].

In lighting, the term "simulation" is used to mean different things depending on the context, and in some cases it refers to a broader concept of lighting design that utilizes simulation internally to calculate lighting performance metrics. Here, we differentiate between lighting design and simulation. We limit the scope of lighting simulation to contain the simulation processes. Typically, only a physical system is simulated as illustrated in Figure 4. Example outputs from these simulations can be luminance, illuminance, and color, which could be processed to calculate performance metrics such as daylight glare probability (DGP) or daylight autonomy (DA), which are used in the lighting design process.

Simulation of behavior can be achieved by two entirely different approaches. The first method is the black-box approach. According to Bossel, its purpose is "to arrive at a description of behavior from observations of one or several identical systems, observing how they behave (output) under different conditions (input), and then using convenient mathematical relationships to relate input to output and *imitate* the behavior of the real system" [Bossel 2007]. The model generated is referred to as surrogate model. The second approach is the glass-box approach. It is used "to attempt an explanation of behavior by modeling the actual processes of the real system" [Bossel 2007]. In this case, *mechanics* of the system should be well understood.

Hence, the aforementioned physical system can be simulated as a glass-box because its actual processes are known to a great extent. The common algorithms for simulating light are radiosity, ray-tracing, and photon-mapping, which are explained later in this chapter. However, the visual system can only be simulated as a black box because the way the system perceives objects is not well known yet. This approach requires a significant amount of data from experimentation for mapping inputs to outputs to reach an acceptable level of accuracy. For this reason, simulating visual system is not a common practice.

In the following we will explore lighting simulation from different perspectives.

2.4.1 Photo-realistic vs physical-based

Lighting simulations can be divided into two main types depending on the rendering method used. The two type mutually benefit from the development of each other.

Photo-realistic rendering is mainly used for production of artistic images and places. It emphasizes the appearance of its output rather than the techniques used to derive it. Anything goes, basically, as long as the final image looks nice [Larson and others 1998].

Physically-based rendering (also known as predictive rendering) focuses on accurate representation and prediction of reality under given conditions and simulates the physical behavior of light as closely as possible in an effort to predict what the final appearance of a design will be. This is not an artist's conception; it is a numerical simulation. The light sources in the calculation emit light with a specific distribution, and the simulation computes the reflections between surfaces until the solution converges. This method was the focus of this research [Larson and others 1998; Ochoa Morales and others 2012]

2.4.2 Glass-box light simulation algorithms

There are two main classes of algorithms for simulating the behavior of light in a glass-box: radiosity and ray-tracing. An extended version of ray-tracing technique is photon-mapping.

Radiosity (radiative flux transfer) is a global illumination algorithm used in 3D computer graphics rendering. In this technique, the surfaces are divided into patches and these patches exchange light energy within a closed system. This method is usually limited to scenes with diffuse surfaces so that the solution matrix is manageable. Compared to other techniques, radiosity requires less computation power and therefore less time for simple geometries. One advantage of this method is a faster walkthrough view of the scene because the simulation yields the total luminance distribution that is independent of the spectator's viewpoint [Chen 2003; Ochoa and others 2012].

Ray-tracing is a technique for generating an image by tracing the path of light through pixels in an image plane and simulating the effects of its encounters with virtual objects. The technique is capable of producing a very high degree of visual realism, usually higher than that of typical scanline rendering methods, but at a greater computational cost. Ray-tracing is capable of simulating a wide variety of optical effects such as reflection and refraction, scattering, and dispersion phenomena (such as chromatic aberration). In ray-tracing, each viewpoint requires a new ray tracing run, which can be a problem in walkthrough simulations. The technique is good for simulations where specular and partly specular materials are involved. It is the technique that gives the most physically correct results. There are though still some phenomena that ray tracing cannot simulate accurately, such as diffuse inter-reflections and caustics [Chen 2003; Ochoa and others 2012].

Photon-mapping is a versatile algorithm capable of simulating global illumination including caustics, diffuse inter-reflections, and participating media in complex scenes. Extending ray-tracing with photon maps yields a method capable of efficiently simulating all types of direct and indirect illumination. Furthermore, the photon map method can handle participating media and is fairly simple to parallelize [Jensen and others 2002].

2.4.3 Black-box lighting simulation methods (surrogate models)

A surrogate model (meta-model or emulator) is an approximation model of the original simulation model. In essence, surrogate models use interpolation to generalize the system behavior from a finite number of data points that relate design parameters to design performance [Wortmann and others 2015]. This interpolation can reduce the computational cost of simulation by orders of magnitude, which enables designers to interact with this model and explore the approximate impact of changing design variables. This leads to a better understanding of the design problem and behavior of the system [Wortmann and others 2015]. Surrogate models are diverse and recently gaining traction in the research community. Surrogate models are also extensively used for optimization. Original models are often utilized for validation and refining the results over the surrogate-based optimization process [Nguyen and others 2014]. Surrogate models are among promising solutions for reducing simulation and optimization time.

2.5 Validation

As discussed, models are simplified in line with the purpose of a problem, hence, they are valid, if at all, only for that specific purpose [Bossel 2007]. Similar to scientific theories, the correctness of the models cannot be proven; models cannot be verified. Correct behavior of a model for a specific setting cannot be generalized for other settings, a premise that is the foundation of surrogate modeling. This is most evident in a special type of surrogate models known as Space Mapping in which a course model is constantly refined by a fine model (either through glass-box simulations or data from experiments) throughout the simulation process to better represent reality [Bossel 2007]. A model (or theory) can only be proven false by showing that reality and simulation differ [Bossel 2007; Popper 2005]. Validity can be established by extensive comparison of model results and experimental data but it is only true until evidence to the contrary appears. These data may come from the literature or from experiments that have been designed to validate the model [Velten 2009].

The CIE has established a procedure for evaluating the output performance of lighting simulation packages. The validation approach is based on testing different aspects of lighting simulation by individual test scenarios. The approach includes validation procedure for both artificial and daylighting and is based on theoretical principles where comparison is done with analytically calculated reference data to avoid uncertainties [Maamari and others 2006a; Maamari and others 2006b]. Two types of reference data are used: data based on analytical calculation and data based on experimental measurements. The first is associated with theoretical scenarios that avoid uncertainties in the reference values. The second type is obtained through experimental measurements, where the scenario and the protocol are defined in a manner that minimizes the uncertainties associated with the measurements. A number of simulation tools (Radiance, DAYSIM, VELUX, VISSLA, DIALux) were compared in paper 1 from a validity point of view.

3 Applications of Lighting Simulation Tools

This chapter explores the applications and limitations of lighting simulation tools and the opportunities that they provide for better lighting analysis.

Lighting simulation enables prediction, assessment, and verification of lighting performance, which has a variety of applications in building design, operation, communication, and education. In building design, “the primary purpose of most forms of lighting simulation is to assist in the design [analysis and optimization] process” [Reinhart 2004]. Following is the list of the topics covered in this chapter:

Simulation Output: simulation outputs can be quantitative/numerical or qualitative/visual. Quantitatively, the programs compute photometric values in physical units in a discrete number of points of space. Qualitatively, the programs generate images of visible radiation comparable to photographs of the real environment [Pellegrino and Caneparo 2001]. In this chapter, metrics calculable only with the help of simulation tools are highlighted.

Stages of design: design process is formally divided into different phases[2], including conceptual, preliminary, scheme, and detailed design [Jacobsen 2007]. In this document, the first three phases are referred to as early design stage and the detailed design is referred to as design development stage. Specific applications of lighting simulation in each stage have been studied. Here the focus is on application of lighting simulation in early design and design development stages.

Optimization: in real world projects, designers often have to deal with conflicting design criteria [Fesanghary and others 2012; Hamdy and others 2011] such as minimum energy consumption versus maximum visual comfort, which increases the need for optimization. Simulation tools have long been used for this purpose; however, the optimization process is still performed manually in the majority of cases, although automated optimization tools are emerging to address this issue. Optimization is discussed from different aspects including optimization issues, complex models, multiple objectives, and integration.

Model integration: while numerous unified tools that act both as a design tool and Building Performance Simulation (BPS) tool exist, building designers still seem to prefer creating and exploring design options in dedicated design tools. This has caused a fragmentation between building design and performance assessment. Integration of BPS with building design can be investigated from user, tool, and model perspectives, of which the model perspective has been investigated in this study.

BIM: BIM is an emerging design platform [Kota and others 2014] that promises to simplify modeling for the multiple disciplines involved in the design process. Building Information Modeling and simulation have a major element in common, modeling. The advantages and shortcomings of BIM in relation to lighting simulation are discussed.

Parametric Modeling: parametric modeling (more precisely generative algorithm modeling) is a recent trend in the AEC industry that is igniting enthusiasm and creativity among researchers and designers. Rhinoceros/Grasshopper popularized parametric modeling. Other design

[2] So called ‘phase model’ view

platforms such as Revit and Vectorworks are joining the trend by offering their own suite of visual programming interfaces. The chapter presents integration of lighting simulation tools with parametric modeling and its applications in lighting design as well as some example case studies.

Communication and education: Aside from the main applications of simulation tools, they provide a tangible medium for communication in the design and construction process as well as a powerful platform for education. These applications of simulation were out of the scope of this research.

3.1 Simulation Output

Boyce argued that the most widely used metrics in today's lighting design practices are limited in terms of their degree of correlation to the desired values. Recently, efforts have been made to introduce new metrics to overcome these limitations [Boyce and Smet 2014; Rea 2013]. Calculating some of them is not possible without using lighting simulation tools. Data visualization and the different types of image presentations available in these tools can help designers 1) to better interpret the simulation results and compare different alternatives; 2) to communicate among different parties; and 3) attain a better understanding of the system behavior to make informed decisions.

Following are some of the new metrics that must use simulation tools for their calculations: climate-based daylight modeling, annual spatial contrast and annual luminance variability, annual DGP, mean room surface exitance (MRSE), luminance-based metrics' analysis of non-visual effects of light, data visualization, and image visualization.

3.1.1 Climate-based daylight modeling

Climate-based daylight modeling (CBDM) is the prediction of various radiant or luminous quantities (e.g., illuminance and luminance) using sun and sky conditions that are derived from standardized annual meteorological datasets [Mardaljevic and others 2009; Reinhart and others 2006]. These metrics are better indicators than the daylight factor in terms of "how skylight and sunlight will be distributed across a space, where and how often visual discomfort caused by glare is likely to occur, and what the stimulus to any ceiling-mounted sensors for an electric lighting or blind control system will be." [Boyce and Smet 2014]. First, the weather data (e.g., .epw file) is fed as an input to the simulation engine. Then, for a given point in a space, illuminances are calculated depending on the period of time, the climate, the window or skylight arrangement, and the orientation of the building. These illuminances are absolute measures and can be calculated for an assumed arbitrary horizontal or vertical plane [Boyce and Smet 2014].

Some of the daylight CBDM metrics include Daylight Autonomy (DA), Useful Daylight Illuminance (UDI), continuous Daylight Autonomy (cDA), and spatial Daylight Autonomy (sDA). DA is defined as the fraction of the occupied times per year, when the required minimum illuminance level at the point can be maintained by daylight alone [David DiLaura 2011]. UDI is another dynamic daylight performance measure. As its name suggests, it aims to determine when daylight levels are "useful" for the occupant, that is, neither too dark (100 lx) nor too bright (2000 lx) [Nabil and Mardaljevic 2005; 2006]. In cDA, unlike earlier definitions of DA, partial credit is attributed to time steps when the daylight illuminance lies below the minimum [Reinhart and others 2006]. Spatial daylight autonomy (sDA) measures daylight illuminance sufficiency for a given area. It is defined as the percentage of floor area that meets or exceeds a specified illuminance level for a specified amount of annual hours [Committee 2012].

Several Radiance-based daylighting tools that can be used to perform dynamic daylight simulations include: DAYSIM, ESP-r, Lightswitch, SPOT (ver. > 4.0) [Reinhart and others 2006].

3.1.2 Annual spatial contrast and annual luminance variability

Since occupants perceive space from a three-dimensional vantage point, illuminance-based metrics such as DA and UDI cannot express the dynamic nature of sunlight from a human perspective. Rockcastle et al. proposed a new family of metrics that quantify the magnitude of contrast-based visual effects and time-based variation within daylit space through the use of time segmented daylight renderings. Annual spatial contrast provides the designer with a more holistic understanding of when and where sunlight impacts the composition of light and shadow within a person's field of view [Andersen and others 2013; Rockcastle and Andersen 2012].

3.1.3 Annual daylight glare probability

In measuring both the quality and quantity of light, there are scarcely any factor more difficult to quantify, more subjective, and yet more important to visual comfort, than glare. There are at least seven recognized glare indexes: VCP, UGR, BGI, CGI, DGR, and DGP [Kleindienst and Andersen 2009]. DGP [Wienold and Christoffersen 2006] is regarded as the most reliable index for side-lit office spaces under daylight conditions. Over the years, it has also evolved into dynamic annual metrics such as simplified DGP (DGPs), which provides a comprehensive yearly analysis of glare with limited computational intensity [Jakubiec and Reinhart 2011; Wienold 2009].

3.1.4 Mean room surface exitance

Mean room surface exitance (MRSE) is the average of flux densities existing, or emerging from all surfaces within the space measured in lm/m2 [Cuttle 2013]. It was introduced by Cuttle, the prime advocate for reforming the current state of internal lighting standards. Central to Cuttle's proposal is considering a more holistic design approach that better relates to what we see [Cuttle 2004; Cuttle 2008; Cuttle 2009; 2013; Cuttle 2015]. Duff proposed a method that utilizes a Radiance lighting simulation engine to calculate MRSE, and high dynamic range (HDR) imaging to estimate levels of MRSE in the field [Duff and others 2015].

3.1.5 Luminance-based metrics

Luminance-based metrics are a generation of metrics that have become calculable thanks to simulation tools. They are established in the research community but need to receive more attention from the industry. Different studies show that luminance-based metrics had a higher correlation to visual performance than illuminance-based metrics did [Gilchrist 2007; Van Den Wymelenberg and Inanici 2015; Zaikina and others 2014]. A number of researchers and the CIE Technical Committee members (TC 3-45) are promoting luminance-based metrics for lighting design [Nakamura 2011].

[Rockcastle and Andersen 2012] classified the existing luminance-based metrics into two main categories. One is the metrics that can predict glare-based discomfort due to high ratios of contrast within the visual field, (e.g., DGP and DGPs). The other is metrics that can evaluate luminance ratios or ranges to infer human preferences for brightness and composition, (e.g., annual spatial contrast and annual luminance variability).

Lighting simulation tools enable the shift from illuminance-based lighting design (that is easier to measure and calculate) to luminance-based design.

3.1.6 Analysis of non-visual effects of light

Lighting simulation tools are developed, used, and validated mainly for computing the visual aspects of lighting. But in recent years, the non-visual effects of light have attracted the attention of researchers. Multi-spectral simulations, which account for the complex interactions of wavelengths between skies, glazing, color in space, and a point of view, can be used to design and analyze circadian lighting in built environments [Inanici and others 2015].

3.1.7 Data visualization

Meaningful data visualization can assist designers in making better design judgments. Some of the data visualization types are histogram, scatter plots, surface plots, tree maps, parallel coordinate plots, contour plots, and gradient vector fields [Pousman and others 2007]. Parallel coordinate plot is especially interesting for qualitative sensitivity analysis and becoming popular in parametric simulations (See Figure 10 in parametric modeling). The emergence of big data gave rise to the modern data visualization techniques which could be utilized in analyzing ever increasing amount data generated throughout the lighting performance assessment process. This new data visualization technologies can greatly help in realizing "form follows data" idea [Ganji Kheybari and others 2015].

3.1.8 Image visualization

Lighting software offers fairly quick and rough visualizations or fairly lengthy and detailed renderings. Once the computer model is established, it is quite convenient to review various lighting scheme's effects on architecture [Steffy 2008]. The software can generate variety of visualization types including false color and iso-contour image, HDR image, annual overview, animation, and so on.

3.2 Stage of Design

Lighting simulation tools can be used in all stages of design. However, since the gains of using these tools in early design stage is higher than other stages, the early stage is discussed in detail in this paper. The design development stage is the primary stage of design and has been at the focus in other literature, therefore, it has been discussed only to a limited extent here.

3.2.1 Early design stage

In building design and construction, the cost of change increases significantly as the design and construction process proceeds. In that sense, gaining knowledge about building performance via simulation in the early design stage can lead to a large savings [Negendahl 2015].
During the early design stage, architects need to interactively compare the outcome of their intentions. Ochoa et al. identifies three characteristics of simulation in this stage as 1) to compare between alternative design solutions; 2) to suggest solutions; and 3) to model with few detail [Ochoa Morales and others 2012].

One of the difficulties designers face in the early design stage is having to deal with an overwhelming number of uncertainties. Rezaee et al. [Rezaee and others 2014] proposed a method based on probability theories to deal with these uncertainties. Another issue is the long computational time in lighting simulations [Sarawgi 2006]. This issue can be solved by adjusting simulation parameters or choosing fast algorithms such as radiosity. The downside is reduced accuracy, which is, in most cases, acceptable in the early design stage. Despite these issues, parametric modeling, a positive trend that has emerged in recent years, is benefiting the early design stage more than the other stages of design (see more in the parametric modeling section). "This trend is fundamentally changing building design into a faster, performance-aware and more flexible process, which eases the production of multiple design alternatives" [Negendahl 2015].

Building performance sketch, a concept for sketching building performance early in building design, proposes the selection of the most expressive tool for each purposes. Donn et al. explored some of the comprehensive simulation tools that might be used to sketch performance during design conceptualization. Lightsolve, LiteVis, Daylight 1-2-3, SPOT, COMFEN, and Ecotect are some of the tools that have been developed with the early design stage in mind [Donn 2010].

3.2.2 Design development

Ochoa et al. identifies three requirements for designers in the design development stage: 1) exploration behavior of design under artificial and daylighting; 2) exploration of functional properties; 3) and refinement of element behavior [Ochoa and others 2012].

Current lighting simulation models can be used after critical parameters such as massing, building position, windows size, and orientation. Reinhart et al. elaborates on the considerations and steps for proper daylight simulation [Reinhart 2011]. Artificial lighting has long been at the focus of lighting designers and computerization of design process sought to address this need. Today, a wide variety of electrical lighting design tools are available in the market. Achieving an optimal performance for specific building components such as glazing and redirecting systems [Page and others 2007] or shades and blinds [Al-Shareef and others 2001] require expert knowledge. [Ochoa and others 2012]

Some of the software tools that can be used in the design development stage are AGi32, ElumTools for Revit, DIALux, Relux, SunTools for AutoCAD, LightUp for SketchUp, and SIMMODEL [O'Donnell 2013].

3.3 Optimization

As elaborated in Chapter 2 and Figure 2 different building elements and systems interact to achieve a variety of values, raising the need to optimize a design solution that is considering multiple objectives, even within a single system such as lighting. In reality, building consists of multiple subsystems, increasing the already complex optimization problem. These subsystems need to be treated as a complete optimized entity rather than the sum of a number of separately designed and optimized subsystems or components [Trcka and Hensen 2007].

Manual optimization of a design problem is achieved by iterative modifications and evaluations of solutions. The performance of each solution is calculated and compared at which point simulation comes into play [Attia and others 2013] Design variables such as window size are modified and simulated. Then, designers try to construct a hypothesis about the relation between the input change and various resulting performance indicators. This hypothesis may not be clear especially when there are numerous parameters to be studied and possibly due to the nonlinearity of the problem. This is an inefficient procedure in time and labor, so achieving an optimal solution is not always guaranteed. To overcome such difficulties, automated simulation based BPO search techniques are used [Attia and others 2013].

> "Automated BPO is a process that aims at the selection of the optimal solutions from a set of available alternatives for a given design, according to a set of performance criteria. Such criteria are expressed as mathematical functions, called objective functions. Automated optimization is a combination of different types of optimization algorithms, setting each algorithm to optimize one or various design functions" [Attia and others 2013].

A typical strategy of the simulation-based optimization is presented in **Error! Reference source not found.**.

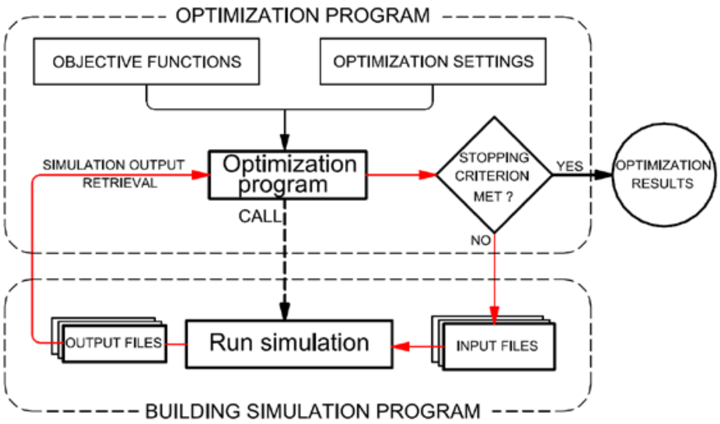


Figure 7. The coupling loop applied to simulation-based optimization in building performance studies [Nguyen and others 2014]

3.3.1 Optimization Issues

The main difficulties in solving building optimization problems by simulation-based methods pertain to the complex natures of building simulation outputs, the expensive computational cost, the scale of the problems, multi-objective design problems, and the uncertainty of many factors during the optimization. The uncertainty includes design variables, environmental variables, model and constraint uncertainty, and so on. Moreover, errors may occur during the optimization process due to insolvable solution spaces, infeasible combination of variables (for instance, windows area that extend the boundary of a surface), output reading errors, and so on. A single simulation failure may halt the entire optimization process. Running parametric simulations before the optimization process can help in minimizing such errors. Some optimization algorithms may fail to draw a distinction between a local optimal solution and a global one (or fall into a trap by a local one), and consider the local optimum as the final solution to the problem. To avoid this issue, new simulation tools should be developed with adjustable precision for solvers that might cause large discontinuities in the outputs [Nguyen and others 2014].

Several optimization tools have been developed but their adoption remains limited mostly to the research community due to the problems in coupling strategies, usability, flexibility, and efficiency in term of both time and performance improvement [Nguyen and others 2014].

3.3.2 Multi-objective optimization in lighting design

In lighting design problems, designers often have to deal with conflicting design criteria such as maximizing daylight and minimizing glare [Wortmann and others 2015]. This is a common issue in many application domains. For this reason, multi-objective optimization (MOO) has long been an active field of research [Köksalan and others 2011; Viola and Roudsari 2013]. Since a single best solution does not exist for MOO-problems, one approach is to provide multiple solutions to the decision maker, also known as a Pareto set [Sorger and others 2016]. The Pareto method does not solve the optimization problem, rather, transforms it from an engineering domain to a managerial domain, which means the problem can be dealt with the feedback from the stakeholders. This process is known as the multi-criteria decision making. Many decision-making techniques have been developed [Triantaphyllou 2013] such as pros and cons, simple prioritization, satisficing, opportunity cost, and bureaucratic, the details of which is out of the scope of this thesis. Another approach is to weight the objectives in order to attain a score, which can then be used for ranking possible solutions for decision making [Sorger and others 2016]. This approach is known as scalarization. Its drawback is the difficulty in estimating the weight factor because the objective functions do not have the same dimension or the same significance [Nguyen and others 2014].

3.3.3 Case studies

Rakha et al. used a genetic algorithm technique to optimize ceiling geometry for better daylight utilization by searching for a curvilinear and mesh shapes that increase daylight uniformity ratios in a space. Radiance was used for calculation and Ecotect was used for form input and visualization [Rakha and Nassar 2011]. A study titled “Simulation-Based Multi-Criteria Decision Making Framework for a More Value Driven Building Design Process” is being conducted in the Jönköping University [Jalilzadehazhari and others 2016].

Shea et al. presented proof-of-concept computational design and optimization tool aimed at facilitating the design of optimized panelized building envelopes for lighting performance and cost criteria. A multi-criteria ant colony optimization method using Pareto filtering is applied, which utilizes Radiance to calculate lighting performance [Shea and others 2006]. Caldas et al. used the concepts of generative and goal-oriented design to propose a computer tool based on genetic algorithm to optimize placement and sizing of windows in an office building for optimal thermal and visual performance. DOE2.1E were used as the simulation engine [Caldas and Norford 2002]. Tsangrassoulis et al. also used genetic algorithm and Radiance lighting simulation program to present a technique for the design of slat-type blinds based on their relative light intensity distribution under a uniform light source [Tsangrassoulis and others 2006]. It is argued that “optimization is not so much about finding the “[globally] optimal” solution, but as much about exploring the design space for alternative [near optimal] solutions.” [Attia and others 2013]

3.4 Model Integration

Model integration has been a concern of both building design software developers and simulation software developers. Today, numerous tools offer an integrated environment for designing and performance assessment. However, designers still seem to prefer to work with dedicated design tools such as ArchiCad, Sketchup, Revit, and Rhino because these tools support the concept of a sketch and provide more freedom. As a result, to assess performance, designers either create a new model from scratch in the simulation tool or manually export a model from the design tool and import it into the simulation tool and further refine it to be usable [Negendahl 2015].

Integration of BPS with building design can be investigated from the user, tool, and model perspective (see Figure 6) and in this study, model integration was the focus. Three methods have emerged for integrating geometric and analytic models as shown in Figure 8. The combined model method is the most obvious approach that can be taken for integration by providing a one-size-fits-all solution. In this approach, the tool is dominant player. To the contrary, central model method puts the emphasis on the model by providing a query language so the tools can retrieve the information of interest from the central model. This approach is most commonly observed in the BIM paradigm−IFC is the most commonly used open standard/schema in BIM. In the distributed model method, the focus is shifted to a middleware that facilitates coupling a design tool to a BPS tool. In parametric modeling[3], a type of distributed model method, the middleware provides an environment for visual programming.

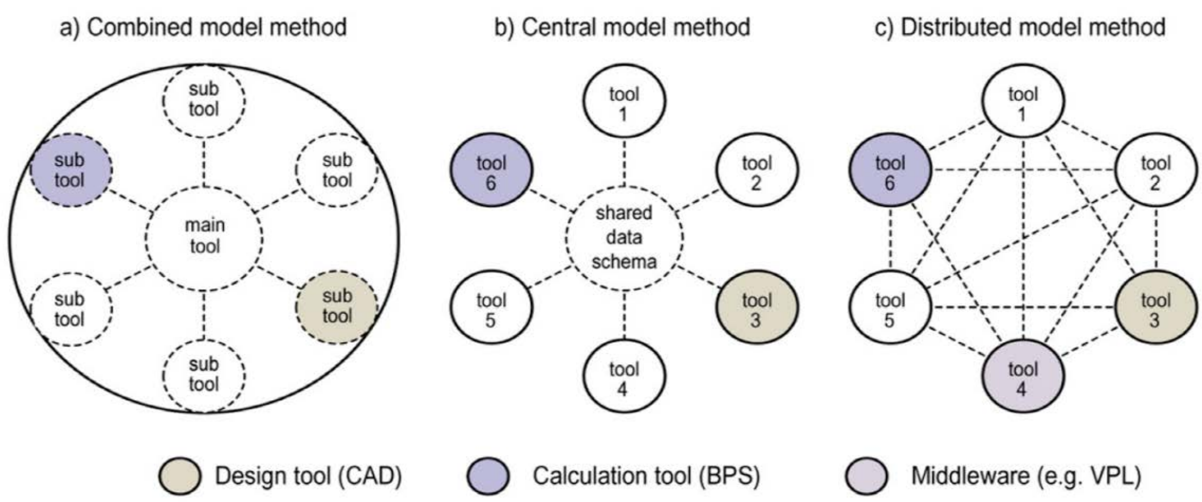


Figure 8. Differences between coupling methods: a) combined model method (typically operated in a simulation package), b) central model method (using a central database/file format/schema), c) distributed model method (utilizing a middleware). Reference: [Negendahl 2015]

Each methods has pros and cons, which the user should consider. Support of runtime coupling is a common feature among the three methods. The combined model method has the highest level of convergence between the geometric and analytical models. The downside is that users are virtually locked into using the vendor's platform as in Autodesk Revit. The central model has the least convergence due to poor interpolation formats and immaturity of the platform, as of today. Here, the user is virtually locked into the central model's schema ecosystem. "The distributed model method, e.g., the framework of Virtual Design Studio(VDS) [Pelken and others 2013], may support the same model convergence as [expected] from a combined model. However, distributed models such as VDS rely on one-way import from a design tool, which essentially shifts the design tool operation into the middleware" [Negendahl 2015].

3.5 BIM

As mentioned, BIM is an emerging design platform [Kota and others 2014] that promises to simplify modeling in the design process for multiple disciplines. However, the promise of an integrated model has not yet been realized. A root cause is that the modeling and simulation processes are purpose-driven (see Chapter 2 Modeling). While models should be as simple as possible for the simulation purpose, BIM tries to be an all-encompassing repository of information [Yan and others 2013]. Information relevant for the purpose of simulation problem needs to be extracted/interpreted from the BIM model [Kota and others 2014] and missing information must be added since each discipline has its own perspective and requirements of a building model [Ochoa Morales and others 2012].

One of main ideas behind BIM is that a building model should not be composed of plain lines and surfaces but of semantically rich building elements that holds non-geometric information

[3] Parametric modeling refers to different concepts. Here, integrated dynamic model or generative algorithm modeling is the meaning of interest. More on that in Parametric Modeling section.

in addition to geometric ones, such as material properties. This is intended to allow each tool to extract and append the information concerning its domain. As convenient as it sounds in theory, reality is different, at least in the case of lighting simulation. Instead of lighting simulation tools being able to retrieve the information of interest from a central model repository, the simulation process usually involves a back-and-forth conversion of the model between BIM tools and simulation tools in multiple manual steps. Another limitation is missing information. Since other disciplines are not concern with material characteristics such as specularity and roughness, this information is almost always missing from the BIM model. In addition, construction material/element vendors rarely provide this information with the BIM objects of their products so it needs to be entered manually and in a separate process than geometry conversion. As a result, research in the integration of BIM with building performance tools has been a main focus of both the developers of the BIM authoring tools and of the building simulation community. [Kota and others 2014] For example, the integration of Autodesk Revit (a popular BIM tool) with Radiance (a validated lighting simulation engine) and DAYSIM (daylight simulation engine based on Radiance) is investigated here, based on an article by Kota et al. who developed a tool for this purpose. Others have reported similar findings and issues in the integration of BIM tools with other simulation tools [Stavrakantonaki 2013; Yan and others 2013] [Welle and others 2012].

Radiance/DAYSIM models require information pertaining to geometry, materials, weather, location, camera view, sky description, date and time, and sensor point data. Geometrical data can be extracted directly from the Revit model. Decorative and other detailed objects are typically excluded to keep the model as simple as possible [Stavrakantonaki 2013]. Radiance materials need reflectance, specularity, and roughness values. Reflectance values can be extracted from Revit material color information. Other information required for Radiance/DAYSIM can be extracted with conversion or interpretation of information in Revit models.

Figure 9 shows the different steps involved in converting a Revit model into a Radiance input file using different utilities. The steps involved in translation are represented as paths (i.e., P1-5) [Kota and others 2014]. This figure captures some of the data exchange and interoperability issues between a BIM authoring tool and a lighting simulation tool.

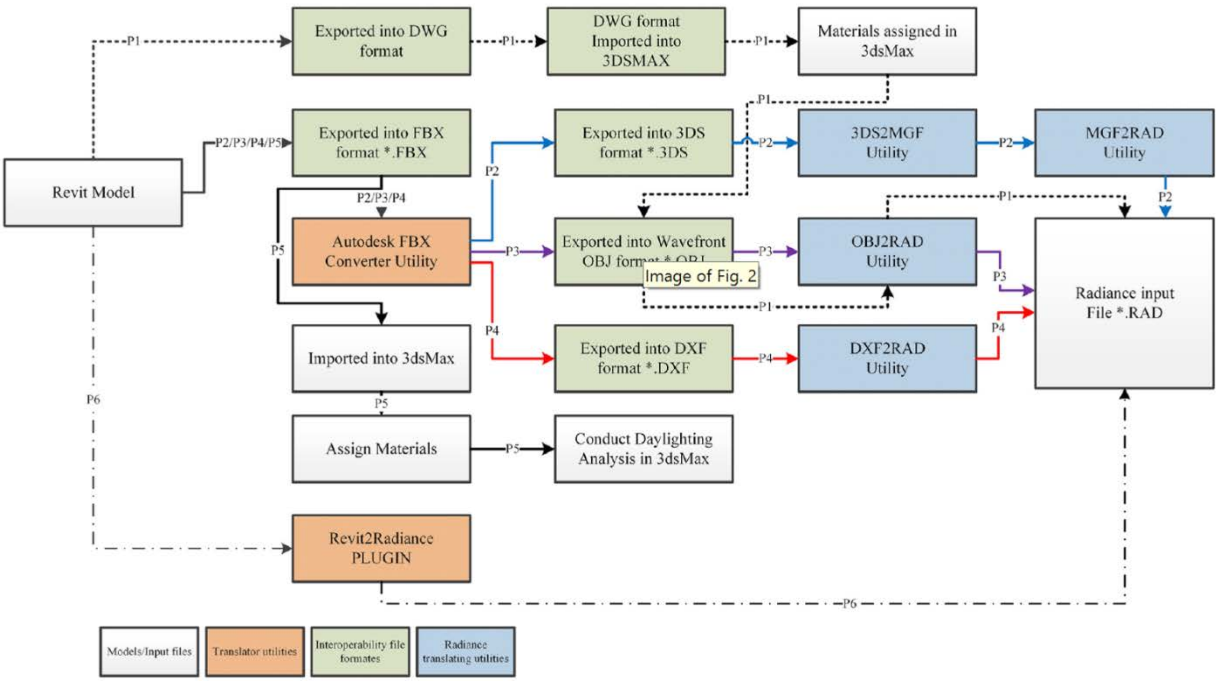


Figure 9. Different translation paths from Revit to Radiance, Reference:[Kota and others 2014]

In addition to manual assignment of missing material information in Revit, window panes need to be adjusted because they are modeled with thickness whereas in Radiance window panes are modeled with zero thickness. Another issue is that converting geometrical files from BIM tools to simulation tools results in different type of errors [Stavrakantonaki 2013]. In addition, a thorough knowledge about each tool is required to carry out the process, which can be a significant challenge for even an experienced architect. Because the architect changes the design iteratively, the whole process becomes tedious, as each translation involves working with several tools and multiple steps [Kota and others 2014].

A new plugin, which mitigates some of the issues discussed above, has been released by Autodesk for Revit (Lighting Analysis). It enables cloud-based calculation of illuminance having Radiance as the core simulation engine.

In conclusion, BIM helps simulation in the modeling phase; however, at present the full potential of BIM to seamlessly provide a solid platform for exploring design solution space combined with solution performance has not been realized.

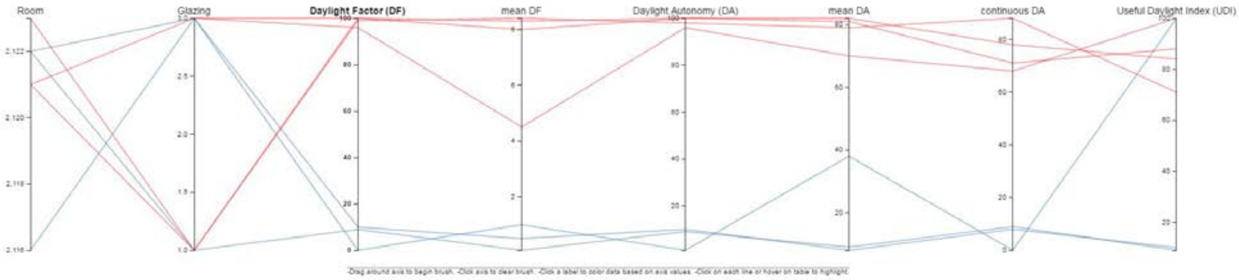
3.6 **Parametric Modeling**

Design alternatives can be created by either manually altering and manipulating the parameters of a model elements or the algorithmic modification of these parameters. The latter is more precisely called “generative algorithm modeling”, as clarified by Stavric et al. [Stavric and Marina 2011]. The paper uses the term “parametric modeling.” Parametric modeling has become popular in the research community and is gaining traction in the industry over the past years as the current platforms such as Grasshopper for Rhino are maturing and the new ones such as Dynamo for Revit and Marionette for Vectorworks are emerging. Attia et al. identified that building designers and engineers need BPS tools that are able to provide quick parametric study and can examine sensitivity and the uncertainty of key design parameters [Attia 2010].

In creating a model through parametric modeling, mathematical operations, dependencies, and functions are used, instead of literal drawing of geometrical objects. These generated elements contain many variables within their internal structure that may be used in the generation of design solution alternatives. This allows for exploration of design solution space, which is not possible using standard modeling tools [Stavric and Marina 2011]. It is important to note that parametric modeling is not limited to geometry; rather, any design variable such as color, scale, and material can be parameterized, hence, algorithmically manipulated [Ochoa Morales and others 2012] [Qingsong and Fukuda 2016].

Rhino+Grasshopper, the most widely used parametric modeling tool, supports a wide range of couplings to various BPS tools via 3rd-party modules such as Ladybug, Honeybee, Geco (Ecotect/Radiance), and DIVA. Ladybug can perform energy and daylighting analysis coupled with EnergyPlus, Radiance, and DAYSIM. It simplifies the process of analysis, automates and expedites the calculations, and provides easy-to-understand graphical visualizations. Honeybee is the extension of Ladybug for more advanced lighting and energy studies [Roudsari and Pak 2013]. Other parametric modeling platforms such as Dynamo for Revit have not hit version 1.0 and Marionette for Vectorworks had not been released at the time of writing.

Being able to generate several alternatives brings about the challenge of performance assessment [Turrin and others 2011]. Like automated optimization, performance-oriented parametric modeling requires simulation of numerous alternatives, an obstacle for its adoption by practitioners. In automated optimization, the best solution(s) is searched by the machine, while in parametric modeling different alternatives are generated and then evaluated for performance analysis. The results of the evaluations (with the exception of radiation and daylighting studies, which typically map the results onto the geometry) are generally presented in the form of reports, spreadsheets, charts, and so on [Roudsari and Pak 2013]. Modern interactive data visualization techniques are increasingly used for visualization of the results. Pollination for Rhino/Grasshopper as an example can perform batch simulation and visualize results as shown in Figure 10, which is also available for Honeybee plugin [Roudsari 2016].



Room	Glazing	Daylight Factor (DF)	mean DF	Daylight Autonomy (DA)	mean DA	continuous DA	Useful Daylight Index (UDI)
2116	3	0	1	1	38	0	100
2121	3	100	8	100	81	71	88
2122	3	10	0.5	10	6	6	10
3120b	3	96	4.5	96	70	68	100
2121	1	100	8.3	100	82	78	84
2122	1	9	.08	9	9	9	9
2123	1	99	8.4	98	79	88	71

Figure 10. Parallel coordinate visualization commonly used for parametric analysis

Illustrative parallel coordinates allow the user to study the sensitivity of parameters in a global-to-local fashion [Sorger and others 2016].

To add to the tools available to designers, automated optimization has been integrated into parametric modeling platforms. Examples are Octopus and Galapagos for Rhino/Grasshopper and Paragen. These tools have also been utilized in combination with lighting simulation tools [Gallas and Halin 2013; González and Fiorito 2015; Roudsari and Pak 2013; Wortmann and others 2015].

4 Summary of Papers

The aim of this research was to investigate lighting simulation tools to find out how they can enable a more value-driven building design process. Some of the results were presented in the form of two papers, which are summarized in this chapter. The original articles are appended to this document.

The focus in the first article was to attain a basic understanding of available performance metrics and existing lighting simulation tools as well as to review and compare these tools based on their ability to calculate these metrics. In the second paper, lighting simulation tools were viewed from the lighting designer's perspective to explore what software features were important to designers and which software tools they most commonly used.

4.1 Paper 1: Comparison of Lighting Simulation Tools with Focus on Lighting Quality

4.1.1 Aim

The aim of this paper was to understand the characteristics of the currently available simulation tools and compare their ability to simulate lighting quality. First, the current numerical metrics for lighting quality are summarized. Then, different simulation tools are evaluated based on a literature study. The outcome summarizes the strength and shortcomings of selected simulation tools.

To achieve this goal, the following questions were framed and addressed:

Q1: How can lighting quality be defined using performance metrics?
Q2: Which characteristics of simulation software should be evaluated?
Q3: What are the available simulation software on the market?
Q4: How can these lighting simulation software help in achieving better lighting quality?

4.1.2 Method

The main method for data collection in this study was literature review. The keywords used in the first step of the search process is shown in Table1.

Table 1 *Search terms (synonyms, broader and narrower terms, and possible related terms)*

Concepts	**lighting simulation tool**	**lighting quality**
Synonym	lighting simulation software	visual comfort
	lighting computer-based tools	maximized visual comfort
	visualization software	lighting performance
	assessment tools for lighting system	lighting value
	lighting computational tools /software	lighting indicator
Broader Terms	building simulation	lighting design
	energy simulation software	
	simulation software	

Narrower Terms	daylight simulation	Indicators (SYNTEZ Projects) e.g., glare
	daylighting prediction	color and light
	software	glare index
	each tool’s names e.g., Radiance, DIALux...	lighting quality Indexes: e.g., daylight
	each indicator's name e.g., calculation methods: Ray tracing	
Related Terms	game animation tools	aesthetics
	computer graphics	health care
	Computer- aided design	human well-being
		interior lighting quality
Alternative Spelling	CAD	color
	SIM	DGIn
Part of Speech/Grammar	lighting simulation tools	filtering other meaning of light
	computer based tools	
	daylight/day	
	light/daylighting	

In the next step, the keywords were updated based on the search results to include specific terms such as “CIE test Case”, “TC3.33”, “CIE171: 2006”. The search was limited to published English literature since 1990 until 2013. See the first chapter for more information on bibliographic databases and resources used as a source.

4.1.3 Q1. The concept of lighting quality and performance metrics

To find the answer for the first question the concept of lighting quality and the related metrics were explored. From the literature, it was clearly observed that there is a strong trend toward improving lighting quality. Although, the community has not yet reached a consensus on the concept of lighting quality, there have been numerous attempts to formulate it from different perspectives. [Arnkil Harald 2011; Boyce 2013; Rea 2013; Veitch 2000; Veitch and Newsham 1996; 1998] Nevertheless, the review showed that some metrics were frequently used for lighting quality such as illuminance-based metrics, luminance-based metrics, daylight availability metrics, glare indexes and color aspects. While illuminance is a lighting quality metric most frequently used in today’s lighting design practices, it does not directly correlate to eyesight. Some researchers [Van Den Wymelenberg and Inanici 2015] advocate that the new lighting quality metrics should be based on luminance despite the complexity in measuring it and the need to use simulation tools for its calculation. Recently, daylight aspects have been increasingly emphasized, especially in the green building industry. Daylight Factor (DF), the most frequently used metric, falls short in providing enough information for evaluating daylight efficiency; hence, new dynamic daylight metrics are proposed such as Daylight Autonomy (DA). A variety of factors contribute to visual comfort, of which glare is the most important and studied factor. Glare is a subjective human sensation for which many metrics have been developed. Two important metrics are DGP and Universal Glare Index (UGI). Color-related metrics are mostly concerned with the light source and do not play an important role among metrics calculated by lighting simulation tools. Recent research [Boyce and Smet 2014; Freyssinier and Rea 2013] has suggested that more than one metric is needed to give a clear picture of the ability of a light source to render colors, at least one for fidelity and one for preference.

Some definitions of lighting quality in the literature propose including the emotional experience (e.g., Boyce "Good lighting is lighting that allows us to see what we need to see quickly and easily, without discomfort, and which does lift the spirit") [Boyce 2013]. The analysis method PERCIFAL presents a number of visual concepts that help in analyzing the character of the light in a space [Arnkil Harald 2011].

4.1.4 Q2: The characteristics of simulation software

The lighting simulation tools can, mainly, be studied from three different aspects: rendering method, calculation algorithms, and inputs/outputs. There are two approaches for rendering: photo-realistic, which is focused on aesthetics, and physically-based, which is aimed at technical applications. The latter was the focus of the study, which tried to reflect and predict the reality as accurate as possible. Calculation algorithms can be classified into two main groups: ray-tracing is the accurate and computationally expensive algorithm. Radiance is the most notable simulation engine that uses this algorithm. Ray-tracing has been extended by photon-mapping algorithm to complement its capabilities. Radiosity is another algorithm developed for speedy simulations though at the cost of accuracy. Inputs and outputs are important in the choice of simulation tools since they determine the accuracy of the simulation as well as interoperability with other tools, which influences the seamlessness of the performance assessment process.

4.1.5 Q3. The available simulation software

Today, a wide variety of lighting simulation and design programs is on the market, each program specializing in different aspects of lighting quality. In addition to simulating quality aspects of lighting, other selection criteria were usability, acceptability, availability, and previous references in literature. It is noteworthy to mention that the number of programs are rapidly increasing, though some have been discontinued or their development virtually abandoned. A detailed list of currently available lighting software packages can be found in "IESNA Software Survey," which is prepared annually by the IESNA Computer Committee and published in *LD+A Magazine*. Another directory of simulation tools is provided and maintained by United States Department of Energy; it includes a short description of the tools capabilities, weaknesses, and strengths. This section of the paper reviewed a number of software that each specialized in different aspects of lighting quality. The programs selected were Radiance, DAYSIM, Evalglare, DIALux, VELUX, and VISSLA.

4.1.6 Q4. The comparison of selected lighting simulation software

In comparing lighting simulation software, first, the validity of lighting simulation outputs was studied from literature that investigated validity in accordance with CIE test cases. Then, the metrics that could be calculated by these programs were compared from four perspectives: illuminance/luminance, daylight, glare, and the underlying lighting simulation algorithm. Radiance was found to be the most established simulation engine that could simulate lighting with high accuracy. Its primary outputs are illuminance and luminance, which, in turn, can be processed further using tools such as Evalglare to calculate glare or DAYSIM to calculate daylight-related metrics. VELUX Daylight Visualizer was another simulation program that specializes in daylighting. DIAlux, the most used program by lighting designers, utilizes radiosity as the simulation algorithm. Finally, VISSLA stood out due to its focus on simulating lighting that takes into account people with impaired vision.

4.1.7 Discussion and conclusion

Current lighting design practices can provide at best “indifferent lighting” quality. Simulation can help in the shift toward “good lighting” by enabling the calculation of advanced metrics such as luminance-based metrics, glare, and dynamic daylight metrics that better correlate to visual comfort than currently used metrics such as illuminance and daylight factor. Simulation tools were studied from three different aspects: rendering method, calculation algorithms, and inputs/outputs. When looking for a simulation tool, the goal is not to find the best tool with respect to these characteristics but to find which tool fits best for the task at hand. For example, in the early design stage, speed might be more important than accuracy for which radiosity would more suitable than ray-tracing. One of the problems observed during the literature review was software obsolescence and abandonment of development projects. To overcome this issue, development projects with limited resources should focus their efforts on one or a limited number of metrics and adopt a modular design strategy that might allow integration with other design and simulation platforms. Radiance is the most notable example which has been extended and integrated by numerous developers and researchers. Finally, special credit should be given to VISSLA, which took a different approach by focusing on simulating lighting, taking into account people with impaired vision.

4.2 **Paper 2: Current Use of Lighting Simulation Tools in Sweden: A Survey**

This paper presents the findings of a web-based survey on the current use of lighting simulation tools in Sweden. The objective was to understand which lighting simulation tools were used in Sweden and to understand the design practitioners' needs, which might be taken into account in future software development projects.

4.2.1 Method

Surveying was the main method of data collection in this study. An online interactive surveying service (www.surveygizmo.com) was used to ask participants' opinions. Since the goal was investigating usage of lighting simulation tools in Sweden, the scope of the study was limited to Sweden. Invitations to participate in the study were sent via email to 54 graduates from the Lighting Design Program at Jönköping University and 81 lighting designers, who were identified from the list of registered companies in the Ljuskultur database (http://ljuskultur.se/). In total, 124 emails were delivered successfully and 31 people took part and filled out the questionnaires. The method and questionnaire for the survey by Reinhart and Fitz [Reinhart and Fitz 2006] was used as a base for this survey, although the domain was extended beyond daylight to include electrical light.

4.2.2 Summary

We found that lighting simulation programs are widely (90%) used for analysis and/or rendering. The great majority of lighting designers tend to consider both daylight and artificial light in their design. However, the respondents paid less attention to daylight compared to artificial light. 65% of respondents included daylight analysis in their lighting design, compared to 96% of the participants who included artificial lighting. The respondents' principal training methods were university courses and self-training. Interior illuminances, glare indexes, and daylight factor were the most commonly calculated simulation outputs. *Ease-of-use* and *accuracy* were identified as the most important factors in the use of the software, while *slowness of simulations process* was the most important cause of dissatisfaction. DIALux was the most popular software program used.

4.2.3 Discussion and conclusion

Users considered many factors in their choice of simulation toolkit of which user friendliness (ease-of-use), accuracy, and speed stood out. Users were also reluctant to work with multiple software tools and preferred a one-size-fits-all software. The majority of participants ignored metrics such as DGP and dynamic daylight performance metrics, which are present only in relatively specialized software programs with relatively complicated user interfaces. If more attention had been given to these key user experience design factors in the development of these programs, it might have resulted in greater use of the advanced metrics. Nonetheless, fixing one issue should not come at the cost of another but an optimal trade-off should be achieved. One such example is sacrificing accuracy for speed. As reported by some designers, low accuracy and low reliability were the main reasons why they did not use certain software tools. Eventually, advancements in computer technology and simulation techniques will contribute to overcoming of the issues regarding simulation time.

The participants' comments in the open-ended questions implied that designers need a better understanding of software tools in terms of capabilities, accuracy, reliability, and the stage in which these tools should be used. The results of this survey show that universities were the main training channel, which highlights that universities can play an important role in educating future lighting designers by offering specialized and advanced courses. This is especially true because of the ongoing paradigm shifts in building modeling from document-based CAD models to object-based BIM models. BIM's emphasis on collaboration is in line with collaborative nature of lighting design processes and the new generation of software applications can provide new methods of design at different levels and stages in an integrated environment. Simulation tools could also be used as an effective educational tool for understanding physical concepts in an interactive environment [Feng 2003; Reinhart and others 2012].

5 Potentials for Improvement

The previous chapters examined lighting simulation from different angles and identified various limitations. Based on these findings, this chapter discusses the potential for improving lighting simulation to achieve better lighting quality. The opportunities are categorized into the following:

- Setting a path for value-driven design in lighting
- Retinal Illuminance Map; a new base metric
- Simulation time and surrogate models
- Paying attention to designer experience
- Taking into account qualitative variables

5.1 Setting a Path for Value-Driven Design in Lighting

This study takes a different approach than that used in other researches to investigate lighting simulation tools by revisiting the original goals of lighting simulation in the context of lighting design for occupied buildings. As Figure 11 illustrates, a design solution should be translated to a final value in a VDD process. Unfortunately, this chain has some imperfect and missing links. The imperfect links are simulation and performance metrics, which have already been discussed. The missing links are the inability to calculate the degree of visual comfort and performance and, consequently, their value. No matter how accurate our simulation and how well-defined our metrics, if they cannot be translated to a comparable value at an aggregate level, they remain ineffective means to support design decisions.

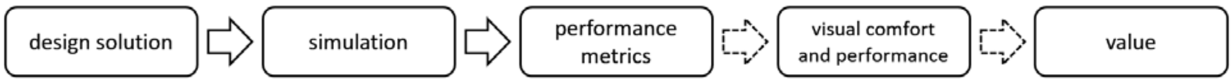


Figure 11. Translation from a design solution to value

If we trace back the origin of the issue, it becomes obvious that the inability to simulate the human visual system is the reason for this broken chain. It would appear that ways could be found to simulate the human visual system. Thermal simulation, another practice for assessing thermal comfort of indoor environment, solved this issue long ago, thanks to universally recognized theories of Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD), originally developed by Fanger [Charles 2003]. In that sense, thermal simulation is complete because it simulates the entire system, including physics and human (as a glass box and black box, respectively). Having such a convenient indicator allows for setting the design criteria to become as simple as setting limiting thresholds (e.g., max 20% PPD as recommended by ASHRAE Standard 55-2010). PPD is an elegant indicator because it is dimensionless and independent from physics, which means that similar approach could be taken in lighting. However, it has its own problems, which need to be rectified or complemented before it could be applied to lighting. PPD's drawback is that it is a pessimist's yardstick, meaning that at best it can lead to "indifferent lighting" (according to Boyce's terminology). To design "good lighting", we should instead or in addition calculate the Predicted Percentage of Elevated (PPE).

One example of a simulating visual system is DGP in which the visual system is simulated using a black-box approach. Another example can be found in VISSLA simulation program, which attempts to take into account people with impaired vision. Having the visual system simulated brings us one step closer to completing the system simulation. The next step is to translate the results to a simple indicator such as PPD. A prerequisite to the translation is compilation and aggregation of disparate number of visual performance and comfort metrics into a single indicator.

5.2 Retinal Illuminance Map; A New Base Metric

The advent of computer simulation has given rise to skepticism of the old methods and metrics. At the center of this lies illuminance (see Chapter 3 and 4)—the most widely used metric in the lighting design practices. Illuminance may be fairly acceptable for some problems (e.g., energy efficiency) but when the problem requires inclusion of the building occupant's visual system within the boundary of the system, illuminance-based metrics become less effective. To address this type of problems, a new approach is put forward here, along the thinking leading to its conception.

Before getting into all the metrics and the arguments for and against them, let's go beyond the boundaries of the current metrics landscape to search for the ultimate metric. First, we need to find the most relevant piece of information for assessing visual comfort and performance. The final point in occupant's visual system where visual comfort and performance are affected could be the eye (e.g., in the case of discomfort glare) or it could be further down the line at the visual association cortex (e.g. for visibility) [Raftopoulos 2009]. Accordingly, the luminance map or the final image formed in the brain would be the best source of information. A luminance map can be calculated using current simulation software; however, obtaining the final image formed in the brain is inconceivable using today's technology and science. The retina is the last frontier up to which the mechanics of the lighting system is understood to a degree that modeling the system as a glass-box is possible. Therefore, the best calculable piece of information is the map of illuminance incident on retina. Retinal illuminance can be calculated for every patch of retina using Equation 1 to obtain a Retinal Illuminance Map (RIM) [Hirning 2014; Troland 1917].

$$\text{Equation 1: } E_r = e_r T \frac{\cos(\theta)}{k^2}$$

Er is retinal illuminance in Trolands (Td); T is ocular transmittance; θ is angular displacement from the line of sight; er is the amount of light entering the eye (Td); k is a constant, which varies, depending upon the experimental conditions and the photometric units used.

Based on this equation and the fact that eyes have different pupil sizes and ocular transmission characteristics, people may experience different visual effects from identical objects [Rea 2000] Therefore, RIM images should be statistically normalized. RIM's superiority over current approaches comes from the fact that it expands the boundary of our system. In a study, Aries [Aries 2003] proposed retinal illuminance as a new design parameter. The closest similar approach to RIM is luminance map—in fact its calculation is required to obtain RIM. Similar to a luminance map, an HDR format can be used to store RIM data. RIM raises the bar for lighting performance metrics in a way that every metric derived from it takes aspects of such an advanced and important matter as eye adaptivity into account.

Different metrics related to visual comfort such as disability glare and visual performance such as visibility can be calculated by further processing of RIM images. For example, each RIM can be searched for glare occurrence using algorithms developed by revising current glare detection algorithms.

In the survey (see Paper 2), some participants pointed out that too much daylight in the outer spaces of a building (i.e. closer to the facades) could lead to a feeling of darkness when occupants walk into the deeper spaces of the building, even if minimum recommended artificial light is provided. This example, and other scenarios which lead to the same issues, show the importance of eye's adaptivity to achieving visual comfort. By arranging RIM images in a 3D tensor (corresponding to the three dimensions of space) and processing the tensor as a whole, it is possible to perform a holistic analysis of an entire space.

There remains a final frontier to be conquered in the system boundary expansion endeavor: human light perception. Khademi propose a method to solve this issue. Though it sounds far-fetched, and it indeed would be using glass-box modeling, it is not impossible using black-box modeling. To do it, enormous amount of data that maps RIM images to visual performance and comfort is needed; this data can be obtained from experiments. Convolutional neural networks or other machine learning techniques can be used to translate RIM tensors directly to visual comfort and performance indexes much like PMV/PPD for thermal comfort. Such an approach would be next to impossible with current metrics because of the high number of variables and lower degree of correlation between those metrics and final perception. This method has the potential to free designers from thinking about a variety of ever-increasing number of metrics to assess visual comfort and performance of their designs [Khademi 2016, in preparation].

5.3 Simulation Time and Surrogate Models

The time intensity of simulation runs is probably highlighted the most by both researchers and practitioners as a major issue. To reduce the simulation time, three strategies are commonly used: 1) geometrical simplification of the model (e.g. converting complex curves and surfaces to interpolations or polygon-based elements) [Ochoa Morales and others 2012]; 2) sampling (e.g. using sample zones from each facade instead of simulating the entire building) [Welle and others 2012]; and 3) surrogate models, which can be especially useful in the early design stage.

Surrogate models can be used because the performance assessment of the design does not need to be highly accurate in the early design stage, unlike the other stages of design. This is the case because in the early stage the designs are created at the conceptual or schematic level [Steffy 2008] where the degree of estimation in the geometrical model is fairly high due to the high number of variables and high level of uncertainty. This has a positive implication because it opens up opportunities for automatic simulation-based optimization in the early design stage, which is virtually impossible later due to the need for high accuracy, which typically requires seeing the system as a glass-box for simulation. The downside is the time-intensity of the simulations even with radiosity algorithm. This constraint is one of the reasons for the absence of automated optimization in the lighting design process [Wortmann and others 2015]. Costa et al. suggest a black-box optimization based on radial basis functions to alleviate this problem, which reduces the number of required simulation runs [Costa and others 2015]. Jia Hu et al. have developed a method that uses surrogate models to predict the lighting and HVAC energy consumption and lighting electricity demand under different risk parameters, such as control strategy, lamp type, weather, and occupancy. The surrogate model uses an adaptive sampling technique for variable sampling to reduce the number of data points sampled [Hu and others 2015].

Design theorist Roy Woodbury envisions architectural design as design space exploration and highlights the need for computational tools to support this vision [Woodbury and Burrow 2006].

In that sense, the surrogate models approximately but quickly evaluate the sensitivity of the performance measure with respect to the design parameters [Costa and others 2015].

5.4 Qualitative Variables

Acknowledging that the requirements of building design are comprised of quantitative elements (i.e. light levels, energy consumption, cost etc.) and qualitative elements (i.e. social impact, lighting quality, esthetics, etc.), building design in general and lighting in particular aims to satisfy multiple criteria beside quantitative performances. Building performance assessment methods has to respect the broad extent of both quantitative and qualitative elements of building design [Negendahl 2015]. Restricting modeling and simulation only to systems where all quantities can be expressed numerically would exclude large classes of dynamic systems such as the human visual system. The inclusion of non-numerical variables is mandated by the scientific requirement for completeness. In the past, the inclusion of such quantities in computer models was difficult because only numerical methods were available for computer simulation. Today, with modern methods of computer-assisted knowledge processing and fuzzy systems analysis, it is possible to include non-numerical as well as numerical components and relationships in the model formulation [Bossel 2007].

5.5 Designer Experience

Often when lighting performance is discussed, the final user experience—occupant experience in this case—is the subject of the investigation. In providing quality, the occupant experience is admittedly the ultimate goal of any design endeavor; however, the means for achieving this goal (i.e. designer experience) should not be disregarded. The quality of an end is a function of the quality of the means (see Figure 12). We have discussed the *end* in detail; here we will highlight some of the values and issues pertaining to the *means*—the designer experience. This discussion is based mostly on the data collected in the survey as presented in Paper 2.

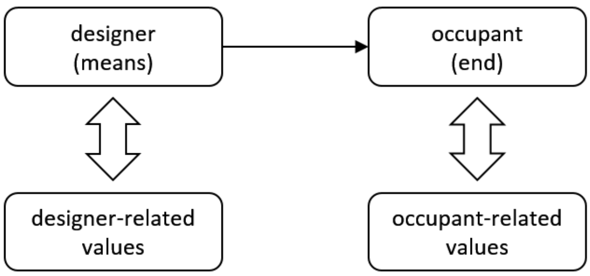


Figure 12. Designer and occupant relation and their related values

A friendly user interface can contribute to a better designer experience to a great extent. Due to relatively small size of lighting simulation market, enough investments are not made by the community to develop software with high quality user interface. Other important issues that designers often complain about are the time intensity of modeling and simulation, and inadequate accuracy. Lighting designers ignored most of the advanced simulation tools because of their inconvenient user interface and/or lack of reasonable simulation speed; therefore, more often than not, designers resorted to simpler design tools despite their lower accuracy and inadequacy in terms of calculable metrics.

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Other potential improvements could be made by using developments in computer hardware especially GPUs. GPUs are promising not only for visualization and rendering but also for computation of non-visual procedures. Of course, improvements to the field of simulation could not be fully covered in this research; rather critical matters have been investigated.

6 Conclusion

6.1 Main Findings

Value-driven design which is a systems engineering strategy, was the main perspective through which the design process was looked at throughout this study. As such, lighting simulation was investigated from a systems engineering perspective in the context of lighting design. This allowed for finding the missing and imperfect links in the solution-to-value chain. The missing links are the inability to translate performance metrics to indicators such as visual comfort and performance, and, in turn, to translate the indicators to a value. A method similar to that of PMV/PPD, which is used in HVAC engineering for thermal simulation, was proposed to fill this systemic gap. It would bring the industry one step closer to realizing VDD.

Systems engineering analysis of lighting simulation also showed how a system definition differs depending on the problem of interest (see Figure 3). It was found that in order to get a more accurate assessment of design solution in terms of values such as visual performance, it was necessary to expand the boundary of the system beyond the physical elements to the point where the value is generated. In this example, the user, especially its visual system, is the point where the final value is generated. Continuing with this example, today it is possible to simulate light up to the retina using a glass-box approach and the metric for that is a RIM. The remaining elements on the path toward visual association cortex can be modeled as a black box.

A major issue in the modeling step of simulation, namely, fragmentation in the modeling process was traced back to the fact that modeling is a purpose-driven process. The purpose of architectural modeling (geometric model) and lighting simulation (analytical model) do not often overlap. Hence, useful information in the geometric model should be extracted and/or interpreted for the analytical model and the missing information should be entered by the simulations to complete the analytical model (see Chapter 3: Model Integration and BIM).

One shortcoming of lighting design tools, especially in the early design stage, is their inability to support design space exploration. The time-intensiveness of simulations exacerbates this issue [Wortmann and others 2015]. Based on numerous examples of using surrogate models in other engineering fields [Bandler and others 2004] [Pedersen and others 2005] as well as specific case studies in lighting design [Costa and others 2015; Wortmann and others 2015], it can be concluded that surrogate modeling can address this problem. At least it could do so in the early design stage where the degree of uncertainty is high and lower accuracies are more acceptable. In addition, surrogate models can make automated optimization of lighting design more practical.

In the first paper, based on usability, acceptability, availability and previous references in literature, six software programs were identified and evaluated: Radiance, DAYSIM, Evalglare, DIALux, VELUX, and VISSLA. It was found that no single tool could meet all the needs of a designer, hence, simulation tool(s) should be selected according to the requirements of project goals and stage of design.

Use of simulation software in Sweden was studied and presented in Paper 2. The results showed that lighting simulation programs were widely (90%) used in Sweden for analysis and/or rendering purposes. The majority of lighting designers considered both daylight and artificial light in their design. DIALux was found to be the most widely used lighting software by participants, which came as a surprise considering that the findings revealed DIALux did poorly in its offerings of advanced performance metrics and was relatively inaccurate. This shows that factors such as ease-of-use and training have more weight than accuracy and the range of metrics in practitioner's eyes.

6.2 Conclusion

The aim of this thesis was to understand the underlying architecture of lighting simulation and to obtain an overview of its characteristics and applications as well as to study the usage of current simulation tools in Sweden. In turn, the findings were applied to identify potential improvements.

This study took on two seemingly opposing approaches for investigating lighting simulation. The first approach was based on VDD, which could have long-term implications. Another approach was based on performance-driven design, which is practically used today but needs improvements to become more effective.

The ideal design scenario would be to give the desired values as inputs to the machine and obtain an optimal solution(s). However, limitations of various kinds prevent realization of such an ideal today and may for the years to come. Therefore, we should not expect simulation and design tools to provide an optimal solution(s), but rather, as design theorist Roy Woodbury [Woodbury and Burrow 2006] puts it, they should provide the means to explore design solution space.

6.3 Future Work

Modern methods of computer-assisted knowledge processing and fuzzy systems analysis can help in analyzing non-numerical components of systems [Bossel 2007]. Applying these techniques in lighting simulation can make them more effective in assessing the qualitative aspects of lighting; therefore, it is an interesting area for future research.

Evidence-based design (EBD) is defined as the process of basing decisions about the built environment on credible research to achieve the best possible outcomes (Levin 2008). How computer-based simulations can be used in an EBD-based process is rather unexplored and needs to be developed. The research in this thesis discussed the extent to which lighting simulations can be used to correctly predict values in a built environment. This is one of the key question to be answered if simulations are to be used in EBD.

VDD is an elegant strategy for maximizing values for the benefit of stakeholders. However, as observed by its original conceiver H. Simon [Simon 1969b], it is not as practical as the performance-based approach. We have identified systemic gaps for enabling VDD; however, filling these gaps requires a shift in the approach to design and developing a set of indicators similar to PPD that can bridge the translation of a design solution to values of interest. This requires expanding the system boundary to the point of value generation (i.e., human, especially the human visual system). A proposal was put forward to achieve this ideal; however, further research and feedback are needed before action can be taken for its realization.

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