DEVELOPMENT OF A PROTOTYPE FOR INTEGRATING BUILDING INFORMATION

MODEL (BIM) WITH DAYLIGHTING SIMULATION TOOLS FOR DESIGNING HIGH-

PERFORMANCE BUILDINGS

A Dissertation

by

SANDEEP KOTA (JOSHUA)

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Chair of Committee,	Dr.Jeff S.Haberl
Committee Members,	Dr.Wei Yan
	Dr.Charles H.Culp
	Dr.Michael B.Pate
Head of Department,	Dr.Robert Warden

May 2020

Major Subject: Architecture

ABSTRACT

The outcome of this study is the development of a prototype

REVIT2RADIANCE add-in program for a Building Information Modeling (BIM)

authoring tool Autodesk Revit to perform daylighting studies with ease by architects and

simulation experts alike for designing High-Performance Buildings. To achieve this,

first, a literature survey of several different daylighting calculation methods and tools

was conducted to identify their capabilities and limitations, which include a comparative

analysis of tools that are widely used and comparative analysis of daylighting simulation

tools was ascertained from the comparative analysis. The results of the comparative

analysis revealed that the state-of-the-art daylighting simulation tool RADIANCE has

the most advanced capabilities to perform daylighting simulation, followed by

RADIANCE based tool DAYSIM.

Second, a survey of the previous methodologies that explored the integration of

CAD (e.g., AutoCAD) or BIM authoring tools (e.g., Revit) with daylighting simulation

tools was conducted. The survey provided: an overview of different aspects involved in

the integration process; the shortcomings of each method; the necessity for a better

integration process; and finally, the need for integration of Revit, a BIM-authoring tool

with RADIANCE and DAYSIM.

Third, for integrating Revit with RADIANCE and DAYSIM, different methods

were explored. First, the conventional method that uses Radiance utilities that facilitate

the translation of geometry created by various CAD-based tools into RADIANCE

geometry and material information. Several significant limitations were observed in

these methods, one of which is the partial translation involving only geometry but not the material information from Revit to RADIANCE. To address these limitations, a second method using a custom prototype REVIT2RADIANCE comprising of several Revit add-in programs was developed using the Revit API and C# programing language. The new prototype provides seamless integration of Revit with RADIANCE and DAYSIM, not only translating both geometry and material information but also simultaneously performing a daylighting simulation using RADIANCE and DAYSIM that generates results in a widely-used format.

Finally, the prototype was tested using two different test cases, one with simple geometry and a second comprising of complex geometry. Validation of the prototype REVIT2RADIANCE was performed to check the accuracy in translating the Revit geometry and material in to RADIANCE and DAYSIM geometry and translating the material information necessary to perform the daylighting simulation. The first validation test was performed by visually comparing the Revit model with the rendered RADIANCE model, generated using the RVIEW program of the input file created by the prototype. In the second validation test, the parameter values of the RADIANCE Materials written by the prototype were compared with the parameter values obtained using hand calculations. Both the validation tests confirmed the accuracy in the translation of geometry and material information contained in Revit into the proper RADIANCE and DAYSIM formats.

DEDICATION

TO MY GOD AND LORD JESUS CHRIST OF NAZARETH

KING of kings and LORD of lords! HALLELUYAH!!!

ACKNOWLEDGEMENTS

I would like to especially thank my parents and sister who have sacrificed so much of their time and resources to support my studies and lift me up with their constant prayers, love, patience and kindness. Without them this research would not have be possible. I would like to also thank my wife for her constant prayer support, love, encouragement and for taking care of the family in my absence so that I could focus and finish this study.

I would specially like to thank my sisters in Christ Arlene and Grace and brother Rama Krishna for their encouragement and prayers and all the brothers and sisters in Christ and church family for their prayer support and help for my studies.

I would like to thank all the staff at Department of Architecture at Texas A&M University for their guidance and support during my studies and I would like to thank the VIT management for granting me leave to rejoin Texas A&M to finish my research. Special thanks to my director Prof. Devi Prasad for his kindness, understanding and support allow me to finish this study. Finally, I would like to thank all my VIT colleagues for their support.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

NOMENCLATURE

GHG	Green House Gases
WMO	World Meteorological Organization
IPCC	Intergovernmental Panel on Climate Change
IEA	International Energy Agency
USEIA	US Energy Information Administration
NZEB	Net-Zero Energy Buildings
BT	Building Technologies Program
USDOE	United States Department of Energy
CBI	Commercial Buildings Integration
HVAC	Heating Ventilation and Air Conditioning
PG&E	Pacific Gas & Electric
AEC	Architectural Engineering Construction
CAD	Computer Aided Design
BIM	Building Information Models
AECO	Architecture, Engineering, Construction and Operation
BPA	Building Performance Analysis
BDS	Building Daylighting Simulation
BEM	Building Energy Modeling
LBNL	Lawrence Berkeley National Laboratory
ESL	Energy Systems Laboratory

NREL	National Renewable Energy Laboratory
CIE	International Commission on Illumination
CBDM	Climate Based Daylight Modeling
DF	Daylight Factor
DA	Daylight Autonomy
cDA	Continuous Daylight Autonomy
DSP	Daylight Saturation Percentage
sDA	Spatial Daylight Autonomy
ASE	Annual Sunlight Exposure
SC	Sky Component
ERC	Externally Reflected Component
IRC	Internally Reflected Component
FC	Foot-candles
UDI	Useful Daylight Illuminance
DSP	Daylight Saturation Percentage
BRS or BGI	BRS glare equation
DGI	Daylight Glare Index
CGI	CIE glare index
VCP	Visual Comfort Probability
UGR	Unified Glare Rating System
DGP	Daylight Glare Probability
DGPs	Simplified Daylight Glare Probability

DC	Daylight Coefficient
GDDM	Graphic Daylight Design Method
CG	Computer Graphics
CFS	Complex Fenestration Systems
BSDF	Bi-directional Scattering Distribution Function
GUI	Graphical User Interface
HDR	High Dynamic Range
T-VIS	Visible Transmittance
BTDF	Bi-directional Transmission Distribution Function
BRDF	Bi-directional Reflection Distribution Function
SHGC	Solar Heat Gain Coefficient
IT	Information Technology
AEC	Architecture/Engineering/ Construction
AECO	Architecture/Engineering/Construction/Operations
BPS	Building Performance Simulation
BES	Building Energy Simulation
DPA	Daylighting Performance Analysis
SA	Structural Analysis
CSV	Comma Separated Values
MDO	Multidisciplinary Design Optimization
IFC	Industrial Foundation Class
API	Application Programing Interface

RGB   Red, Green, and Blue

TABLE OF CONTENTS

LIST OF FIGURES

xvi

xviii

xix

List of Tables

1. INTRODUCTION

The industrial revolution that began in the mid-eighteenth century, provided humans with capabilities well beyond animal and human power. The power for the revolution was derived largely from our ability to use fossil fuel sources for energy production and direct usage. Since then access to clean, affordable, secure, and reliable energy has been a cornerstone for any country's economic growth. Unfortunately, the usage of fossil fuels for energy production releases Green House Gases (GHGs) (e.g., Carbon Dioxide, (CO_2); Methane, (CH_4) and Nitrous Oxide, (N_2O)) into the atmosphere. Global GHG emissions due to human activities have grown since pre-industrial times, with an increase of 70% between 1970 and 2010 (Edenhofer et al., 2014). Changes in the atmospheric concentrations of greenhouse gases (GHGs) and aerosols, land cover and solar radiation have altered the energy balance of the climate system leading to an increase in the global temperatures causing global warming.

In order to begin to address the issue of global warming, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) have constituted the Intergovernmental Panel on Climate Change (IPCC) to be responsible for the issues related to climate change. The IPCC provides governments at all levels with scientific information that they can use to develop sustainable climate policies. There are several governmental agencies that publish energy usage and GHGs emissions statistics, one such organization is International Energy Agency (IEA), another is U.S. Energy Information Administration (USEIA).
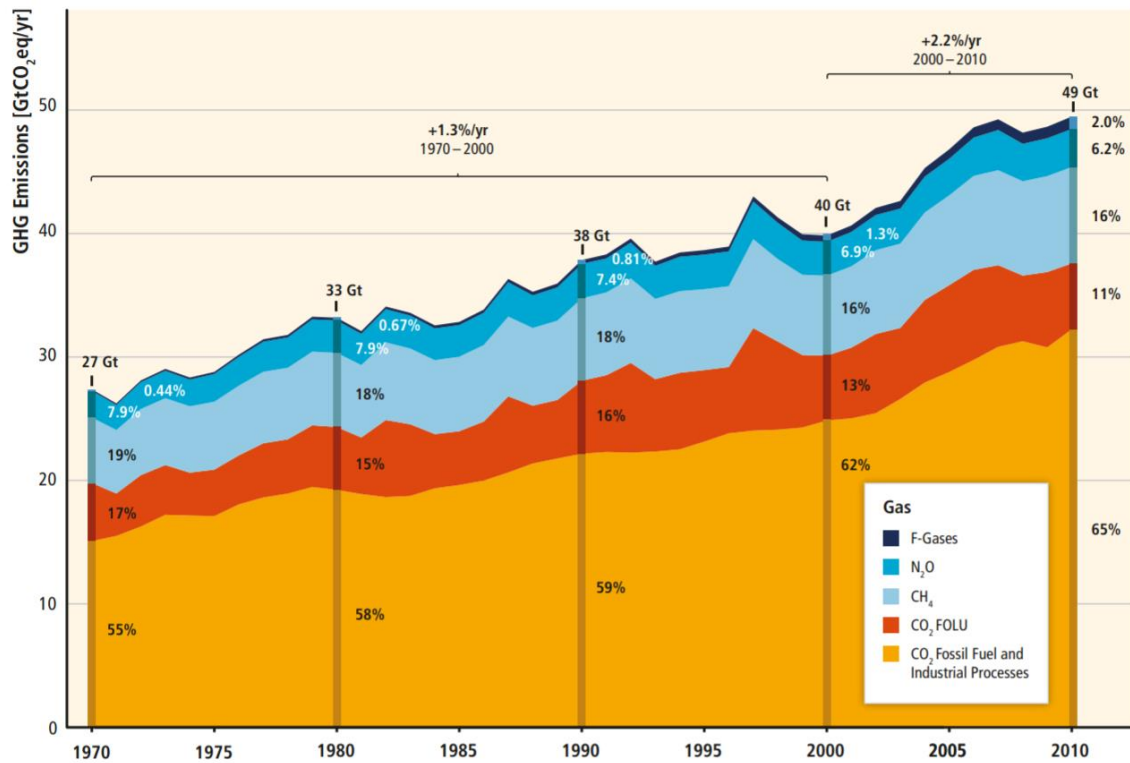
Figure 1.1: Total Annual Anthropogenic GHG Emissions by Groups of Gases 1970 – 2010 (Edenhofer et al., 2014)

In 2015 the world energy consumption was 575Quads[1] . The EIA projections are expected to increase to 736 Quadrillion Btu by 2040 (International Energy Agency, 2018). In 2010 the global energy-related (CO_2) emissions rose to 49 Gigatons of (CO_2) (Figure 1.1). Therefore, there is a growing need to reduce the global energy consumption and the related GHG emissions around the globe to begin to mitigate the impact on climate change and its associated risks without impeding the well-being of humanity. Several strategies have been proposed for reducing the CO_2 for the different contributing

---

[1] A Quad is a unit of energy equal to 10^{15} (a short-scale quadrillion) Btu

sectors. Some of the strategies include replacing the use of coal with natural gas in the generation of the power used by the building sector. Another strategy is to develop a portfolio of energy-efficient policies for implementing in the building sector (Edenhofer et al., 2014).

The increased use of fossil fuels can be attributed to the increase in energy use for all end-use sectors (Fletcher, 2007). The United States alone consumes 25% of total world oil production. In light of the dwindling natural resources, the United States Congress passed a legislative Act called The Energy Independence and Security Act of 2007 (originally named the Clean Energy Act of 2007) that provides an energy policy for the United States to reduce the U.S dependence on foreign oil for its energy needs. The act also seeks to reduce pollution and invest in Research and Development (R&D) for clean-energy technologies in the United States to create jobs. The bill discusses energy policy in many areas. In the Title IV-energy savings in buildings and industry, Subtitle B – High-Performance Commercial Buildings section of the bill addresses the initiatives related to high-performance commercial buildings and Net-Zero Energy Buildings (NZEB) primarily commercial buildings.

In 2018 the source US. Energy consumption is 101.2 Quads where the top three energy-consuming sectors were transportation, industries, and buildings (Figure 1.2) (U.S. Energy Information Administration, 2019). Among these three, buildings have the lowest portion with 21.35%. One of the main energy sources that are consumed by buildings is electricity generated by burning coal and other non-renewable sources.

Unfortunately, burning coal contributes significantly to the generation of CO2 one of the

main GHG gas that contributes to global warming.
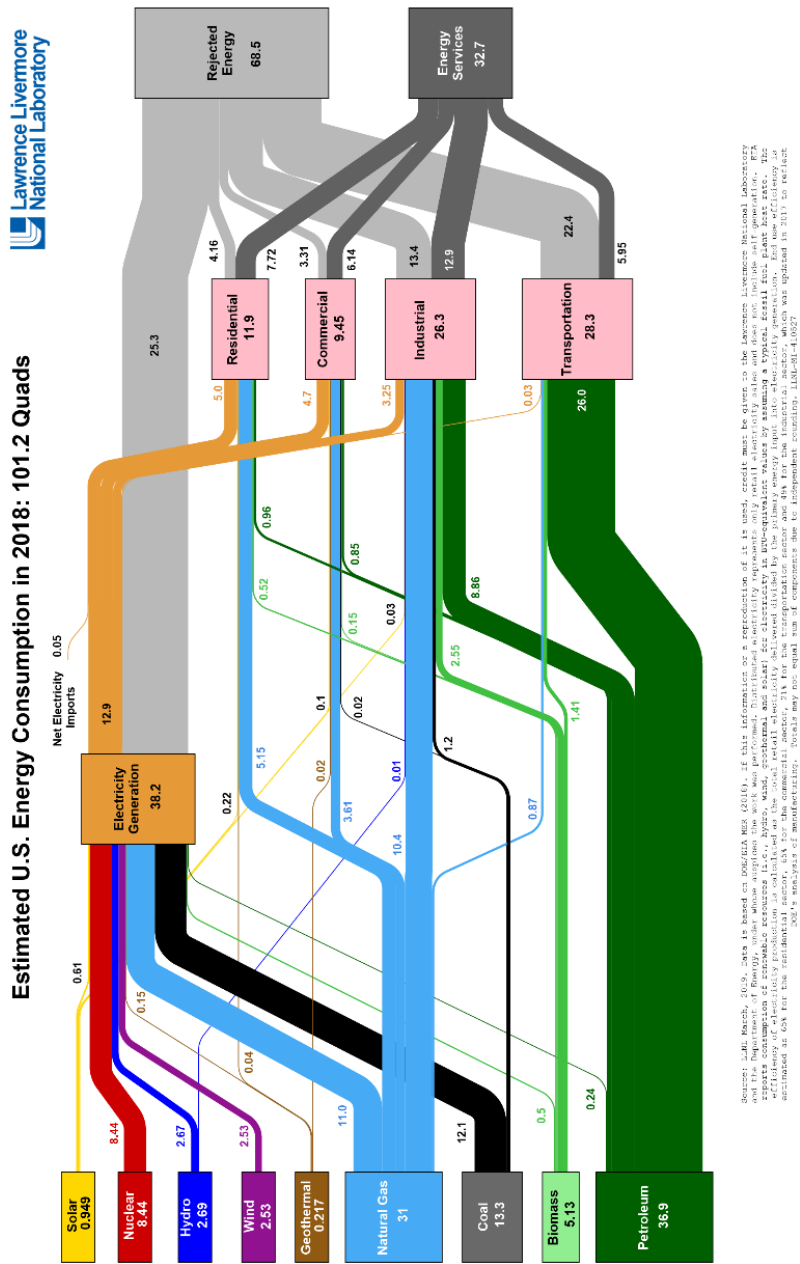
Figure 1.2: United States Energy Consumption in 2018[2]

The Building Technologies Program (BT) that was initiated by the United States Department of Energy (USDOE) helps to address The Energy Independence and Security Act of 2007. The BT program makes recommendations to reduce energy intensity and make energy efficiency in buildings a national priority (BT, 2008). The Commercial Buildings Integration effort (CBI), a subprogram under the BT program, was initiated to achieve significant energy savings in new and existing commercial buildings. CBI's goal is to significantly improve the efficiency of new and existing commercial buildings to reduce national energy demand and also to create new technologies and design approaches that will enable net-zero energy buildings (NZEB[3]) (CBI, 2008).

However, significant barriers remain before NZEB can be realized across a broad class of buildings. One of the approaches that were proposed to overcome the challenges inherent in designing and operating high-performance buildings and NZEBs is systems integration (Torcellini, Pless, Deru, & Crawley, 2006). Building systems integration means the design, construction and operation of a commercial building as an integrated system to maximize energy performance and occupant satisfaction (BT, 2008). Systems integration would allow multiple renewable sources to provide a building with its energy needs better. For example, careful daylighting design involves the proper specification of building orientation, window area, high performance of windows, proper interior design,

---

[3] A NZEB is a residential or commercial building with greatly reduced energy needs accomplished through efficiency gains such that the total net annual energy needs of the building can be supplied with renewable technologies.

and the control of the supplemental electric lighting systems so as to maximize the use of natural light and minimize the use of non-renewable energy use.

In 2018 commercial buildings in the United States were consuming 9.4 Quads of energy annually (CBI, 2008). The major energy demands in commercial buildings include: lighting, heating, cooling, water heating, ventilation, and plug loads. Lighting energy use alone comprises over 25-40% of building energy use and Heating Ventilation and Air Conditioning (HVAC) consume one-third of commercial building's primary energy use (Krarti, 2012).

1.1. A Case for Daylighting

According to the Pacific Gas & Electric (PG&E) company, "daylighting is one of the single largest new opportunities for saving energy in commercial building" (Koti & Addison, 2007). Also, effective daylighting is necessary for the design and is also an essential strategy for realizing low-energy and low-carbon buildings (Konis & Selkowitz, 2017). Daylight not only offsets the use of electricity for lighting, it also reduces the cooling load associated with artificial lighting, although there is often an increase in the cooling load with increased glazing that is not properly designed. Also, it is well established through research that occupants of buildings prefer to work in daylight areas compared to areas with electrical lighting as it can have a positive impact on their mood and their productivity (De Carli, De Giuli, & Zecchin, 2008).

1.2. Building Information Modeling

Earlier in the Architectural Engineering Construction (AEC) industries Computer-Aided Design (CAD) CAD-based tools were used for generating and sharing

building data/ information, such as 2D drawings representing spatial planning and 3D

models for visualizing of the buildings (Eastman, Teicholz, Sacks, & Liston, 2011).

During the 1980s a new digital technology emerged, called a Building Product Model

that was mainly created to share product information among different parties that are

involved in its development. The models representing buildings were initially called

Building Product Models that were later called Building Information Models (BIM).

Currently, Building Information Modeling (BIM) technology is now widely used and

has been adopted in the architecture, engineering, construction and operation (AECO)

industry. By its definition, it contains or should contain a complete set of information

about the life cycle of a building in the form of a digital model (Kumar, 2008). The BIM

models of a project are usually created using tools called BIM-authoring tools (Eastman

et al., 2011). Also, central to BIM is the parametric modeling that helps designers

explore different alternatives for design optimization by quickly changing certain

parameters that automatically update the whole design and simulate the results of the

change (Aish & Woodbury, 2005).

1.2.1. NZEBs, Building Performance Analysis, and BIM

One of the aspects of the building design process is the Building Performance

Analysis (BPA) that provides feedback about the building design in the early and

schematic stage of the design that can be used for design optimization. The BPA

involves several different types of analyses such as building energy assessment,

daylighting, sunlight and shadow analysis, solar radiation analysis etc. The BPA is a

prerequisite for designing high-performance buildings, some of the well-known

examples of building where BPA was used for designing are the San Francisco Federal

Building (McConahey, Haves, & Christ, 2002) and Net Zero Buildings on the NREL

Campus[4]. Each of these analyses were carried-out with building performance simulation

tools that needed (e.g., Energy, Daylight) domain-specific building data that can be

provided by BIM models. Traditionally, in BPA engineers who build the building energy

models act as assistants to architects and use the professional simulation tools in their

domain such as: 1) building energy performance, 2) daylighting, 3) solar analysis, etc.

(Jin, Zhong, Ma, Hashemi, & Ding, 2019). Unfortunately, translating the geometric data

from an architectural model into an energy model involves manual coding by energy

modelers. This process is less efficient, susceptible to coding errors and highly non-

standardized. In addition, any major modification to the architectural models and the

subsequent re-running of the simulation is a cumbersome process that includes

expensive multiple iterations of the design.

Several studies have been performed to integrate BIM with BPA tools to study

the different types of performance analysis (Jin et al., 2019). In one of the study, the

BIM tool Revit was parametrically integrated with a building energy performance tool

for optimization studies (Asl, Bergin, AdamMenter, & Yan, 2014). Today, the efficient

design of High-Performance and Net-Zero Energy buildings require an accurate BPA, so

developing a BIM-based parametric daylighting simulation tool can help the study of

the performance of different daylighting strategies used in the design of

---

[4] https://www.nrel.gov/about/sustainable-buildings.html

High-Performance and Net-Zero Buildings. Such can new tool can also help in the optimization of building design with respect to daylighting analysis.

1.3. Motivation

Utilization of daylighting in a building requires the evaluation of different daylighting strategies to determine how they perform in terms of providing adequate lighting levels as well as a comfortable luminous environment. Over the years, several daylighting performance simulation tools have been developed to study Building Daylight Performance (Kota & Haberl, 2009). Several of these tools also can perform the thermal simulation of a building with a high degree of accuracy (Oh & Haberl, 2016a, 2016b).

1.4. Purpose and Objectives

The purpose of the present research is to develop a new prototype for integrating a new BIM-authoring tool with a Building Daylighting Simulation tools to study the performance of different daylighting strategies for use in a high-performance building. The following objectives will be achieved in the present research

1. Creating a fully-automated prototype for integrating a Building Information Model (BIM) with a Building Daylighting Simulation (BDS) tool that can be easily used by architects and building performance simulation professionals to quickly and accurately study the performance of the different daylighting strategies for high-performance buildings.

2. Testing of the new prototype tool using simple and complex building models for validating that the accurate data transfer between the BIM and BDS tools.

1.5. Organization of the Dissertation

Chapter 1 discusses the background of energy usage in the world and associated global issues. It also discusses the contribution of buildings to such issues and reviews strategies adopted to mitigate the negative impact of fossil fuel use. It also presents a compelling case for developing new tools and methodologies to study the daylighting performance in buildings. Chapter 2 presents the literature review relevant for this study and the associated findings. Chapter 3 discusses the significance and limitations of the research. Chapter 4 presents the methodology that has been used in this study for developing the new prototype, which Include integrating BIM and daylight simulation tools. Chapter 5 discusses the different translators for achieving the integration between the BIM and BDS tools and the associated issues in the process. Chapter 6 discusses, in detail the development of prototype REVIT2RADIANCE for integrating BIM with BDS tools, RADIANCE and DAYSIM. Chapter 7 discuss the testing of the prototype and the associated results, conclusion and future research.

2. LITERATUR REVIEW

2.1. Introduction

The categories of literature that are the most relevant to this dissertation are:

1. The analytical concepts and methods used in daylighting analysis of buildings

2. Computational analysis tools and techniques used in daylighting analysis

3. Strengths and the limitations of these computational tools used for daylighting Analysis.

4. Different daylighting strategies used for buildings that can be readily modeled with the available tools.

5. Computational tools that are used for thermal analysis of buildings and their use in daylighting analysis.

3. Building Information Modeling (BIM) and its use in Building Energy Modeling (BEM) and daylighting analysis.

The sources of literature reviewed include journals (ASHRAE Transactions, Building and Environment, Energy, Energy and Buildings, Solar Energy, LEUKOS and Lighting Research and Technology); conference proceedings (ASHRAE, ACEEE, IBPSA, Simbuild and SIGGRAPH); ASHRAE Handbooks (ASHRAE 2003, 2004, 2005 and 2009); building energy codes (ASHRAE 90.1 1989, 1999, 2000, 2004, 2007 and 2010); IES Lighting Handbook (IES 2007); books (Duffie and Beckman 2006, Stein and Reynolds 2010, Carmody et al. 2007; Hopkinson et al. 1966; Simon and Bean 2001;Ward and Rob 2003); publications by the Lawrence Berkeley National Laboratory (LBNL), the Energy Systems Laboratory at Texas A&M University (ESL), the National

Renewable Energy Laboratory (NREL); and the User News of: RADIANCE, BUILDING SIMULATION, DOE2.1e, eQUEST, EnergyPlus, RADIANCE and DAYSIM, etc.

2.2. Sky Models

Daylighting in a building is the direct result of the amount of beam and diffused light coming into a space from the beam sunlight and diffuse skylight. The luminance distribution of the diffused sky makes a tremendous impact on the amount of light entering the interior spaces of the building. In 1921 Kimball and Hand performed the first studies that recorded sky luminance distribution outside the city of Chicago (Herbert & Irving, 1921).

2.2.1. Overcast Sky Model

From the previous studies, Kimball and Hand proposed two sky models: one sky models an overcast sky and the second one is clear sky model. Later in 1942 Moon and Spencer proposed an empirical formula for an average overcast sky (Hopkinson, Petherbridge, & Longmore, 1966). In 1955 the International Commission on Illumination (CIE) adopted the Moon-Spencer formula as the standard for computing the overcast sky luminance distribution (Equation 2-1). Figure 2.1 shows the CIE overcast sky luminance distribution.

$$L_\theta = \frac{L_Z(1 + b\cos\theta)}{1 + b}$$

Equation 2-1

$L_\theta = $ *Luminance of the Sky patch that is at an angle θ with the ground plane.*
$L_Z = $ *Luminance of Zenith.*

Figure 2.1: RADIANCE Image of CIE Overcast Sky (Source: Author)

2.2.2. Fully Overcast Sky

In 1951, McDermott and Gordon-Smith proposed a formula to calculate the luminance distribution of fully overcast sky (as cited in Hopkinson et al., 1966).

2.2.3. Clear Sky Model

From the studies performed, Kimball and Hand also proposed a sky model for a clear sky. The model proposed by Kimball and Hand did not take the Rayleigh scattering of light through the atmosphere into consideration. In 1929 Pokrowski, introduced a new formula to calculate the luminance distribution of a clear cloudless sky taking Rayleigh scattering into account (Hopkinson et al., 1966). During the same period, Kettler

proposed a formula for calculating the luminance distribution of the clear blue sky that

CIE adopted in 1965 as the standard for computing the luminance distribution of the

clear blue sky with the sun (Hopkinson et al., 1966). Figure 2.2 shows the RADIANCE

image of the CIE clear sky model.
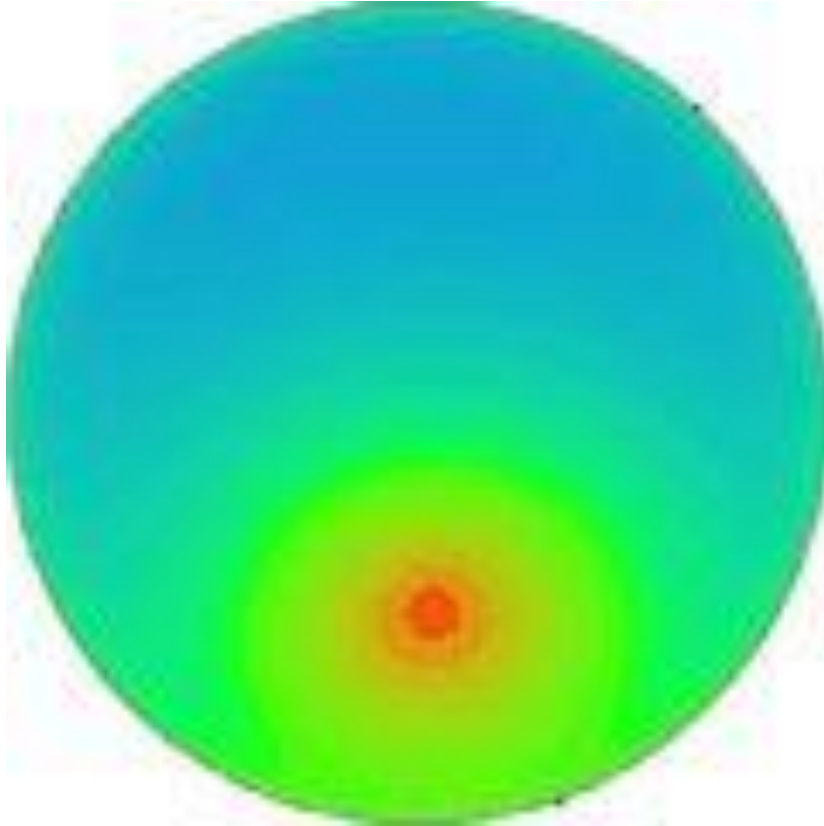
Figure 2.2: RADIANCE Image of CIE Clear Sky Model (Source: Author)

2.2.4. Intermediate Sky Model

In 1985 Nakamura proposed a formula for luminance distribution of two sky

models that include Clear Turbid Sky and Intermediate Sky. Figure 2.3 shows a

RADIANCE image of the intermediate sky model (Igawa, Nakamura, & Matsuura,

1999).
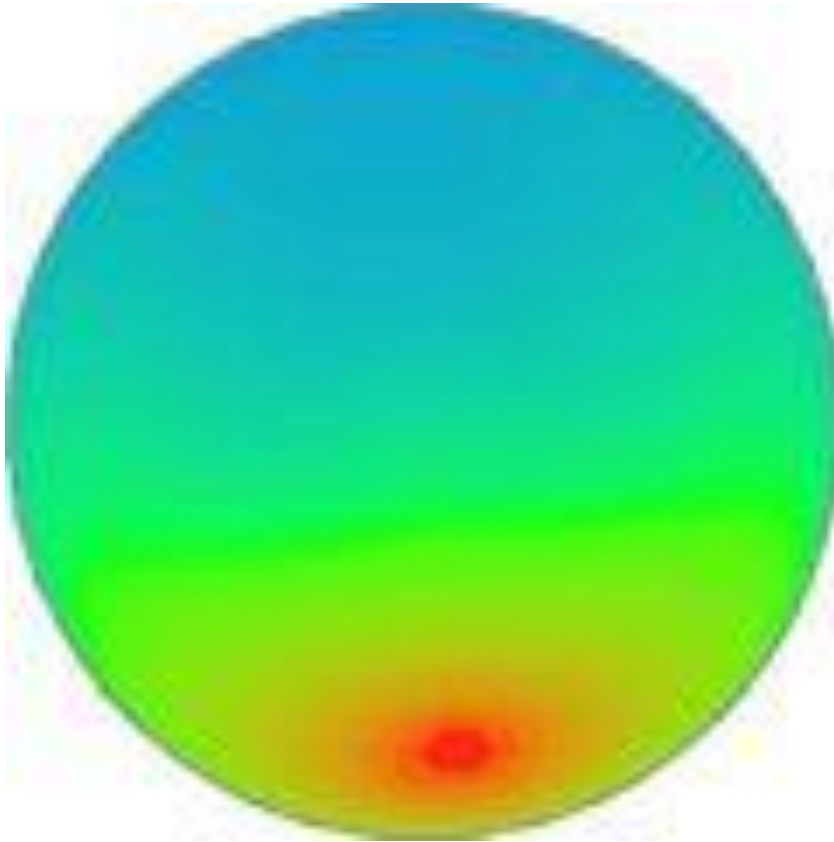
Figure 2.3: RADIANCE Image of CIE Intermediate Sky Model (Source: Author)

2.2.5. All-Weather Sky-Model

Finally, Perez proposed an all-weather sky model that uses routine irradiance measurements to produce the mean instantaneous sky luminance angular distribution patterns for all sky conditions, including: overcast, clear, and partly cloudy. The All-weather sky model proposed by Perez (1993) is considered to be the most accurate sky model that can produce luminance distribution of any sky model.

2.2.6. Summary

Of all the sky models that have been developed, the All-weather sky model proposed by Perez et al., (1993) is considered to be one of the best models as it can

38

model several types of sky types given the solar data for a location. This model has been incorporated into very sophisticated daylight simulation tools such as the GENDAYLIT[5] program of RADIANCE (Ward and Rubinstein, 1988) and DAYSIM (Reinhart and Herkel, 2001) that are used to predict annual daylight performance of the buildings.

2.3. Daylight Performance Indicators or Metrics

Daylight performance indicators provide information about how a building is performing in terms of the quality of daylight. Over the years, many indicators have been developed to quantify the daylighting performance of the buildings. Some of the metrics are static in nature that use a standard sky luminance distribution model not considering the temporal variation in the sky luminous distribution or the effect of the sun of luminance distributions in the room. While other metrics have been developed that are called dynamic, because they relate to the Climate Based Daylight Modeling (CBDM[6]) considering the temporal variation of sky luminous distribution due to a change in the solar radiation. The following daylight performance indicators are discussed in the next sections include: the Daylight Factor (DF), Daylight Autonomy (DA), Continuous Daylight Autonomy (cDA), Daylight Saturation Percentage (DSP), Spatial Daylight Autonomy(sDA) and Annual Sunlight Exposure (ASE).

---

[5] https://www.RADIANCE-online.org/learning/documentation/manual-pages/pdfs/gendaylit.pdf
[6] Climate-Based Daylight Modeling (CBDM) is the prediction of various radiant or luminous quantities (e.g., Irradiance, illuminance, radiance and luminance) using sun and sky conditions that are derived from standard meteorological datasets.

2.3.1. Daylight Factor (DF)

2.3.1.1. Definition

The concept of the DF was first proposed by Trotter in (1911). The DF is a

daylighting performance indicator for the interior illumination of a room. Often the DF

is expressed as a percentage of the ratio of daylight illumination at a point on a given

plane compared to the light received directly or indirectly from the sky of an assumed or

known luminance distribution divided by the illumination on an exterior horizontal plane

under the same sky condition (i.e., an unobstructed hemisphere of the sky (James, 1992).

Equation 2-2 shows the formula to calculate the Daylight Factor (DF) for a room.

$$DF = \frac{E_{in}}{E_{out}} \; x \; 100 \; \%$$

Equation 2-2

E_{in} = *Indoor Illumination at a point indoor of a space*
E_{out} = *Outdoor Illuminance from unobstructed sky*

When computing the DF, the direct sunlight is excluded from both the interior

and exterior values of illumination. The DF is divided into three components that include

a Sky Component (SC), an Externally Reflect Component (ERC), and an Internally

Reflect Component (IRC). Table 2.1 shows the three components of DF. The summation

of these three components gives the total DF. Unfortunately, DF has some severe

limitations. First, it cannot represent the change in illumination levels indoor due to the

temporal variations of sky luminance. Second, the orientation of the window opening in

the building facade does not affect the DF calculation. Figure 2.4 shows the three

components used to calculate the Daylight Factor (DF)

Table 2.1: Components of the Daylight Factor (DF)

Sky Component	SC
Externally Reflected Component	ERC
Internally Reflected Component	IRC

2.3.1.2. Advantages and Limitations

Unfortunately, the DF has some severe limitations: First, it cannot represent a change in illumination levels indoor due to the temporal variation of sky luminance. Second, the orientation of the window opening in the building facade does not affect the DF calculation. Therefore, it is considered to be a static metric that does not provides details about the spatial distribution of daylighting under a changing sun position and sky luminance distribution over time.
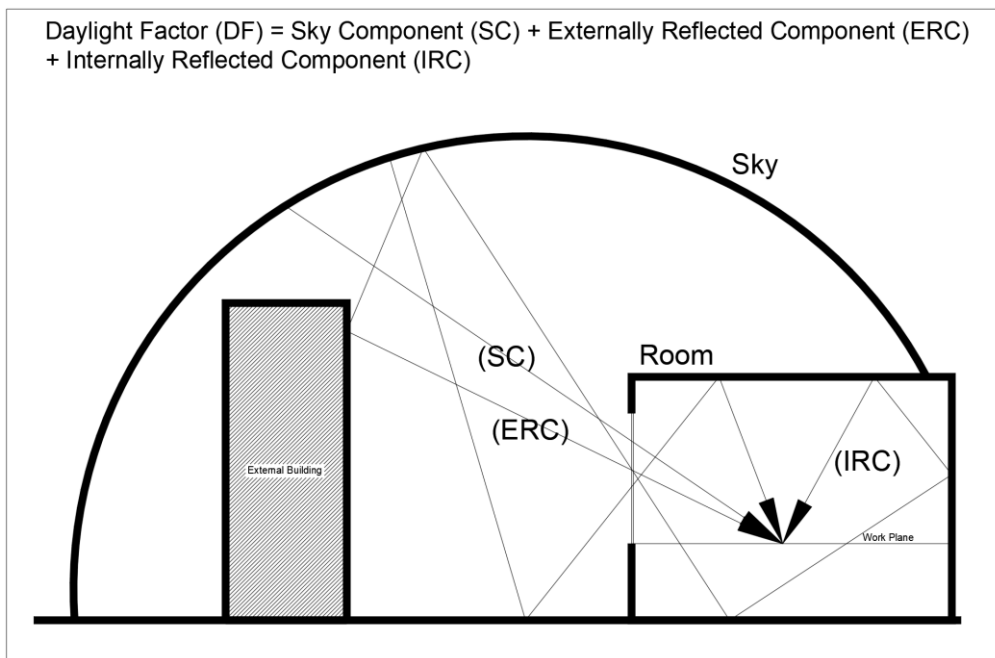
Figure 2.4: Component of Daylight Factor (Source: Adapted from Iversen et al.,(2013))

2.3.2. Daylight Autonomy (DA)

2.3.2.1. Definition

The Daylight Autonomy (DA) is a measure of how often a minimum work plane illuminance threshold of 50 foot-candles (FC) can be maintained by daylighting alone. It is expressed as the percentage (%) of the occupied time during the year when a minimum work plane illuminance threshold of 50 FC can be maintained by daylighting alone.

2.3.2.2. Advantages and Limitations

The Daylighting Autonomy method has several limitations. First, Daylight Autonomy fails to give the significance of daylight illuminances that are below the 50 FC threshold but that are nevertheless valued by occupants and may also have the potential to displace all or part of the supplemental electric lighting loads. Second, Daylight Autonomy does not account for the time when the threshold illuminance was exceeded at any particular instant, that can inform a user about glare and sometimes thermal discomfort (Azza Nabil & Mardaljevic, 2006).

2.3.3. Continuous Daylight Autonomy (cDA)

In 2006 a new metric was introduced by Rogers (Christoph F. Reinhart, Mardaljevic, & Rogers, 2006) called the Continuous Daylight Autonomy (cDA) as a basic modification of Daylight Autonomy (DA). The theory behind its development is that the cDA awards partial credit, in a linear fashion, to values below the user-defined threshold. For example, if the Daylight Autonomy (DA) threshold is specified as 300 lux, and if a specific point in the interior of a room records a value of 150 lux, whereas

the DA for the point would get 0 credit where as the cDA gives it a partial credit of

(150/300Lux = 0.5) of 0.5 for that time step.

2.3.4. Useful Daylight Illuminance

2.3.4.1. Definition

One of the recently developed daylight performance indicators is the Useful

Daylight Illuminance (UDI) (A Nabil & Mardaljevic, 2006). Useful daylight

illuminances are defined as those illuminances that fall within the range of 100-2000 lx.

The range used to define the limits of useful daylight illuminance is based on a

comprehensive review of the data from field studies of occupant behavior under daylit

conditions.

2.3.4.2. Advantages & Limitations

The UDI addresses some of the issues not addressed by the DF and DA. First, it

is a climate-based analysis and represents the indoor illumination distribution for a

whole year as a function of outdoor time-varying sky and sun conditions. The UDI

provides information about useful daylight illuminance, and it provides information

about the excessive levels of daylight that are associated with glare, occupant discomfort

and unwanted direct solar gains.

2.3.5. Daylight Saturation Percentage (DSP)

2.3.5.1. Definition

Daylight Saturation Percentage (DSP) is the change in the UDI parameters. It

displaces the minimum limit of illumination that can be evaluated to 40 Foot-candles or

43

400 Lux, and the upper limit of UDI to 400 Foot-candles or 4,300 lux instead of 2,300

Lux, that is the upper limit for UDI.

2.3.6. Spatial Daylight Autonomy (sDA)

The Spatial Daylight Autonomy (sDA) is defined as the percent of an analysis

area that meets a minimum horizontal daylight illumination level (e.g., 300 Lux) for a

specified fraction (e.g., 50%) of the operating hours per year (Heschong, 2012).

2.3.7. Annual Sunlight Exposure (ASE)

2.3.7.1. Definition

The Annual Sunlight Exposure (ASE) describes how much of the space receives

too much direct sunlight, that can cause visual discomfort (i.e., glare) or an increase in

cooling loads. Specifically, ASE measures the percentage of floor area that receives at

least 1,000 lux for at least 250 occupied hours per year (IESNA, 2012).

2.3.8. Analysis and Summary of Daylight Performance Metrics

Table 2.2 provides a list of different daylight performance indicators and metrics.

In the table there are several criteria against which each metric is evaluated. The top row

of the table provides the criteria. Each criterion has a specific weight. The first four

have10 points and the last four have 20 points as they report on spatial comfort (i.e.,

Thermal and Luminous), as well as temporal and special illuminance variations. If the

metric can report a parameter, it gives yes or no (Yes = 1) (NO = 0). Each parameter

weight is multiplied by the value (i.e. 0 or 1) and the total weighted sum, normalized to

100% is obtained for each metric. From this simple analysis, the dynamic matrices,

Useful Daylight Illuminance (UDI), Daylight Saturation Percentage (DSP) and Spatial

Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) had the higher scores

that proved to be better for evaluating the luminous environment of a space.

Table 2.2: Daylight Performance Indicators or Metrics (Source: Author)

Name of the Metric	Notation	Units	Type of Metric (Static = 0) (Dynamic =1)	Consider Sun	Time Varying Ski Luminace Distribution	Affect of Window Orientation on indoor Illumination Levels	Thermal Comfort (Over Heating Period/ Cooling Load)	Visual Comfort (Glare)	Spatial Distribution of Illumination Levels in Space	Temporal Distribution of Illumination Levels in Space	Wighted Sum (%)
Weightage %			10	10	10	10	20	20	20	20	120
Daylight Factor	DF	Percentage (%)	Static / 0	No / 0	No / 0	No / 0	No / 0	No / 0	No / 0	No / 0	0.00
Daylight Autonomy	DA	Percentage (%) of Occupied Hrs	Dynamic CBDM based / 1	Yes / 1	Yes / 1	Yes / 1	No / 0	No / 0	No / 0	Yes / 1	50.00
Continuous Daylight Autonomy	cDA	Percentage (%) of Occupied Hrs	Dynamic CBDM based / 1	Yes / 1	Yes / 1	Yes / 1	No / 0	No / 0	No / 0	No / 0	33.33
Useful Daylight Illuminance	UDI	Lux (Range 100-2500)	Dynamic CBDM based / 1	Yes / 1	Yes / 1	Yes / 1	Yes / 1	Yes / 1	No / 0	No / 1	83.33
Daylight Saturation Percentage	DSP	Lux (Range 400-4000)	Dynamic CBDM based / 1	Yes / 1	Yes / 1	Yes / 1	Yes / 1	Yes / 1	No / 0	No / 1	83.33
Spatial Daylight Autonomy	sDA	% of Space, Lux and Hours	Dynamic CBDM based / 1	Yes / 1	Yes / 1	Yes / 1	Yes / 1	No / 0	Yes / 1	Yes / 1	83.33
Annual Sunlight Exposure	ASE	% of Space, Lux and Hours	Dynamic CBDM based / 1	Yes / 1	Yes / 1	Yes / 1	Yes / 1	Yes / 1	Yes / 1	Yes / 1	100.00

2.4. Glare Indices

The aim of good daylight design is first, to provide the target illuminance levels over the work plain to perform a visual task effectively and second, to ensure that the space is visually comfortable and a pleasing environment. Unfortunately, glare has been one of the major issues in daylight design. There as several types of glare that can be perceived by the human eye in an environment. These are, distracting glare, discomforting glare, disabling glare, and blinding glare. Over the year's researchers have proposed different glare indices to quantify glare levels in a day-lit space. These indices are: BRS or BGI, DGI, CGI, VCP, UGR, DGP and DGPs.

2.4.1. BRS or BGI Glare Index

In 1950, Hopkinson and Petherbridge developed the BRS glare equation (BRS or BGI) (Equation 2-3) at the Building Research Station in England (as cited in Hopkinson et al., 1966). The advantage of this equation is that it can account for glare from small sources such as small artificial light sources as it is primarily developed to compute glare for artificial lighting. However, it has limitation to account for glare from large lighting sources such as daylight coming from a large window into a space. The graphical representation of some of the photometric parameters which are used in BGI glare equation are given in Figure 2.5. One of the parameter which is essential for computing the BGI and other glare indices is Guth's position index (W. Kim & Kim, 2010). Guth had developed an equation (Equation 2-4) to compute the position index, where α is the angle from vertical of the plane containing the source and the line of sight in degrees and β the angle between the line of sight and the line from the observer to the source (W.

46

Kim & Kim, 2010; Jan Wienold, 2014). Figure 2.6 shows the angles α and β used for computing Guth's position index for a light source.

$$BGI = 10log_{10}0.478 \sum_{i=1}^{n} \frac{L_s^{1.6}\omega_s^{0.8}}{L_b P^{1.6}}$$ Equation 2-3

$L_s = Luminance\ of\ the\ Source$
$L_b = Luminance\ of\ the\ Background$
$P = Guth's\ position\ Index$
$\omega_s = Solid\ angle\ subtended\ by\ the\ source$
$n = Number\ of\ glare\ sourcese$

Glare Source Luminance L_S
Solid Angle ω_S
Background Luminance L_b
View direction
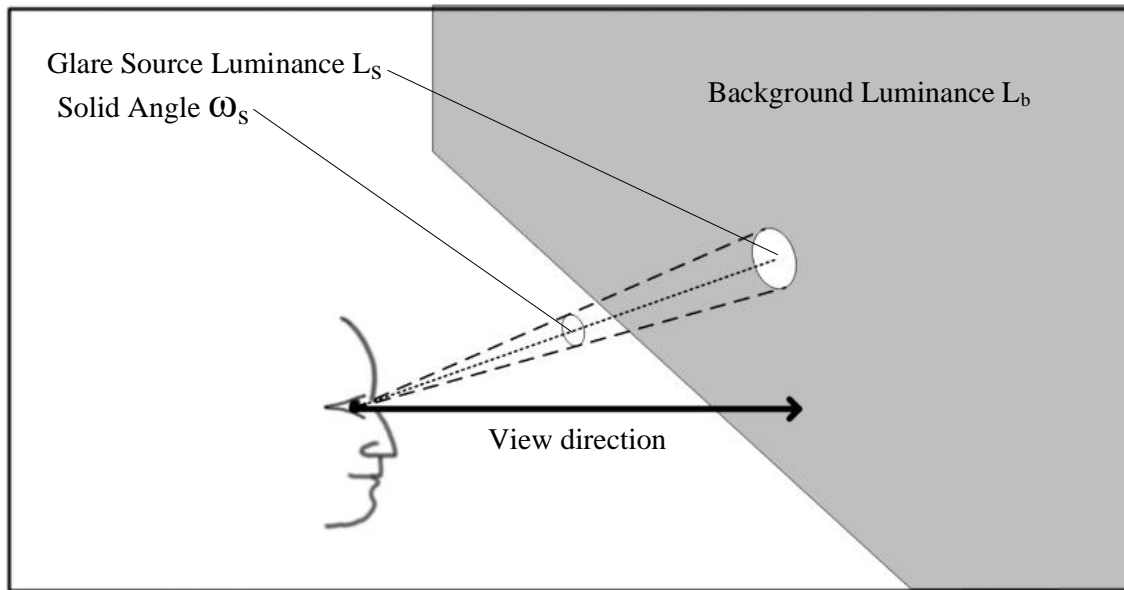
Figure 2.5:Graphical Representation of Photometric Parameter Used in Different Glare Equations (Source: Adapted from (Walkling & Schierz, 2011))

$$P = exp\ [\left(35.2 - 0.31889\alpha - 1.22e^{-\frac{2\alpha}{9}}\right)10^{-3}\beta$$
$$+ (21 + 0.26667\alpha - 0.002963\alpha^2)10^{-5}\beta^2]$$ Equation 2-4

$\alpha = Angle\ from\ vertical\ of\ the\ plane\ containing\ the\ source\ and\ the\ line\ of\ sight$
$\beta = Angle\ between\ the\ line\ of\ sight\ and\ the\ line\ from\ the\ observer\ of\ the\ source$
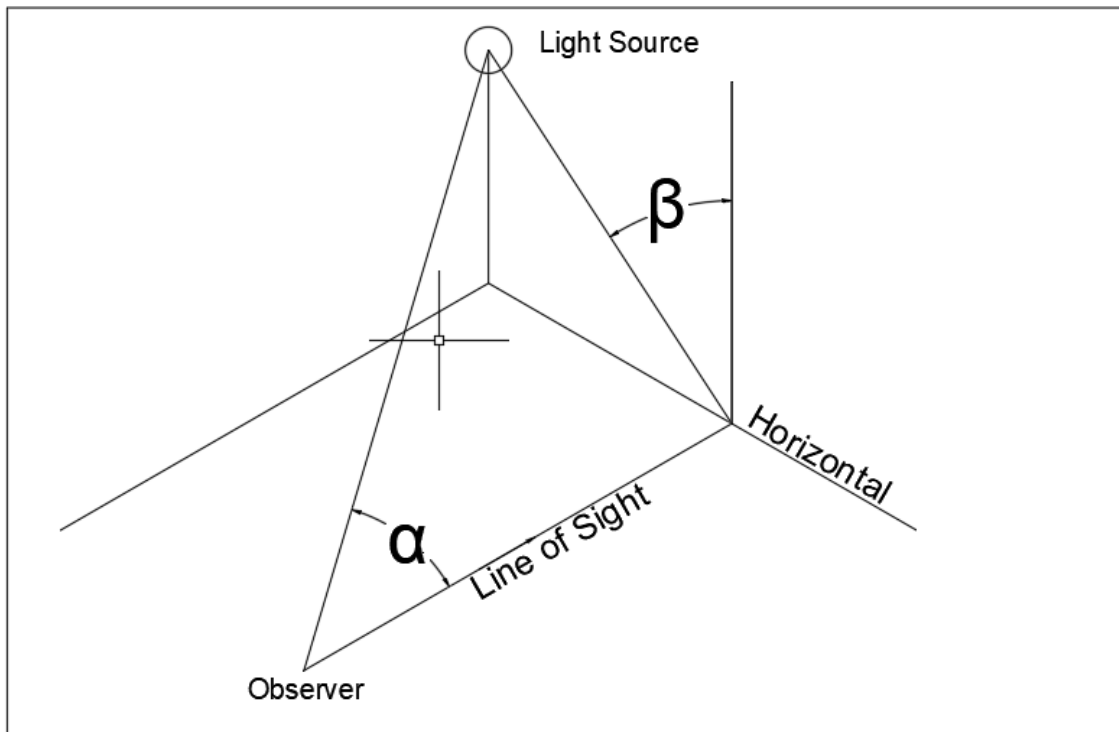
Figure 2.6: The Angles (α & β) used for computing Guth's Position Index (Source: Adapted from (Jan Wienold, 2014))

2.4.2. DGI Glare Index

In 1972, BRS and Cornell University developed the Daylight Glare Index (DGI), that is a modification of the BGI to predict glare from large sources such as windows in a space (Hopkinson, 1972). Direct sunlight and light coming from a large window can be accounted for in DGI. Later, in 1982, the Cornell DGI glare equation was incorporated into the daylight module of DOE-2.1b a building energy simulation program. Equation 2-5 gives the equation for DGI and Table 2.3 gives the values of degree of perceived glare for DGI glare index.

$$DGI = 10log_{10}0.48\sum_{i=1}^{n}\frac{L_s^{1.6}\Omega_s^{0.8}}{L_b + 0.07\omega_s^{0.5}L_S} \qquad \text{Equation 2-5}$$

$\Omega_s = in(sr)$ *is the solid angle subtended by the glare source modified by position of the source with respect to the field of view and Guth's position index*

2.4.3. CGI Glare Index

In 1979 Einhorn developed a glare equation that is adopted by CIE with a slight modification and is referred to as CIE Glare Index (CGI) (Wienold and Christoffersen, 2006). The equation requires direct and indirect illuminance to calculate the glare. This glare index was later incorporated in the RADIANCE daylight simulation tool (G Ward, 1992). Table 2.3 gives the values of the degree of perceived glare for the CGI glare index. This was mainly developed to correct the mathematical inconsistence that are in the DGI glare index. Equation 2-6 gives the equation of the CGI glare index.

$$CGI = 8log_{10}2\frac{[1 + (^{E_d}/_{500})]}{E_d + E_i}\sum_{i=1}^{n}\frac{L_s^2\,\omega_s}{P^2} \qquad \text{Equation 2-6}$$

$E_d\ (Lux) =$ *is the direct vertical illuminance at the eye due to all sources*
$E_i\ (Lux) =$ *is the indirect illuminance at the eye* $E_i = \pi L_b$.
$L_s = Luminance\ of\ the\ Source$
$L_b = Luminance\ of\ the\ Background$
$P = Guth's\ position\ Index$
$\omega_s = Solid\ angle\ subtended\ by\ the\ source$

2.4.4. Visual Comfort Probability (VCP)

The Visual Comfort Probability (VCP) of a lighting system is an estimate of the percentage of people who do not find a lighting system uncomfortable from a glare

49

perspective, and therefore is expressed as a number between 0 and 100 (Mistrick &

Choi, 1999). However, VCP is not appropriate for daylight-based glare (Suk et al.,

2013). Table 2.3 gives the values of the degree of perceived glare for VCP glare index.

Equation 2-7 gives the equation for Visual Comfort Probability (VCP).

$$VCP = 279 - 110[\ log_{10}2 \sum_{i=1}^{n}(\frac{0.5L_{si}(20.4\omega_{si} + 1.52\omega_{si}^{0.2} - 0.075)}{P * E_{avg}^{0.44}})^{n^{-0.014}}$$
<div align="right">Equation 2-7</div>

2.4.5. CIE's Unified Glare Rating System (UGR)

The CIE proposed a unified glare rating system (UGR), that incorporates Guth's

position index and combines aspects of CGI and BGI to evaluate glare sensations for an

artificial lighting system (Wienold and Christoffersen, 2006). UGR values generally

range from 10 to 30 where a high value indicates significant discomfort glare, and a low

value indicates little discomfort glare. Even though UGR is used to report of the glare

from artificial light sources it cannot be used for daylighting calculations. Table 2.3

gives the values of degree of perceived glare for UGR glare index. Equation 2-8 gives

the equation of the Unified Glare Rating (UGR).

$$UGR = 8log_{10}\frac{0.25}{L_b}\sum_{i=1}^{n}\frac{L_s^2\ \omega_s}{P^2}$$
<div align="right">Equation 2-8</div>

$L_s\ =\ Luminance\ of\ the\ Source$
$L_b\ =\ Luminance\ of\ the\ Background$
$P\ \ =\ Guth's\ position\ Index$
$\omega_s\ =\ Solid\ angle\ subtended\ by\ the\ source$

2.4.6. Daylight Glare Probability (DGP)

Daylight Glare Probability (DGP) is a probability that a person is disturbed instead of the magnitude of the glare. DGP is a function of the vertical eye illuminance as well as on the glare source luminance, including its solid angle and its position index. Compared to existing glare indices, DGP shows a very strong correlation with the user's response regarding glare perception (Wienold and Christoffersen, 2006). Table 2.3 gives the values of degree of perceived glare for DGP glare index and Equation 2-9 gives the equation for Daylight Glare Probability (DGP).

$$DGP = 5.87 * 10^{-5}E_v + 9.18 * 10^{-2}log(1 + \sum_{i=1}^{n} \frac{L_{si}^2 \, \omega_{si}}{E_v^{1.87}P_i^2}) + 0.16 \qquad \text{Equation 2-9}$$

$$
\begin{aligned}
E_v \; (Lux) \quad &= \; Verical \; eye \; illumination \\
L_s \; (cd/m^2) &= \; Luminance \; of \; the \; Source \\
\omega_s \quad\quad &= \; Solid \; angle \; of \; source \\
P \quad\quad\quad &= \; Position \; index
\end{aligned}
$$

2.4.7. Simplified Daylight Glare Probability (DGPs)

Wienold also developed a simplified glare index that is a correlation between vertical illuminance and to the levels of glare. This can be measured or calculated. The vertical illuminance level that is used in the equation can be easily calculated using daylight simulation tools such as RADIANCE or DAYSIM by locating a calculation grid at the human eye or measured with an illuminance meter at human eye point (Suk et al., 2013). Equation 2-10 gives the equation for calculating Simplified Daylight Glare Probability (DGPs).

$$DGPs = 6.22 * 10^{-5} * E_v + 0.184$$

<div align="right">Equation 2-10</div>

$E_v (Lux) = Verical\ eye\ illumination$

The simplified formula has limitations – the simplified equation does not take the influence of individual glare sources. Therefore, the DGPs can be applied only in cases where no direct sun or specular reflection hits the eye of the observer. This means that DGPs cannot be used for absolute glare factor conditions that include a direct view of glare sources in the field of view (Suk et al., 2013).

Table 2.3: Degree of Glare in Different Glare Indices (Source: Suk et al.,(2013)).

Degree of Perceived Glare	CGI	UGR	VCP	DGI	DGP
Imperceptible	<13	<13	80-100	<18	<0.35
Perceptible	13-22	13-22	60-80	18-24	0.35-0.4
Disturbing	22-28	22-28	40-60	24-31	0.4-0.45
Intolerable	>28	>28	<40	<31	>0.45

2.4.8. Summary of Glare Indices

Off all the glare indices it is found that the Daylight Glare Probability (DGP) is considered one of the best daylight glare indices to account for the glare due to daylight as it has been specially developed to study glare in the daylit spaces. The DGP is derived from field experiments that incorporated test subjects with a wide variety of scenarios over a period of time at two different test locations. Also, a very strong correlation with the user's response regarding glare perception was found in the DGP equation. A Simplified Daylight Glare Probability (DGPs) is a simplified version of DGP is even more easy to use to compute glare probability under certain scenarios.

2.5. Daylight Estimation in Buildings

Daylight levels in a space can be expressed either in an absolute term, as an illumination value in Lumen/ft^2, or as a percentage (%) using the DF (Hopkinson et al., 1966). Daylight at a point on a plane in the interior of a space consists of : 1) light coming directly from the visible part of the sky through the glazing 2) Light reflected from the ground through the window and reaching the point; and 3) Light reflected from external obstructions that enters the space through a window and reaches a point after inter-reflections from the interior surfaces of the room (Hopkinson et al., 1966). The total illumination at the reference point in the room is then the summation of these three components. Different methods are used to compute these three components.

2.5.1. Components of Daylight

Daylight coming into the interiors of a space through a window consists of three components these are: Sky Component (SC), Externally Reflected Component (ERC), and Internally Reflected Component (IRC)(Hopkinson et al., 1966).

2.5.2. Sky Components (SC)

The Sky Component (SC) is the illumination reaching the point inside the room considered for the direct measurement directly from the sky. In some of the cases, the sky component will be zero if no sky is visible from the point of measurement. Figure 2.7 shows the (SC) of the DF.
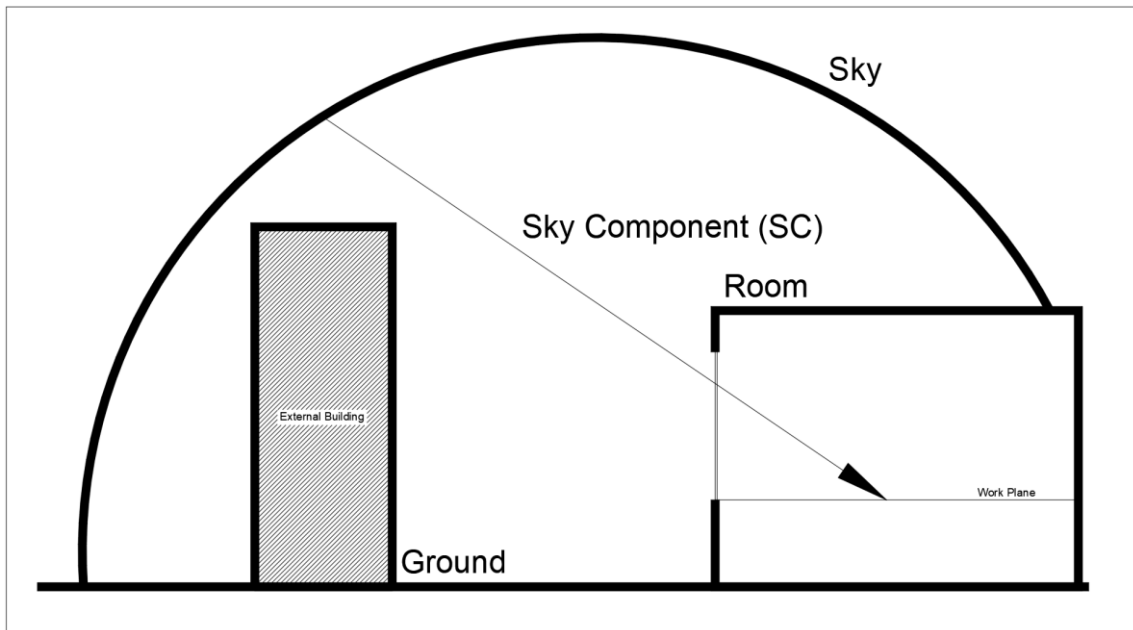
Figure 2.7: Sky Component (SC) of the Daylight Factor (DF) (Source: Adapted from Iversen et al., (2013))

2.5.3. Externally Reflected Component (ERC)

The Externally Reflected Component (ERC) is the illuminance reaching the point inside the room after the light from the sky has reflected from an exterior surface (i.e., Adjacent Building) and then reaches the point being considered. Figure 2.8 shows the ERC of the DF.

2.5.4. Internally Reflected Component

The Internally Reflected Component (IRC) is the illuminance that reaches a point inside the room after the light coming through the window undergoes inter-reflection from the room surfaces. Figure 2.9 shows the IRC of DF.
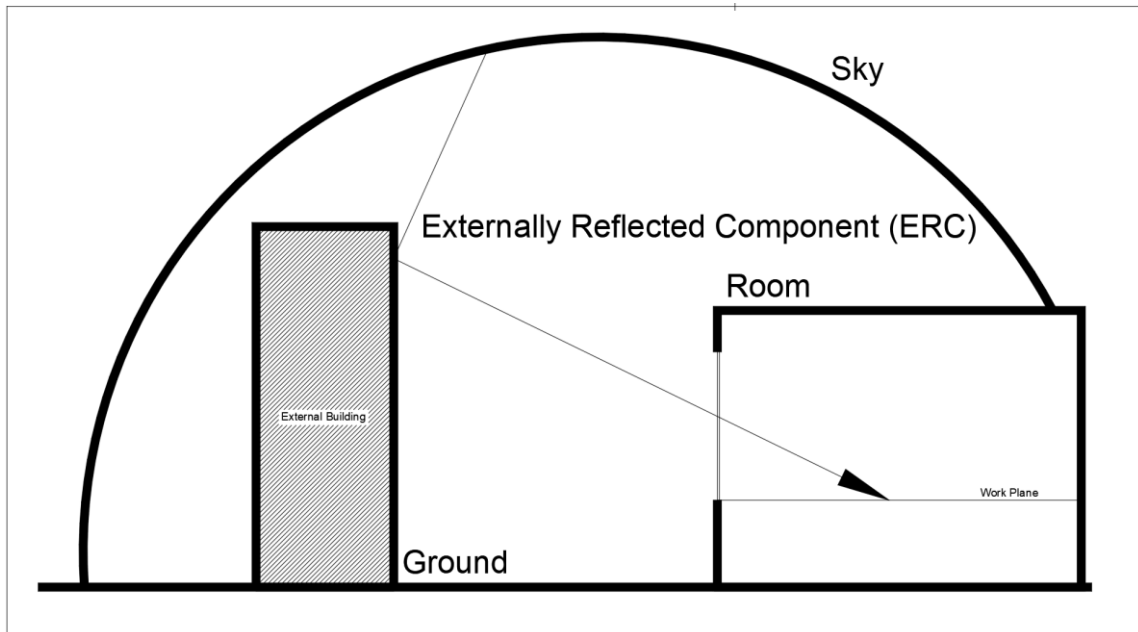
Figure 2.8: Externally Reflected Component (ERC) of the Daylight Factor (DF) (Source: Adapted from Iversen et al.,(2013))
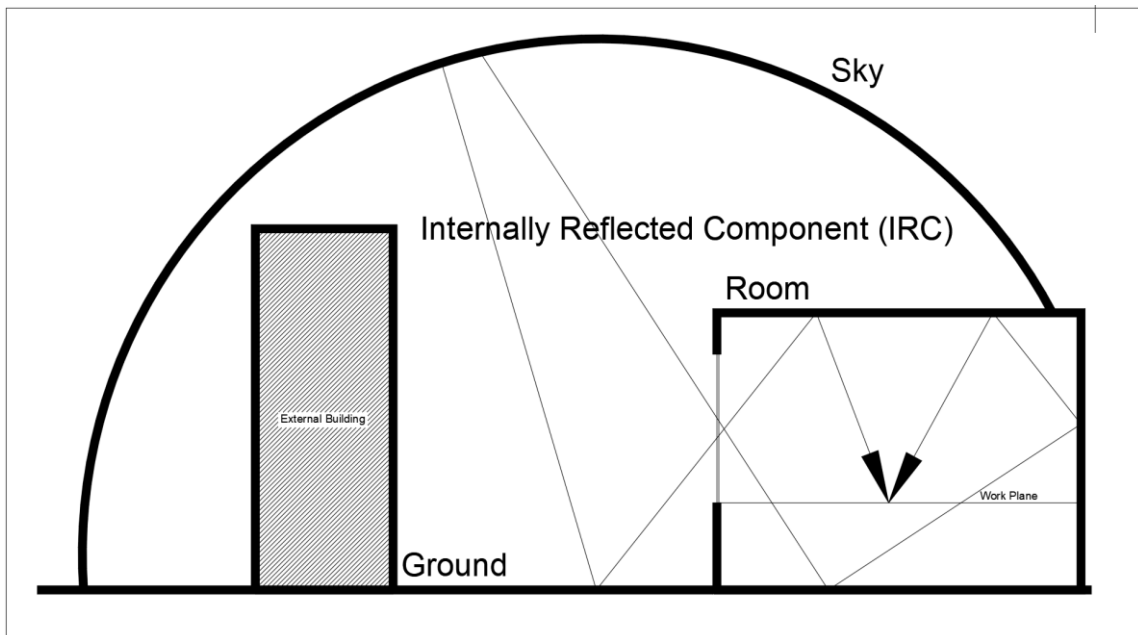
Figure 2.9: Internally Reflected Component (IRC) of the Daylight Factor (DF) (Source: Adapted from Iversen et al.,(2013))

2.5.5. Daylighting Calculation Tools

One of the prime concerns in daylighting research in buildings is the assessment

of the luminous environment and performance. Many methods have been developed to

assess daylight levels in buildings. The initial methods were mainly graphical in nature

until the wide-spread use of computers. Later, researchers developed several non-

graphical and empirical methods to compute different components of daylight (i.e., Sky-

component, Externally Reflected Component & Internally Reflected Component).

2.5.5.1. Introduction

Daylighting calculation methods can be broadly classified into two types,

Daylight Factor (DF) methods that use the concept proposed by Trotter (Trotter, 1911;

Walsh, 1951) and Daylight Coefficient (DC) methods (P. R. Tregenza & Waters, 1983a).

Almost all the tools that are currently used to calculate daylight levels either use the

Daylight Factor (DF) or the Daylight Coefficient (DC) concept. Figure 2.10 shows a

flow diagram of the different methods developed to calculate various components of

daylight under DF & DC concepts.

2.5.5.2. Tools Developed Under Daylight Factor (DF)Concept

Daylight levels can be expressed either in absolute term, as an illumination value

in lumens per square foot lm /ft^2, or as a percentage using the DF (Hopkinson et al.,

1966). The Daylight Factor (DF) consists of three components; these are the Sky

Component (SC), the Externally Reflected Component (ERC), and the Internally

Reflected Component (IRC). The total DF is the summation of these three components.
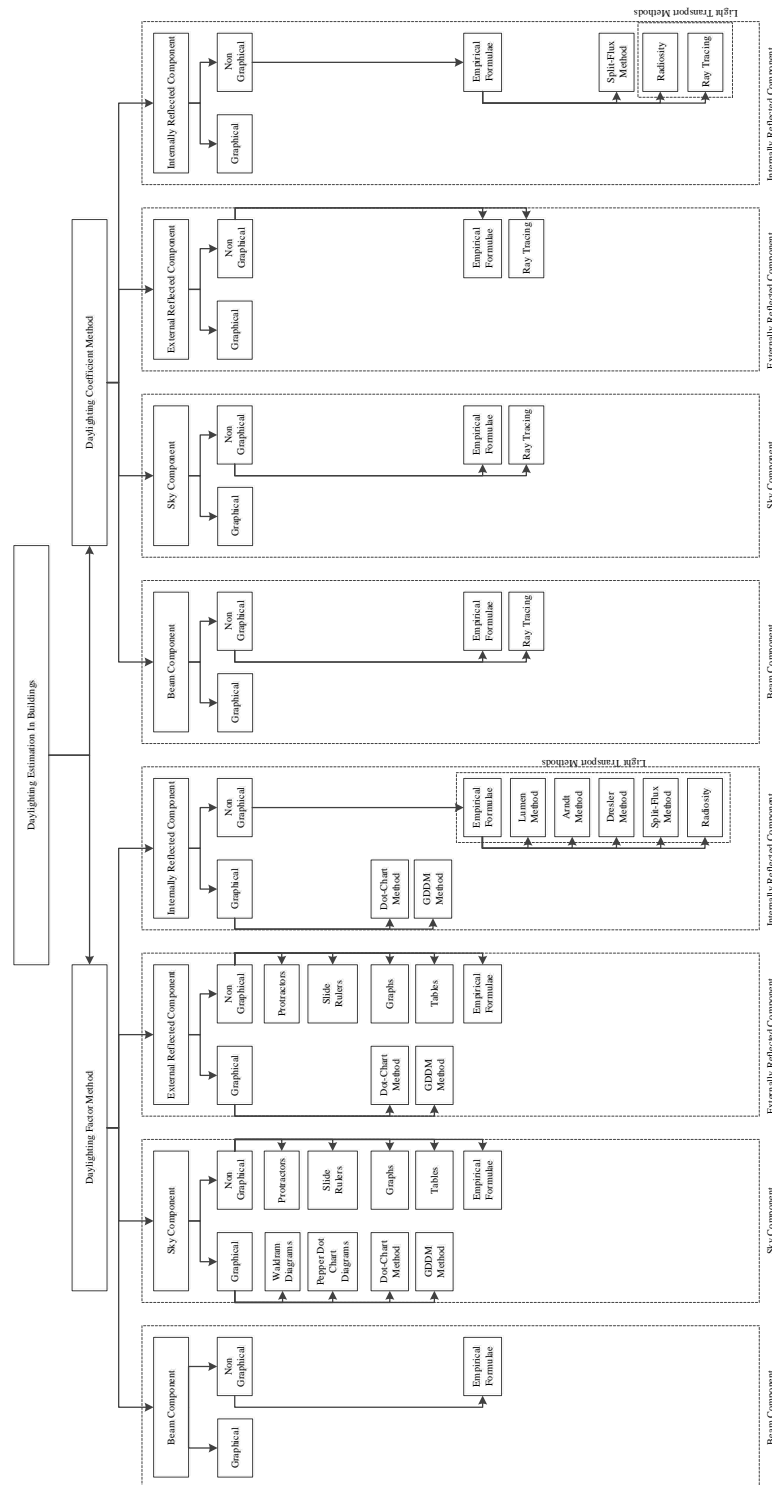
Figure 2.10: Methods Developed to Compute Different Components of Daylight Factor (DF) and Daylight Coefficient (DC) Methods (Source: Author)

57

Different tools have been developed over time to compute these three components either individually or to give a total DF. These tools can be classified mainly into two main categories, graphical and non-graphical. In Figure 2.10, the daylight calculation methods have been divided into two major types that are DF and DC. Each method is divided into three components, SC, ERC and IRC. In addition, for each component, the methods developed are divided into graphical and non-graphical methods and listed below.

2.5.5.3. Graphical Tools for Compute Sky Component

Some of the graphical methods for computing the sky component of the daylight factor are: 1) Waldram Diagrams, 2) Pepper-dot Chart Method, and 3) Pilkington dot chart method. These graphical methods were popular among the architectural community as they could be used in conjunction with architectural building plans to estimate the daylight levels and performance of the building at the early design stages of the design and construction of the buildings.

2.5.5.4. Waldram Diagrams

Waldram diagrams are one of the earliest tools developed to graphically determining the sky component of the daylight factor. These are developed by Waldram and Waldram in 1923 (Hopkinson et al., 1966). The diagram represents the projection of half of the sky vault. The curved lines are the altitude angle of the sky and the vertical lines also known as droop lines, are the azimuth angles. The window aperture is traced on the line as per the altitude angle of the window top and azimuth angles of the window sides. The sky component is the ratio of the visible sky through the window to that of

twice the area of the diagram (Figure 2.11). Also, the external obstructions could be

traced on to the diagram. However, while tracing the window and external obstruction,

the vertical angle scale becomes distorted to account for non- uniform CIE sky.

Therefore, this method only provides the SC of the daylight factor and cannot provide

the ERC and IRC that are essential to computing the overall DF.
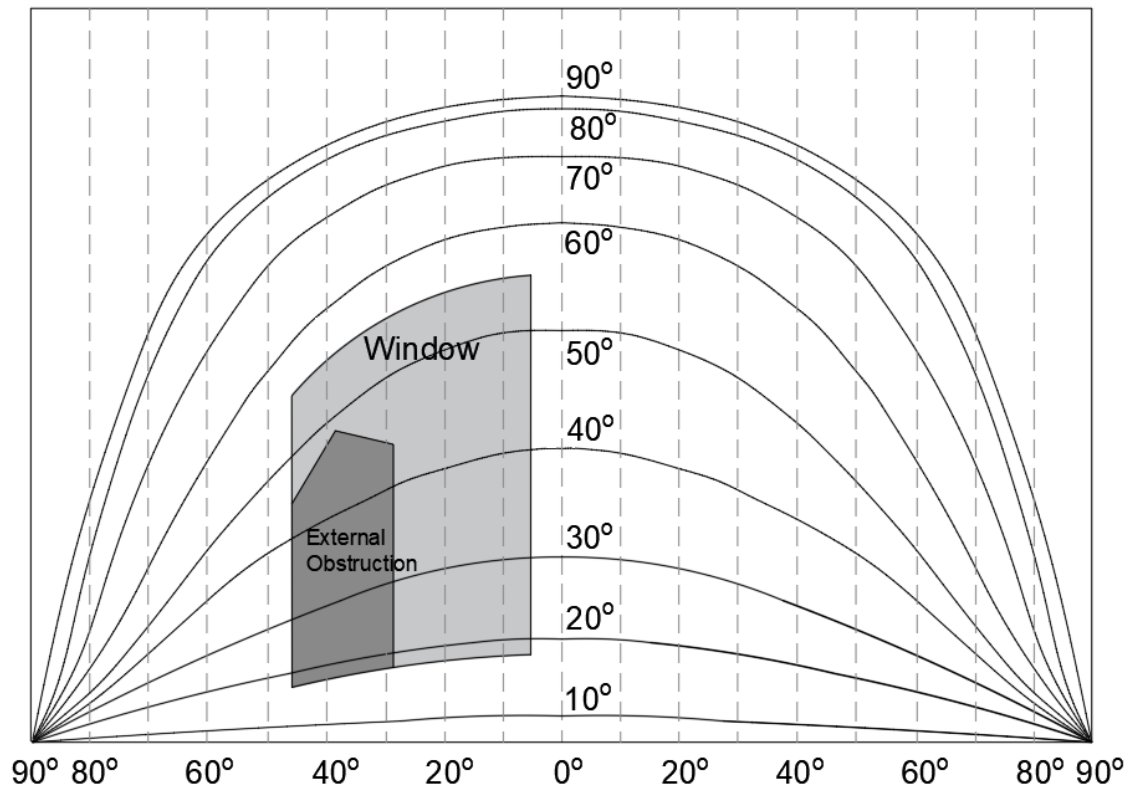
Figure 2.11: Waldram Diagram for CIE Overcast Sky (Source: Adapted from Baker and Steemers (2014))

2.5.5.5. Pepper-dot Chart Method

The pepper-dot chart (Figure 2.12) method was developed by Pleijel in 1954 (as cited in

Hopkinson et al., 1966). This overcomes the limitations of the Waldrum diagram that

introduced the distortion while tracing the window aperture of the buildings onto the chart. In the pepper-dot chart the tracing of the window aperture can be done easily without distortions, and the direct component of the daylight factor can be obtained by counting the dots that fall within the contours of the projection. The great advantage of this kind of diagram is that the density of the dots accounts for the non-linearity of the illumination so that projections can be made without deformations. However, the drawback is that counting the dots can become a very tedious task.
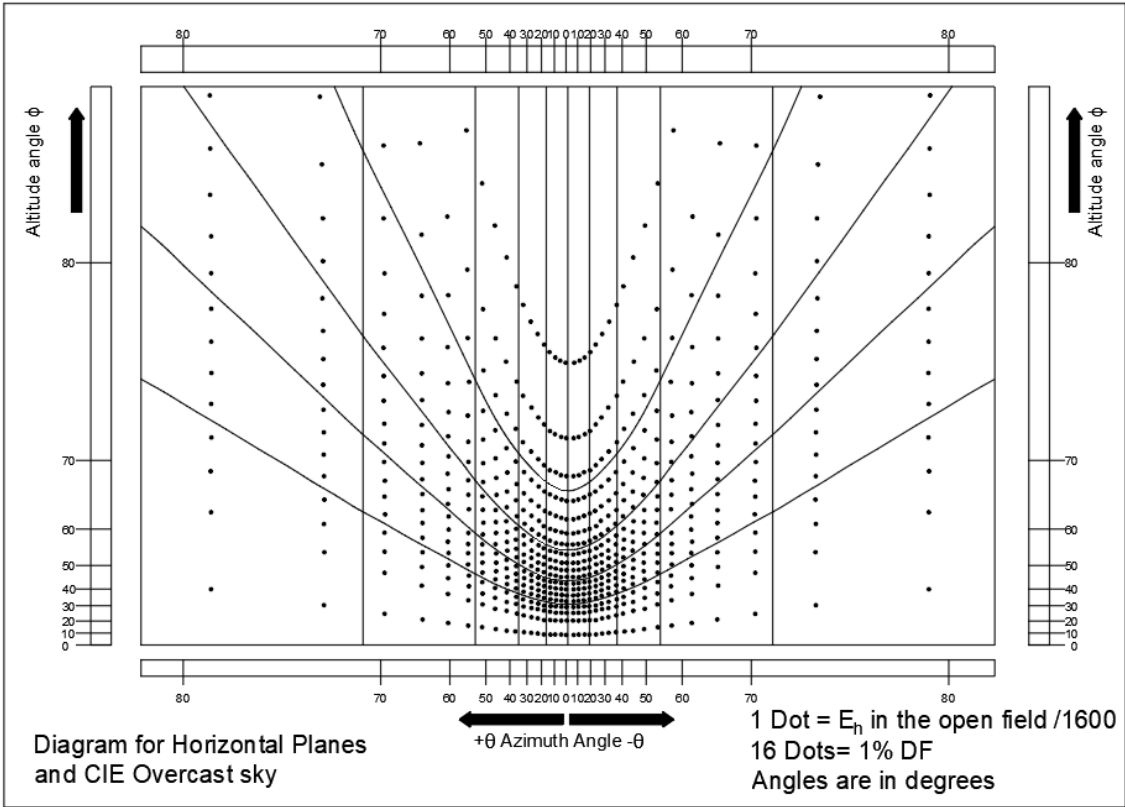
Figure 2.12: Pleijel Pepper-dot Chart for CIE Sky (Source: Adapted from Geebelen (2003))

2.5.5.6. Pilkington dot diagram Method

Another method that has been used to compute the SC and ERC is the Pilkington dot diagram (Baker et al., 2013). In this method, a perspective of the room is created with a fixed length of 25mm. The vanishing point of the perspective is coincides with that of the center point of the Pepper chart. The number of dots are also counted to obtain the SC. Each dot represents 0.1% of the sky component (Figure 2.13).
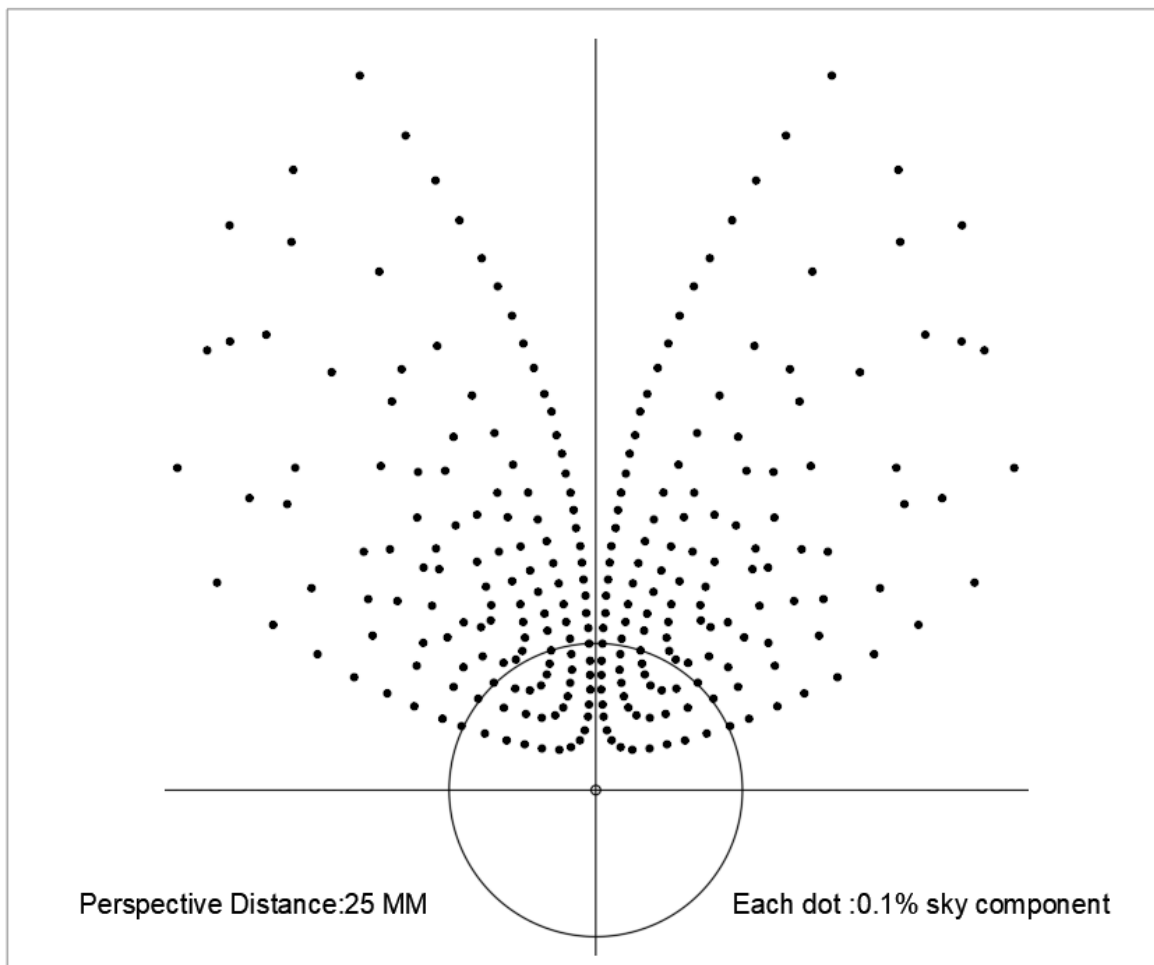
Figure 2.13: Pilkington Dot Diagram (Source: Adapted from Szokolay (2014))

2.5.6. Sky component Non-Graphical-Tools

Some of the Non-graphical methods and tools that have been developed to compute the SC of the DF are: 1) Daylight Protractors (Geometrical Device), 2) Slide rulers 3) Ready-to-use graphs, and 4) Tables to calculate the DF. Some of these tools give the overall daylight factor instead of just SC, unlike in the graphical method.

2.5.6.1. Daylight Protractors

A well-known geometrical device for calculating DF are the daylight protractors developed by Dufton in 1946 for an overcast sky. Dufton developed a total of 10 protractors with developed for the uniform sky (Figure 2.14), and five for the CIE overcast sky (Figure 2.15). Later, in 1982 Bryan and Clasberg developed daylight protractors for clear sky and overcast sky (Bryan and Carlberg, 1985). Today, the total set includes 12 protractors 10 for clear sky and 2 for an overcast sky.

2.5.6.2. B.R.S Daylight Factor Slide-Rule Calculator

The B.R.S. Daylight Factor Slide-Rule Calculator (Figure 2.16) is a single-stage calculator that allows one to determine the total daylight, and direct daylight together with the reflected daylight, for points at different distances from the window, considering the reflectance of the principal room surfaces. The calculator can also be used in reverse to obtain a reflectance when the necessary daylight factor is specified.
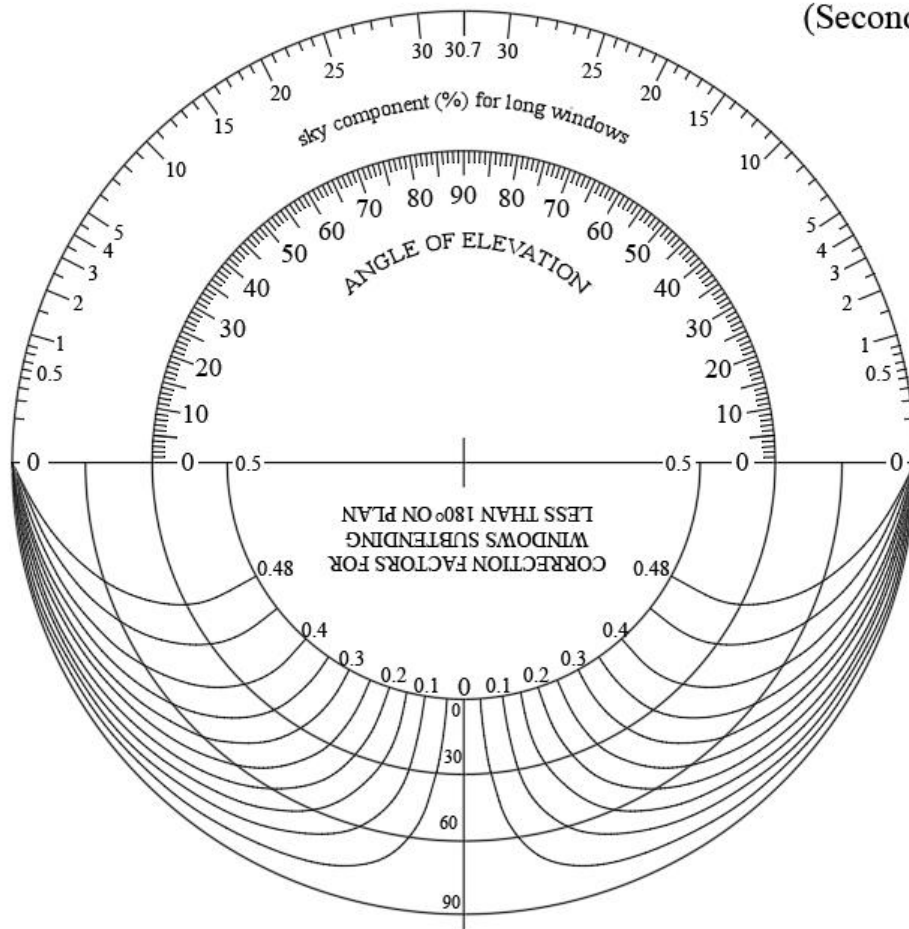
Figure 2.14: BRS Daylight Protractor for a Uniform Sky (Source: Adapted from Geebelen (2003))

Figure 2.15: BRS Daylight Protractor for a Overcast Sky (Source: Adapted from Geebelen (2003))
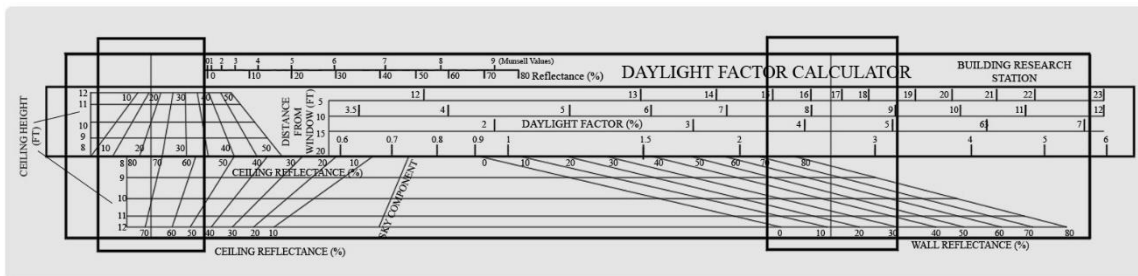
Figure 2.16: BRS Daylight Factor Calculator (Source: Adapted from (Yip, 1972))

2.5.6.3. Ready-to-use Graphs

The daylight graphs developed by Desler consisted of graphs relating daylight levels with the dimensions of the room interior and the windows. The purpose of the diagrams was to enable the architect to readily obtain the maximum permissible depth of the room for a known fenestration after he assumed a certain limiting standard of Daylight Factor (Figure 2.17).
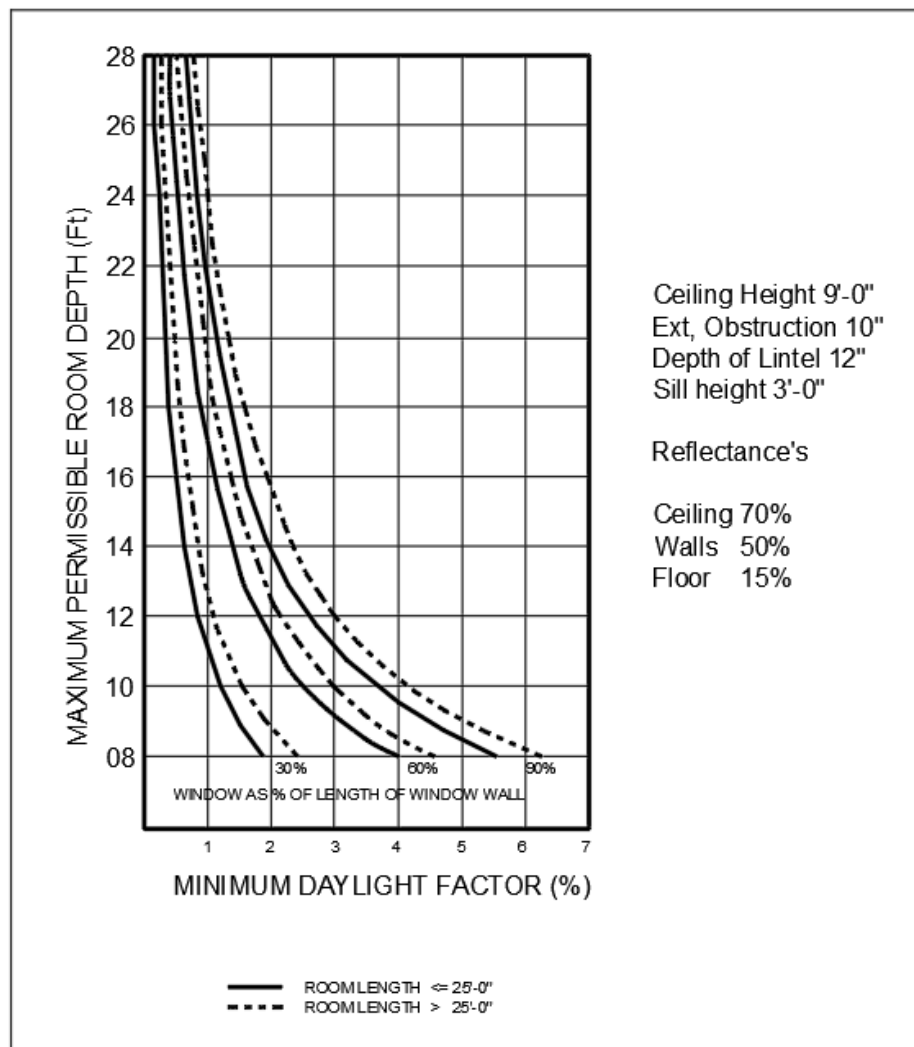
Figure 2.17: Ready to Use Daylight Graphs (Source: Adapted from (Yip, 1972))

2.5.6.4. Table to Calculate Daylight Factor

The B.R.S Simplified Daylight tables were one of the fastest means to obtain the

components of Daylight Factors. They give the value of the sky component directly for a

reference point (Figure 2.18).

Sky Components (C.I.E Standard Overcast Sky) for Vertical Glazed Rectangular Windows

Ratio H/D = Height of the Window Above the Working Plane: Distance from Window

H/D	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.2	1.4	1.6	1.8	2.0	2.5	3.0	4.0	6.0	∞	Angle of Obstruction
∞	1.3	2.5	3.7	4.9	5.9	6.9	7.7	8.4	9.0	9.6	10.7	11.6	12.2	12.6	13.0	13.7	14.2	14.6	14.9	15.0	90°
5.0	1.2	2.4	3.7	4.8	5.9	6.8	7.6	8.3	8.8	9.4	10.5	11.1	11.7	12.3	12.7	13.3	13.7	14.0	14.1	14.2	79°
4.0	1.2	2.4	3.6	4.7	5.8	6.7	7.4	8.2	8.7	9.2	10.3	10.9	11.4	12.0	12.4	12.9	13.3	13.5	13.6	13.7	76°
3.5	1.2	2.4	3.6	4.6	5.7	6.6	7.3	8.0	8.5	9.0	10.1	10.6	11.1	11.8	12.2	12.6	12.9	13.2	13.2	13.3	72°
3.0	1.2	2.3	3.5	4.5	5.5	6.4	7.1	7.8	8.2	8.7	9.8	10.2	10.7	11.3	11.7	12.0	12.4	12.5	12.6	12.7	72°
2.8	1.1	2.3	3.4	4.5	5.4	6.3	7.0	7.6	8.1	8.6	9.6	10.0	10.5	11.1	11.4	11.7	12.0	12.2	12.3	12.3	70°
2.6	1.1	2.2	3.4	4.4	5.3	6.2	6.8	7.5	7.9	8.4	9.3	9.8	10.2	10.8	11.1	11.4	11.7	11.8	11.9	11.9	69°
2.4	1.1	2.2	3.3	4.3	5.2	6.0	6.6	7.3	7.7	8.1	9.1	9.5	10.0	10.4	10.7	11.0	11.2	11.3	11.4	11.5	67°
2.2	1.1	2.1	3.2	4.1	5.0	5.8	6.4	7.0	7.4	7.9	8.7	9.1	9.6	10.0	10.2	10.5	10.7	10.8	10.9	10.9	66°
2.0	1.0	2.0	3.1	4.0	4.8	5.6	6.2	6.7	7.1	7.5	8.3	8.7	9.1	9.5	9.7	9.9	10.0	10.1	10.2	10.3	63°
1.9	1.0	2.0	3.0	3.9	4.7	5.4	6.0	6.5	6.9	7.3	8.1	8.5	8.8	9.2	9.4	9.6	9.7	9.8	9.9	9.9	62°
1.8	0.97	1.9	2.9	3.8	4.6	5.3	5.8	6.3	6.7	7.1	7.8	8.2	8.5	8.8	9.0	9.2	9.3	9.4	9.5	9.5	61°
1.7	0.94	1.9	2.8	3.6	4.4	5.1	5.6	6.1	6.5	6.8	7.5	7.8	8.2	8.5	8.6	8.8	8.9	9.0	9.1	9.1	60°
1.6	0.90	1.8	2.7	3.5	4.2	4.9	5.4	5.8	6.2	6.5	7.2	7.5	7.8	8.1	8.2	8.4	8.5	8.6	8.6	8.6	58°
1.5	0.86	1.7	2.6	3.3	4.0	4.6	5.1	5.6	5.9	6.2	6.8	7.1	7.4	7.6	7.8	7.9	8.0	8.0	8.1	8.1	56°
1.4	0.82	1.6	2.4	3.2	3.8	4.4	4.8	5.2	5.6	5.9	6.4	6.7	7.0	7.2	7.3	7.4	7.5	7.5	7.6	7.6	54°
1.3	0.8	1.5	2.3	2.9	3.6	4.1	4.5	4.9	5.2	5.5	5.9	6.2	6.4	6.6	6.7	6.8	6.9	6.9	6.9	7.0	52°
1.2	0.7	1.4	2.1	2.7	3.3	3.8	4.2	4.5	4.8	5.0	5.4	5.7	5.9	6.0	6.1	6.2	6.2	6.3	6.3	6.3	50°
1.1	0.65	1.3	1.9	2.5	3.0	3.4	3.8	4.1	4.3	4.6	4.9	5.1	5.3	5.4	5.5	5.6	5.6	5.7	5.7	5.7	48°
1.0	0.6	1.1	1.7	2.2	2.6	3.0	3.3	3.6	3.8	4.0	4.3	4.5	4.6	4.7	4.7	4.8	4.8	4.9	5.0	5.0	45°
0.9	0.50	1.0	1.5	1.9	2.2	2.6	2.8	3.1	3.3	3.4	3.7	3.8	3.9	4.0	4.0	4.0	4.1	4.1	4.2	4.2	42°
0.8	0.4	0.83	1.2	1.6	1.9	2.2	2.4	2.6	2.7	2.9	3.1	3.2	3.3	3.3	3.3	3.3	3.4	3.4	3.4	3.4	39°
0.7	0.33	0.68	0.97	1.3	1.5	1.7	1.9	2.1	2.2	2.3	2.5	2.5	2.6	2.6	2.6	2.6	2.7	2.7	2.8	2.8	35°
0.6	0.2	0.53	0.74	0.98	1.2	1.4	1.5	1.6	1.7	1.8	1.9	1.9	2.0	2.0	2.0	2.1	2.1	2.1	2.1	2.1	31°
0.5	0.16	0.39	0.52	0.70	0.82	0.97	1.0	1.1	1.2	1.3	1.4	1.4	1.4	1.4	1.5	1.5	1.5	1.5	1.5	1.5	27°
0.4	0.1	0.3	0.3	0.5	0.5	0.6	0.7	0.8	0.8	0.9	0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	22°
03	0.06	0.14	0.18	0.26	0.30	0.34	0.38	0.42	0.44	0.5	0.49	0.50	0.50	0.5I	0.5	0.52	0.52	0.52	0.53	0.53	17°
0.2	0.03	0.06	0.09	0.11	0.12	0.14	0.16	0.20	0.21	0.21	0.22	0.22	0.22	0.22	0.2	0.23	0.23	0.23	0.24	0.24	11°
0.1	0.01	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.07	0.07	0.07	0.07	0.08	0.08	6°
0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.2	1.4	1.6	1.8	2.0	2.5	3.0	4.0	6.0	∞	0°

Ratio W/D = Width of Window to one Side of Normal: Distance from Window

Figure 2.18: B.R.S Daylight Factor Table for Sky Component (Source: Adapted from (Yip, 1972))

Also available are the tables for quickly determining the I.R.C based on room surface

reflectance and window-to-floor ration and percentage of the window to floor area ratio.

2.5.7. Externally Reflected Component (ERC)-Graphical

For calculating the ERC, there are graphical and non-graphical tools. Some of the

graphical tools that are used to compute ERC are 1) Dot- Chart method 2) Graphic

Daylight Design Method (GDDM) method. GDDM method is used to compute overall daylight factor

2.5.7.1. Dot Chart method

The dot chart method has been discussed in (Section 2.5.5.5). Similar to the calculation of the SC, the number of dots are calculated and multiplied by a factor for calculating ERC. The value of the ERC will be less compared with the SC as it is light from the sky reflected off of external obstructions and entering into the room.

2.5.7.2. Graphic Daylight Design Method (GDDM)

The Graphic Daylight Design Method (GDDM) is one of the graphical methods that gives overall DF (Figure 2.19). The GDDM was developed by Millet and Bedrick (1980) for computing the total DF for a standard CIE overcast sky. Later, in 1980, the GDDM method was extended to calculate the DF for the clear sky (as cited in Moore, 1985). The advantage of this method is that it gives Daylight Factor (DF) contours overlaid on the architectural plan that are more useful than the numerical output from other methods. However, to use this method, a designer need a library of 200 patterns (i.e., Isolux contours) that covers different daylight design situations. To develop these patterns a lighting simulation program called UWLIGHT was used and lighting distribution patterns (i.e., Isolux contours) for side-lighting and top-lighting were developed. To make the method more generalizable for different architectural plans, the height-to-width proportion (H/W) was used to identify the windows (Figure 2.19). The placement of the isolux contours on the plan was determined by the ratio of the sill

67

above the work plane (S) to the height of the window (H). A detailed example of this method is given in (Grondzik & Kwok, 2019).
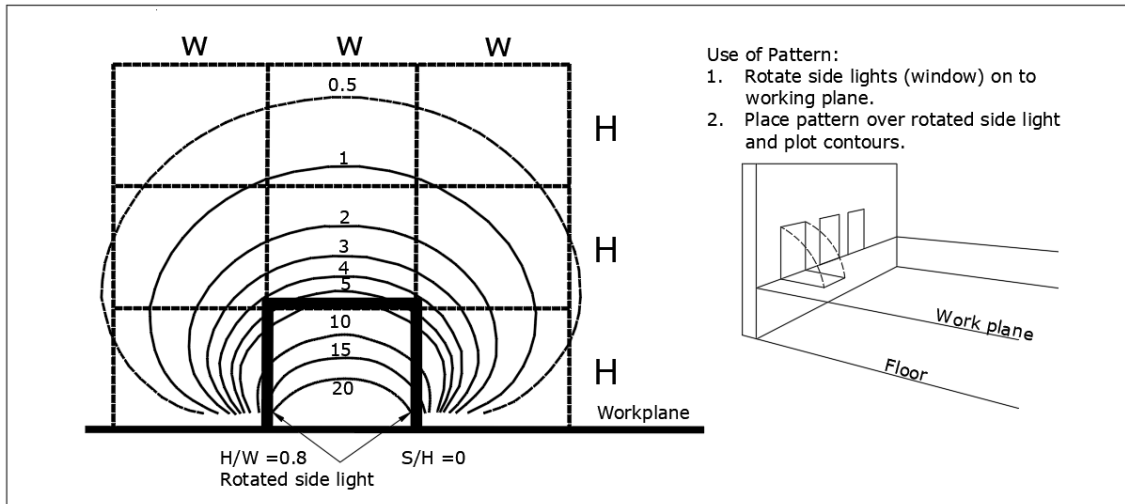
Figure 2.19: A Daylight Iso-Lux Contour Pattern for a Window in Graphic Daylight Design Method Selected Based on H/W Ratio and S/H Ratio (Source: Adapted from (Grondzik & Kwok, 2019))

2.5.8. Externally Reflected Component (ERC)-Non-graphical

The non-graphical tools and methods for computing ERC are the same as that of SC. Some of them are: 1. Protractors, 2. Slide Rulers, 3. Graphs, and 4. Tables. Each of these are discussed in previous chapters.

2.5.9. Tools and Methods for Calculating Internally Reflected Component (IRC)

Among the three components of DF, the computation of IRC is difficult compared to SC and ERC. The methods that have been develop to calculate the Internally Reflected Component are mostly non-graphical in nature. Some of them are in the form of ready-to-use tables and some are empirical formulas. These tabulated method and formulas are discussed in the following sections.

2.5.9.1. Ready to Use tables for IRC

The B.R.S Simplified Daylight Tables are a quick way to find out the Daylight Factors for a specific room. Apart from giving the value of the sky component directly for a reference point the simplified tables also give the IRC that can be read directly after we make certain assumptions have been made. Based on room surface reflectance and window-to-floor ratio and percentage of window-to-floor area ratio I.R.C could be quickly determined (Figure 2.20).

Ratio- Actual glass area to floor area	Actual glass area (% of floor area)	Floor Reflectance (%)											
		10				20				40			
		Wall Reflectance (%)											
		20	40	60	80	20	40	60	80	20	40	60	80
1:50	2	-	-	0.1	0.2	-	0.1	0.1	0.2	-	0.1	0.2	0.2
1;20	5	0.1	0.1	0.2	0.4	0.1	0.2	0.3	0.5	0.1	0.2	0.4	0.6
1:14	7	0.1	0.2	0.3	0.5	0.1	0.2	0.4	0.6	0.2	0.3	0.6	0.8
1:10	10	0.1	0.2	0.4	0.7	0.2	0.3	0.6	0.9	0.3	0.5	0.8	1.2
1:6.7	15	0.2	0.4	0.6	1	0.2	0.5	0.8	1.3	0.4	0.7	1.1	1.7
1:5	20	0.2	0.5	0.8	1.4	0.3	0.6	1.1	1.7	0.5	0.9	1.5	2.3
1:4	25	0.3	0.6	1	1.7	0.4	0.8	1.3	2	0.6	1.1	1.8	2.8
1:3.3	30	0.3	0.7	1.2	2	0.5	0.9	1.5	2.4	0.8	1.3	2.1	3.3
1;2.9	35	0.4	0.8	1.4	2.3	0.5	1	1.8	2.8	0.9	1.5	2.4	3.8
1:2.5	40	0.5	0.9	1.6	2.6	0.6	1.2	2	3.1	1	1.7	2.7	4.2
1:2.2	45	0.5	1	1.8	2.9	0.7	1.3	2.2	3.4	1.2	1.9	3	4.6
1:2	50	0.6	1.1	1.9	3.1	0.8	1.4	2.3	3.7	1.3	2.1	3.2	4.9
Conversion factor to obtain average value of I.R.C		x1.9	x1.5	x1.3	x1.2	x1.8	x1.4	x1.3	x1.2	x1.6	x1.4	x1.2	x1.1

Figure 2.20: B.R.S Daylight Factor Table for Internally Reflected Component (Source: Adapted from (Yip, 1972))

2.5.9.2. Empirical Formula for IRC

The most difficult step in calculating the daylight levels at a point inside a space is computing the IRC (i.e., the light entering through a window and that reflects off interior surfaces and reaches the work-plane or a point in space). Over time many formulae have been developed by different researchers to compute the IRC, which include both simple and very sophisticated mathematical models have been developed. Two of the advanced mathematical methods are the Radiosity and Ray-tracing methods. These two methods were developed and later incorporated into lighting analysis and

daylighting simulation tools that are currently used for performing simulations by architects and engineers. In addition to the advanced tools, other tools have been developed, including, the lumen method, the Dresler method, the Arndt method and the Split-Flux method for computing the IRC component of the DF.

2.5.9.3. Lumen Method

In 1928 Fruhling developed an empirical formula for calculating the DF, called the Lumen method (Equation 2-11 and Equation 2-12) (Dresler, 1954). The formula developed uses a Coefficient of Utilization, for which he developed a series of utilization factor tables. Unfortunately, Fruhling's formula did not consider the light coming from the ground, external reflected components or inter-reflection of light in the room for computing the DF.

$$Average\ Daylight\ Factor = F * U * \frac{A_g}{A_f} * 100\% \qquad \text{Equation 2-11}$$

$$Average\ Daylight\ Factor = \frac{E_w}{E_f} * U * \frac{A_g}{A_f} * 100\% \qquad \text{Equation 2-12}$$

$F =\ Flux\ falling\ on\ window\ pane$
$U =\ Coefficient\ of\ Utilization$
$A_g =\ Area\ of\ the\ glass\ of\ window$
$A_f =\ Area\ of\ the\ Floor\ of\ the\ Room$

2.5.9.4. Ulbricht Sphere Principle

An integrating sphere (also known as an Ulbricht sphere) is an optical component consisting of a hollow spherical cavity with its interior coated with a diffuse white reflective coating, with small holes for entrance and exit ports for light. Its relevant property is a uniform internal scattering or diffusing of light effect (Arecchi, Messadi, & Koshel, 2010). Light entering and incident on any point on the inner surface are, by multiple scattering reflections, distributed equally to all other points which is similar to light entering through window, getting inter-reflected and reaching a point in a space (Figure 2.21).
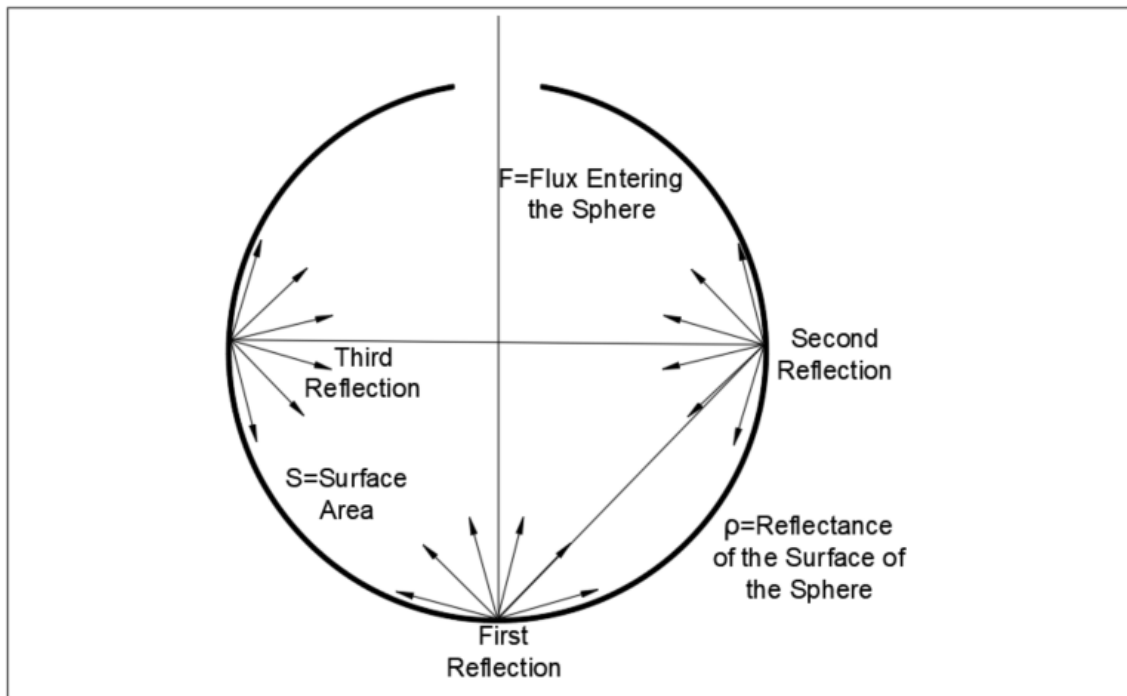
Figure 2.21: Working Concept of Ulbricht Sphere (Source: Adapted from (P. Tregenza & Wilson, 2011))

2.5.9.5. Dresler Method

The Dresler method (1954) is based on the principle of inter-reflection of light in the Ulbricht sphere. It extends the Lumen method for calculating the IRC for a given room with a window. Dresler developed his method by considering flux entering the window and reflected off the walls, ceiling and floor of a room.

2.5.9.6. Arndt Method

In a different study Arndt proposed a formula for computing the IRC. This method is also based on the lumen method and it uses the concept of inter-reflection of the Ulbricht sphere. In his method the distribution of the primary flux entering the room through the window is not the considered for calculation of the IRC (Dresler, 1954). As a result, it is considered to be a simplified method and less accurate in predicting the IRC compared to Dresler's method.

2.5.9.7. Split-Flux Method

Later, in 1954, Hopkinson proposed a new method, called the split-flux method, that is an empirical formula for calculating the IRC, which based on the formula proposed by Arndt (Hopkinson et al., 1954). Figure 2.22 shows the concept of the split-flux method of computing the IRC. The split-flux method assumes that the luminous flux entering the room through a window is calculated in two parts. In this method, the window is divided in two by a imaginary horizontal plane passing through the center of the window (Figure 2.22a). In the split-flux method the flux coming down from the sky is calculated, including any external obstructions above the imaginary plane (Figure 2.22b). Next flux coming up from the ground is calculated including any external

obstructions falling below the imaginary plane (Figure 2.22c). The downward luminous

flux summations are then multiplied times the average reflectance of the lower surfaces

of the room; and the upward flux summations are multiplied times the reflectance of the

upper surfaces of the room (Figure 2.22d). Finally, the unit sphere method is applied for

the inter-reflection of the light. Later, Tregenza proposed a modification to the split-flux

formula to include large vertical obstructions, such as projecting wings on the side of a

building, and overhanging canopies (P. R. Tregenza, 1989).

2.5.9.8. Limitations of the Split Flux Method

There are several limitation with the split-flux method: 1) It only works well with

those kinds of geometry that closely resemble a sphere (i.e., such as a square or

rectangle-type shape) (as cited in Hopkinson et al., 1966); 2) the Split-flux method

cannot predict illumination levels accurately at a point very close or far away from the

window in a spaces 3) the Split-flux method is not recommended for rooms whose depth

measured from the exterior wall containing the window is more than three times greater

than ceiling height. 4) The Split-flux method cannot handle complex daylighting
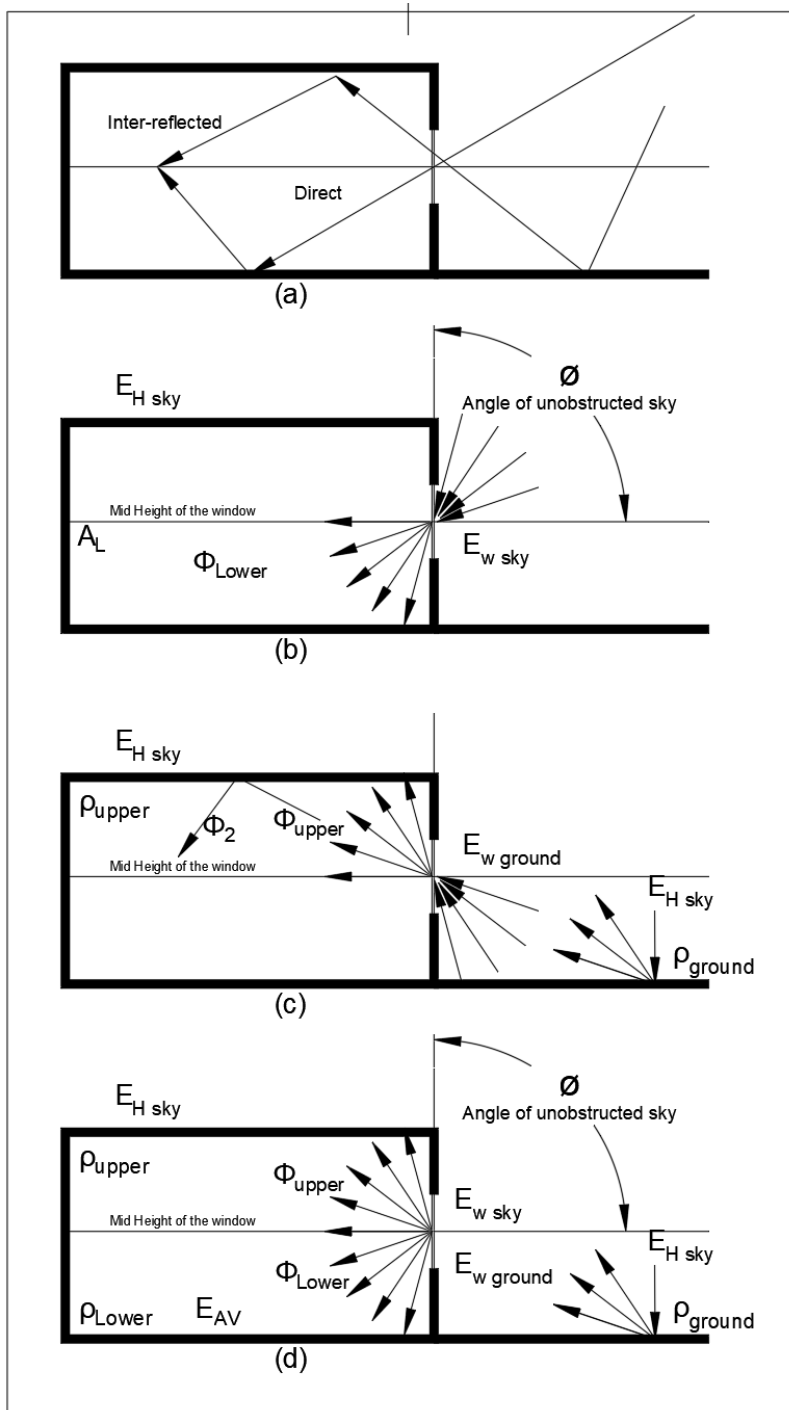
Figure 2.22: BRS Split-Flux Method: (a) Imaginary Line Passing Through the Window (b) Sky Component (c) Ground Component (d) Overall Split Flux Principle (Source: Adapted from (Hopkinson et al., 1966))

strategies such as light shelves or reflective overhangs that are highly directional and force more light onto the ceiling in a room (Baker, 1990). This is because the split-flux method assumes that the room behaves like an integrating sphere with perfectly diffusing interior surfaces and with no internal obstructions. It therefore works best for rooms that are close to cubical in shape, and have diffuse surfaces, (which is usually not the case for most rooms), and for rooms that have no internal partitions. In such cases (i.e., non-cubical rooms) the method can over-predict the internally reflected illuminance near the back of the room by a factor of two or more (Winkelmann & Selkowitz, 1985)

2.5.9.9. Radiosity Method

In the radiosity method the space is divided into a mesh of patches (Figure 2.23). All the patches are considered as Lambertian reflectors, which means that the room has a constant luminance across each patch, independent of the viewing direction. In addition, the flux that leaves each patch is calculated using Lambert's cosine law. Therefore, each patch receives and reflects light back into the space. The whole calculation process is iterative and proceeds until all the reflected flux has finally been absorbed. Dilaura & Hauser (1978) developed flux transfer algorithms that are based on the radiosity method. Several other researchers have also developed radiosity calculation algorithms. Modest (1982), Selkowitz et al (1982), and Kim et al (1988) also developed radiosity algorithms (as cited in Carroll & Hitchcock, 2005).
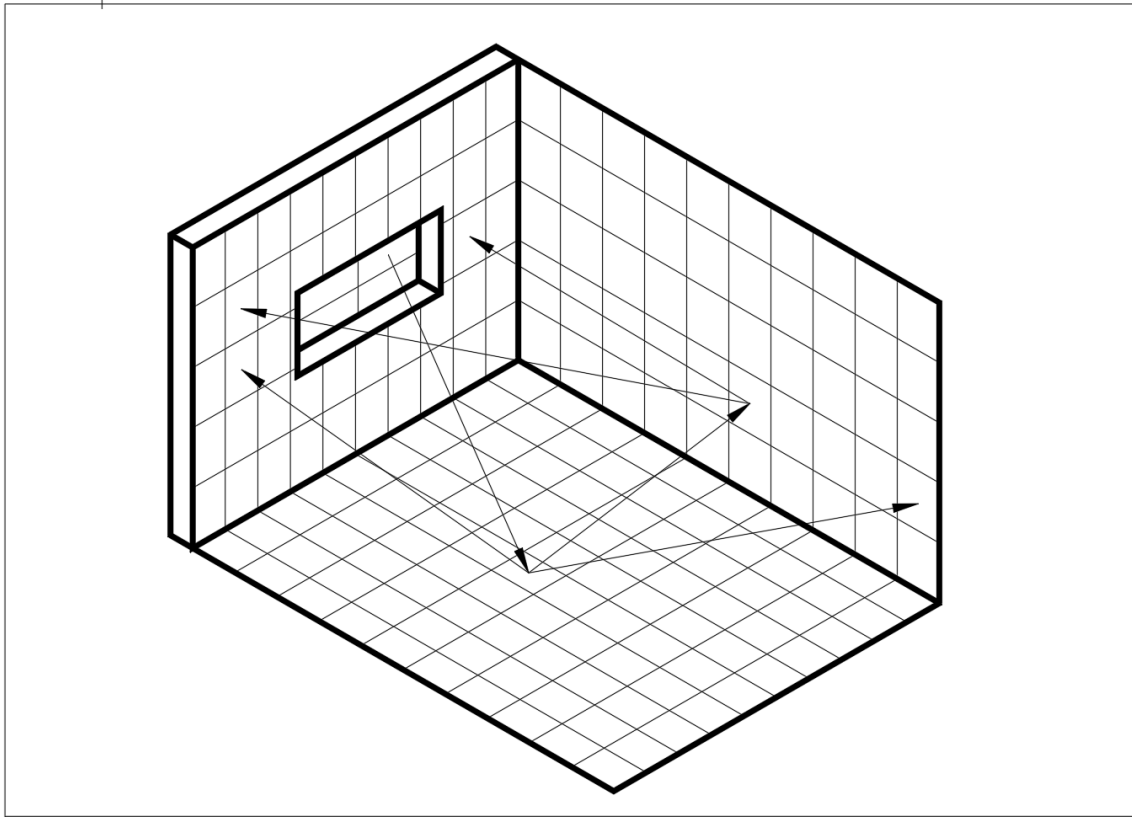
Figure 2.23: Radiosity Method in That Surfaces Are Divided into Patches and the Flux Transfer is Computed Between These Patches. (Source: Adapted from (Autodesk., 2017))

2.5.9.10. Limitations of the Radiosity Method

Unfortunately, the calculation of the view factors between different patches is one of the most difficult parts of this method, and since view factors have to be calculated and stored, the amount of data storage required increases as a function of the number of patches. Also, the radiosity-based method for calculating the IRC assumes all the surfaces to be Lambertian (i.e., perfectly diffuse), which means this method cannot model specular (i.e., mirror-like) reflections effectively (Tsangrassoulis & Bourdakis, 2003).

2.5.9.11. Raytracing

One of the techniques that are used in daylighting calculations is the Computer Graphics (CG) based ray-tracing technique. The first ray-tracing algorithms were developed by Whitted (2005). The ray-tracing technique was primarily used in image synthesis. Ray-tracing can be classified as one of two types, forward and backward ray-tracing.

2.5.9.12. Forward Raytracing

In essence ray-tracing, as the name implies, is tracing of the path of the light ray from the source to the eye. In forward ray-tracing the rays are generated at a light source in all directions; some of these rays travel toward objects in the scene (i.e., the environment), interact with the objects, strike the image plane and finally reach the eye (Figure 2.24). Ray-tracing is a close approximation to how the light reaches the eye in the real world. Most often, in forward ray-tracing many of the light rays generated at the source that interact with the objects in the scene do not reach the eye and contribute to the image. In fact, only a few of them ever reach the eye contributing to an image. As a result, forward ray-tracing is computationally very time consuming to track all the rays that do not contribute to the image or reach the eye.

2.5.9.13. Backward Raytracing

James Arvo (1986) introduced a new concept called backward ray-tracing. In backward ray-tracing the rays are generated from the eye and are then traced backward towards the light source (Figure 2.25). As a result, in backward ray-tracing only those rays are considered that pass through the image plane and strike the objects and are

traced to the light source. Since the number of rays generated in the backward ray-tracing method are fewer than the forward ray-tracing method; backward ray-tracing method is computationally much faster than the forward ray-tracing method (Glassner, 2002). However, the accuracy of the results is the same.

2.5.9.14. Advantage of Ray-Tracing Over Split-Flux and Radiosity Methods

One of the inherent assumptions in calculating the IRC using the Split-Flux and Radiosity Methods is that in both of these methods surfaces are treated as Lambertian (perfectly diffuse), which means these methods cannot model specular reflections effectively (Tsangrassoulis & Bourdakis, 2003). However, ray-tracing techniques can model both Lambertian and Specular surfaces with good accuracy.
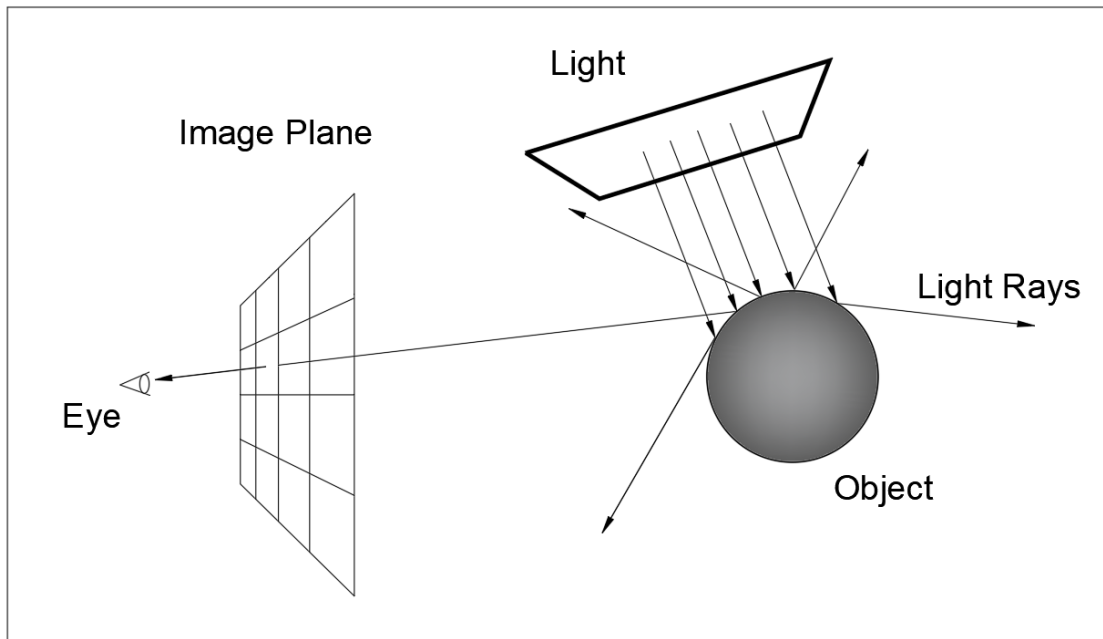
Figure 2.24: Forward Raytracing (adapted from "COEN 290 Computer Graphics I—Week 8—Ray Tracing,"(Source: Adapted from (B Grantham, 2008))
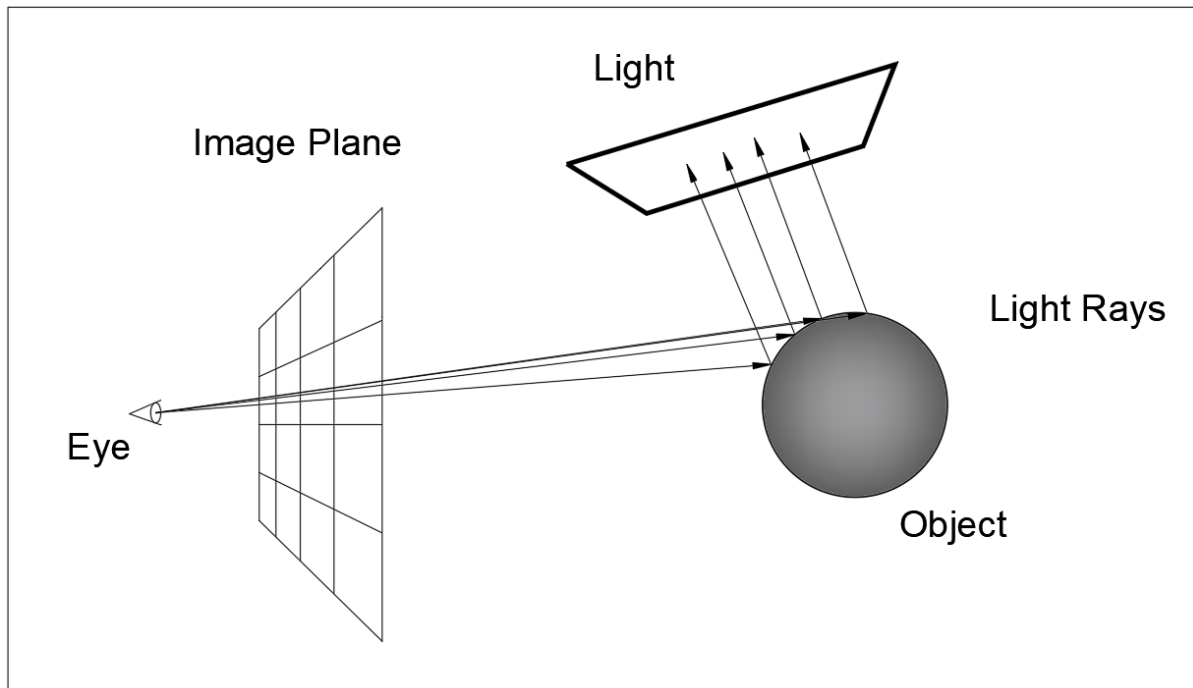
Figure 2.25: Backward Raytracing (adapted from "COEN 290 Computer Graphics I—Week 8—Ray Tracing," (Source: Adapted from (B Grantham, 2008))

2.5.10. Daylight Coefficient Method

The concept of the Daylight Coefficients (DC) was first introduced by Tregenza (1983). This method was developed because it was found that DF methods could not accurately predict the illumination levels at a point on a plane for a time-varying sky luminance distribution. In addition, the Daylight Factor method cannot predict illumination levels directly from the sun. The concept of the DCs depends on the idea of dividing up the sky into a large number of very small patches (Figure 2.26) at a location described by an altitude θ and azimuth Φ angle (P. R. Tregenza, 1987; P. R. Tregenza & Waters, 1983a).
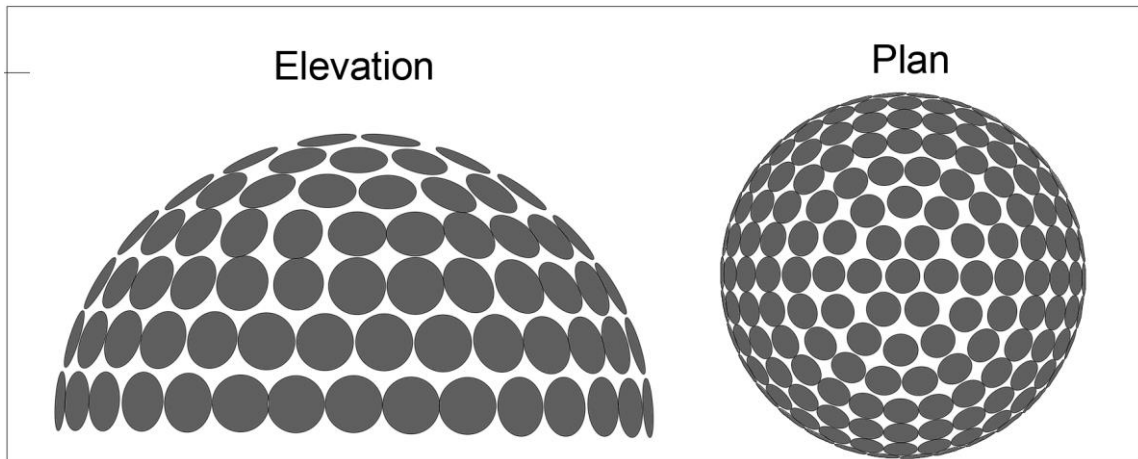
Figure 2.26: Sky Sub Divisions Elevation and Plan view (Source: Adapted from Tregenza (1987))

Illumination from each patch is calculated at the reference point on the plane in the space as given by Equation 2-13 . The total illumination at the point **E** is given by the summation of illumination from each patch (Equation 2-14). The advantage of the DC is that it can calculate illumination levels at a reference point for a wide variety of skies as well as the illuminance due to direct sunlight (P. R. Tregenza, 1993). Figure 2.27 graphically represent different parameters which are used in DC method.

$$\Delta E = D_{\theta\phi} L_{\theta\phi} \Delta S_{\theta\phi}$$

Equation 2-13

$\Delta E = \ Illumination\ at\ a\ point\ in\ space\ from\ small\ patch\ of\ the\ sky.$
$L_{\theta\phi} = Luminance\ of\ the\ sky\ patch.$
$\Delta S_{\theta\phi} = \ Solid\ angle\ subtended\ by\ sky\ patch.$
$D_{\theta\phi} = \ Daylight\ Coefficient\ of\ a\ single\ patch.$
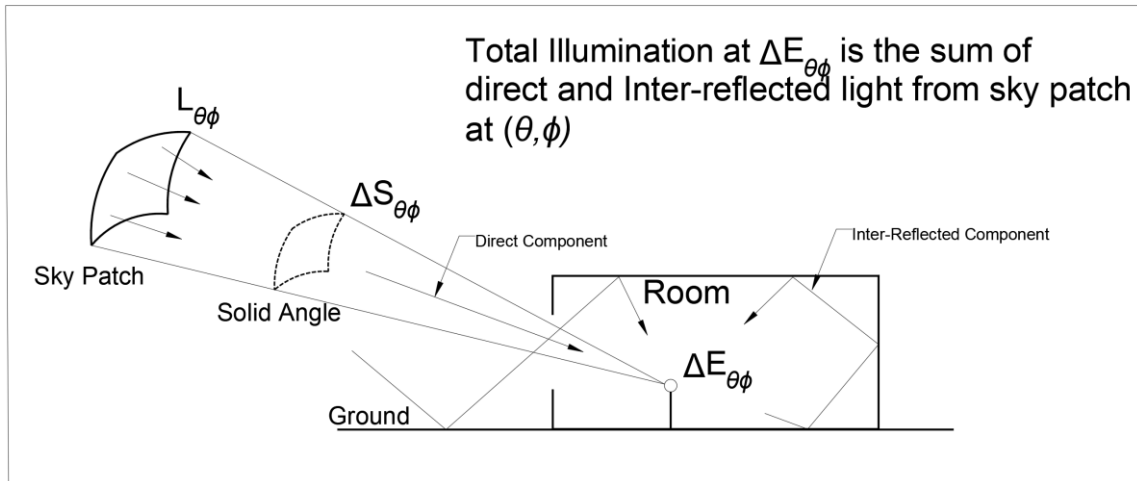
Figure 2.27: Illumination (Direct and Inter-reflected) From Sky Patch Received at a Point Space (Source: Adapted form Mardaljevic (2000a)).

$$E = \int_0^{2\pi} \int_0^{\pi/2} D_{\theta\phi} L_{\theta\phi} cos\theta d\theta d\phi$$

Equation 2-14

$E =$ *Illumination at a point in space from sky.*
$L_{\theta\phi} =$ *Luminance of the sky patch.*
$D_{\theta\phi} =$ *Daylight Coefficient of a single patch.*

The DC analysis has two parts, in the first part of the analysis, the room dimensions and surface characteristics are entered and the DCs are calculated. In the second part, these DCs are then multiplied by the sky luminance values and the solid angle constants to give the internal illumination.

2.5.10.1. Non-Graphical Methods for Computing Daylight Coefficients

The non-graphical methods in the Daylight Coefficient (DC) method are the same as those of the Daylight Factor (DC) method. DC's as the DF can also be divided into different components for the Sky Component (SC), the External Reflected Component (ERC), and the Internal Reflected Component (IRC) (Figure 2.28). The total

Daylight Coefficient for a given point in the room is the summation of the individual components. Using this method, it is possible to compute Daylight Coefficient for a point in the room for the direct (i.e. Sky Component) and inter-reflected light (i.e., The Internal Reflected Component) separately (P. R. Tregenza & Waters, 1983a).
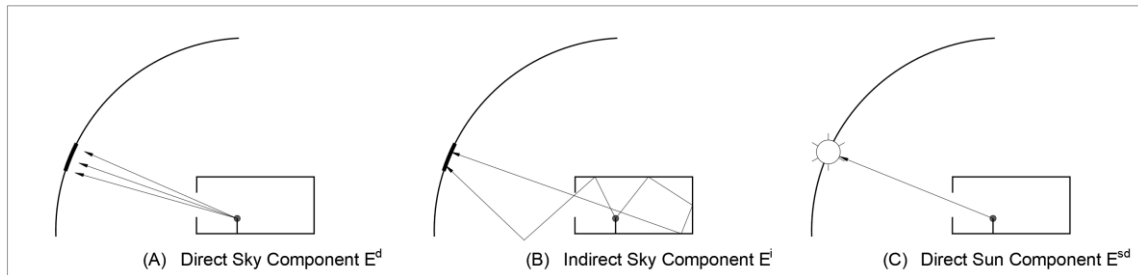
Figure 2.28: Calculation of Different Components of Daylight Coefficient Method (Source: Adapted from Mardaljevic (2000))

2.5.10.2. Split-Flux Method and its Limitations

Using the Split-Flux method Tregenza showed how the IRC of the Daylight-Coefficient can be computed for a given point in the room (P. R. Tregenza & Waters, 1983a). First the coefficient of the light reflected first by the ground and then by the upper surfaces of the room are calculated as a separate component. Next the light that enters the window and is reflected initially by the lower parts of the room are than computed and then added to get the total IRC. The split-flux method has the same accuracy issues when computing the IRC of the DF. These same limitations extend for computing the DC for a given room.

2.5.10.3. Radiosity Method and its Limitations

Tregenza demonstrated how Finite element calculations (FEM) can be used to compute DCs for multiple points in a room (P. R. Tregenza & Waters, 1983a). Later he

demonstrated that the FEM which is also called as the Radiosity Method can be used for calculating inter-reflections of light in a room that are used to compute DC's for multiple points. Later, Littlefair described that the computational load of calculating the DCs using Radiosity methods for a given geometry could be reduced using other numerical methods such as Gaussian integration (Littlefair, 1992). Littlefair also suggested that computer graphic techniques, such as ray-tracing and Monte-Carlo techniques could be used to find room-reflected DCs, which was also suggested by Tregenza. He also stated that the FEM and other techniques of direct-flux calculations were far more efficient than the Monte-Carlo method when it comes to easy problems with simple geometries. However, he showed the Monte-Carlo method was superior for complex geometry problems (P. R. Tregenza, 1993).

2.5.11. Daylight Computer Simulation Tools

Over the years many daylighting simulations tools have been developed that have incorporated some of the previously mentioned methods that were developed to compute daylighting quantities. The outputs of Lumen-Micro consist of numerical tables of illumination levels, iso-contour maps in the plan view and maps of illumination levels onto a plan, section or elevation views and perspective drawings. Lumen-Micro could also model clear and diffuse glazing, overhangs, and selected controls (such as venetian blinds). The program took into consideration external obstructions including adjacent sunlit surfaces and sky lit surfaces inside and outside the room (Moore, 1985).

Table 2.4 provides a list of different daylighting simulation tools and the methods they employ. These range from simple tools to highly sophisticated computer

simulations tools that can predict the hour-by-hour indoor illumination levels. Column

two in the table gives the name of the tool and column three gives the reference for the

tool. Column four shows whether the tool is a proprietary tool or an open source tool.

The last column gives the type of method (i.e., DF or DC) that the tool employees to

perform the daylighting calculation. Finally, column 3 show these tools fall into one of

the three categories for computing the IRC (i.e., split-flux, radiosity, and ray-tracing).

2.5.12. Tools for Implementing the Daylight Factor Method

In the preceding sections several daylighting simulations tools that used the

concept of the Daylight Factor (DF) proposed by Trotter (1911) were discussed. These

tools have different sky-models and techniques for computing the IRC component of the

DF. Some of these tools are simple to use and others are very sophisticated, performing

different types of analysis and producing different types of output.

2.5.12.1. Daylight Factor Quick Tools

2.5.12.1.1. Light

One of the early tools that was developed to study the artificial lighting, was

commissioned in 1968 by a lamp manufacturing company, is the LIGHT program. It can

compute lighting levels for a maximum of 100 sensor points specified by the user for a

room (Altman, 2005). However, it was not capable of computing the daylighting for a

given room.

Table 2.4: Daylight Simulation Tools (Source: Author)

SNo	Name of the Simulation tool	Reference of the Study	Split Flux (SF Radiosity (R) Raytracing (RT)	Open Source (OS) Proprietary (P)	Daylight Factor (DF) Daylight Coefficient (DC)
1	LIGHT, ENERGY	(Altman, 2005)	-	P	DF
2	Quicklite-I		-	P	DF
3	Gensys-III		-	P	DF
4	Cooper Lighting Luxicon 2.3	(IESNA, 2002)	-	P	DF
5	Integra Inspire Lighting Design		-	P	DF
6	Relux Professional 2007	(Evangelos & David, 2005)	RT	P	DF
7	Rayfront	(IESNA, 2002)	RT	P	DF
8	Lumen Micro 2000	(Ubbelohde & Humann., 1998)	R	P	DF
9	SUPERLITE		R	OS	DF
10	DOE-2.1e	(Winkelmann et al., 1993)	SF	OS	DF
11	EnergyPlus	(Crawley et al., 2001)	SF, R	OS	DF
12	eQuest	(Hirsch, 2010)	SF	OS	DF
13	Lightscape	(Ubbelohde & Humann., 1998)	R	P	DF
14	Desktop RADIANCE	(Estes et al., 2004)	RT	OS	DF
15	FormZ		RT	P	DF
16	Spectra	(Ubbelohde & Humann., 1998)	-	P	DF
17	Genlux	(IESNA, 2002)	RT	P	DF
18	Ecotect	(Marsh, 1997)	SP	P	DF
19	3DSMAX	(Reinhart and Breton, 2009)	RT	P	DF
20	IES<VE>	(Contoyannis, 2010)	RT	P	DF
21	ADELINE	(Reinhart and Herkel, 2001)	RT	OS	DF
22	RADIANCE	(G Ward, 1994; G Ward & Rubinstein, 1988)	RT	OS	DC
23	ESP-r	(Clarke et al., 1998)	RT	OS	DC
24	DAYSIM	(Reinhart and Herkel, 2001)	RT	OS	DC

2.5.12.1.2. Quicklite-I and ENERGY

Bryan (1981) developed a daylighting program called Quicklite-I. This program runs on a Texas Instrument (TI)-59 programmable calculator. It calculates the interior horizontal illumination or daylight factors for a window. It predicts daylighting levels from a window for the CIE clear and overcast skies. The IRC was computed using the split-flux method. Later, Bryan and Kringal developed it as a computer program for the Apple II computer and the IBM Personal Computer (Moore, 1985). During the same period, DiLaura and Lighting Technologies developed a daylighting analysis program called ENERGY for the IBM PC. The ENERGY program predicts the daylight illumination under CIE overcast and clear sky conditions. In the ENERGY program the IRC is computed using the Radiosity method based on algorithms developed by Bryan and Clear (Moore, 1985).

2.5.12.1.3. Lumen-Micro 2000

During the 1970s DiLaura developed a new electric lighting simulation program called Lumen-I. Shortly after that the Lumen-II program was developed by him (as cited in Altman, 2005). Later, in 1981 DiLaura and Kambich developed the Lumen-III program, a sophisticated daylight illumination calculation program. In 1983 an enhanced version of Lumen III called Lumen-Micro 1.0 was released by Lighting Technologies. The currently available version of Lumen-Micro is version 2000. Lumen-Micro can model CIE clear, partly cloudy and overcast sky models for daylighting calculations. The IRC in lumen-micro is computed using flux transfer algorithms developed by DiLaura and Hauser (Moore, 1985). In the earlier versions (i.e. Lumen I, II & III) the IRC was

computed using the Split-Flux method. In the later version, the Inter Reflected

Component (IRC) is computed using the Radiosity method developed by DiLaura and

Kambich (Ubbelohde & Humann., 1998).

The outputs of Lumen-Micro consist of numerical tables of illumination levels,

iso-contour maps in the plan view and maps of illumination levels onto a plan, section or

elevation views and perspective drawings. Lumen-Micro could also model clear and

diffuse glazing, overhangs, and selected controls (such as venetian blinds). The program

took into consideration external obstructions including adjacent sunlit surfaces and sky

lit surfaces inside and outside the room (Moore, 1985).

2.5.12.1.4. SUPERLITE

Selkowitz developed a daylighting simulation tool called SUPERLITE

(Selkowitz et al., 1982) at the Lawrence Berkley National Lab (LBNL). SUPERLITE

takes input parameters such as the exterior sun and sky conditions, site obstructions,

varying fenestrations, and shading device details and interior room properties and

predicts the spatial distribution of the illuminance in a room. SUPERLITE can model

uniformly overcast; CIE standard overcast and CIE clear sky models with or without sun

for daylighting calculations (Ubbelohde & Humann., 1998). SUPERLITE uses the

modified Radiosity algorithms developed by Modest, Selkowitz et al. and Kim et al. (as

cited in Carroll & Hitchcock, 2005) for computing the Inter Reflected Component (IRC)

instead of using the split-flux method. It has been extensively validated against physical

models under an artificial sky (Moore, 1985). Some of the output SUPERLITE can

provide are illumination and luminance levels in tabular form, iso-contour plots or

Daylight Factor values that are generated by an auxiliary graphing program.

2.5.12.1.5. DOE 2.1e

In 1982 LBNL developed a computer simulation program called DOE-2

primarily for building energy performance analysis (Oh & Haberl, 2016a). In DOE-2.1b

a new daylighting simulation module was introduced. The DOE-2.1b daylighting

module, in conjunction with the thermal simulation, determines the total energy impact

of daylighting strategies based upon an hour-by-hour analysis of daylight availability,

site conditions and window management (Winkelmann et al., 1993; Winkelmann &

Selkowitz, 1985). The DOE-2 daylighting calculations consists of three main stages of

calculations. In the first stage, a pre-processor calculates the DFs that are later used in

the hourly loads' calculation. These DF's are calculated with the standard CIE overcast

and clear sky conditions for a series of 20 different solar altitude and azimuth values

covering the annual range of sun positions.

In stage two, an hourly daylighting calculation is performed for every hour that

the sun is above the horizon. For each hour the illuminance from each window is found

by interpolating the stored daylight factors using current sun positions and cloud cover,

that are multiplied with the current-hour exterior horizontal illumination. Glare from the

window is also calculated. If the glare control options are specified, the program will

automatically close window blinds to decrease glare to a pre-defined comfort levels.

In stage three, the program simulates the lighting control system to determine the

auxiliary or supplemental electrical lighting energy needed to make up the difference

between the daylighting level and the design illuminance to maintain a pre-selected

lighting level at the specified sensor points within the room. For computing the IRC

DOE-2.1e uses the split-flux method (Winkelmann et al., 1993; Winkelmann &

Selkowitz, 1985). For glare calculations it uses the Cornell-BRS `large-source' formula

derived from Hopkinson (Winkelmann et al., 1993; Winkelmann & Selkowitz, 1985).

2.5.12.1.6. Limitations of DOE-2.1e

Unfortunately, DOE-2.1e has limitations when it comes to daylighting

calculations. DOE-2 uses only two sky models: the CIE overcast and clear sky models,

that do not represent the entire range of naturally occurring skies. In addition, the split-

flux method used to compute the IRC only provides accurate answers for certain kinds

of geometry that closely resemble a sphere (such as a square or rectangular shaped

room) (Hopkinson et al., 1954). Also, DOE-2 cannot simulate daylighting strategies such

as light shelves because only one side of the shade of the light shelf (i.e., the upper

outside projection) is taken to have a luminous property (Winkelmann et al., 1993).

DOE-2 cannot simulate Complex Fenestration Systems (CFS), or account for light

coming from adjacent spaces or atrium spaces. In addition, because it treats surfaces as

perfect diffusers it cannot take into consideration the properties of the materials such as

specularity or glossiness. As a result, the daylighting algorithms in DOE-2 are limited to

calculating simple geometries, without complex daylighting strategies such as light

shelves or atrium spaces. Dang (as cited in Koti & Addison, 2007) showed that the split-

flux method used in DOE-2 over-predicts the light levels at the lighting sensors (used for

dimming the lighting) location if they are located deeper in space (i.e., Away from the

window). Finally, the shading calculations in DOE-2 are also very simplified. In DOE-2 any shadings elements are provided for windows, DOE-2 calculates the shading profile for the first day of the month and uses the same profile for the rest of the month instead of computing the shading for the everyday of the month.

2.5.12.1.7. eQUEST (DOE-2.2+Wizard+Graphics)

One of the derivatives of the DOE-2.1e is DOE-2.3, that is the simulation engine behind eQUEST (Hirsch, 2010). Both eQUEST and DOE-2.3 use the same daylight calculation methods (i.e., Split-Flux method) as that of DOE-2.1e program and have the same limitation that of DOE-2.1e.

2.5.12.1.8. EnergyPlus 9.2.0

EnergyPlus is a new building energy performance analysis tool similar to DOE-2.1e and eQUEST. EnergyPlus has a built-in daylighting calculation module. In EnergyPlus The daylight simulation module determines the daylight levels at a given reference point in the room for the room geometry and surface and window properties. Daylighting calculations in EnergyPlus can be performed using a built-in daylighting module and also a special plug-in program called DELIGHT.

Both modules can simulate daylighting as well as supplemental electric lighting. The built-in module in EnergyPlus is referred to as the detailed calculation method. Both modules (i.e. The detailed method and DELIGHT) use four different sky models: clear, clear turbid, intermediate and overcast for generating sky luminance distribution for daylight calculations (Ellis et al., 2004). In the detailed method and the earlier versions of DELIGHT the DOE-2 split-flux method was adopted for calculating the Inter

Reflected Component (IRC). However, in the later versions of DELIGHT the Radiosity-based algorithms that were developed for SUPERLITE by Modest, Selkowitz et al. and Kim et al. were adopted (Hitchcock & Carroll, 2003). In the detailed method only two sensor points per space are used for electric lighting control, whereas in DELIGHT a maximum of 100 sensor points can be placed arbitrarily in the space. The latest version of the program is DELIGHT 2.0 (Hitchcock & Carroll, 2003). This version has the capability of simulating Complex Fenestration Systems (CFS) (as cited in Hitchcock & Carroll, 2003). by reading the Bi-directional Scattering Distribution Function (BSDF) dataset files for simulating CFS that are either generated experimentally or generated using tools such as WINDOWS 7 (Robin et al., 2019) to determine the energy impact of daylighting strategies on a building.

2.5.12.1.9. Autodesk ECOTECT

ECOTECT is a software package with a unique approach to conceptual building design. It couples an intuitive 3-D design interface with a comprehensive set of performance analysis tools and interactive information display (Marsh, 2003). These include overshadowing and solar reflection; sun penetration and shading device design; solar access and photovoltaic/heat collection; hourly thermal comfort and monthly space loads; natural and artificial lighting levels; acoustic reflections and reverberation times; and project cost and environmental impact (Roberts & Marsh, 2001). The latest version of the ECOTECT is Version 5.6.0.1. As the complexity of the model increases, the model can also be exported to a range of application-specific tools for more detailed analysis. There are two ways a daylighting analysis can be performed using ECOTECT:

1) using the built-in simulation engine or 2) by exporting the geometry and material

properties to a more sophisticated daylight simulation tools such as RADIANCE and

DAYSIM. The built-in simulation engine has three sky models: the CIE overcast sky, an

intermediate sky and a clear sky with and without the sun. ECOTECT uses the split-flux

method for computing the IRC (Marsh, 1997). For a detailed daylighting analysis the

geometry and the material properties can be exported to RADIANCE (Marsh, 2003) or

DAYSIM (Reinhart and Fitz, 2004). Once the analysis is completed these results can be

imported back into ECOTECT and can be viewed. In the detailed analysis mode,

ECOTECT serves only as a graphical user interface (GUI) and a results viewer for

RADIANCE and DAYSIM. The built-in daylighting analysis module can only perform

an analysis for a single day. For performing an annual daylighting simulation the

geometry and the material properties can be exported into DAYSIM and an annual

simulation can be conducted. Even though ECOTECT is unique software offering good

modeling flexibility and a wide variety of analyses, for a detailed daylighting analysis it

has to rely on more accurate and sophisticated simulation tools such as RADIANCE and

DAYSIM.

**2.5.12.2. Daylight Simulation Tools Implementing Daylight Coefficient (DC)
Methodology**

The following sections discuss the tools that can perform a daylight simulation

adopting the Daylight Coefficient (DC) concept. Some of the computer simulations tools

that use DC concept are RADIANCE, DAYSIM and ESP-r. Out of these three tools,

only RADIANCE is a stand-alone daylighting simulation tool and DAYSIM and ESP-r uses a derivative of RADIANCE as their simulation engine.

2.5.12.2.1. DAYSIM

In 1999, Reinhart and Herkel proposed a new method called DAYSIM for predicting the annual daylight illuminance distribution in a space (Reinhart and Herkel, 2001). In another paper, Reinhart & Walkenhorst (2001) also presented the validation results of the newly developed method in comparison to the measured data for a simple office building model. DAYSIM is a RADIANCE-based (G Ward & Rubinstein, 1988) daylight simulation tool that uses the Daylight Coefficient method (P. R. Tregenza & Waters, 1983b) and the Perez all-weather sky luminance model (Perez et al., 1993) for predicting illumination levels in a space. It predicts illumination levels at a point in the space for all 8,760 hours of the year. DAYSIM is a climate-based daylighting analysis tool that calculates a short-time-step development of indoor illumination level with the time-varying sky luminance distribution. DAYSIM also provides a daylighting analysis matrix such as the Daylight Autonomy (DA) and Useful Daylight Illuminances (UDI) that can be visualized using different graphical tools such as ECOTECT. In conjunction with a daylighting analysis, DAYSIM also has an occupancy behavior model incorporated into it, called LIGHTSWITCH. It predicts the occupant's interaction with manually or automatically controlled electric lighting system and blinds for a given space based on the indoor illumination levels.

The result of this analysis is a special file called the internal gains file for coupling DAYSIM with a thermal simulation program. The internal gain file

'intgain.csv' contains data related to the occupancy, and blind settings (if used) and the electric lighting load for space. Recently, a glare analysis module called EVALGLARE (Wienold & Christoffersen, 2006) has been integrated into the new version DAYSIM 3.0, that predicts glare problems due to daylight in an office space. EVALGLARE identifies glare sources and evaluates the anticipated magnitude of the glare source (An & Mason, 2010). In addition to these capabilities, DAYSIM also has the capability to simulate advanced daylighting systems such as light-shelves and windows with blinds using the RADIANCE ray-tracing techniques with improved accuracy. DAYSIM comes with a graphical user interface that makes it very user-friendly to specify the building information and weather data for a daylighting simulation. Unfortunately, DAYSIM does not have the capability of simulating Complex Fenestration Systems (CFS) such as windows with the blind systems embedded in between the glass panels.

2.5.12.2.2. ESP-r

ESP-r is a building energy performance analysis tool that can be used for a wide variety of analyses. The core philosophy behind the ESP-r is integrating different individual analysis to provide an integrated solution (Clarke et al., 1998). To perform a daylighting analysis ESP-r is linked at run-time with the RADIANCE simulation engine (Milan, 1999). For the simulation of a space control settings such as a lighting set point, switch - off reference lighting level, switch - off delay time, minimum dimming light output, minimum electric power of lights and the sensor positions are also specified. The Daylight Coefficient (DC) method uses the Perez all-weather sky model and RADIANCE for computing the indoor illumination levels (Milan & Macdonald, 1999).

In their study, Reinhart & Herkel (2001) compared the method that DAYSIM adopts with the method adopted by ESP-r for predicting the indoor illumination levels. Even though both tools used the DC method and the Perez all-weather sky model, there was a considerable difference in the illumination levels predicted by the two programs. When the results were compared with the base-case results generated by the RADIANCE, DAYSIM outperformed ESP-r in terms of predicting the indoor same illumination levels that RADIANCE predicted and took less time to perform the simulation.

2.5.12.2.3. RADIANCE Lighting Simulation System

RADIANCE is a state-of-the-art illuminance prediction and synthetic imaging system based on the ray-tracing method (G Ward, 1994; G Ward & Rubinstein, 1988). It was developed at Lawrence Berkeley National Laboratories (LBNL). It is a physically-based lighting program that allows accurate calculation of interior luminance/illuminance levels. RADIANCE employs the Monte-Carlo and backward ray-tracing techniques to calculate illumination at a point or on a surface inside a space (G Ward & Rubinstein, 1988). There are no limitations to the number of surfaces that RADIANCE can handle for a given geometry that can vary from few surfaces to thousands of surfaces generated by using built-in geometry generators or CAD tools that are then translated into RADIANCE format which is human-readable and text-based. RADIANCE comes with two programs to produce the sky luminance distribution for the daylighting calculations. The first program is the GENSKY program that develops sky patterns such as the CIE standard overcast sky or a clear sky with and without sun description. The second program, GENDAYLIT, is a sky model generator (John

Mardaljevic, 2000a, 2000b) that produces a RADIANCE description based on the Perez all-weather sky model (John Mardaljevic, 2000a, 2000b). It can produce overcast to clear, through partly cloudy, skies based on the input given. The GENDAYLIT program takes direct and diffuse components of solar radiation as inputs to generate sky description. These quantities are the commonly accessible data from any climatic file for a given location.

The standard output of RADIANCE is High Dynamic Range (HDR) images that has radiometric values that RADIANCE presents in the pixels of the image or illumination levels calculated at a user-specified sensor points in a given space. RADIANCE comes with many programs that take generated images as input to perform different kinds of analysis. RADIANCE can provide a human-sensitive image that represents how a human eye perceives a given illuminated environment. It also produces Iso-contour, false-color images of luminance, illuminance and daylight factor (DF) levels overlaid on a generated image for a given space.

In a recent study, Mardaljevic explained how RADIANCE could be used to compute DCs and how an annual daylighting simulation could be carried out on a building to assess its long-term daylighting performance (John Mardaljevic, 1995, 2000b). He also presented the results of the validation of RADIANCE using real sky scan data (John Mardaljevic, 1995). RADIANCE normally uses the CIE glare index (CGI) to analyze the visual comfort of a space (G Ward, 1992).

Wienold and Christoffersen (2006) developed a new glare analysis tool called EVALGLARE that calculates different glare indices such as the Daylight Glare

Probability (DGP), Daylight Glare Index (DGI), Unified Glare Rating (UGR), Visual Comfort Probability (VCP), and CIE Glare Index (CGI). This has been incorporated into RADIANCE for performing a visual comfort analysis (Wienold & Christoffersen, 2006). Also, the latest version (RADIANCE Version 4.0) has the capability of simulating Complex Fenestration Systems (CFS) (Konstantoglou et al., 2009; Saxena et al., 2010; Ward, 2009). In the following sections, new tools that have been developed to perform the annual simulations with CFS are discussed in detail.

2.5.12.3. Comparative Analysis of Different Daylight Simulation tools

Table 2.6 gives a comparative analysis of different daylight simulation tools that are discussed in the preceding sections. Part I of the Table 2.6 gives the comparison based on several criteria such as: type of sky models they adopt; type of daylighting method used; static or dynamic based system; types of method adopted to compute IRC; and different types of strategies or capability the tools can simulate. Table 2.5 gives rubrics based on a simple scoring chart shown in Part-II of Table 2.6 for different daylight simulation tools compared and a total score for each tool is calculated. From the scores it can be concluded that RADIANCE with a score of 24 is the most accurate as well as the most sophisticated tool that has the capability of performing daylighting performance simulations of several different strategies followed by DAYSIM (score 19) and ESP-r (score 19).

Table 2.5 : Rubrics Adopted for Comparison of Different Daylight Simulation Tools

Sky Models	Score
Clear, Overcast with Sun	1
Clear, Intermediate and Overcast with and without Sun	2
Clear, Clear turbid, Intermediate and Overcast with Sun	3
Perez All-Weather Sky model	4
Method Adopted	
Daylight Factor	1
Daylight Coefficient	2
Type of Daylighting system	
Static	1
Dynamic	2
Climate Based Daylight Modeling	
No	0
Yes	1
Method used for computing internal reflected component	
Split-Flux	1
Radiosity	2
Ray-Tracing	3
Strategies	
No	0
Yes	1

Table 2.6: Comparison of Daylight Simulation Tools

Part-I

Characteristics / Tools	EnergyPlus	DOE-2.1e	eQUEST	LUMEN MICRO	SUPERLITE	RADIANCE	DAYSIM	ECOTECT	ESP-r
Sky Models	Clear, Clear turbid, Intermediate and Overcast with Sun	Clear, Overcast with Sun	Clear, Overcast with Sun	Clear, Overcast with Sun	Clear, Overcast with Sun	Perez All-Weather Sky model	Perez All-Weather Sky model	Clear, Intermediate and Overcast with and without Sun	Perez All-Weather Sky model
Method Adopted	Daylight Factor	Daylight Factor	Daylight Factor	Daylight Factor	Daylight Factor	Daylight Coefficient	Daylight Coefficient	Daylight Factor	Daylight Coefficient
Type of Daylighting system	Dynamic	Dynamic	Dynamic	Static	Static	Static/ Dynamic	Dynamic	Static	Dynamic
	Hour-by-Hour	Hour-by-Hour	Hour-by-Hour	Snapshot	Snapshot	Hour-by-Hour (Time consuming)	Hour-by-Hour	Snapshot	Hour-by-Hour
Climate Based Daylight Modeling	YES	YES	YES	NO	NO	YES	YES	NO	YES
Method used for computing internal reflected component (IRC)	Radiosity method	Split-flux method	Split-flux method	Radiosity method	Radiosity method	Backward ray-tracing	Backward ray-tracing	Split-flux method	Backward ray-tracing
Side lights simulation	YES	YES	YES	YES	YES	YES	YES	YES	YES
Sky light simulation	YES	YES	YES	YES	YES	YES	YES	YES	YES
Light shelves simulation	YES	NO	NO	YES	YES	YES	YES	NO	YES
Light from Atrium	YES	NO	NO	YES	YES	YES	YES	NO	YES
Light from adjacent spaces	NO	NO	NO	YES	YES	YES	YES	NO	YES
Complex fenestration systems (CFS)	YES	NO	NO	NO	NO	YES	NO	NO	NO
Capability of reading BSDF datasets	YES	NO	NO	NO	NO	YES	NO	NO	NO
3-Phase Method	NO	NO	NO	NO	NO	YES	NO	NO	NO
5-Phase Method	NO	NO	NO	NO	NO	YES	NO	NO	NO
F-Matrix Method	NO	NO	NO	NO	NO	YES	NO	NO	NO

Part-II

Characteristics / Tools	EnergyPlus	DOE-2.1e	eQUEST	LUMEN MICRO	SUPERLITE	RADIANCE	DAYSIM	ECOTECT	ESP-r
Sky Models	3	1	1	1	1	4	4	2	4
Method Adopted	1	1	1	1	1	2	2	1	2
Type of Daylighting system	2	2	2	1	1	2	2	1	2
	2	2	2	1	1	2	2	1	2
Climate Based Daylight Modeling	1	1	1	0	0	1	1	0	1
Method used for computing internal reflected component (IRC)	2	1	1	2	2	3	3	1	3
Side lights simulation	1	1	1	1	1	1	1	1	1
Sky light simulation	1	1	1	1	1	1	1	1	1
Light shelves simulation	1	0	0	1	1	1	1	0	1
Light from Atrium	1	0	0	1	1	1	1	0	1
Complex fenestration systems (CFS)	1	0	0	0	1	1	0	0	0
Capability of reading BSDF datasets	1	0	0	0	0	1	0	0	0
3-Phase Method	0	0	0	0	0	1	0	0	0
5-Phase Method	0	0	0	0	0	1	0	0	0
Total Score	16	10	10	10	11	23	19	9	19

2.5.12.4. Comparative Studies of Different Daylight Simulation Tools

Over the years many researchers have performed studies that compared the capabilities of different daylight simulation tools. Table 2.7 gives a summary of different studies performed by several researchers that compared daylight simulation tools. In all these studies it was found that the RADIANCE was the most accurate program for predicting the indoor illumination levels. The output of RADIANCE was also used as a benchmark to rigorously test and validated the other programs. One of the simulation tools that is a modified version of RADIANCE called DAYSIM was found to accurately predict illumination levels using less computation time compared to the conventional RADIANCE method. The studies show RADIANCE and DAYSIM were by far the most accurate daylighting simulation tools that are presently available that are climate-based and that have adopted the ray-tracing and Daylighting Coefficient methods for predicting indoor illumination levels.

2.6. Daylight Strategies for Buildings

The main purpose and use of a daylighting system like that of any other lighting system in the building, is to provide a prescribed amount of light in an architectural space while ensuring good visual performance and providing sufficient lighting contrast for visual comfort. Daylighting strategies or systems include everything needed to make daylighting function as an environmental system in the buildings including the daylight Aperture; the glazing media; the shade and sun control elements. The primary way daylight is provided into the interiors of a space is through side windows or skylights located on top of the roof. Table 2.8 and Figure 2.29 give different types and sub-types,

description and benefits of side-lighting strategies. Table 2.9 and Figure 2.30 give

different types, description and benefits of top lighting strategies.

Table 2.7: Studies Comparing Different Daylighting Simulation Tools

S:No	Study / Reference	Tools Compared	Best among the Tools Compared	Remarks
1	(Estes et al., 2004)	1.Lightscape 2.Desktop RADIANCE 3.Lumen Micro 4.Form Z	Desktop RADIANCE	1) In all these studies it was found that the RADIANCE was the most accurate in predicting the indoor illumination levels. 2) However, RADIANCE takes the longest time to perform an analysis.
2	(Ubbelohde and Humann, 1998)	1.Lumen Micro 2.SUPERLITE 3.RADIANCE 4.Lightscape	Desktop RADIANCE	
3	(Evangelos & David, 2005)	1.Desktop RADIANCE 2.Rayfront 3.Relux 2004 4.Lightscape	Desktop RADIANCE	
4	(Reinhart and Herkel, 2001)	1.ADELINE 2.0 2.ESPR-r 3.DAYSIM 4.RADIANCE	RADIANCE & DAYSIM	1) RADIANCE was the benchmark to rigorously test and validated the other programs. 2) RADIANCE simulation was extremely time consuming in prediction the illumination levels compared to DAYSIM
5	(Reinhart and Breton, 2009)	1.DAYSIM 2.Autodesk 3DSMAX	DAYSIM	1) DAYSIM has been more rigorously validated compared to 3DS MAX.

Table 2.8: Side Lighting Strategies for Admitting of Daylight into a Space

Classification	Type	Sub-Type	Description
Side Lighting Strategies	Single side lighting		This strategy is a single window located in the side wall of a space.
	Bilateral side lighting		In bilateral strategy light enters the space from two side directions.
	Multilateral lighting		In multilateral light enters into space through multiple directions
	Clerestory windows		Clerestory windows are windows with sill heights greater than seven feet above the floor.
	Light shelves	Internal	Provides shading from middle window position and re-direct sunlight from high position windows. Depth of shelves depends on visual need, orientation, and latitude and window height.
		External	
	Borrowed light		As a concept borrowed light allows sharing of light to adjacent spaces when the geometry and depth of perimeter spaces permit. For example corridor lighting gained through translucent partitions or glass block.

2.6.1. Shading Systems for Daylighting Strategies

There are many types of shading systems for vertical window (Figure 2.31). A daylighting strategy is a combination of shading system and window. Shading systems can be classified into two types; internal and external shading systems. Internal shading systems are venation blinds, roller shades or curtains. External shading systems include overhangs, window setback, vertical fins, and overhangs with vertical fins. There are also louver shades that provide diffuse light while still shading the window.

Single-Side Daylighting

Bilateral Daylighting
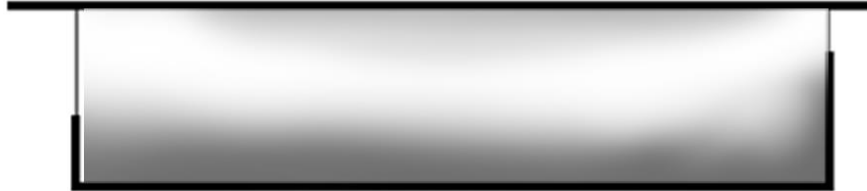
Multilateral Daylighting
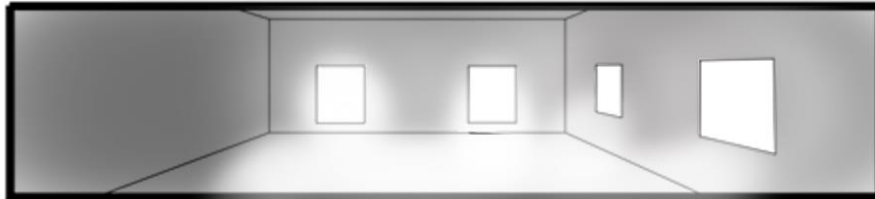
Light Shelf for Daylighting

Clearstory Window for Daylighting

Borrowed Light for Daylighting

Figure 2.29: Side Lighting Strategies (Source: Adapted from (Lechner, 2014))

Table 2.9: Top Lighting Strategies of Admitting of Daylight into a Space

Classification	Type	Sub-Type	Description
Top Lighting Strategies	Skylights	Flat	Sky lights are windows placed flat or on sloped roofs. These can provide a uniform level of illumination throughout the space when skylights are spaced using a ratio of 1.5 times the ceiling height. The shape of the skylight also affects how much daylight can be provide at different times of the day.
		Bubble	
		Pyramid	
		Ridge type	
	Light Wells		Light wells are a primary component of sky lighting systems. They bring the light through the roof and ceiling structure, and they simultaneously provide a means for controlling the incoming daylight before it enters the main space. A light well is similar to an electric light fixture. It is designed to distribute the light and to shield the viewer from an overly bright light source. Light wells can be designed in a wide variety of shapes. The simplest are vertical-sided shafts, that are the same size as the skylight opening. More elaborate wells have splayed or sloping sides that spread the light more broadly through the space.
	Roof Monitors	Saw tooth	Roof monitors are extrusion through the roof, with vertical glass areas. Roof monitors can be classified into two main types: sloped and vertical monitors. The sloped roof monitors have vertical glass element with a sloped roof. One good examples of a sloped roof monitor is a saw tooth roof monitors.
		Vertical	
	Atrium and Light Wells		The atrium, or light well, is a core lighting technique used in many modern multi-storey buildings. The center of the building is open with a glazed element at the top to bring natural light into the core of the building.
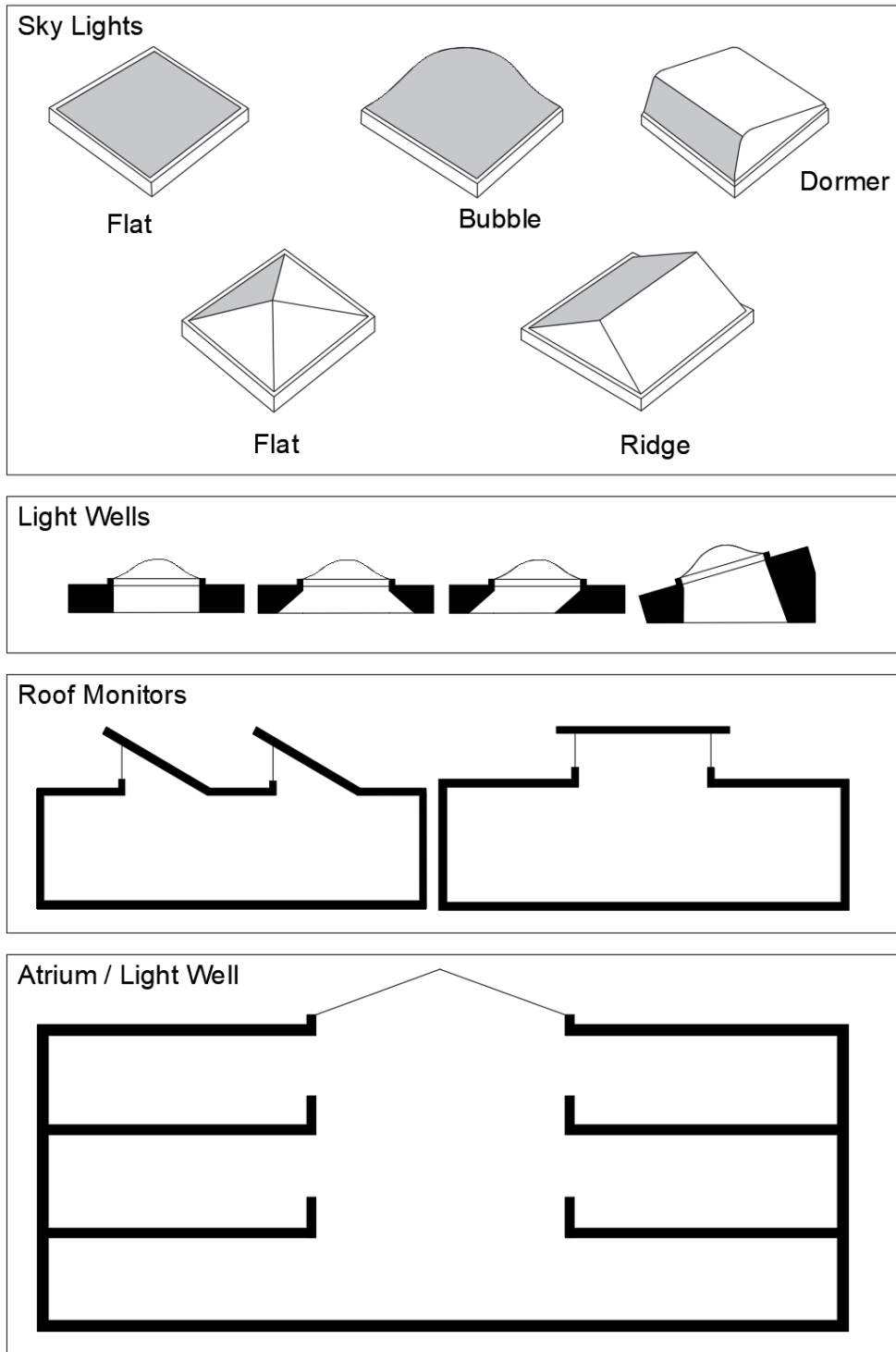
Figure 2.30: Different Types of Top Lighting Strategies (Source: Adapted from Skylighting Design Guidelines (Energy Design Resources, 2014),(Lechner, 2014))
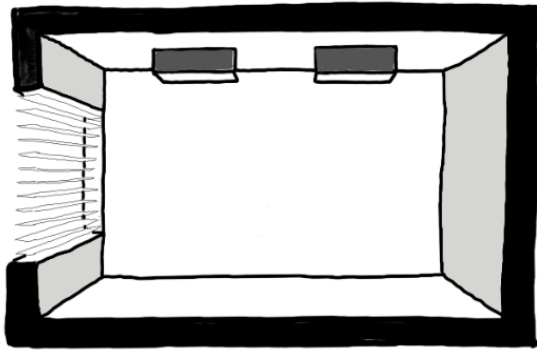
Venetian Blinds
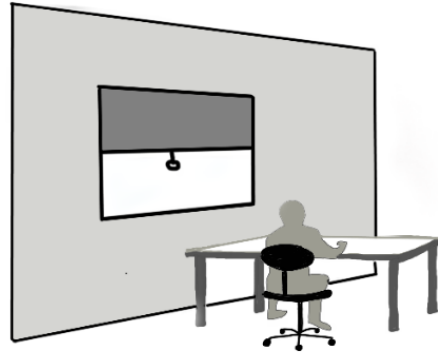
Roller Shade
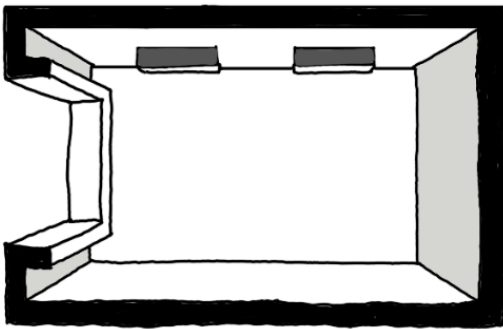
Window Setback
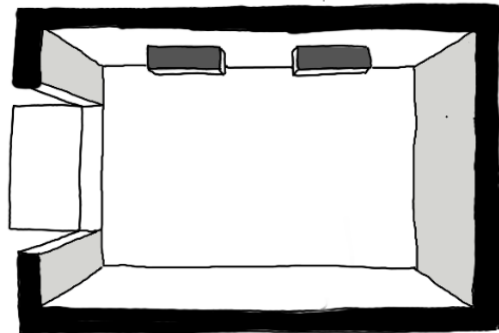
Vertical Fins
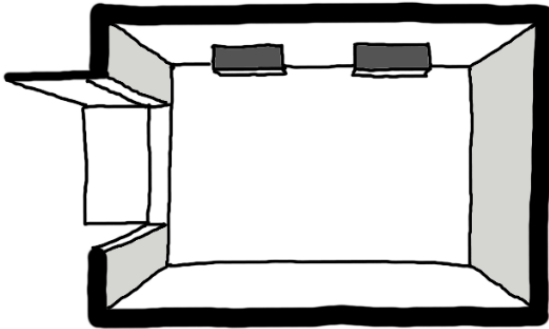
Overhangs & Fins
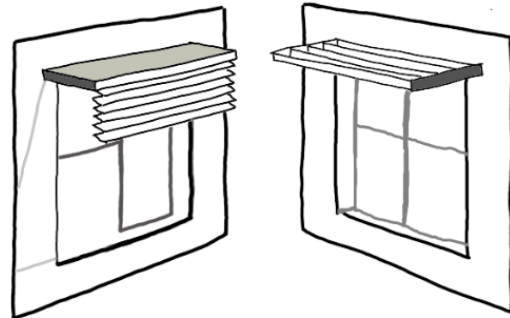
Louder Shades

Figure 2.31: Different Types of Shading Devices (Source: Adapted from (Carmody et al., 2004))

2.6.2. Innovative Daylight Strategies

Although, ordinary windows and conventional daylighting strategies can adequately meet some of the daylighting needs of the space, in many cases these is not sufficient light to direct daylight deep into a space. Recently, several new technologies and solutions have been developed that extend the daylight performance beyond that of the conventional solutions. These strategies work by introducing reflective or refractive components into the glazing system. Some of the strategies also provide shading of the indoor space from sunlight that can reduce glare and solar gains while others do not. These are broadly classified into two categories

1. Daylight systems with shading (Table 2.10)

2. Daylight systems without shading using direct sunlight (Table 2.11)

2.6.2.1. Daylight systems with Shading

Table 2.10: Innovative Daylight Systems with Shading

Type	Examples
Daylighting systems with shading that rely primarily on a diffuse skylight (Figure 2.32a)	1. Prismatic panels 2. Prisms and Venetian blinds 3. Sun protecting mirror elements 4. Anidolic, zenithal opening 5. Directional, selective shading systems with concentrating Holo-graphic Optical Elements (HOE) 6. Transparent shading system with HOE based on total reflection
Daylighting systems with shading using sunlight (Figure 2.32b)	1. Light guiding shade 2. Louvers and blinds 3. Light shelf for redirection of sunlight 4. Glazing with reflecting profiles 5. Skylight with Laser Cut Panels (LCPs) 6. Anidolic solar blinds

2.6.2.2. Daylight Systems Without Shading

Daylighting systems without shading are designed primarily to redirect daylight to areas away from a window or skylight opening. These systems may or may not block direct sunlight. These systems are further classified into four different categories:

Table 2.11: Innovative Daylight Systems without Shading

Type	Examples
Diffuse light-guiding systems (Figure 2.32c)	1. Light Shelf 2. Anidolic Integrated Systems 3. Anidolic Ceiling 4. Fish System 5. Zenith Light guiding elements with HOEs
Direct light-guiding systems (Figure 2.32d)	1. Laser Cut Panel 2. Prismatic Panel 3. HOEs in the Skylight 4. Sun Directing Glass
Light-scattering systems (Figure 2.32e)	
Light transport systems (Figure 2.32f)	1. Heliostat 2. Light Pipe 3. Solar Tube 4. Fibers 5. Light-guiding ceiling

A:Daylight systems with shading that rely primarily on diffuse sky

Prismatic
panels

Prism and
venetian
blinds

Sun protecting
mirror elements

Anidolic
zenithal
opening

Directional
selective shading
system with
concentrating
holographic optical
element (HOE)

Transparent
shading system
with HOE based
on total reflection

B:Daylight systems with shading using direct sunlight

Light
Guiding
Shade

Louvers
and
blinds

Light shelf
for
redirection
of sunlight

Glazing
with
reflecting
profiles
(Okasolar)

Skylight
with Laser
Cut Panel
(LCPs)

Turnable
Lamellas

Anidolic
solar blinds

C:Diffuse Light-guiding daylighting systems without shading

Light shelf

Anidolic
integrated
system

Anidolic
ceiling

Fish system

Zenith light guiding
element with HOEs

D:Direct light-guiding daylighting systems
without shading

E:Light-scattering systems

Laser cut panels

Prismatic Panels

HOEs in the
skylight

Sun-directing
glass

Scattering
systems

F:Light transprot daylighting systems without shading

Heliostat

Light Pipe

Solar Tube

Fibers
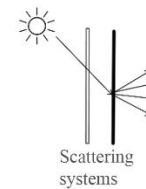
Light-guiding
ceiling
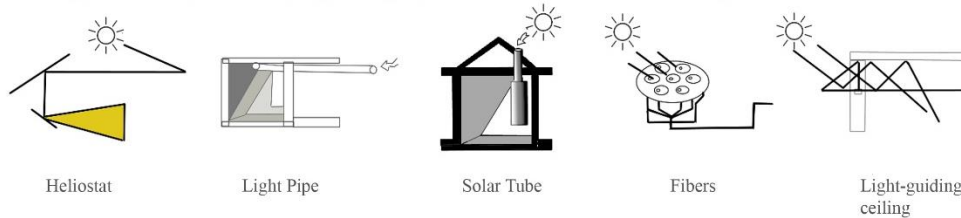
Figure 2.32: Innovative Daylighting Strategies (Source: Adapted from Johnsen and Watkins(2010))

2.6.3. Complex Fenestration Systems

Recently, several new commercial buildings are using special kinds of window systems called Complex Fenestration System (CFS). These window systems have several benefits

1. Optimize daylighting.

2. Provide protection from direct sunlight entering the interior of the spaces.

3. Enhance the luminous environment by directing lighting deep into the space.

These systems typically include one or more diffusing layers (e.g., Venetian blinds, fritted glass, cloth or laser cut panels) between the transparent layers (e.g., clear glass, tinted or low-e glass) in a window system. Unfortunately, algorithms and methods normally adopted to simulated windows with specular layers for daylighting simulations tools cannot be used for simulating the CFS without introducing significant errors into the daylighting analysis. This is because the values such T-VIS for glazing systems with specular layers were calculated assuming the properties are isotropic in nature. However, the properties of the CFS (i.e., T-Vis) change as the direction of the incident angle changes, making these properties anisotropic in nature (Figure 2.33). This requires whole new methods to simulate and evaluate their performance in terms of daylight.
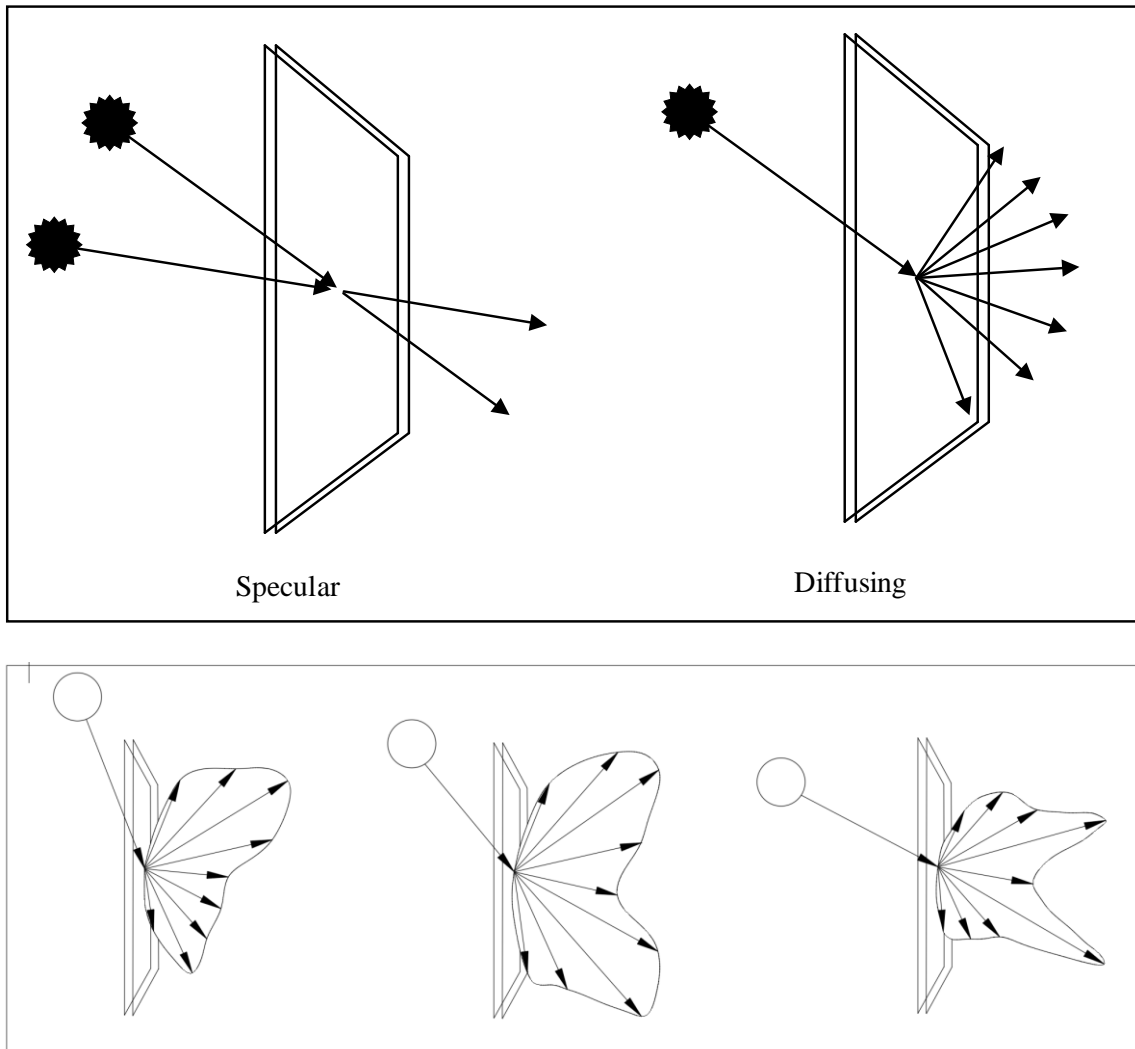
Figure 2.33: Isotropic Properties of Simple Fenestration systems and Anisotropic Properties of CFS (Source: Adapted from (Andy McNeil, 2014))

Recently, new methods have been developed to calculate the Visible Transmittance (T-VIS) used for daylighting analysis that can be used for an anisotropic window (Konstantoglou et al., 2009). Typically, Bi-directional Scattering Distribution Function (BSDF) (Figure 2.34) information is required to evaluation daylighting distribution through CFS windows, (Andersen et al., 2003). A BSDF is the combination of Bi-directional Transmission Distribution Function (BTDF) and Bi-directional

Reflection Distribution Function (BRDF). A BSDF characterizes light transmission,

reflection and directional distribution of a surface or product such as window pane or

shading layers such as blinds, roller shades etc.
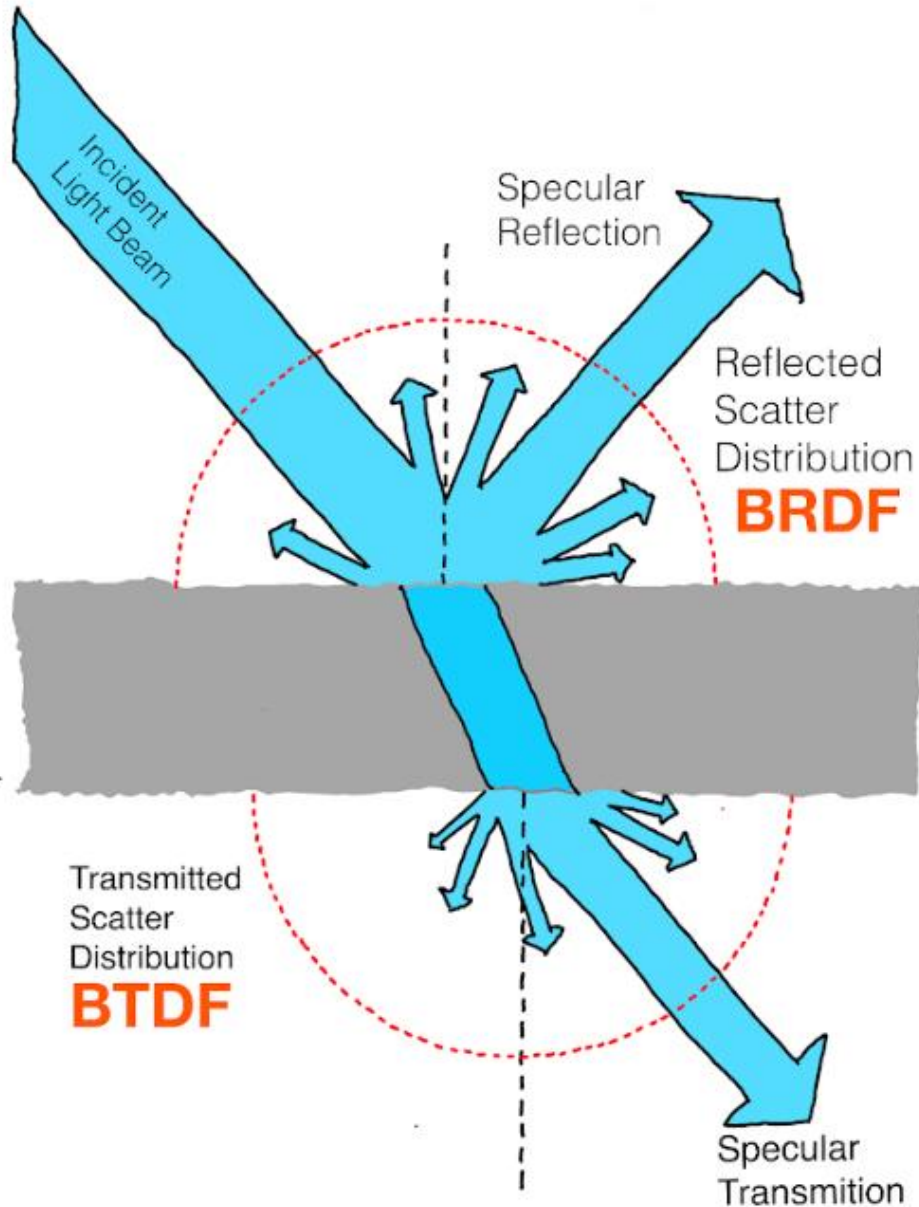
Figure 2.34: Bi-directional Transmission Distribution Function of Complex Fenestration
System (CFS) (Source: Adapted form (Andy McNeil, 2014))

2.6.3.1. Methods developed to Evaluate CFS

In the past decades, there has been significant work devoted to the evaluation of the optical, daylighting and energy performance of CFS. For example ISO 15099 standards (ISO, 2003) contains a validated model to compute the optical and long-wave radiation characteristics of CFS for a slat-type blinds. In a different research projects sponsored by ASHRAE and DOE, Klems developed a method called the matrix method to find the Solar Heat Gain Coefficient (SHGC) of Complex Fenestration Systems with venetian blinds (J H Klems, 1993). This model was adopted by LBNL for calculating the properties of the CFS with blinds and has been incorporated into the LBNL WINDOWS 6 program and later versions.

2.6.3.2. Acquisition of BSDF Data

The BSDF data can be measured either experimentally, analytically or using combinations of both methods (Andersen et al., 2003). Experimentally BTDF information can be obtained using a special instrument called photogoniometer (Figure 2.35). Unfortunately, acquiring BTDF data is a time-consuming process and the technology is not always readily available. In another study researchers tried to obtain BTDF data using ray-tracing techniques by exactly replicating the experimental methods. The results obtained are in close agreement with the experimental data Marilyne Andersen et al. (2003).
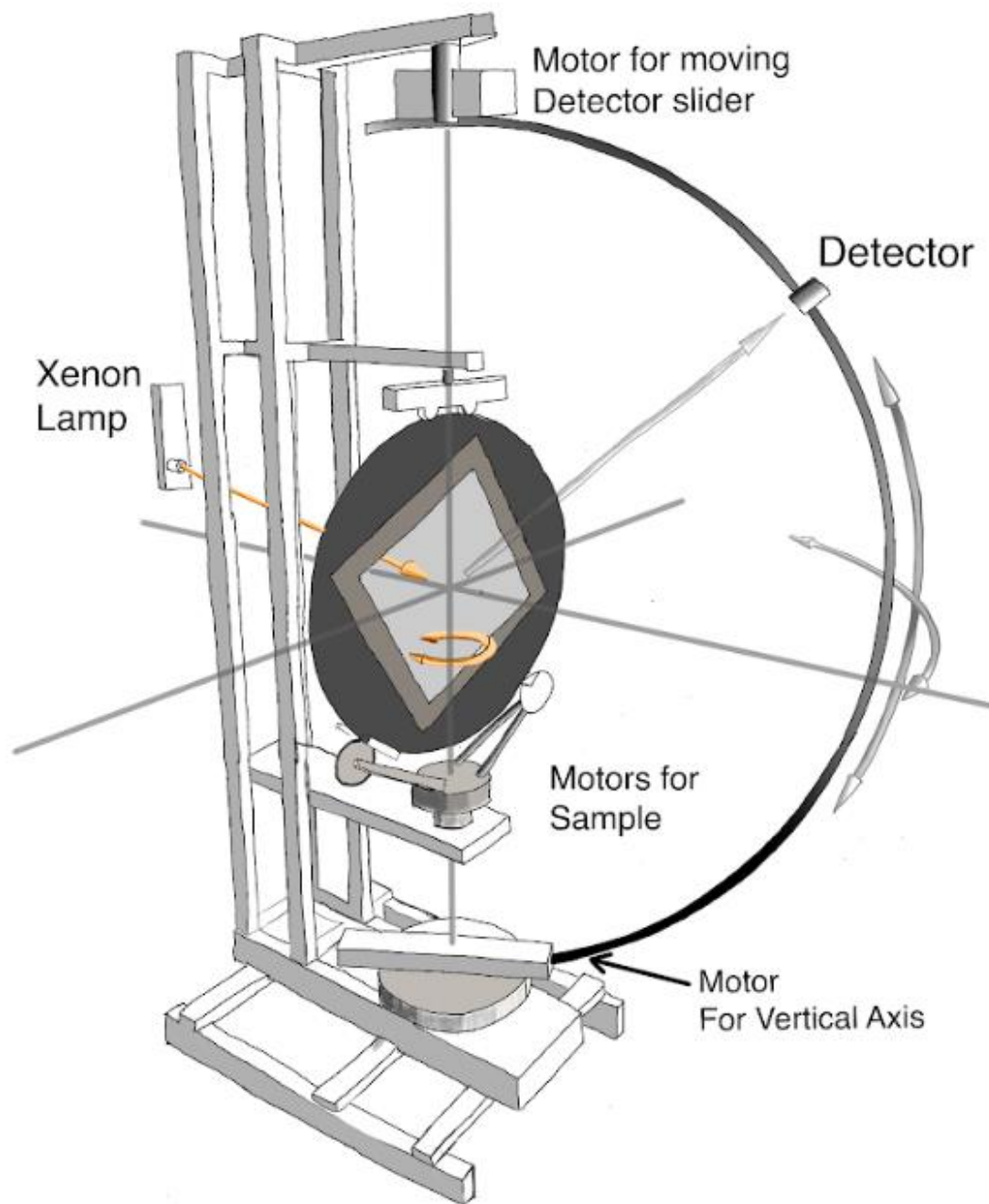
Figure 2.35: Photogoniometer (Source: Adapted from Apian-Bennewitz and Von Der Hardt (1998))

However, the instruments used to obtain BSDF data experimentally are not readily available to many end-use researchers and designers who use BTDF information to simulate the performance of these window systems using simulation tools. Also, research in this field acknowledges that measuring the BTDF will most likely not be conducted by designers and end users of these simulation tools (Konstantoglou et al., 2009).

2.6.4. Tools that can Generate BSDF Data

2.6.4.1. LBNL Windows Program

In the version 6.0 of LBNL WINDOWS program several new functions were incorporated to generate a BSDF data-set for CFS (R Mitchell, 2008). Some of these use the ISO 15099 Venetian blinds model based on the Radiosity method and Matrix Layers calculation method (Klems, 1994), that combines the BSDF properties of each layer of the window systems to produce the overall BSDF of the window system. Window layers such are Venetian blinds can be readily defined from the WINDOWS 6 database. Others layers, that cannot be modeled by WINDOWS 6 but can be read using a measured BSDF data-set acquired either through experimental or ray-tracing techniques. Once all the layer properties are defined, WINDOW 6 can produces an overall window system BSDF (i.e., shades + glass +frame) output file that can be used by a simulation tool that has the capability of using BSDF files. LBNL has designed an XML data scheme to store the BSDF data of the CFS (Figure 2.36). The current version of the WINDOWS program is Version 7.7.07.

```
<?xml version="1.0" encoding="UTF-8"?>
<Layer xmlns="http://windows.lbl.gov"
xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:schemaLocation="http://windows.lbl.gov BSDF.xsd">
<Material><Name>My Test Material</Name></Material>
<DataDefinition>
        <AngleBasis>
                <AngleBasisType>Incidence</AngleBasisType>
                <AngleBasisBlock>
                        <Theta>0</Theta>
                        <Phi>0</Phi>
                </AngleBasisBlock>
        </AngleBasis>
        <AngleBasis>
                <AngleBasisType>Transmission Front and Back</AngleBasisType>
                <AngleBasisBlock>
                        <Theta>0</Theta>
                        <Phi>0</Phi>
                </AngleBasisBlock>
        </AngleBasis>
        <AngleBasis>
```

Figure 2.36: LBNL XML Schema for Storing BSDF Data of CFS[7]

Apart from implementing the ISO 15099 model WINDOWS 7.7 can implement

additional shading devices. A full list of shading devices can be found in (Figure 2.37).

The results produced by the Radiosity-based model of the WINDOWS 6 have been

compared with Monte-Carlo ray-tracing method and found to be in good agreement

(Rubin et al., 2007).

2.6.4.2. gebBSDF

One of the RADIANCE utilities that was developed recently is genBSDF. This

utility takes a RADIANCE description of scene (e.g., window geometry with shading

layers) and materials to create a Bidirectional Scattering Distribution Function (BSDF)

XML file. To accomplish this, it adopts a forward ray tracing methodology in its

---

[7] https://windows.lbl.gov/sites/default/files/Downloads/window6-1-therm6-1-research-doc.pdf

1	**Horizontal louvered blinds, aka Venetian blinds**	
2	**Vertical Louvered blinds**	
3	**Cellular shades, aka Honeycomb shades**	
4	**Pleated shades**	
5	**Roller shades**	
6	**Solar screens**	
7	**Woven shades (idealized "fabric" consisting of regularity-spaced threads - something like insect screen or very regularly woven fabric)**	
8	**Fritted glazing**	
9	**Diffusing Glazing**	

Figure 2.37: List of Shading Devices that can be Simulated by LBNL Windows 7 Program[8]

---

[8] https://windows.lbl.gov/sites/default/files/Downloads/window6-complexglazingsummary.pdf

computation to create a BSDF file of the windows system. These XML files can be used by other RADIANCE utilities to simulate the daylighting performance of a window system. A detailed report describing how to create a BSDF XML file using genBSDF with examples has been published by LBNL (McNeil et al., 2013). Also, a special utility called BSDF the viewer has be created to visualize the output of XML file (McNeil et al., 2013).

2.6.5. Tools that can utilize BSDF Data

There are two tools that can use BSDF data file generated for the Complex Fenestration Systems (CFS) to perform daylighting analysis: Energy Plus and RADIANCE.

2.6.5.1. Energy Plus

Energy Plus uses a special program called DELIGHT to perform the daylighting analysis that employs the radiosity method for computing the IRC. New capabilities were added to the DELIGHT routines to read the BSDF data file to simulate the daylighting performance CFS (Carroll & Hitchcock, 2005; Hitchcock & Carroll, 2003).

2.6.5.2. RADIANCE

The capabilities of simulating the Complex Fenestration Systems was first incorporated into RADIANCE in version 3.9. One of the original programs of RADIANCE called *mkillum*[9] was modified to read BSDF XML file generated by Windows 6 to simulate light distribution through CFS (Konstantoglou et al., 2009). The *mkillum* approach works well in simulating the CFS, however, it has certain limitations.

---

[9] https://floyd.lbl.gov/RADIANCE/man_html/mkillum.1.html

The *mkillum* method that can be adopted to simulate performance of the CFS cannot be used for annual simulation as it is prohibitively time consuming. In their study they simulated two different types of window configurations with different types of Venetian blinds. The results obtained were compared with the results from the physical model and showed close agreement.

2.6.5.3. Annual Simulation Using CFS in RADIANCE

The DC method was primarily developed to perform annual daylight simulation for a wide variety of sky conditions. Mardaljevic (1995) successfully implemented the use of the DC method in RADIANCE using a simple fenestration systems. Shortly after this and Reinhart and Herkel (2001) developed a tool called DAYSIM that is based on RADIANCE, to implement the DC method to compute the internal illumination using weather data for a given site. The *mkillum* method that can be adopted to simulate performance of the CFS cannot be used for an annual simulation as it is prohibitively time consuming. In RADIANCE 4.0 new tools were added to specifically perform climate based annual daylighting simulation using CFS. Saxena et al. (2010) has present a methodology called "Dynamic RADIANCE" using BSDF data for CFS to conduct an annual daylight simulation taking the advantage of some of the new capabilities of RADIANCE.

2.6.5.4. Dynamic RADIANCE Method

In the Daylight Coefficient method, the illumination inside the room is the summation of the product of Daylight Coefficient of each patch and its luminance.

$$i = C * s$$ Equation 2-15

i= Illumination vector.
C = Daylight coefficient matrix.
s = Sky luminance vector for each patch.

The [C] and [s] can be treated as matrices and the multiplication of these matrices gives the total illumination [E] at a point in space. The above equation (Equation 2-15) can be used to compute the luminance distribution for an ordinary fenestration system. However, for CFS the equation has to be formulated in a different way. This was first introduced by Saxena et al. (2010) where the authors proposed a new methodology that treats the flux transfer from the sky to a point inside of a room as a series of matrices that combined will yield illumination levels.

2.6.5.5. 3-Phase Method

A further modification to this concept was developed that was called the 3-Phase method which include a detail step-by-step tutorial with examples (McNeil, 2013). In the 3-Phase method the flux transfer is broken into the following three phases for independent simulation: 1) Sky to exterior of fenestration; 2) Transmission through fenestration and 3) Interior of fenestration into the simulated space (McNeil, 2013). Figure 2.38 shows the different phases and matrixes involved in the Three-Phase method. The governing equation is given by (Equation 2-16 and Equation 2-17).
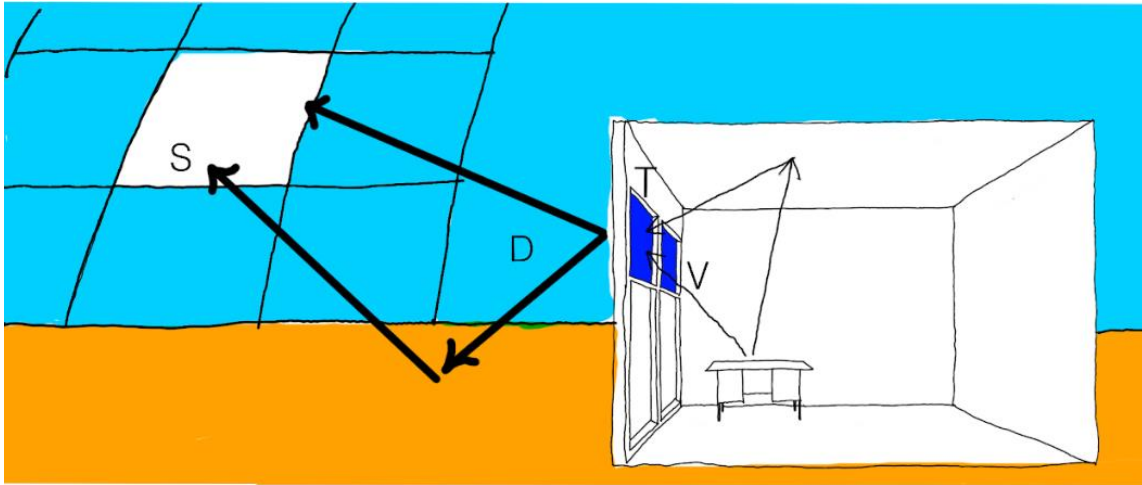
Figure 2.38: Different Phases and Matrixes of Flux Transfer Involved in Three-Phase Method (Source: Adapted from McNeil (2014))

$$i = VTDs \qquad \text{Equation 2-16}$$

$$I = VTDS \qquad \text{Equation 2-17}$$

where
i= a point in time illuminance value or luminance value
I = matrix containing time series of illuminance or luminance result
V = view matrix, relating outgoing directions on window to desired results at interior
T = transmission matrix, relating incident window directions to exiting directions (BSDF)
D = daylight matrix, relating sky patches to incident directions on window
s = sky vector, assigning luminance values to patches representing sky directions.
S = sky matrix, a collection of sky vectors

Usually, the Transmission matrix [T] (Figure 2.39) can be created using the tools that generate a BSDF file such as Windows 7, TracePRO[10] or RADIANCE genBSDF. The other matrices that need to be computed are the View matrix [V] (Figure 2.40) and

---

[10] Commercial raytracing package (https://www.lambdares.com/tracepro/)

Daylight Matrix [D] (Figure 2.41) the Sky Vectors[s] or the Sky Matrix [S]. Once the

matrices are computed these can be multiplied to obtain the total illumination at a point

in space under any given sky condition or time series data for a whole year. Several new

tools have been developed and incorporated in RADIANCE for creating matrices and

perform annual daylight calculations are incorporated into RADIANCE. Table 2.12

gives a brief description of the RADIANCE utility programs that are used for computing

different matrices used for performing annual daylight simulation incorporating CFS.
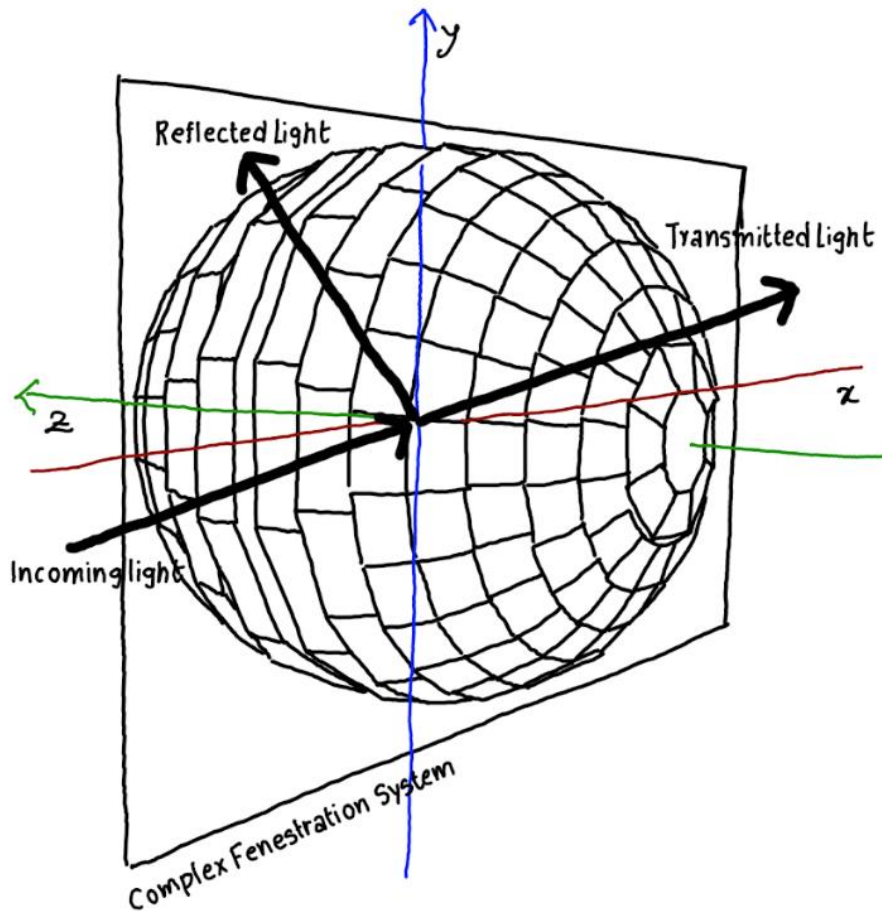
Figure 2.39: Schematic Diagram of BSDF That Represent The Relation Between
Incoming Light and Transmitted Light for a CFS (Source: Adapted from Sun et al.,
(2017))

122
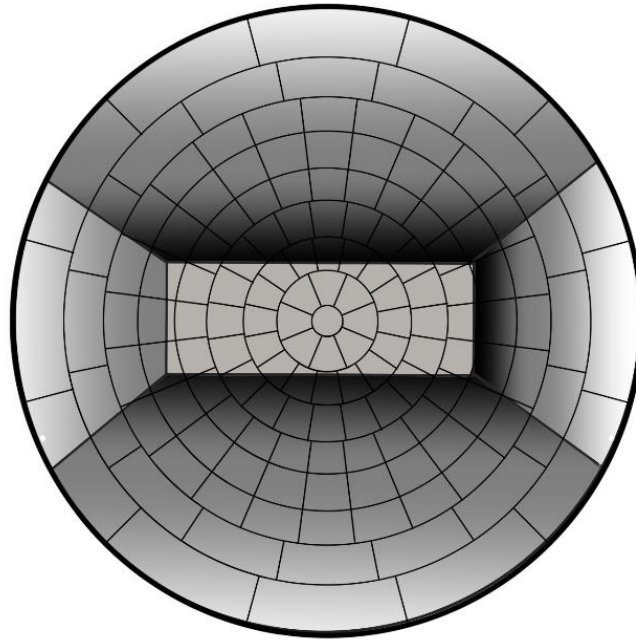
Figure 2.40: View Matrix [V] Contains Coefficients Relating Energy Leaving a Window in Klems Direction Bins Energy Incident at a Sensor Point or Image Pixel (Source: Adapted from McNeil (2014))
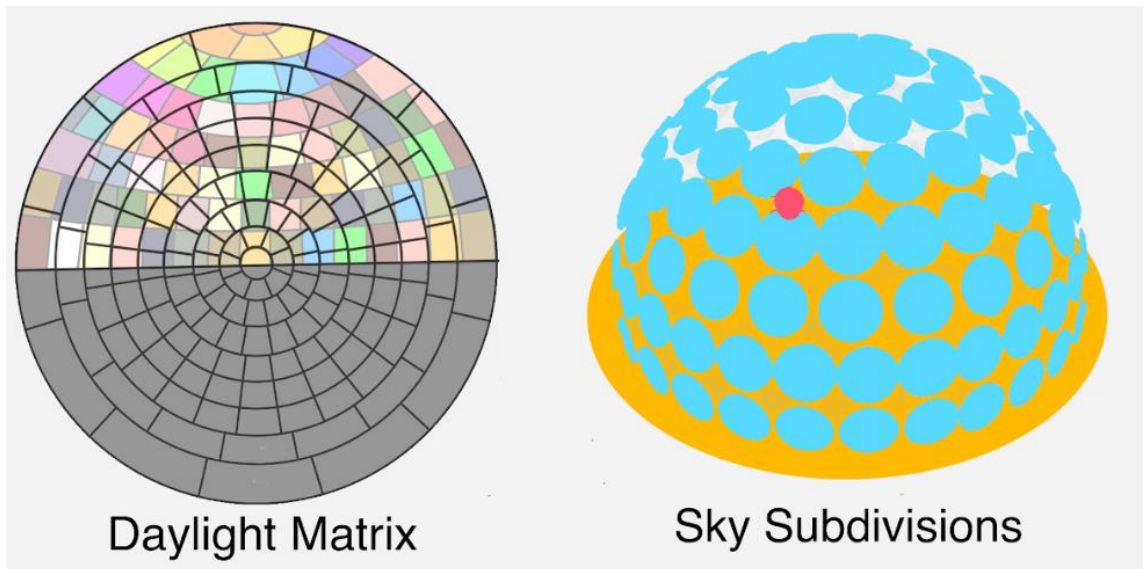
Figure 2.41: Daylight Matrix [D] Defining the Flux Transfer from Klems Division of the Outside of the Window to the Sky Division and Sky Sub Divisions(Adapted from[11]).

---

[11] https://www.energy.gov/sites/prod/files/2017/04/f34/6_35515b_Lee_031617-1130.pdf

Table 2.12: RADIANCE Tools for Performing Annual Daylight Simulation with CFS

Name of the Tool	Description
Genskyvec	Is a program that accepts a sky description to create sky vectors[s]. The sky description can be given using Gensky[12] or Gendaylit[13] RADIANCE utility.
Gendaymtx	Is a program that accepts a weather file to create the sky matrices [S] that is used to create a time series of illumination values. It reads *.wea file that can be obtained from energy plus weather data using a utility distributed with DAYSIM epw2wea[14]
Genklemsamp	Is a program that takes a RADIANCE window description and generates sampling rays for klems divisions (Figure 2.42) that are then passed to Rcontrib RADIANCE program to compute daylight matrix [D]
Rcontrib	Is a program to compute contribution coefficients. It can be used to generate the daylight matrix [D] contributing coefficients for window from sky divisions or View matrix [V] characterizing the relationship between light leaving a window and arriving at a point. Rcontrib accepts a sensor point file and a RADIANCE file description to compute the View matrix.
Dctimestep	Is a program that is used to multiply all the matrices to generate the final results that can be a time series illumination file or a picture having RADIANCE values.
rfluxmtx	Computes the flux transfer matrix(es) for a RADIANCE scene. It is a program that takes a RADIANCE window and sky description to create a daylight matrix [D]. It is a new program that bypasses the genklemsamp to compute daylight matrices. However, it run with rcontrib in the background to compute the daylight matrix and view matrix [V]
rmaxtop	Is a program that is used to multiply different matrices to generate final results. It has the same functionality as that of Dctimestep with additional functionalities.

[12] Gensky produces a RADIANCE scene description for the CIE standard sky distribution at the given month, day and time

[13] Gendaylit produces a RADIANCE scene description based on an angular distribution of the daylight sources (direct + diffuse) for the given atmospheric conditions (direct and diffuse component of the solar radiation), date and local standard time. The default output is the radiance of the sun (direct) and the sky (diffuse) integrated over the visible spectral range (380-780 nm). The diffuse angular distribution is calculated using the Perez et al sky luminance distribution model

[14] http://DAYSIM.ning.com/
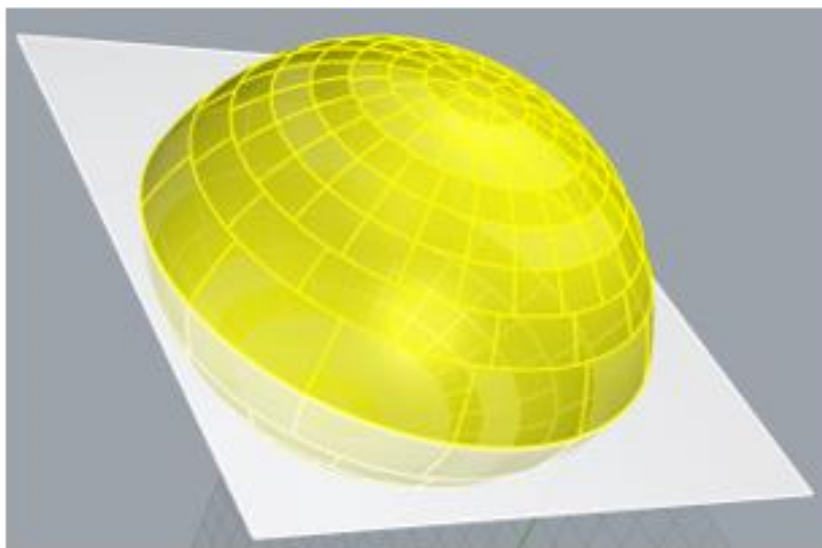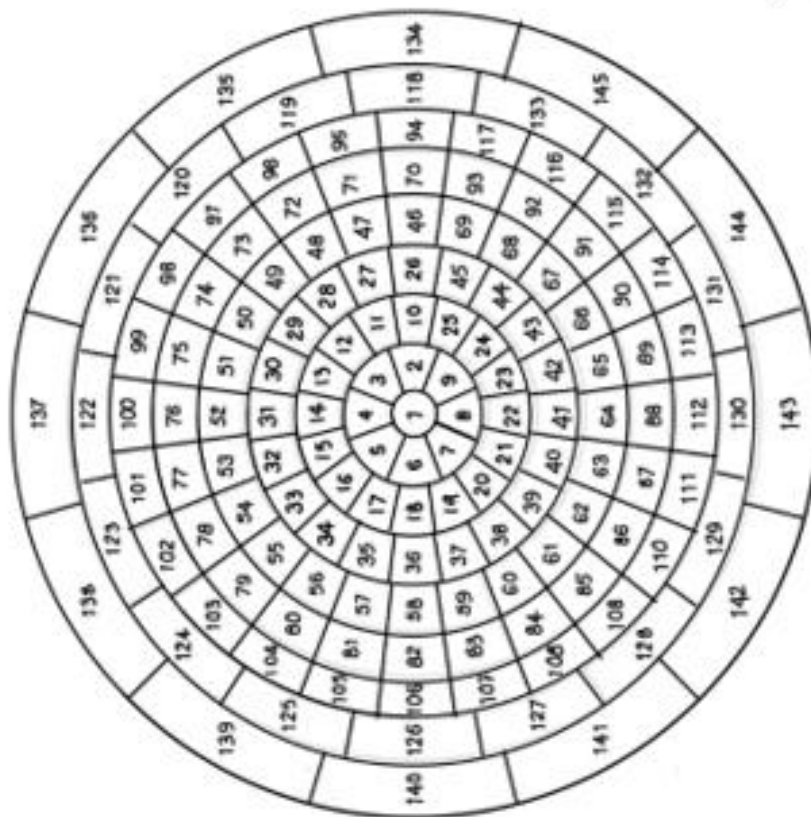
Figure 2.42: Klems 145-Patch Hemispherical Basis with Numbered Subdivisions (Source: Adapted from McNeil (2014))

125

2.6.5.6. Five-Phase Method

The 5-Phase method is a modified 3-Phase method that was mainly developed to model

the beam component with greater accuracy (McNeil, 2013). The governing equation for

3-Phase method is (Equation 2-18)

$$I_{3ph} = VTDS$$

Equation 2-18

Whereas for the 5-Phase method (Equation 2-19)

$$I_{5ph} = VTDS - V_d T_d D_d S_{sd} + C_{ds} V_{sun}$$

Equation 2-19

I = Result matrix containing time series of illuminance or luminance result.
V = View matrix, relating outgoing directions on window to desired results at interior.
V_d = Direct only view matrix.
T = Transmission matrix, relating incident window directions to exiting directions (BSDF).
D = Daylight matrix, relating sky patches to incident directions on window.
D_d = Direct only daylight matrix.
C_{ds} = Coefficient matrix for direct sun relating RADIANCE of many sun positions to direct illuminance at a sensor point using a BSDF with proxy geometry or a variable resolution BSDF material.
S = Sky matrix, a collection of sky vectors.
S_{ds} = Sky matrix containing only the sun luminance (no sky luminance).
S_{sun} = Direct sun matrix containing the RADIANCE and position of the sun.

More specifically, the 5-phase method handles the direct solar component separately

from the sky and inter-reflected solar component to achieve an improved accuracy of the

distribution of direct sunlight in a room for complex glazing systems (CFS).

2.6.6. Computer Aided Design (CAD)

The advent of Information Technology (IT) into Architecture/Engineering/

Construction (AEC) has led to the development of Computer Aided Design (CAD) tools

that have replaced the manual drafting of building plans. Several different tools have

been developed to assist in the processes of designing building. Early tools were mostly capable of generating 2D drawings. Over time the ability to view a building in 3D became available (Eastman et al., 2011). Currently, some of the well-known tools that are used in the AEC industry are AutoCAD (Omura, 1989), ArchiCAD (Martens & Peter, 2004), Bently Architecture Microstation V8 (Conforti, 2010) Sketchup (Chopra, 2012), and Rhino 5 (McNeel, 2015) etc. Several of these tools have been linked with Building Performance Simulation tools for performing different types of simulation analysis such as thermal and daylighting analysis (Bennewitz et al.,1998). Integration of these tools with Building Daylight Simulation tools have been discussed in the following sections.

2.6.7. Building Information Modeling (BIM)

Building Information Modeling (BIM) is an emerging technology in the Architecture/Engineering/Construction/Operations (AECO) industry. BIM, is the digital representation of the physical and functional characteristics of a facility that serves as a shared knowledge resource for information about a facility (NIMBS, 2007). As a process, BIM is a digital representation of the processes of design and construction used to facilitate the efficient exchange and interoperability of information across disciplines and phases the of design, construction and operation (Eastman et al., 2011). BIM is a semantically rich, object-oriented information modeling process that provides access to comprehensive building data, including components and their properties used in: design, construction, and operation of buildings (Lee et al., 2006). The parametric design

capability of BIM also enables quick, interactive, real-time design changes to assist in the decision process (Rundell & Stowe, 2005).

Over the years many tools have been developed that have incorporated the fundamental concepts of BIM, called BIM authoring tools. Some of the well know BIM authoring tools presently available are Autodesk Revit (Autodesk, 2013), Bentley Microstation V8 (Conforti, 2010) and ArchiCAD (Fischer & Golubkow, 2010). These tools provide many advantages and capabilities for supporting design and construction of buildings. They provide an interface to the underlying data structure of the different element in the building that are linked together. For example, the authoring tools provide a class hierarchy of building elements expressing the fundamental architectonic semantics such as: walls, windows, doors, roofs, floors, and the relations between walls and windows and others elements in the building. Since BIM is an integrated database of graphic and non-graphic attributes of building objects it also supports engineering and construction analysis that typically require information about the building components. The main differences in the geometry representation between CAD tools and BIM tool is that by default the building elements such as walls, floors, roofs and windows, columns and any other building elements are represented with thickness and contain attribute information the is not the case with the CAD modeling tools where the geometry has to be explicitly modeled as 3D solids representing a component that may not represent reality.

2.6.8. CAD to Daylight Simulation Tools

Many of the daylighting simulation tools include simulation engines that require a definition of the building geometry in a three-dimensional coordinate system including material properties assigned to the geometry for performing daylight simulation. Several of the current sophisticated tools allow geometry and materials properties to be input as human-readable, text-based files in their respective syntax. For example, SUPERLITE, RADIANCE and DAYSIM input files are human-readable text files that are interpreted by the programs to conduct the daylight simulation. However, the manual preparation of the input file for a given building geometry is a time-consuming process that is vulnerable to user input mistakes. To resolve this and to make input file preparation more convenient and easier, several of the CAD modeling tools are linked with different daylighting simulation tools. Generally, the CAD tools assist in the creating the geometry, assigning the material properties and subsequently export the model into text-based, tool-specific input files for simulation. Some of the well-known CAD based daylight simulations (i.e., the tools that have CAD-modeling tool as the front-end) are Desktop RADIANCE, ADELINE, Ecotect, Sketch-up open-studio plugin to DAYSIM and Rhinoceros Grasshopper plug-in to RADIANCE and DAYSIM.

2.6.8.1. Advanced Daylighting and Electric Lighting Integrated New Environment (ADELINE 2.0)

ADELINE is an integrated lighting design computerized tool for performing daylighting and electric lighting simulation collaboratively developed by several

organization[15] (Galasiu & Atif, 2002). ADELINE comes with SCRIBE-Modeler as the CAD interface and is connected to SUPERLITE and RADIANCE to perform daylighting and lighting simulations. Once the geometry is created with SCRIBE-Modeler, the geometry is assigned the materials from the in-built database by a special program called PLINK. PLINK also helps to define the climate data for performing daylighting analysis. To use PLINK the user creates the material information which is exported into a text-based input file for use by SUPERLITE and RADIANCE for performing daylight simulation.

2.6.8.2. Desktop RADIANCE

Desktop RADIANCE is another CAD-based daylighting and electric lighting simulation tools similar to ADELINE with AutoCAD as the interface for the geometry modeling and assigning materials and RADIANCE as the simulation engine (Mistrick, 2000). Desktop RADIANCE uses a custom developed program called RADOUT written in the C programing language to link AutoCAD with RADIANCE (G Ward & Rubinstein, 1988). RADOUT runs in AutoCAD environment and facilitates the translation of the CAD geometry into RADIANCE input files for performing the daylighting analysis. Apart from having a CAD interface for creating the geometry Desktop RADIANCE also has a pre-defined RADIANCE materials and light fixture libraries for assigning materials and defining electric lighting for a scene. Once the

---

[15] Danish Building Research Institute, Denmark; LESO-PB (Laboratoire d´Energie Solaire et de Physique du Batiment) at the Ecole Polytechnique Fédérale de Lausanne , Switzerland; Fraunhofer-Institute of Building Physics , Germany (Task lead); Lawrence Berkeley National Laboratory , U.S.A. Swiss Material Testing Institute EMPA, Switzerland

geometry is created and material properties entered, the camera view, sky model and lighting are defined by the RADOUT program that exports the scene into RADIANCE input file. Once the RADIANCE input file is created, different RADIANCE utilities are called using MS Windows BATCH scripting for performing the daylighting analysis (Mistrick, 2000). In addition to AutoCAD, RADIANCE also has many utility programs that help in converting different geometry formats used by CAD-based tools into the RADIANCE format for performing a daylighting simulation (Ward and Shakespeare, 1998).

2.6.8.3. DIVA for Rhino and Grasshopper

Another CAD-based modeling tool that is similar to AutoCAD is the Rhinoceros 3D a Nurbs modeling program (McNeel, 2015). It has been linked to RADIANCE and DAYSIM (Lagios et al., 2010) using a custom-developed special plug-in called the DIVA. Rhinoceros provides a graphical user interface for creating the geometry and the DIVA plug-in facilitates, defining of the sensor grid, assign materials to different surface and exports the models to RADIANCE and DAYSIM input formats. DIVA also helps in providing the weather file necessary for an annual daylight simulation. Once the scene is defined with all the necessary settings for a daylight simulation DIVA exports the scene data and automatically performs the daylighting simulation using RADIANCE and DAYSIM to produce results. These results include: The annual illumination profile for at sensor location and daylight matrices such as the Daylight Factor (DF), Daylight Autonomy (DA) and the Useful Daylight Illuminance (UDI). Initially DIVA was integrated with Rhino for performing the daylighting analysis. More recently DIVA was

integrated with Grasshopper using a plug-in for Rhinoceros as a graphical algorithm editor that allows designers with no formal scripting experience to quickly generate parametric forms (Lagios et al., 2010).

2.6.8.4. Ladybug and Honeybee Plug-in for Rhino and Grasshopper

Ladybug is a free, open-source environmental plugin for Grasshopper3D. Ladybug offers a full range of environmental analysis in a single parametric platform (Figure 2.43). It also generates interactive 2D and 3D graphics for weather data visualization to support the decision-making process during the early design stages (Roudsari & Pak, 2013). Ladybug also provides daylighting modeling by using a validated simulation RADIANCE (Ward, 1994), and DAYSIM (Reinhart and Walkenhorst, 2001). Similar to Ladybug, Honeybee is designed to run an analysis on building masses using a combined building energy performance/daylighting using EnergyPlus, RADIANCE and DAYSIM (Figure 2.44). Once the user defines the masses using grasshopper and provides the heights, Honeybee automatically processes the intersection of masses, finding adjacent surfaces, subdivides the masses, assigns construction to the surfaces, and simulation specific data for each space to perform the simulation. Honeybee also calculates and adds the openings to the geometry based on the percentage of the opening specified by the users.

For daylighting simulation, a user should provide test surfaces or test points (i.e., surfaces or points with actual luminance measurements) and RADIANCE simulation parameters such as the number of bounces, sampling, and weather file. By default,

Honeybee uses an identical geometry for both the energy and daylighting studies, and

extracts material properties for daylighting simulation from the construction.
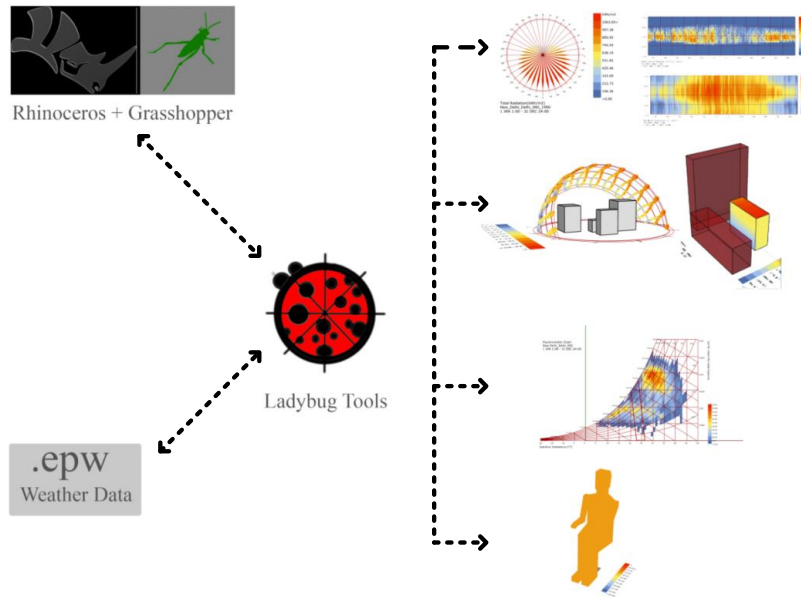
Figure 2.43: Ladybug Plug-in for Grasshopper for Doing Environmental Analysis
(Adapted from: https://parametricmonkey.com/2016/03/13/ladybug-honeybee/).
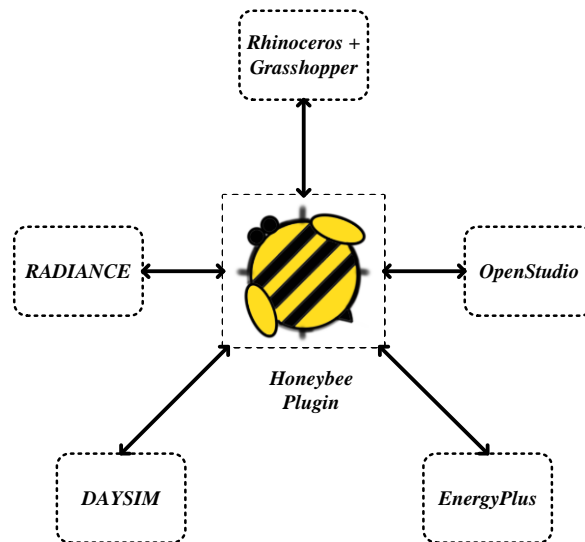
Figure 2.44: Honeybee Plug-in for Grasshopper for Doing Thermal and Daylighting
Analysis. (Source: Adapted from: https://parametricmonkey.com/2016/03/13/ladybug-honeybee/)

This technique simplifies the process and avoids possible user input errors (Roudsari & Pak, 2013). Advanced users can overwrite the default values, and can add more details to the daylighting model for more accurate studies (e.g., adding wall thickness, or internal partitions, etc.). Many of the currently available tools only export the geometries from the design environment to simulation files and read the result back. However, ladybug provides a two-way import/export connection so the user can import back from the simulation file and visualize it in Rhino/Grasshopper environment before executing the simulation. Also, Honeybee re-imports the results of the daylighting simulation visualization for daylighting and energy simulations so users can map the results with the geometries. Apart from standard daylight matrices such as Daylight Autonomy (DA) and Useful Daylight Illuminances (UDI) Honeybee also offers customization of the viewing of the results. There are two versions of Honeybee: legacy and Honeybee [+]. The methodology of performing Climate Based annual daylighting simulation incorporating CFSs using 3-Phase method and 5-Phase method are also incorporated in the latest Honeybee (Roudsari 2019).

2.6.8.5. Ladybug plug-in for Revit-Dynamo

Dynamo is a visual programming tool for Autodesk Revit similar as Grasshopper for Rhino. Dynamo enables users to use Visual Programming to process data and compose custom algorithms. Users can create geometries and manipulate models in Revit or within Dynamo (Mousiadis & Mengana, 2016). Recently a Ladybug plug-in called Ladybugdynamo has been created for Dynamo to perform the different environmental analysis in the Revit-Dynamo environment such as the weather, sun path

and radiation analysis. The plug-in is in the early development stage and new

functionality is expected to be incorporated in the future (Roudsari, 2018).

2.6.9. Summary of CAD to Daylight Simulation Tools

Table 2.13 gives the summary of the integration of CAD tools with daylighting

simulation tools. From all the above studies one common aspect can be inferred that a

custom program was developed to export geometry, material data and climatic data from

CAD tools to daylight simulation tools. In all the previous studies the daylighting tools

with that CAD tools that are integrated are RADIANCE and DAYSIM. These CAD

tools however represent the building geometry elements mostly as thin surfaces of walls,

or roofs with specific thickness that are presentative of real-world projects. Modeling the

building with representative thickness is possible with additional effort which is a

default option in BIM tools.

Table 2.13: Summary of CAD to Daylighting Simulation Tools

Program Name	CAD Tool for Building Geometry	Program to Export	Daylight Simulation Engine	Remarks
ADELINE	Scribe Modeler	PLINK	SUPERLITE RADIANCE	1. A custom program to facilitate the linking. 2. Static Daylighting Analysis.
Desktop RADIANCE	AutoCAD	RADOUT	RADIANCE	1. A custom program to facilitate the linking. 2. Static Daylighting Analysis.
DIVA	Rhino / Grasshopper	DIVA	RADIANCE and DAYSIM	1. A custom program to facilitate the linking. 2. Parametric simulation is possible due to parametric capability of Grasshopper Plug-in. 3. Climate-based analysis / Annual Simulation.
Ladybug and Honeybee	Rhino/ Grasshopper	Ladybug and Honeybee	RADIANCE and DAYSIM	1. A custom program to facilitate the linking. 2. Parametric simulation is possible due to parametric capability of Grasshopper Plug-in. 3. Climate-based analysis/ Annual Simulation.

Figure 2.45 show a room modeled using Rhino 3D, a CAD-based geometry creation tools in which the walls are represented as thin surfaces. The thickness of the wall is modeled using series of connected surfaces. However, Figure 2.46 shows a room created using the BIM authoring tool Revit in which the walls, by default, are modeled with thickness closely representing the element of the real building.
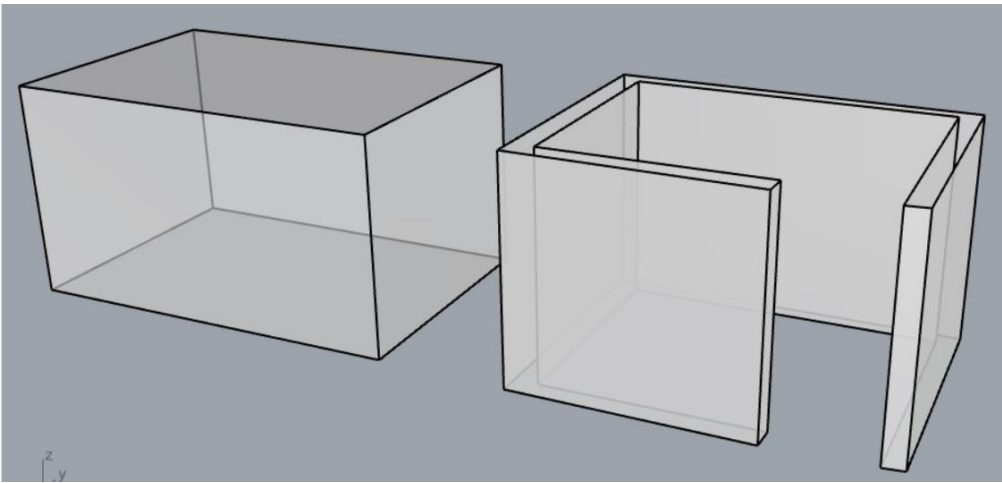
Figure 2.45: Modeling of Geometry in Rhino 3D a CAD Bases Geometry Creation Tool in Which Geometry is Modeled as Thin Surfaces (Source: Author)
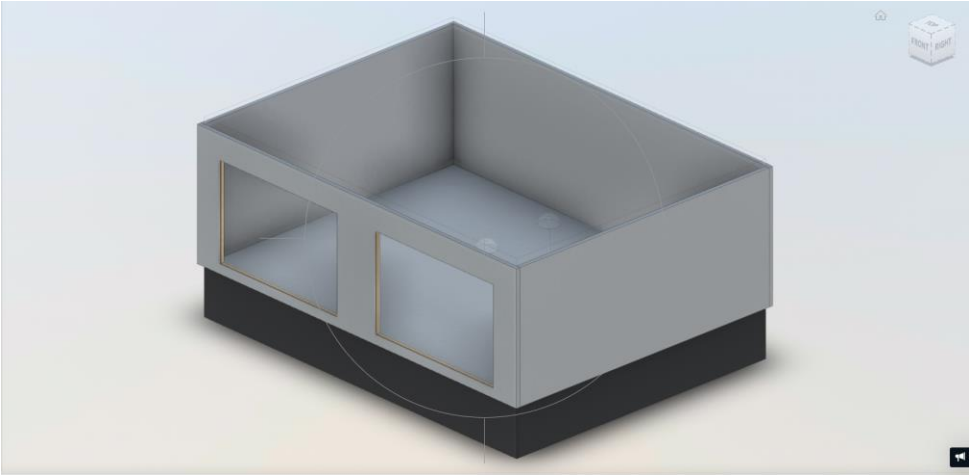
Figure 2.46: Modeling of Geometry in Revit a BIM Authoring Tool that Models Geometry with Thickness (Source: Author)

2.6.10. BIM-to-Building Performance Simulation (BPS) Tools

Presently, a major effort is underway of using the BIM data for different kinds of Building Performance Analyses (BPA) such as Building Energy Simulation (BES), Daylighting Performance Analysis (DPA), Structural Analysis (SA), estimation, quantity take off and Facility Management, etc. Several studies have explored the possibilities of linking BIM tools with Building Energy Simulation tools. In one of the projects a CAD tool-to-EnergyPlus was explored using the IFC data model (Bazjanac, 2002).

In another study the RIUSKA building energy simulation tool, that uses the DOE-2.1e energy simulation engine was linked with the IFC interface to BIM tools to enable energy simulation (Jokela et al., 1997). In other study the Modalica Building Library (Wetter et al., 2014) was integrated with the Revit BIM-authoring tool (Kim et al., 2015). These studies demonstrate that there is a great desire to link BIM to Building Energy Simulation tools (BIM to BES). In the past several of the CAD tools such as AutoCAD, and Rhino 3d were linked with several daylighting simulation tools such as SUPERLITE, RADIANCE, DAYSIM and ESPr. However, these tools were not true BIM tools that can model the building that closely represent reality.

Rob Shakespeare side[16]:

"At the last RADIANCE Workshop, there was some discussion regarding converting REVIT models to RADIANCE, with materials and named surfaces parsed into readable. rad datasets. As REVIT has essentially become the architectural industry modeling tool, the pipeline to RADIANCE is an important one. It seems that the latest version of Sketchup has some challenges with the very helpful su2rad, written quite a while ago. I heard that others were using some other pipelines, perhaps integrating obj2rad, etc. I would appreciate your sharing conversion pipelines that interface with the MOST CURRENT releases of REVIT, SKETCHUP, etc. Hopefully a generous and

---

[16] https://discourse.radiance-online.org/t/revit-to-radiance-pipeline/1948

expert code person would consider writing a direct REVIT plugin for this purpose. There might be modest financial encouragement to fill this gap. I do realize that it may be short-lived as AutoDESK releases are moving targets, yet to engage the full RADIANCE tool kit for lighting design and analysis on REVIT generated models, will keep RADIANCE on the forefront and accessible to a broader audience"

From Shakespeare's statement it can be seen that there is a great need for linking BIM authoring open-source tools such as Revit with daylighting simulation tools especially RADIANCE as it is considered the state-or-the-art daylighting simulation tool and RADIANCE-based tools such as DAYSIM.

2.6.11. BIM to Daylight Simulation Tools

In recent years many studies have been published that integrated BIM-based tools with daylighting simulation tools. Some of the studies used the Autodesk Revit to 3dsMax daylighting simulation tool (Reinhart and Breton, 2009) and the ThermalOpt from BIM modeling tool to daylighting simulation tools RADIANCE through the IFC data file using custom developed plug-ins (Welle et al., 2011).

2.6.11.1. Autodesk Revit Architecture to 3dsMAX Design Studio 2009 with Exposure

Revit Architecture is a BIM authoring tool developed by Autodesk. 3dsMAX design studio 2009 is also a product of Autodesk, that is used mostly for animation and rendering. Recently, the daylighting simulation capability has been added into 3dsMAX design studio 2009 by adding a new module called Exposure. Exposure enables the user to perform a physically-based, accurate daylighting simulation. The simulation engine in the exposure is a ray-tracer called mental ray. Both, time-series renderings of High Dynamic Range (HDR) images as well as climate based annual daylighting simulation

can be conducted using an exposure a plug-in in 3dsMAX. Figure 2.47 shows the overall

workflow to perform a daylighting simulation and analysis using Revit and 3DS Max .

To compute the daylight matrices such as the daylight factor and illumination levels

3dsMAX uses a CIE overcast and clear sky modules and for climate-based daylighting

simulation it uses Perez all weather sky model (Reinhart and Breton, 2009). For annual

daylighting simulation 3dsMAX uses the EnergyPlus EPW format weather file.

3dsMAX has been validated by comparing the results with measure data as well as with

RADIANCE and DAYSIM daylighting simulating tools results for a different number of

cases extending from simple windows to Complex Fenestration Systems consisting of

shades, light shelves and indoor venetian blind systems (Reinhart and Breton, 2009). In

the annual daylighting analysis, the user can place sensor points in the interior of the
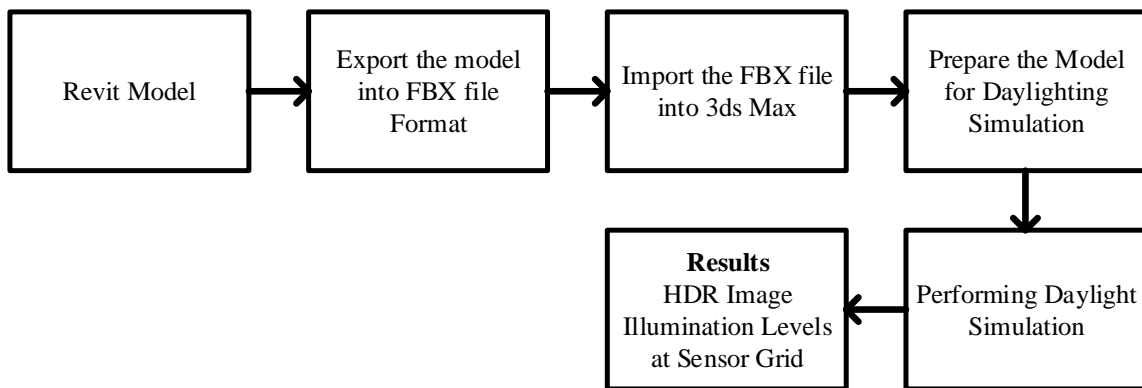
Figure 2.47 Workflow to Perform Daylighting Simulation and Analysis Using Revit and
Autodesk 3DS Max

spaces and 3dsMAX computes the annual daylighting profile at these sensor locations.

This data can be further exported into comma separated values file (CSV) for post-

processing in any statistical software. Apart from that also the illumination levels (Lux/

139

Foot Candles) can be displayed on a rendered image by specifying an imaginary grid on top of the image. The interoperability between Revit and 3dsMAX is achieved through a special file format called FBX. Once the model is created in Revit it is necessary that a camera view is specified to be exported into FBX file format. The FBX file format contains the geometry and material information necessary for the daylighting analysis in the 3dsMax. The file can then be imported into 3dsMAX through import option.

However, in order to do a physically accurate daylighting simulation, a series of checks have to be performed. First, for a physically-based lighting calculation the mental ray rendered has to be selected within 3dsMax. Second, invalid light types (such as standard lights and standard sunlight objects) within the scene imported from the Revit model have to be replaced by selecting daylight system in 3dsMAX. Third, some of the non-physical materials that are imported from Revit have to be replaced by physically-based materials for a correct lighting analysis. 3dsMAX provides two types of materials that are recognized as physical-based material by mental ray renderer, these are the mental ray "Architectural & Design Material" and "ProMaterials" material types. A check has then to be performed to identify invalid materials in the project and the materials replaced by physical-based materials. Another major aspect that is important in the preparation of a scene for a daylight analysis in 3dsMAX is modeling of the glass panes. By default, the window glass panes in the 3dsMAX are considered as a solid block. However, 3dsMAX offers two methods to model light traversing through the window panes. In the first method the user can specify for the renderer how to account for the attenuation of light as well as the refraction of light as it traverses through the

140

volume of the panes. Unfortunately this method is very time consuming. In second

method the user can specify to the renderer to attenuate the light without accounting for

refraction while passing through the glass sheet. The second method saves rendering

time considerably. However, the workflow of performing the daylighting analysis from

Revit to 3dsMAX is considerably convenient but still needs manual checking and

preparing the scene for accurate daylight simulation. At best the process can be

described as semi-automated. Also compared to RADIANCE and DAYSIM the

rendering engine mental ray in 3dsMAX has not been extensively validated.

2.6.11.2. ThermalOpt Daylighting Simulation

ThermalOpt is a methodology for automated BIM-based simulation intended for

use in Multidisciplinary Design Optimization (MDO) environments (Welle et al., 2011).

It can perform both thermal and daylighting simulations to support the study of the effect

of daylighting on the thermal performance. It uses EnergyPlus for the thermal simulation

and RADIANCE for daylighting simulation. ThermalOpt is implemented via four

different plugins: (1) IFC2ThermalSim, (2)ThermalSim, (3) EnergyPlus Wrapper, and a

(4) RADIANCE Wrapper (Figure 2.48). In ThermalOpt, the building description is

represented in the IFC BIM interoperability format and translated into the EnergyPlus

input format. Geometry for daylighting simulation using RADIANCE is taken from the

EnergyPlus model. The EnergyPlus model does not represent the actual geometry of

BIM. Therefore, taking the geometry from EnergyPlus does not give accurate geometry

for daylighting simulation. Even though the whole process is automated, the geometry

for the daylighting simulation is not the same as the BIM model, that can alter the

results.
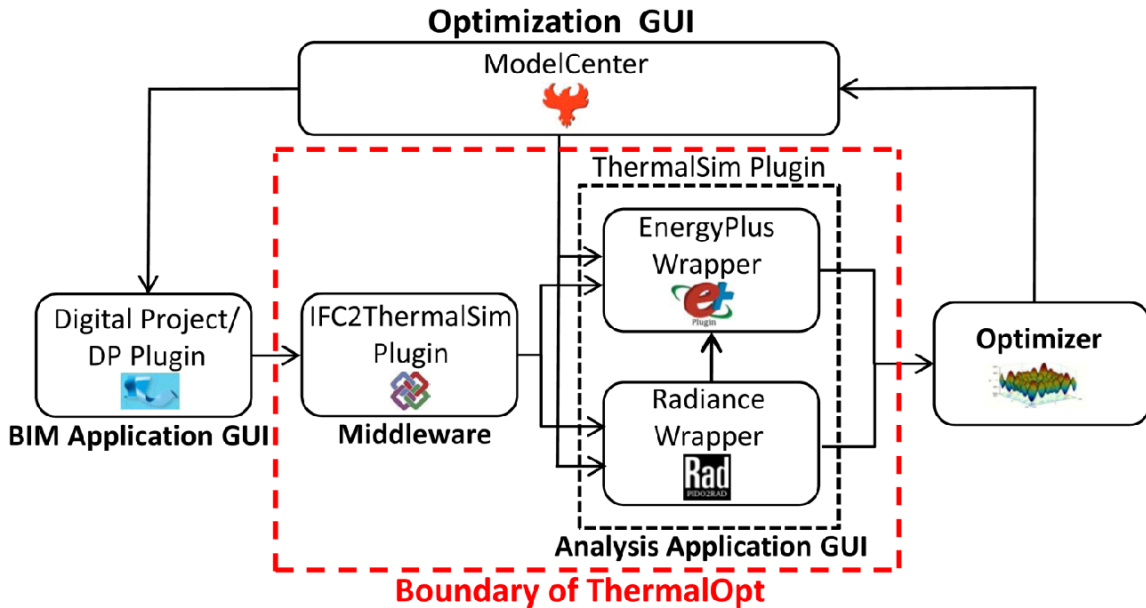
Figure 2.48: Workflow using in ThemalOPT (Source: (Welle et al., 2011))

2.6.11.3. SEFAIRA Daylighting Analysis Tool

SEFAIRA is a plug-in that can be used for SketchUp and Autodesk Revit to

perform Building Performance Analysis, such as an energy and daylighting analysis in

the early stages of design (Truesdell, Andrew, & Vladimir, 2018). It uses cloud-

computing technology to perform the analysis and visualize the results in the model. The

daylighting analysis is carried out using the RADIANCE and DAYSIM daylighting

simulation tools. The main daylighting simulation engine is RADIANCE. SEFAIRA

takes up the building geometry from SketchUp defined as planes or Revit described as

objects/ solids, and converts them into planar polygon surfaces and translates them into RADIANCE geometry polygons creating an input file. It also classifies the user-defined geometry into two categories. If the user defines a surface as the window it will be classified as window glazing and the rest of the surfaces are classified as massing. Based on the classification, SEFIRA assigns two materials, for massing, RADIANCE plastic material primitive and for windows glass material primitive are assigned. For daylighting simulation, SEFIRA employs sensor-based simulation; once the user classifies a SketchUp plane or Revit Object as the floor surface, SEFAIRA creates a sensor gird parallel to the floor with an offset from the floor which is 30 inches. SEFAIRA provides the following sensor-based analyses: 1) Point in time illuminance; 2) Climate-specific annual Illuminance (Daylight Autonomy); 3) Direct sunlight ; and 4) Daylight Factor (Truesdell et al., 2018). However, SEFIRA uses a fixed-reflectance value for the geometry classified as "massing" whether it is a wall, ceiling/roof or floor. This limitation can affect the simulation results if the floor or ceiling has a different reflectance value other than the fixed value (i.e., 0.4).

2.7. Summary of the Literature Review

2.7.1. Sky Models

Several researchers have proposed different sky models that have been incorporated into different daylighting simulation methods and tools. Of all these sky models the All-weather sky model by Perez et al. (1993) is considered the best model that can produce any type of sky model given the weather data.

2.7.2. Methods of Daylighting calculation

The two primary methods that have been developed to perform the daylight calculation: the Daylight Factor (DF) method and the Daylight Coefficient (DC) method. Of these two-methods the DC method is considered to be more reliable as it addresses the shortcoming of the DF method and is specially developed to perform a climate-based annual daylighting analysis.

2.7.3. Tools for daylighting calculation

2.7.3.1. Early Tools

Over the years several methods and tools were developed for performing daylight analysis. Some of these tools are graphical and others are non-graphical. Some of the tools provide only one of the components of the DF, while others give a total DF. The earlier tools provided a quick estimate of the daylighting levels for a given space However these, are not very accurate in terms of the estimation of daylight levels throughout the entire space and the Daylight Factor.

2.7.3.2. IRC Computational Method

Computing the Internal Reflected Component (IRC) is challenging compared to computing the Sky Component (SC) and the Externally Reflected Component (ERC). Several non-graphical methods have been proposed (i.e., algorithms) for computing the IRC. The three most popular methods that have been widely used in the daylighting simulations tools are the Split-flux method, the Radiosity Method and the Raytracing. The split-flux method can accurately simulate a room of certain shapes and configurations and the Radiosity method has limitations in terms computational expense

in computing the form factors as the scene being analyzed becomes complex. Both the methods treat the surfaces as Lambertian and cannot handle specular surfaces, that are effortlessly handled by Raytracing. The Raytracing method is considered to be one of the best methods for computing the IRC for performing a daylight simulation.

2.7.3.3. Daylight Coefficient and Ray Tracing Based Daylight simulation tools

Of the numerous tools that have been developed (Table 2.6) some of them are proprietary and others are open source. The tools that employ the DC method with Raytracing are considered to be more accurate. These are RADIANCE, and RADIANCE based DAYSIM and ESPr. Also, RADIANCE and DAYSIM are considered to be more accurate as reported by several comparative studies of different daylight simulations by different researchers.

2.7.4. CAD to Daylighting Tools

Several CAD-based tools such as AutoCAD and Rhino3d have been integrated with daylight simulation tools like RADIANCE and DAYSIM. Rhino has a Grasshopper3d plug-in offering parametric modeling capabilities while Ladybug and Honeybee plug-ins integrate Rhino with performance tools such as Energy Plus for building energy performance analysis and RADIANCE and DAYSIM for daylighting analysis. However, these 3d Modeling tools do not offer 3d Modeling that is comparable to BIM authoring tools that can model building elements with real thicknesses that are major setback if one has to perform a daylighting analysis of a real building. However, with additional effort thickness information about t surface can be modeled using these tools to better match the real building scenario. Currently in BIM authoring tools this is

145

the default method of modeling the geometry. Owing to the above limitations and the popularity of BIM-authoring tools in the AEC industry linking daylight performance simulation tools with BIM-authoring tools has many advantages.

2.7.5. BIM-to-Daylighting Simulation Tools

In one study Revit was linked to RADIANCE (Welle et al., 2011) using an IFC data file to transfer the Revit model geometry information into the Energy Plus simulation file where the geometry for RADIANCE was taken from the Energy Plus input file. Unfortunately, the geometry of the EnergyPlus model is not the same as that of the BIM model as the walls in the BIM are represented with thicknesses whereas in EnergyPlus simulation, they are represented with zero thickness. So, the translation of the geometry from EnergyPlus to RADIANCE is not the same as Revit to RADIANCE. In a second study Revit is integrated with 3dsMAX Mental Ray (Reinhart and Breton, 2009) for performing daylighting analysis. The translation was achieved through a proprietary plug-in called the FBX converter that converts a Revit model to 3DS model. Unfortunately, the method needed many manual checks to prepare the BIM model for the daylight simulation. Also, the daylight simulation engine in the study was not extensively validated compared to RADIANCE or DAYSIM. In the third study using SEFAIRA, only one reflectance value (i.e., 0.4) was used for all the surfaces classified as massing in contrast to real buildings having different reflectance for each of the building elements such as walls, floor and ceiling/ roof.

146

3. SIGNIFICANCE AND LIMITATIONS

3.1. Expected contribution of the Study

The main contribution of the present study is to develop an public prototype tool called *REVIT2RADIANCE* tool that can be used in the REVIT BIM environment to perform a daylighting analysis of a given building and daylighting strategies. The usual process of preparing an input file for daylighting analysis from an architectural view involves multiple steps involving considerably complexities that are usually performed by a lighting professional who are trained in the process of performing daylight simulations. The present prototype helps reduce the complexity so that students, architects and lighting professionals can perform accurate daylighting simulations with increased ease.

3.2. Scope and Limitations

The purpose of this study is to develop and test an open-source prototype tool to perform a daylighting simulation using BIM models. To accomplish this, first, a literature survey of different daylighting simulations tools was performed in terms of their capabilities and limitations to identify the best daylight simulation tools. Second, a survey of how daylighting performance tools were integrated with CAD and BIM based tools to identify the potentials and shortcoming in integration process was performed. Third, the development of a prototype to seamlessly integrate the BIM authoring tool with daylight simulation tools that addresses the identified limitation and shortcoming was accomplished.

Following are the limitation of the study:

- The validation of the selected daylight simulation tools will rely on the previously published validations in the literature.

- Two test cases, one simple model and one complex model, will be used to demonstrate the prototypes to determine if the BIM data is accurately being translated into a daylight input file for the daylight simulation.

- The simulation of Complex Fenestration Systems (CFSs) is not considered with the present prototype. Instead only ordinary fenestration systems such as simple vertical glazing or tinted glazing will be used.

- The prototype will be developed for one BIM authoring tools that will be identified through the literature review.

- A glare analysis is not considered for the present study. However, a method for incorporating it will be provided.

4. METHODOLOGY

4.1.1. Overview of the Methodology

This chapter describes the methodology followed in this dissertation. As previously mentioned, the aim of this study is to develop a prototype for automatically integrating Building Information Model (BIM) such as Revit with a Building Daylighting Simulation (BDS) tools such as RADIANCE or DAYSIM. Figure 4.1 presents the methodology in a flowchart. The methodology followed can be summarized into eight sections. Section 1 discusses about the different features that are pertinent to the daylight study and identifies the important information related to this study. For example, sky models that are used in the daylighting simulation, daylight matrices that are necessary for the assessing the performance of daylighting in space and glare indices to assess the visual comfort of the daylit space as well as daylight calculation methods that have been developed to perform the daylight analysis of the building.

Section 2 discusses the selection of best daylighting models using the features that are studied in the Section 1. Section 3 identifies the relevant criteria for the comparative analysis of the daylight simulation tools. These criteria include the outcome of Section 2 that reviewed the best methods that have been developed. Section 4 primary focusses on daylight simulation tools that have been developed over time that incorporate the methods that are discussed in Section 1. In addition, a comparative analysis of the selected tools that are widely used for daylighting analysis is provided. Even though there are several daylighting performance methods and tools developed only the selected tools that were reviewed were used for the comparative analysis as these tools are

widely used and advance then earlier methods and simplified tools that were previously

developed. Section 5 discusses the selection of the best daylighting simulation tools

based on the comparative analysis of Section 4. Section 6 reviews interfacing the CAD

modeling tools with the daylight simulation tools to identify the methods of integrating

the tools and the limitations involved in the approaches. Also, interfacing the BIM tools

with daylighting simulation tools has been surveyed to identify the precedence,

methodologies and limitations. Section 7 discusses the ways to integrate the BIM tools

with BDS tools using available translators and also identifies the issues involved.

Section 8 discusses the development and testing of the prototype.
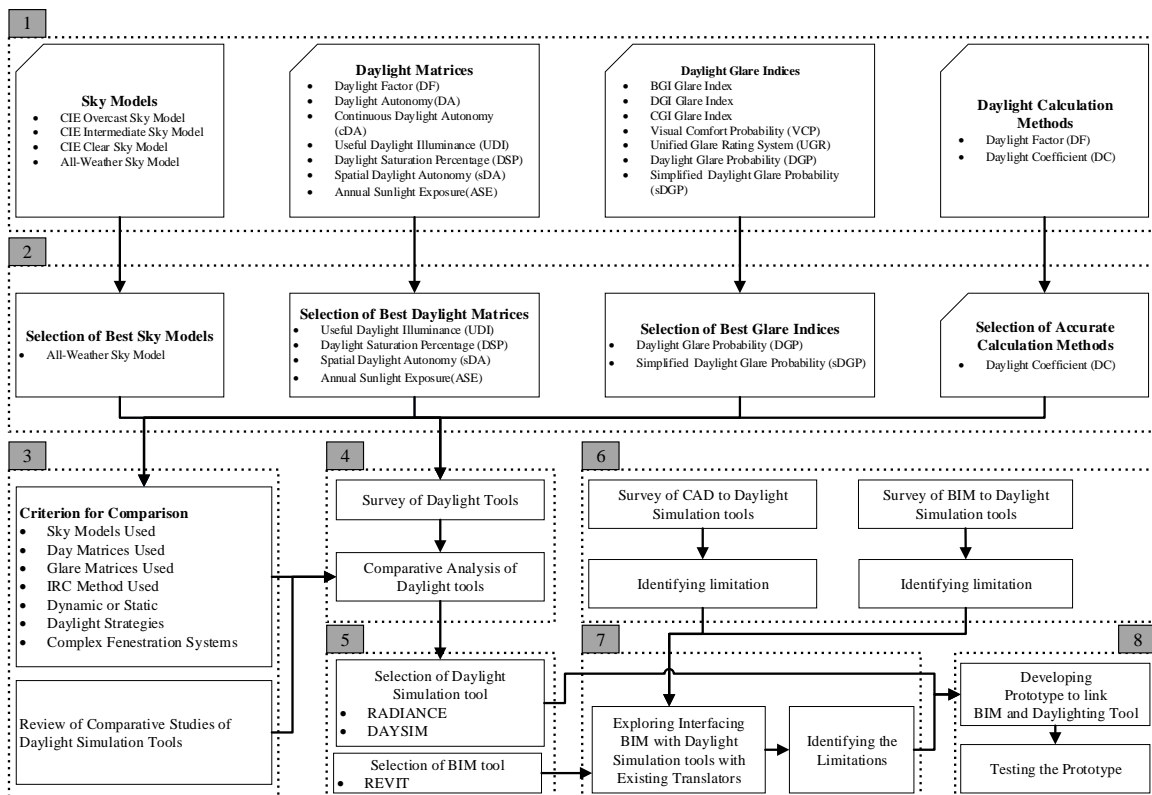
Figure 4.1: Methodology Followed in the Study

150

4.1.2. Sky Models

Daylight performance of a space depends on the luminous distribution of the sky that surrounds the building. Several sky models have been proposed by different researchers. A literature review was carried out to identify different types of sky models. The review also helped to identify the sky models that were the most accurate.

4.1.3. Daylight Methods

A literature review was conducted to identify different types of methods that have been developed to perform daylight calculations including their advantages and limitations. From the inception of the earliest daylighting calculating method two methods have been developed that are known as the Daylight Factor (DF) and Daylight Coefficient (DC) methods. The DC method was found to be the most robust and the most accurate.

4.1.4. Daylighting Matrices

Several daylight matrices have been developed that were reviewed regarding their advantages and limitations. A simple analysis, based on selected criteria was performed to ascertain the daylighting features that were the most informative in reporting the daylighting performance of the daylit spaces.

4.1.5. Glare Indices

Similar to daylight indices and matrices a survey of glare indices was performed to understand the different types of glare indices that were developed and their advantages and limitations. The study helped identify the glare indices that were more informative in reporting the daylight quality in a space.

4.1.6. Daylight Tools

An extensive literature review of daylighting methods and simulation tools was performed for the present study. The methods and tools ranges from simple graphical methods to computer-based daylighting simulation tools with robust daylighting analysis capabilities producing different kinds of analysis results. Also, tools having the capabilities of simulating different types of fenestration systems extending from simple to Complex Fenestration Systems CFSs were reviewed.

4.1.7. Comparative Analysis of Daylight Simulation Tools

From the literature review of the daylighting simulation tools several criteria were identified for comparing different daylighting simulation tools. Only the computer-based simulation tools were selected for comparison as these are the current tools that: use multiple sky models; The DF or DC daylighting methods; conduct daylighting analysis of different types of fenestration systems; employ different algorithms for computing the Internal Reflected Component (IRC); and also provided different types of analysis results. An evaluation rubric was created based on the criterion identified and each tool was scored. Among the tools that were reviewed RADIANCE and the RADIANCE-based DAYSIM and ESP-r were most accurate best tools that have the capability of the performing daylighting simulation for different types of scenarios. From the comparison RADIANCE was identified to be the state-of-the-art daylighting simulation tools that can be used for daylighting simulation followed by DAYSIM. Also, several studies were reviewed that have performed comparative analyses of the different daylight simulation tools. The review of these previous studies also showed that

RADIANCE and DAYSIM are the most accurate tools for performing daylighting simulations.

4.1.8. CAD to Daylighting Simulation Tools

Some of the daylight simulation tools are computer programs or simulation engines that require a text-based input file to perform a simulation. A literature review was conducted to understand how the different CAD tools, that are widely used by architects for visualization for buildings have been integrated with daylight simulation tools for performing a daylighting analysis of the space. The study revealed a greater need for efficiently integrating an architectural visualization tool with daylighting analysis tools.

4.2. BIM Authoring Tools

In the Architecture/Engineering/Construction/Operations (AECO) industry a new technology called Building Information Modeling (BIM) is being used for representing and sharing information about a facility (e.g., building) among the different stakeholders who are in the Architecture/Engineering/Construction/Operations process. Several types of BIM tools are commonly being used to create the building model and share the data between the different parties. These tools are called BIM-authoring tools that have a rich data representation of the building model that can be used for different types of architectural and engineering analysis. Several studies have been conducted by different researchers linking BIM tools with Building Performance Simulation tools for energy and daylighting analysis, that strongly indicates the need for such integration. Autodesk Revit (Autodesk, 2013) one of the BIM-authoring tools that has become very popular in

the AECO industry and is widely used. Also, the literature revealed a greater need among the daylighting research community for integrating Revit with RADIANCE similar to tools that provide CAD-to-RADIANCE and CAD-to-DAYSIM translations.

4.2.1. BIM-to-Daylighting Simulation Tools

The present study revealed the need for integrating BIM with daylight simulation tools. As result a literature review was conducted to identify the prior studies in order to see how BIM tools were integrated with daylight simulation tools. The study also helped identify the shortcomings of the previously published methods and provided an idea about how these issues could be resolved that was the motivation for the development of the new prototype.

4.3. Developing the Prototype Revit-to-RADIANCE and DAYSIM

As a part of this study a new prototype was developed, for developing using two different approaches. The first approach was based on the utilizing the RADIANCE translator that was available with the RADIANCE program to link the BIM Revit program with RADIANCE and DAYSIM programs. The second approach was the development of a custom Revit plug-in using the Revit API programing language to link Revit with RADIANCE

4.3.1. Conventional Method

The RADIANCE lighting simulation tool comes with several geometry translation tools that can translate a CAD geometry model data into the RADIANCE input format. Several of these tools were explored to translate the Revit geometry data into RADIANCE and DAYSIM.

4.3.2. Custom Prototype

The conventional method of translating the CAD geometry model using RADIANCE geometry translators revealed several limitations. Unfortunately, in order to have the Revit geometry and material data translated using the conventional method required several steps that resulted in a loss in data in the process. This motivated the need to develop and publicly-available, custom Prototype called REVIT2RADIANCE and a Revit Plug-in using the Revit API programing language for integrating daylighting analysis using RADIANCE and DAYSIM into the Revit modeling environment.

5. REVIT-TO-RADIANCE AND REVIT-TO-DAYSIM[17]

5.1. Introduction

Part of the present research is the work performed for a National Science Foundation project entitled Physical Building Information Modeling (PBIM). The PBIM project aims to integrate BIM with building performance analysis tools across multiple domains, that includes thermal and daylighting simulations (Yan et al., 2013). The development of the prototype for the current study was created as part of the PBIM project. For the current research Autodesk Revit has been chosen over other BIM-authoring tools that were available because it has a rich parametric BIM-authoring capability and is widely used in the industry as well as in academia by students. The main aim of the project was to integrate BIM with RADIANCE and DAYSIM by automatically translating the Revit models into RADIANCE and DAYSIM input files. In addition, the prototype performed the daylighting simulation and generated the results.

In a prior study (McGrew, 2006) a Revit model was translated into a RADIANCE input file by converting the Revit model into different file formats using several different geometry translation tools. The major findings reported by the study were: (1) translating the Revit data into RADIANCE required multiple steps to convert Revit geometry into a RADIANCE geometry, (2) a manual intervention was required in the whole process, and (3) certain missing information was required that had to be added manually to create a complete RADIANCE input file. Therefore, in this current research,

---

[17] A part of this chapter is reprinted with permission form "Building Information Modeling (BIM)-based daylighting simulation and analysis" by Kota, S., Haberl, J. S., Clayton, M. J., & Yan, W., 2014. Energy and Buildings, 81, 391–403, Copyright 2014 by Elsevier B.V.

the aim is to develop an automated translator to provide a REVIT-to-RADIANCE and

DAYSIM simulation in order to significantly reduce the model preparation time and to

allow the parametric modeling advantages of Revit.

5.1.1. RADIANCE Utility Program

RADIANCE has several utility programs for converting a wide variety of CAD

geometry data formats into the RADIANCE input format. Table 5.1 gives some of the

widely recognized data formats, that are used by different CAD-based tools. Several

methods were explored using these utility program to convert a Revit model to a

RADIANCE input file.

Table 5.1: CAD Geometry Data Formats

File type	Developer	Reference
DWG	Autodesk	(Kumar, 2008)
3DS	Autodesk	(McHenry & Bajcsy, 2008)
DXF	Autodesk	(Kumar, 2008)
OBJ	Wavefront	(McHenry & Bajcsy, 2008)
MGF	developed particularly for RADIANCE	(Ward et al., 1996).

Autodesk also offers a comprehensive exporting utility called the FBX[18] (Filmbox)

Converter that convert the Revit file into a proprietary file format called the FBX format

(Autodesk, 2011). Further this converter can convert the FBX file format into different

geometry file formats (Table 5.1) such as DWG, DXF, OBJ and 3DS. For the present

project, to converting a BIM into a daylighting simulation model, a Revit model was

_____

[18] https://en.wikipedia.org/wiki/FBX

first exported into the FBX file format and then subsequently into the DXF, OBJ and

3DS using the FBX Converter (Figure 5.1).
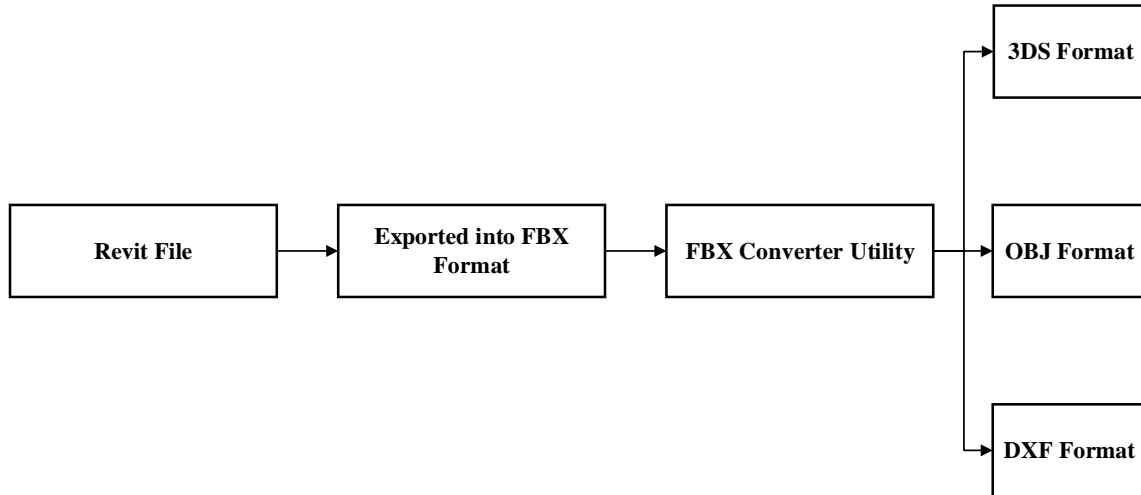
Figure 5.1: Presently Available Method to Convert a Revit Model into Different CAD Formats

After converting the Revit file format to different CAD formats using the FBX

converter, different RADIANCE utility programs, DXF2RAD[19], OBJ2RAD[20],

3DS2MGF[21], and MGF2RAD[22] were used to convert the CAD formats into the

RADIANCE input file format. Figure 5.2 shows the different steps involved in

converting a Revit model into a RADIANCE input file format using these different

utilities. The steps involved in translation using the different utilities are represented as

paths (i.e. P1, P2, P3, . . .). P6 is the translation path describing the proposed method in

this study. The method proposed is a more direct path involving only one step for

---

[19] https://www.schorsch.com/en/download/dxf2rad/manual.html
[20] https://floyd.lbl.gov/radiance/man_html/obj2rad.1.html
[21] https://floyd.lbl.gov/mgf/mgfhtml/3ds2mgf.html
[22] https://floyd.lbl.gov/radiance/man_html/mgf2rad.1.html

creating the RADIANCE input file and for performing the daylight simulation. The main

advantage of this method is that it is easy to use and does not require an in-depth

knowledge of the different tools, that are needed in the other paths. Table 5.2 shows the

steps involved in each method for converting a Revit model into RADIANCE and

DAYSIM input files.
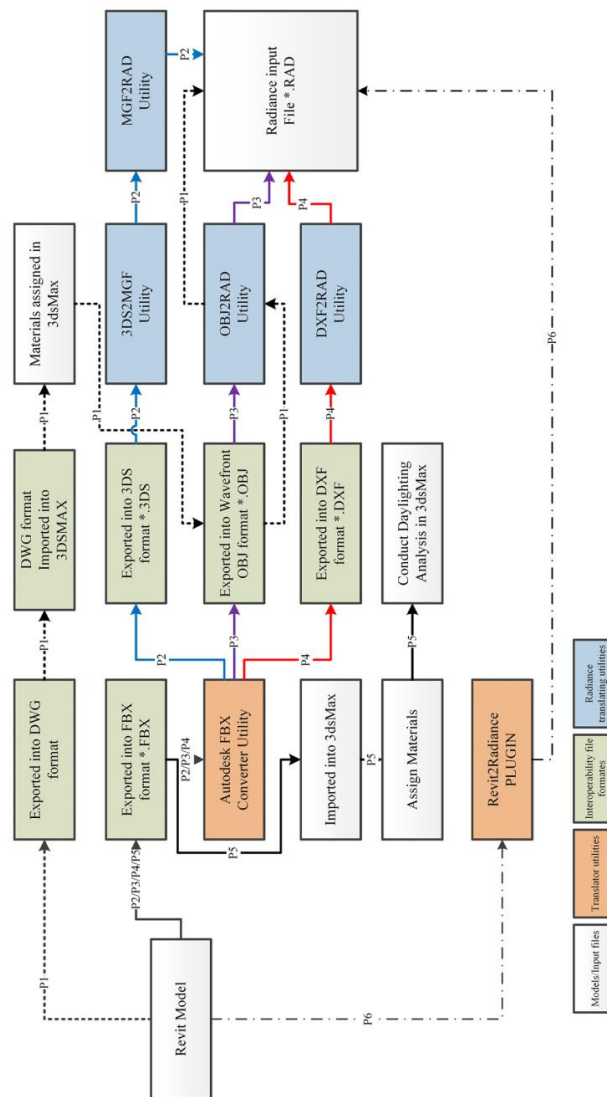
Figure 5.2: Different Translation Paths from Revit to RADIANCE: P1, P2, P3, P4 and
P5 are the Paths of Existing Methods, and P6 is the Path of our Proposed New Method.
(Source: (Kota et al., 2014))

159

Table 5.2: Steps Involved in Each Path for Converting a Revit Model into RADIANCE/DAYSIM Input Files (Source: (Kota et al., 2014))

Path Name	Revit file exporting/translating	Importing to other programs	Assigning materials or Exporting to other formats	Exporting/Converting	Exporting/Converting	No. of steps
P1	Exported into DWG format	DWG format imported into 3DS Max	Materials assigned in 3ds Max	Exported into Wavefront OBJ format	Exported into Radiance format using OBJ2RAD utility	5
P2	Exported to FBX format	Imported into Autodesk FBX converter utility	Exported into 3DS format *.3ds	Converted into MGF format using 3DS2MGF	Converted into Radiance format using MGF2RAD utility	5
P3	Exported to FBX format	Imported into Autodesk FBX converter utility	Exported into Wavefront OBJ format *.OBJ	Converted into Radiance format using OBJ2RAD utility		4
P4	Exported to FBX format	Imported into Autodesk FBX converter utility	Exported into DXF format *.DXF	Converted into Radiance format using DXF2RAD utility		4
P5	Exported to FBX format	Imported into Autodesk 3ds Max	Materials assigned in 3ds Max	Simulated in 3ds Max		4
P6	Translated into Radiance input file using our Revit2Radiance Add-in Program					1

160

5.1.2. Issues Involved in the Revit to Daylighting Translation Using RADIANCE

Utilities

5.1.2.1. Only Geometry Information

Only the geometry information can be exported automatically using the

RADIANCE utilities. However, the associated material information for creating a

complete RADIANCE input files for conducting the daylighting simulation cannot be

automatically translated. This requires a manual assignment of the RADIANCE material

information for the conducting the daylighting simulation.

5.1.2.2. Difference in the Modeling of Window Pane

There is a difference in the modeling of windows in Revit and RADIANCE. In

Revit the window panes are modeled with a thickness whereas in RADIANCE window

panes are modeled with zero thickness (Figure 5.3). Prior to the new method the existing

method of translating the model using the existing utilities could not automatically

convert window panes as required for RADIANCE simulation. Therefore, manual

adjustment was needed for modeling the windows with the existing methods, which can

be very time consuming.
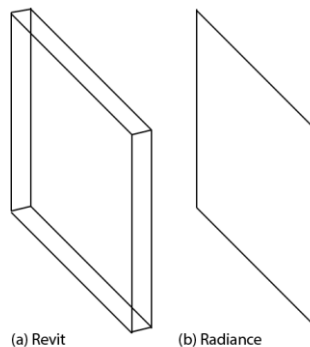
(a) Revit   (b) Radiance

Figure 5.3: Window Pane Modeling Convention (A) Revit Models with Thickness (B)
RADIANCE Model with Zero Thickness. (Source:(Kota et al., 2014))

5.1.2.3. OBJ File Format to RADIANCE File Format

During the translation, some errors were identified while converting an OBJ file format into a RADIANCE file format using OBJ2RAD utility. This was mainly due to an error in the translation by the FBX utility in translating the FBX to OBJ file format. A manual inspection of the OBJ geometry file created by the FBX translator revealed some strange characters in the OBJ input file that was caused during the translation using the OBJ2RAD utility (Figure 5.4).

```
vn  1.000000  0.000000  0.000000
vn -1.#QNAN0 -1.#QNAN0 -1.#QNAN0
vn -1.#QNAN0 -1.#QNAN0 -1.#QNAN0
vn -1.#QNAN0 -1.#QNAN0 -1.#QNAN0
vn -1.#QNAN0 -1.#QNAN0 -1.#QNAN0
vn -1.#QNAN0 -1.#QNAN0 -1.#QNAN0
vn -1.#QNAN0 -1.#QNAN0 -1.#QNAN0
vn -1.#QNAN0 -1.#QNAN0 -1.#QNAN0
```

Figure 5.4: Errors Observed in the OBJ File Format Created by FBX Converter (Source: Author)

5.1.2.4. Multiple Steps from the file format 3DS to the RADIANCE input file Format and the Errors Involved

It was also observed that converting the OBJ and DXF to RAD file format was a one-step process, but converting the 3DS to RAD format was a two-step process. Therefore during the process of converting the 3DS to MGF format using the 3DS2MGF utility, an error occurred resulting in the MGF file not being created (Figure 5.5).

```
DOS Shell Prompt                                                          _|□|×|
C:\radiance\bin\CTF_0320-3DView>3ds2mgf CTF_0320-3DView.3ds  CTF_0320-3DView3.RAD


Autodesk 3D Studio to Raytracer file Translator. Feb/96
Version 2.0 Copyright (c) 1996 Steve Anger and Jeff Bowermaster

Output to: CTF_0320-3DView3.mgf

Please wait; Processing...
Working on: Basic_W2
Working on: Basic_W1
Working on: Basic_W
Working on: Basic_Wall
Working on: Fixed_32
Working on: Fixed_31
Working on: Fixed_3
Working on: Fixed_3_91
Working on: Floor_CSE4
Working on: Basic_Roof
3ds2mgf: unexpected EOF

C:\radiance\bin\CTF_0320-3DView>
```

Figure 5.5: Errors Reported by 3DS2RAD Utility (Source: Author)

5.1.2.5. Successful Path DXF2RAD

The only path that successfully translated the geometry from a Revit model to the

RADIANCE input file (without material definition) was the DXF2RAD translator

(Figure 5.6). Only Geometry Could be Extracted from the DXF File but not Material

Definition.


```
## Radiance geometry file "<stdout>"
## Converted by dxf2rad 0.9: Mon Mar 28 12:02:06 2011
## dxf2rad CTF_0320-3DView.dxf

l_basic_wall_a2b3c2e1_exterior__160749_ polygon l_basic_wall_a2b3c2e1_exterior__160749_.0.1
0
0
9
        0       -6.910156       8.044922
        0       -3       8.044922
        0       0       0

l_basic_wall_a2b3c2e1_exterior__160749_ polygon l_basic_wall_a2b3c2e1_exterior__160749_.1.1
0
0
9
        0       0       20
        0       0       0
        0       -3       8.044922

l_basic_wall_a2b3c2e1_exterior__160749_ polygon l_basic_wall_a2b3c2e1_exterior__160749_.2.1
0
0
9
        0       -6.910156       8.044922
        0       -10     0
        0       -10     20
```

Figure 5.6: The RADIANCE Input File Created from a DXF File Using the DXF2RAD
Utility. (Source:Author)

163

5.1.3. Final Observations and Possible Solutions

Unfortunately, each of the above methods that were explored that used the RADIANCE utility programs had their own limitations. Therefore, numerous steps are involved in the process of translating the Revit model into the RADIANCE input file using utility programs. Furthermore, a geometric reduction needed to be performed due to the difference in the modeling convention followed by the BIM and the daylighting simulation tools that adds the material definitions for the daylighting simulation. These methods require, a thorough knowledge about each of the utility programs to carry out the translation process, a significant challenge for even an experienced architect or a simulation expert.

As the architect iteratively changes the design the whole translation process becomes a tedious task, as each translation involves working with several tools involving multiple steps. Furthermore, the architect cannot study design alternatives quickly due to the laborious process involved in each method. Owing to these reasons, translating the Revit models into the RADIANCE input files (i.e., Geometry and Material information) directly and automatically (i.e., integrating the daylighting analysis into the Revit modeling environment), involving minimal human intervention that produces results in a process that is quick and user friendly is proposed. The development of the prototype is explained in detail in Chapter 6.

6. RAVIT2RADIANCE PROTOTYPE

6.1. Introduction

Based on the problems found with the conventional method (i.e., translating the BIM Revit model into RADIANCE and DAYSIM input file) using RADIANCE utility programs it was clearly evident that developing a prototype that can facilitate the seamless integration of BIM with daylighting simulation tools was necessary. Therefore, for the current study, a new prototype was developed and validated using several building models. To facilitate the automatic data transfer from Revit to RADIANCE and DAYSIM, a prototype Revit2RADIANCE program was developed.

The prototype takes the building information, both geometric and non-geometric such as material properties, from a BIM Revit model and translates it into RADIANCE and DAYSIM input files. Revit offers advanced functionality for accessing the building data using the Revit Application Programming Interface (API). Therefore, the prototype tool advantage of Revit's (API) using the C# programming language.

Revit models have geometry, materials, location, date and time, and camera view data. The prototype extracts these data through the API, formats it, adds other relevant data (i.e., sensor point data) that are not available in the Revit model and generates RADIANCE and DAYSIM input files. In Revit, building geometry information is represented as solids comprised of surfaces. Therefore, the prototype extracts the surface information as triangle meshes. Also, after translating the Revit models into RADIANCE/DAYSIM input files the prototype performs the daylighting simulation and helps visualiz the results without any manual intervention. Several advantages associated

with this method are: 1) It helps avoid errors due to the manual input of the data in preparing the simulation input files; 2) and it makes the process of performing the analysis more user-friendly for the designers (i.e., architects, engineers and students) who are not well acquainted with the usage of daylighting simulation tools.

6.1.1. Add-in Programs

To create the prototype a total of four Revit add-in programs were developed that can automatically translate BIM models into simulation models, simulates the building performance, and generate an analysis result. Table 6.1 shows the add-in programs and the respective tasks they accomplish. Figure 6.1 shows the overall workflow of REVIT2RADIANCE. Figure 6.2 shows the workflow with the add-in programs. In the subsequent sections, each of the add-in programs is explained in detail.

Table 6.1: Revit Add-in Programs (REVIT2RADIANCE modules) for Translating Revit Models into RADIANCE Input Files. (Source:(Kota et al., 2014))

SNo	Name of the Add-In Program	Action Accomplished by the Add-in
1	Parameter File Creation	Creates a default shared parameter file in the project directory for adding shared parameters that are needed for defining building materials in the Add-in #2 below
2	Adding Material Parameters	Adds user-defined shared parameters for building materials that are necessary for holding materials data for RADIANCE models.
3	Reading Material Information	Reads values of the created shared material parameters
4	Model Translator	Translates the Revit model's geometry and material data into RADIANCE and DAYSIM input files and automatically run the simulation programs to generate the results.
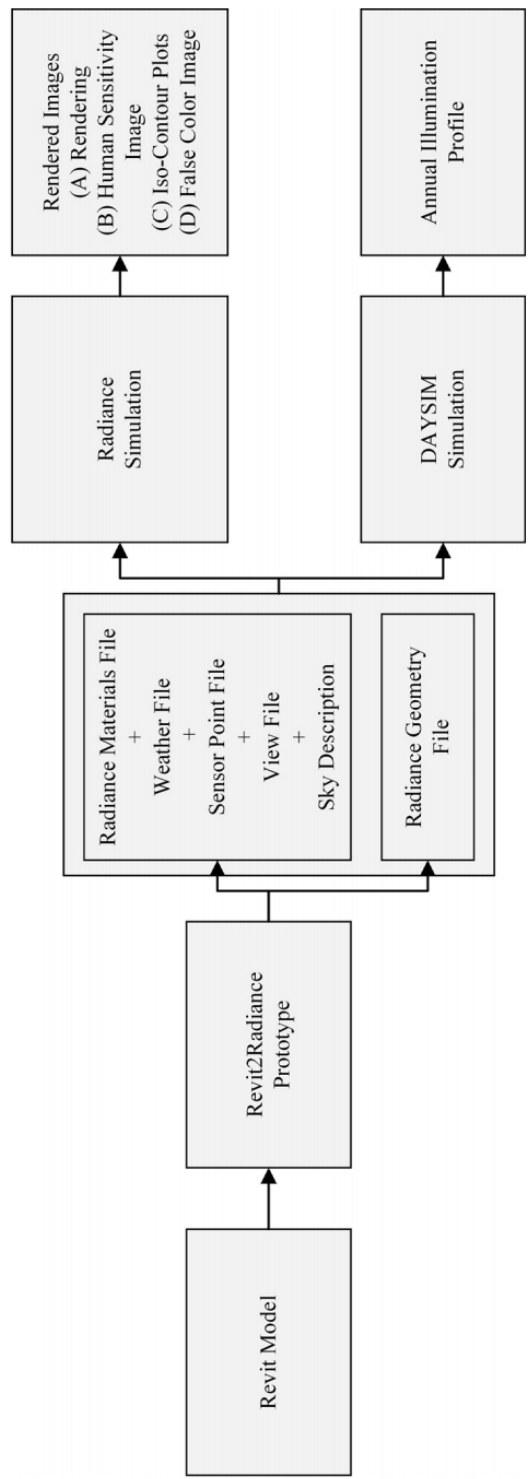
Figure 6.1: REVIT2RADIANCE Workflow (Source:(Kota et al., 2014))
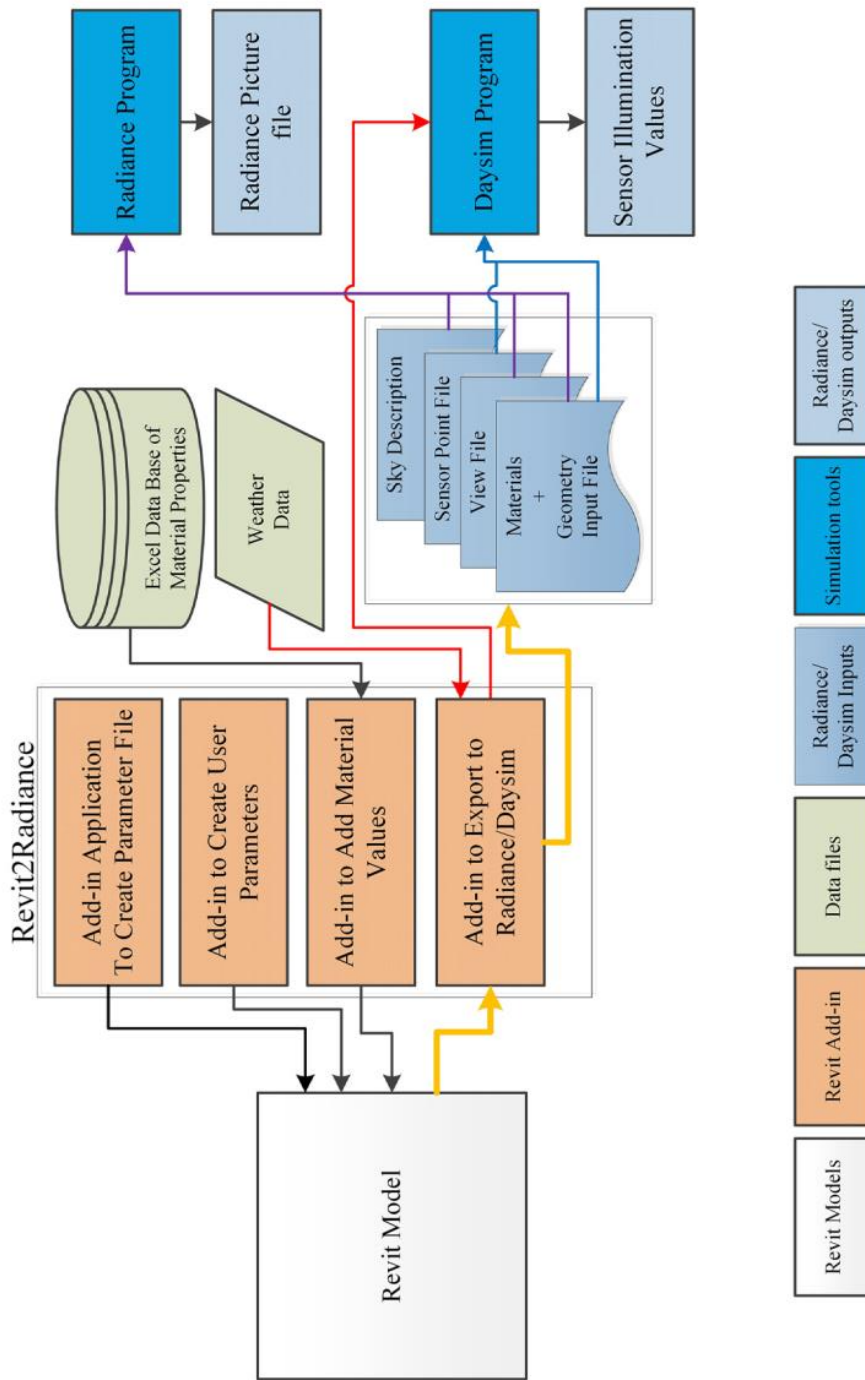
Figure 6.2: The Overall Process of Translating a Revit Model into RADIANCE/DAYSIM Input Files (Source:(Kota et al., 2014))

6.1.2. Parameter File Creation

A Revit model has building geometry and material information associated with the geometry. Materials are assigned to geometry through the Revit material database. The material in Revit has multiple parameters and values assigned to them. For example, one of the material parameters is "color" that gives the color property of the material in terms of the Red, Green, and Blue (RGB) channels (Figure 6.3). In RADIANCE there are different material types (Crone, 1992). One of the basic material types is 'Plastic' that has a color component (i.e., RGB Reflectance), specularity and a roughness information (Figure 6.4). The color is defined by Red, Green and Blue reflectance values (Crone, 1992). The color information of the Revit materials was used to obtain the reflectance value for the RADIANCE materials. Given the color values in the RGB of a surface it is possible to compute the reflectance of the material through a brightness formula (Equation 6-1).
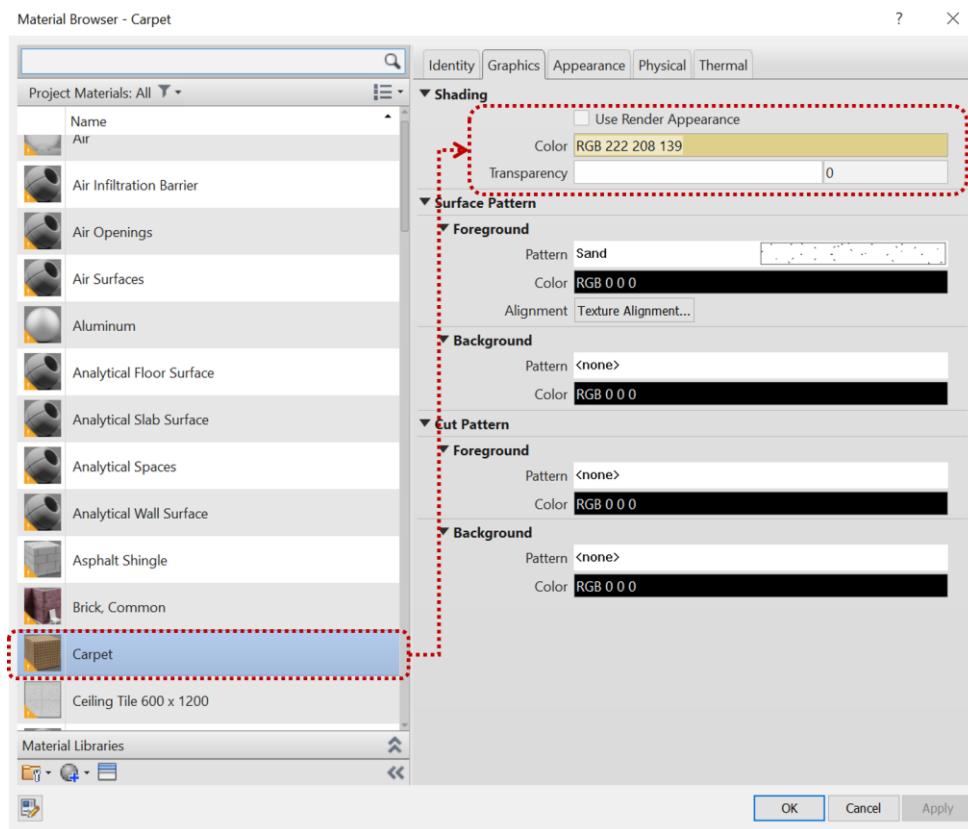
Figure 6.3: Revit Material Database and Material Color Properties (Source: Author)
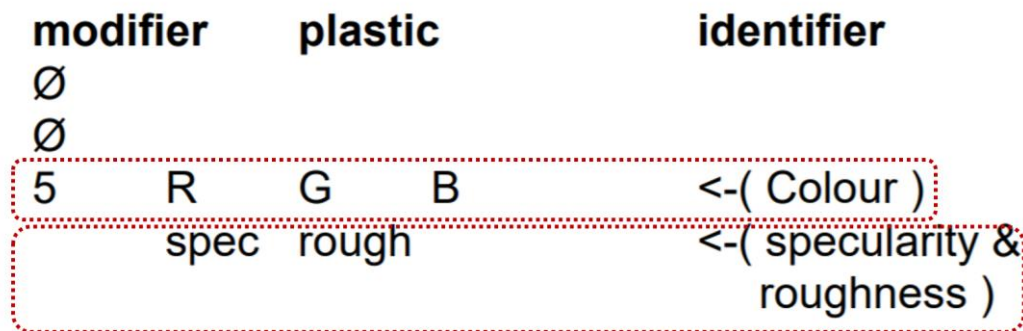
Figure 6.4: RADIANCE Plastic Material Specification Color (RGB) and Specularity and Roughness (Source: Crone (1992))

The Average Reflectance value is computed using the following formula (Equation 6-1) for the standard RADIANCE R, G, and B components of the reflectance (Ward, G. and Shakespeare, 1998)

$$Average\ Reflectance = 0.256 * R + 0.670 * G + 0.065 * B$$

Equation 6-1

where R, G, and B are normalized values. For this prototype, the default Revit material R, G, and B values were used (in the range of 0–255), normalized, and used to calculate Average Reflectance using the above equation (Equation 6-1). In the new method the same Average Reflectance was used as the RADIANCE RGB values for calculating the illumination levels and rendering grayscale images in RADIANCE. The rendered grayscale images can help visualize the illumination levels without the effects of chromaticity. For rendering color images, Equation 6-1 does not need to be called by REVIT2RADIANCE and the normalized Revit RGB, instead the Average Reflectance value, will be used as the RADIANCE RGB. In addition, if the users intend to use a measured RGB value of a material instead of the default values in Revit, they can modify the values in Revit.

6.1.2.1. Adding RADIANCE Specularity and Roughness Information

Revit materials do not have specularity and roughness values that are necessary for a complete RADIANCE material description. Therefore, it is necessary that these values be first added to each material in the Revit material database. Revit offers the functionality for adding user-defined parameters called custom parameters. In the

present project this functionality was used through API programming to add specularity

and roughness parameters to each Revit material. In order to add user-defined

parameters, a shared parameter file must be created first for all the parameters. The first

add-in program creates this shared parameter file.

6.1.3. Adding Material Parameters

Once the default shared parameter file is created, the second add-in program

"Adding Material Parameter" adds the two custom parameters "Specularity" and

"Roughness" to the model that then appear in the custom parameter list of each material

in Revit (Figure 6.5).

6.1.4. Reading Material Information

As described briefly in the earlier Section 6.1.2 "Parameter File Creation",

RADIANCE materials have reflectance, specularity and roughness values. Reflectance is

defined with individual channel reflectances (i.e., red-reflectance, blue-reflectance and

green reflectance) along with specularity and roughness. Specularity and roughness

values must be added to the parameters created for each Revit material (i.e., adding

appropriate values to the shared parameters for each material). In order to ascertain
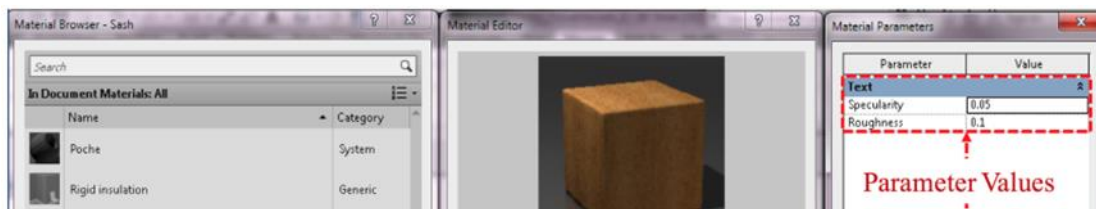
Figure 6.5: RADIANCE Material Parameters Added to Revit Materials Using Custom
Parameters (Source:(Kota et al., 2014))

specularity and roughness values for Revit materials, the Revit materials were compared

with similar material types for the RADIANCE material data that are available from

different databases. The specularity and roughness values of these RADIANCE

materials were then adopted for Revit materials. Finally, a list was created in an Excel

spreadsheet containing Revit material names with their corresponding specularity and

roughness values taken from RADIANCE materials.

The "Reading Material Information" add-in program reads the Excel database

file containing the specularity and roughness values (Figure 6.6) and assigns these values

to the custom parameters created for each material in the earlier steps. At this point each

material in the Revit material database has all the necessary information that can be

translated into a RADIANCE material description.

Revit Material	Radiance Properties	
	Specularity	Roughness
Asphalt	0.05	0.1
Roofing-asphalt Shingle	0.05	0.1
Site - Asphalt	0.05	0.1
Masonry - Brick	0	0.1
Masonry - Brick Soldier Course	0	0.1
Masonry - Tile	0	0.1

Figure 6.6: Excel Database File Containing the Specularity and Roughness Values of
Different Revit Materials (Source: Author)

6.1.5. RADIANCE Sky Model and View Description

RADIANCE requires a sky, a view and a scene description. There are different

ways a sky description can be modeled in RADIANCE. For example, providing the

latitude, longitude, and time of the day, the RADIANCE utility Gensky[23] can create a

sky description. In Revit, each view has sun setting parameters, that also provide access

to location (latitude and longitude) information and the time of the day (month, day, and

hour) for shadow calculating and image rendering purposes (Figure 6.7). For the present

prototype, this information is accessed, formatted, and provided to the Gensky program

to create the sky description by the new prototype. Similarly, the camera view

information is translated from BIM into a RADIANCE view description that is

necessary to produce RADIANCE images that can be post-processed for different

analyses using RADIANCE utility programs.
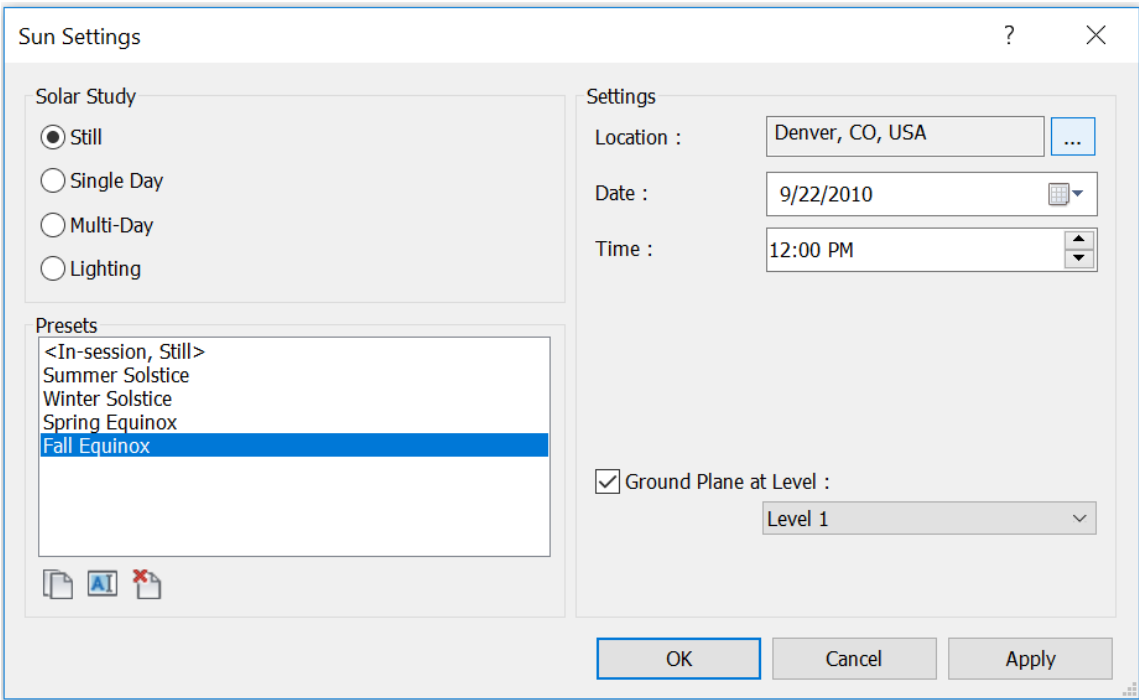
Figure 6.7: Revit Sun Setting Parameters for Each View (Source: (Autodesk, 2013))

---

[23] https://floyd.lbl.gov/radiance/man_html/gensky.1.html

6.1.6. Sensor Point Description

In RADIANCE the simulation results can be displayed as images, numerical values, or illumination contour plots. Apart from producing an image that has the photometric information for a given camera view and scene description, RADIANCE can also compute lighting levels at a specific location inside a given space by specifying a sensor point. The sensor point is specified by giving the X, Y and Z coordinates and view directions that report the illumination levels calculated by RADIANCE. For the new prototype, a sensor object was created as a custom Revit family that the user can place inside or outside of the building to compute the illumination levels (Figure 6.8). The new prototype automatically translates the coordinates of the sensor locations into the sensor points coordinates for both RADIANCE and DAYSIM.
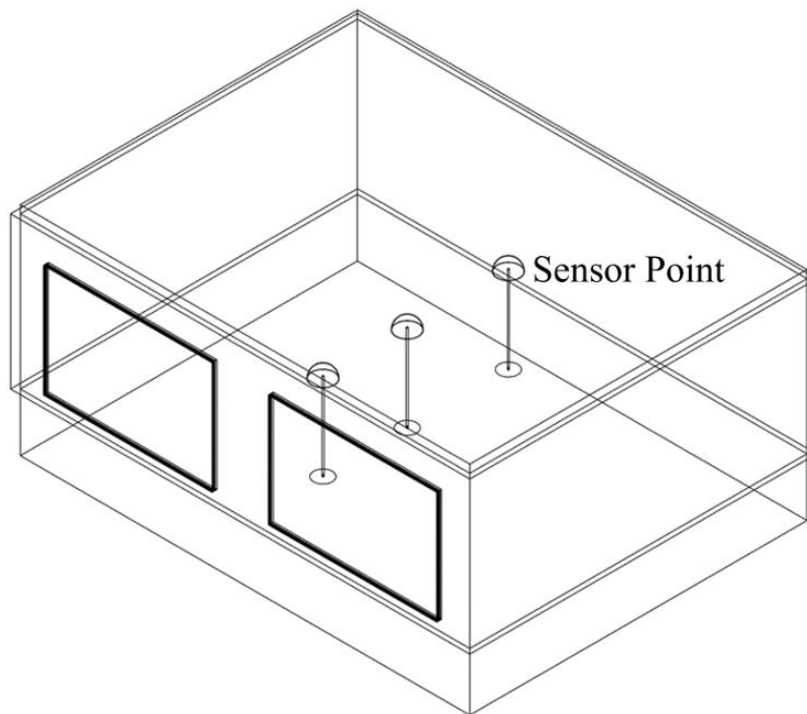
Figure 6.8: Custom Revit Family Used as Sensor Object (Source:(Autodesk, 2013))

6.1.7. Weather file for DAYSIM

A DAYSIM daylighting simulation uses a different sky description program called Gendaylit, that uses a weather file to generate a sky description for the annual daylighting analysis based on the Perez all-weather sky model (Reinhart and Walkenhorst, 2001). DAYSIM uses the EnergyPlus weather data format, that is readily available for many different locations throughout the world. In the present project, the EnergyPlus weather file is formatted automatically into the DAYSIM weather format by the epw2wea[24] program that comes with DAYSIM installation.

6.1.8. Model Translator

The main add-in program of the new prototype is the Model Translator. It translates the project information, including: geometry, materials, weather, location, date and time, and sensor point data into the proper format for RADIANCE/DAYSIM input files. The following are the input files created and organized into a project folder structure created by Model Translator routine (Figure 6.9). The RADIANCE material file, that has the RADIANCE material descriptions is translated from the Revit materials file.

1. RADIANCE geometry file, that has the RADIANCE geometry description translated from the Revit model geometry.

2. A RADIANCE camera view file for generating RADIANCE images.

3. The RADIANCE sky description files.

4. A weather file required by the DAYSIM program.

---

[24] https://www.radiance-online.org/learning/documentation/manual-pages/pdfs/epw2wea.pdf/view

5. Two batch files, that have RADIANCE and DAYSIM commands to sequentially

execute the RADIANCE and DAYSIM routines to produce the results

The Model Translator also runs the batch files that automatically launches both the

programs. Once the simulations are complete all the results are automatically written to a

folder in the project directory (Figure 6.9).

6.1.9. Window Glass Pane Translation

One of the challenges encountered in translating the geometry of BIM models

into the RADIANCE input file format is the translation of the window glass panes. BIM

represents building geometry as surfaces or solids that can have multiple surfaces

depending on the shape or the geometry of the surface (Figure 6.10A) show a solid of a

window pane).

The Model Translator add-in converts each surface of a solid into a RADIANCE

geometry surface with material information attached to it. In Revit, window panes are

mostly cuboids of 6 surfaces with two of the surfaces representing the outside and inside

surfaces of a single pane of glass and other four representing the sides of the glass pane

(Figure 6.10B). Unfortunately, translating the window glass pane solid into 6 individual

glass panes will lead to a wrong model in RADIANCE because RADIANCE would

create internal reflections of light among the 6 surfaces of the glass pane. In

RADIANCE the window should be represented as a single surface without any thickness

(Figure 6.10C). To represent the Revit window glass pane correctly with a RADIANCE

window model (i.e., from Figure 6.10A to C) only one surface of the Revit glass pane

177

has to be translated. Therefore, an algorithm was developed to translate only one surface (i.e. the front surface of the glass pane) into a RADIANCE glass surface.
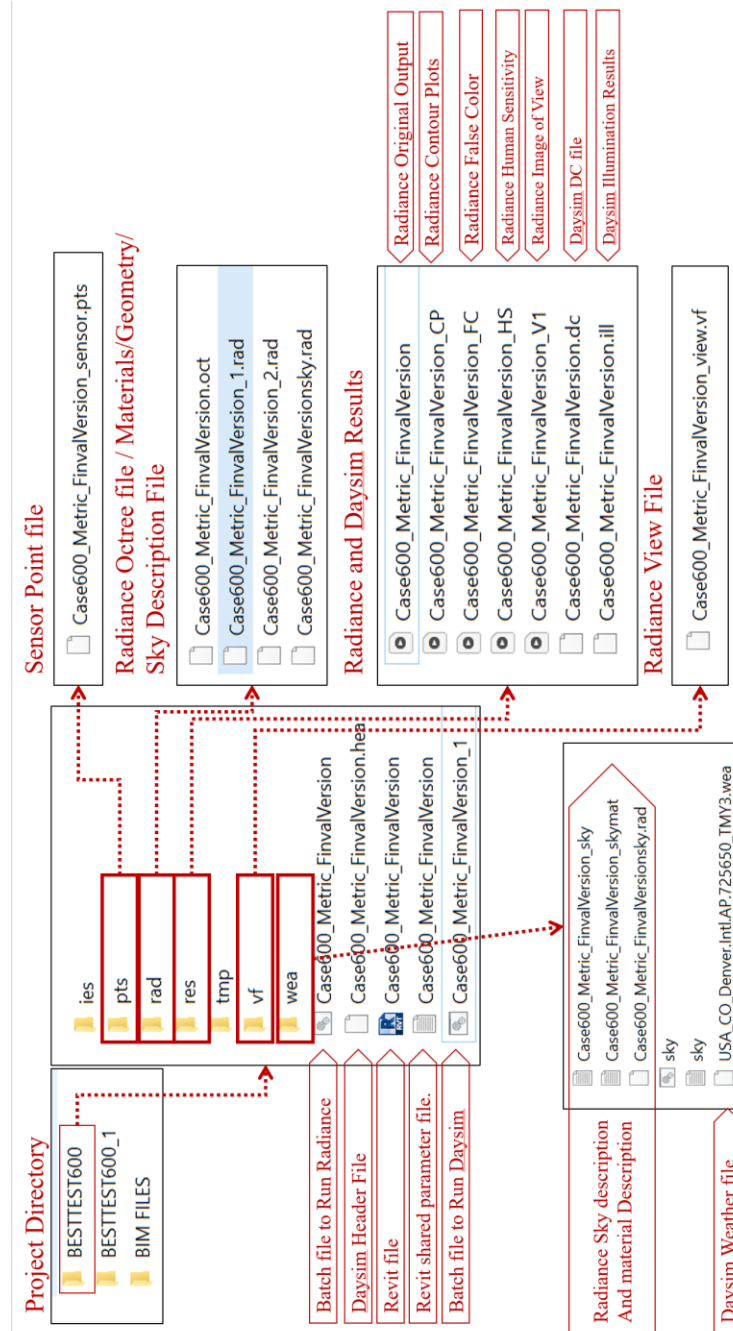
Figure 6.9: Input and Output Files Created by Model Translator Add-in (Source: Author)

178
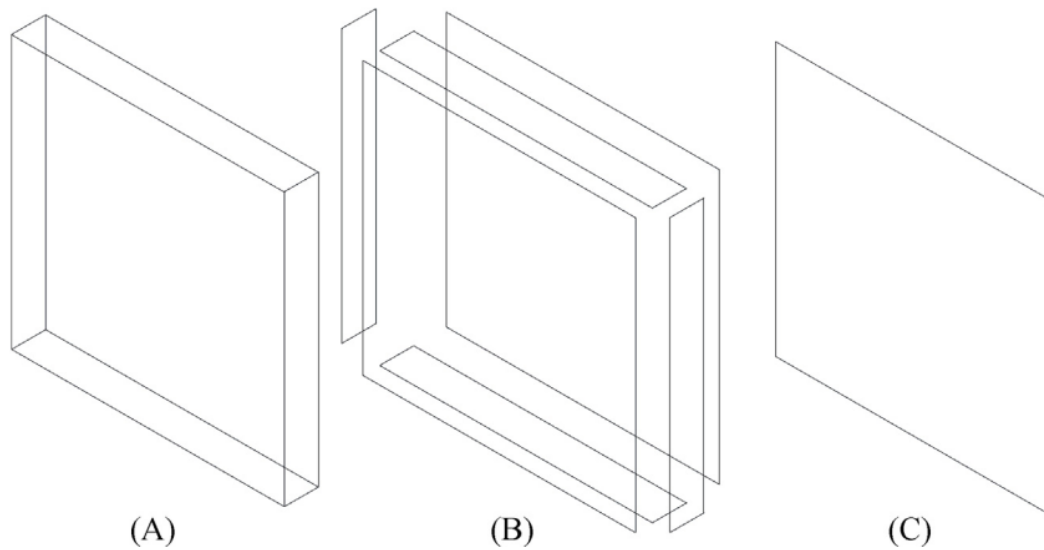
Figure 6.10: Window Pane Representation: (A) A Solid Representing a Window Pane in a Revit Model; (B) Six Individual Surfaces of the Solid in Revit; and (C) RADIANCE Representation of the Window Pane, that is one Surface Without Thickness (Source:(Kota et al., 2014))

6.1.10. Running the Prototype (Revit Add-in programs)

In order to perform the daylighting simulation, Add-in programs need to be loaded into Revit and accessed under the "External Tools" menu. Figure 6.11 shows the Add-In Manager with all the Add-in programs loaded. The sequence (a–e) shows the steps to load the programs and the sequence (1–4, displayed alphabetically based on the program names in the Add-In Manager) shows the order of execution of the programs to perform BIM-based daylighting analysis. Once the main program (4) is executed, the Revit model is translated into RADIANCE and DAYSIM input files, and RADIANCE and DAYSIM programs are launched automatically to perform the daylighting simulation (Figure 6.12).
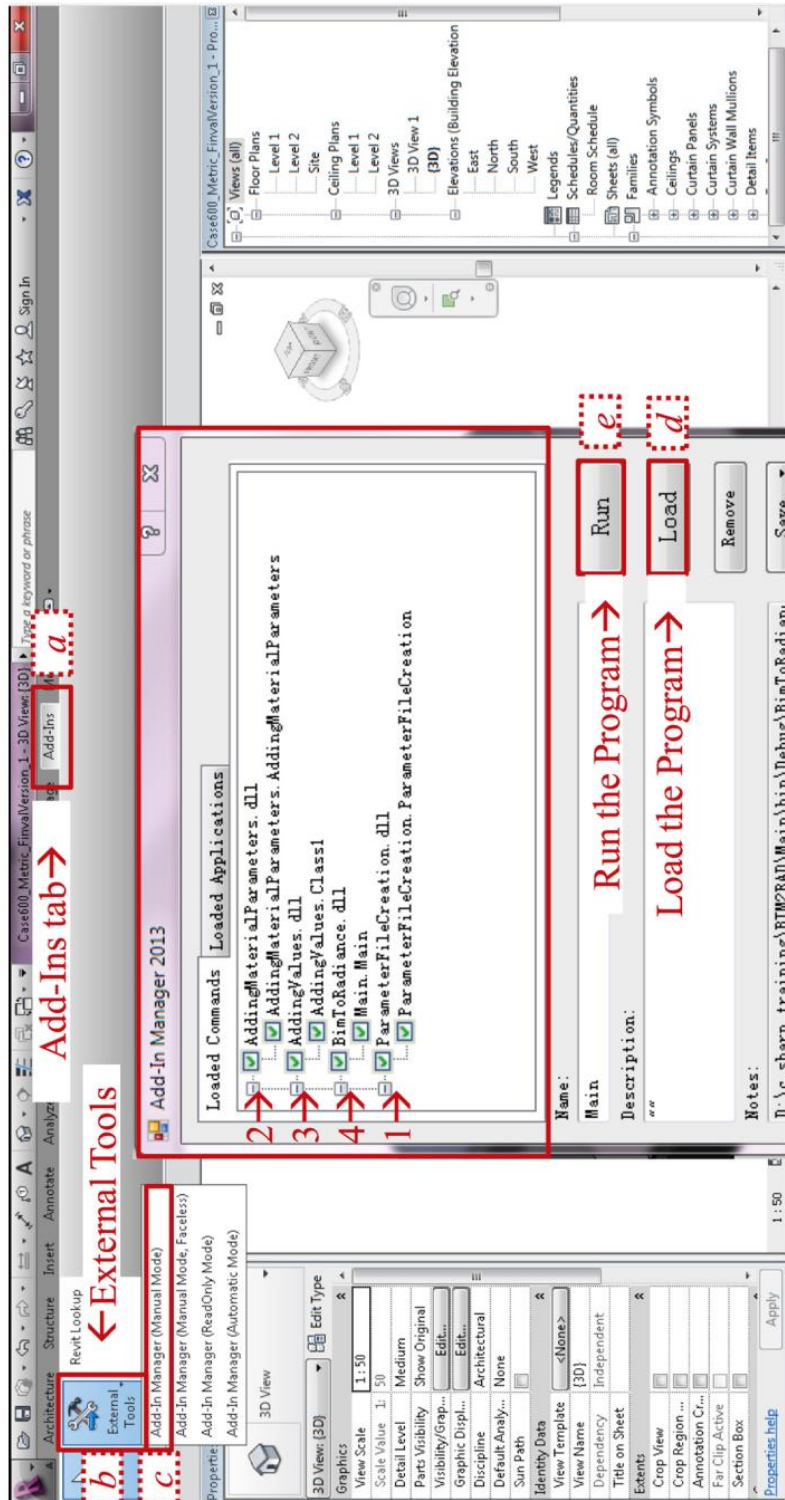
Figure 6.11: Launching the REVIT2RADIANCE Prototype (Source:(Kota et al., 2014))
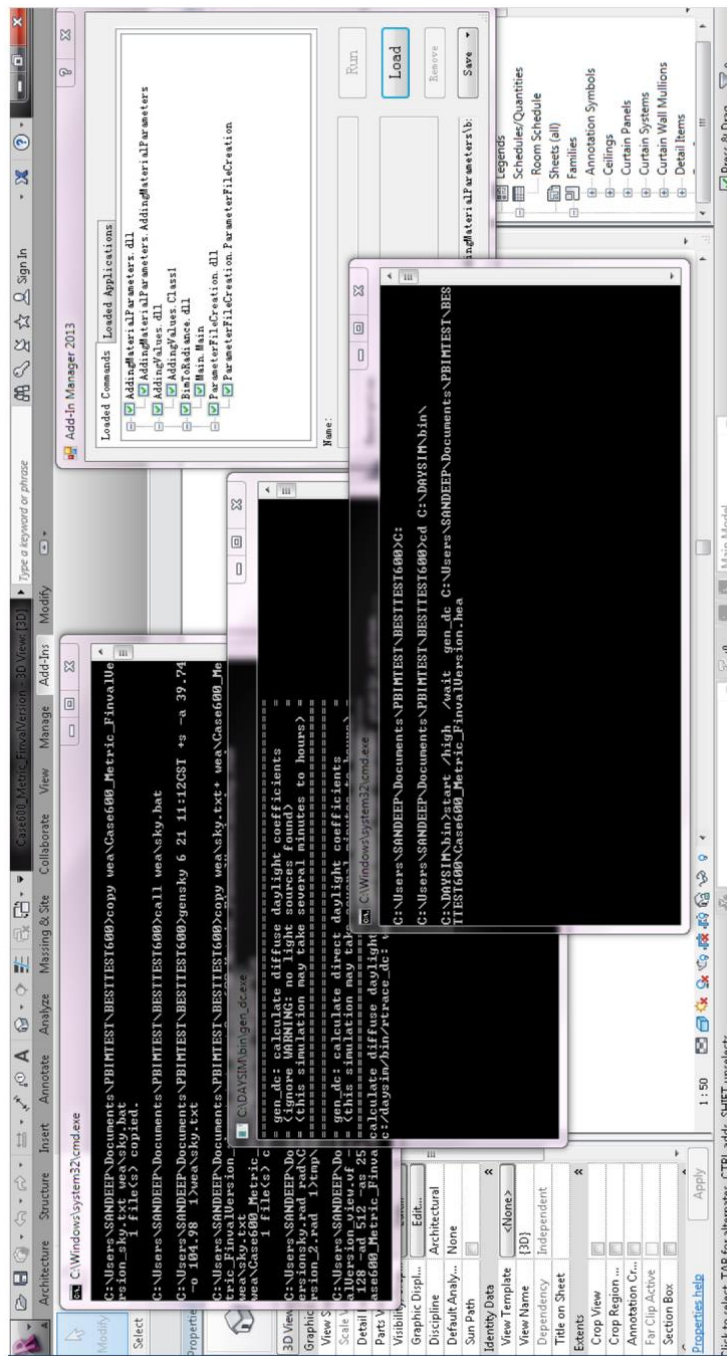
Figure 6.12 Daylighting Simulation in RADIANCE and DAYSIM Based on a BIM
Model. The RADIANCE Commands are Executed Automatically by the
REVIT2RADIANCE Add-ins (Source:(Kota et al., 2014))

7. VALIDATION OF THE NEW PROTOTYPE

7.1. Test cases and validation

Two test cases were simulated to validate the integration of BIM-to-daylighting

simulation tools (i.e., REVIT2RADIANCE prototype). The validation focused on the

accurate translation of the geometry, material data, daylighting simulation and

generation of the outputs. The first test case was BESTTEST Case 600 building model

that has been used for validation of the BIM-based thermal analysis tools developed as a

part of PBIM project (ASHRAE, 2014). The second case was a Revit model of the

Stanford Solar-decathlon 2013 house that is considerably more complex that the simple

BESTTEST Case 600 building model (ASHRAE, 2014).

7.1.1. BESTTEST Case 600 and validation

For testing the prototype, a BESTEST Case 600 building's BIM model was

created in Revit (Figure 7.1). The reason for using this building for testing is that the

same BIM model of the building can be used for testing the translations from BIM to

both thermal and daylighting simulations, while the thermal simulation results can be

validated with the benchmark results (Yan et al., 2013). Figure 7.1 shows the 3D BIM

model, the floor plan, section view, the window locations, and the placement of the

daylight sensors. Table 7.1 provides the project and material description, that are used

for the RADIANCE and DAYSIM simulations. Table 7.2 provides the RADIANCE

RPICT rendering setting options. These values are the default values used by the

prototype for RADIANCE image-based rendering. The values for each parameter are

given in literature[25] of the RADIANCE which yields reasonably accurate simulation.

The weather location used for the simulation is Denver, Colorado. The sky description

used is for summer solstice (June 21st) with the sun option turned on in the Gensky

program. The time for the simulation in RADIANCE was set to 12:00 Noon.
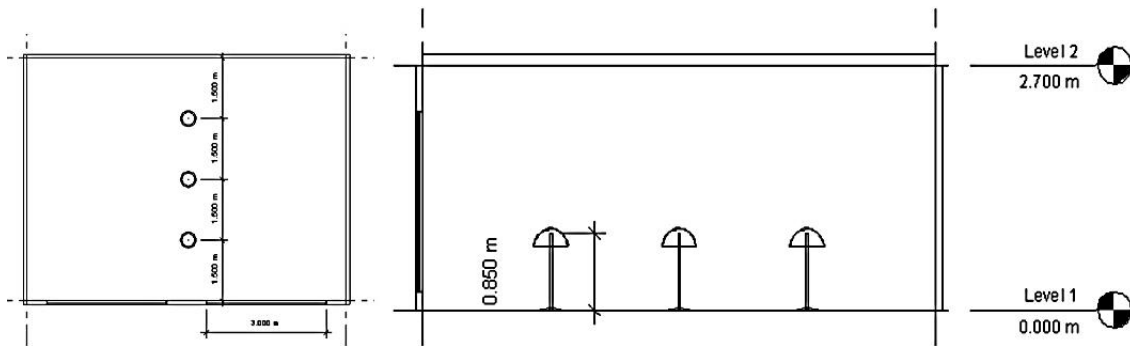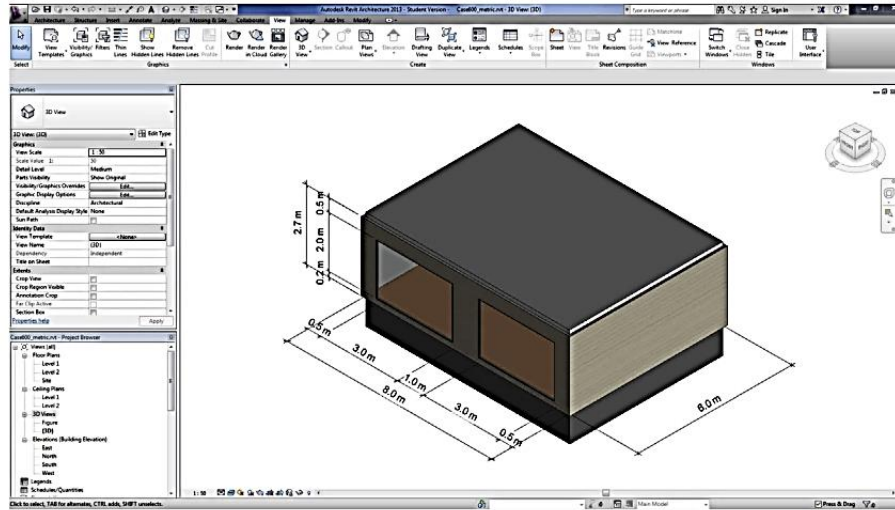
Figure 7.1: BESTEST Case 600 BIM: 3D, Floor Plan, and Section Views of the Model
Showing the Dimensions of the Room, the Locations of the Windows, and the Sensors
(Source:(Kota et al., 2014))

---

[25] https://floyd.lbl.gov/radiance/refer/Notes/rpict_options.html

Table 7.1: Project and Material Description (Source:(Kota et al., 2014))

Building parameters	Values
Location	Denver, CO
Length of the room	6 M
Width of the room	8 M
No. of windows	2
Dimensions of windows	$3\,M \times 2\,M$
Wall reflectance	0.5
Floor reflectance	0.2
Roof/ceiling reflectance	0.8
Window transmittance	0.75

Table 7.2 Rendering Settings adopted for REVIT2RADIANCE prototype for RADIANCE Simulation.

Param	Description	Value
-ps	pixel sampling rate	4
-pt	sampling threshold	0.05
-pj	anti-aliasing jitter	0.9
-dp	direct pretest density	512
-ab	ambient bounces	2
-aa	ambient accuracy	0.15
-ar	ambient resolution	128
-ad	ambient divisions	512
-as	ambient super-samples	256
-lr	limit reflection	8
-lw	limit weight	0.002

The results of the experiment include the results of the RADIANCE and DAYSIM programs. The results from the RADIANCE program are primarily images, that have photometric data. The results of the DAYSIM program are the calculated annual illumination data. The simulation results are then written into a result folder in the project directory. The RADIANCE image generating utility program takes the geometry and materials files, the sky description file, and the view description to generate an image of the room (Figure 7.2A) that shows the illumination levels. Once the image was generated, three images are generated from the first image by post-processing: (1) the human sensitive image (Figure 7.2B), (2) the iso-lux contour plot (Figure 7.2C), and (3) the false color image (Figure 7.2D). Similar to RADIANCE, by taking the geometry, material, weather, and sensor point files, DAYSIM performs an annual illumination simulation at the specified sensor points. An annual illumination profile file (*.ill) is then written into the project folder. Figure 7.3 gives the annual illumination profile of the DAYSIM results.

For the present prototype REVIT2RADIANCE, a validation study was conducted. The validation study was not intended to find the absolute accuracy of the simulation results since the simulation engines RADIANCE and DAYSIM have already validated in other research (Mardaljevic, 2000a; Reinhart and Walkenhorst, 2001). Instead, the aim of the validation was to ascertain that the automatically-translated Revit model geometry and material information was accurately translated into the RADIANCE/DAYSIM input file having the geometry and material data for performing the daylighting simulation.

185
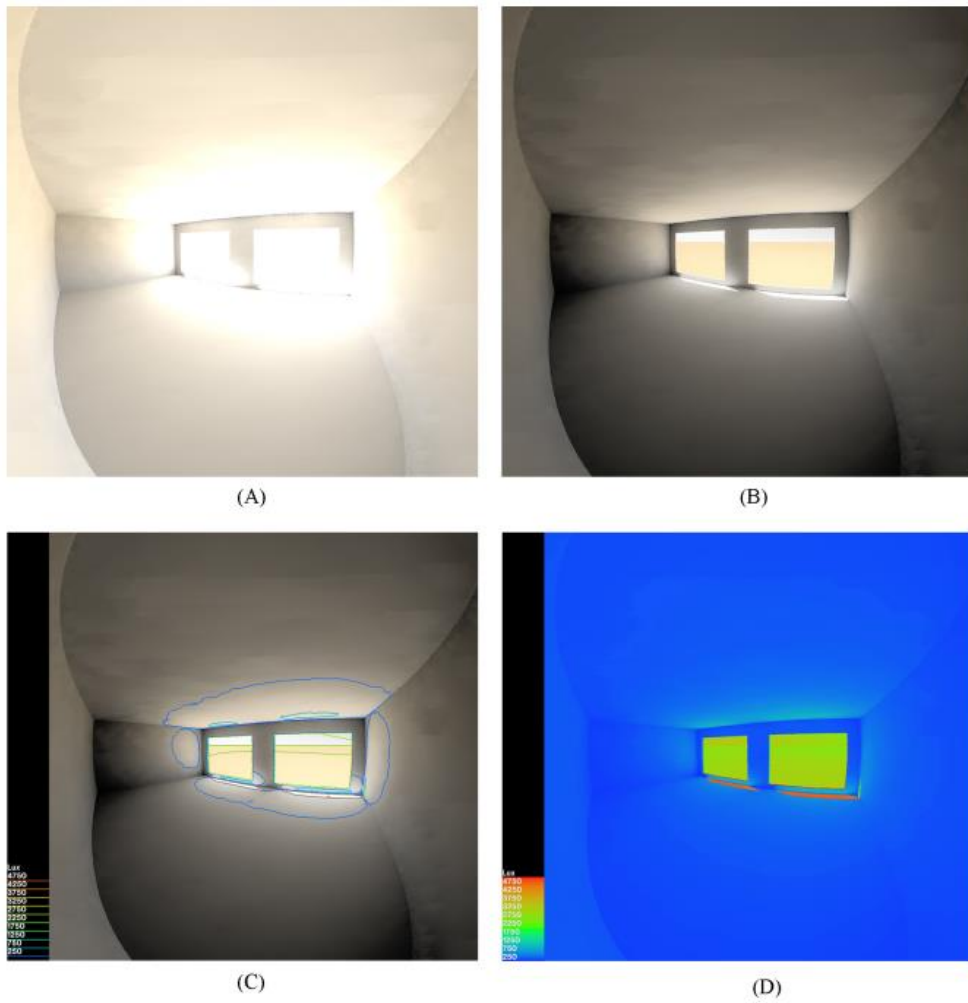
Figure 7.2: RADIANCE Simulation Results: (A) Rendering, (B) Human Sensitivity Image, (C) Iso-Contour Plots, and (D) False Color Image Showing Illumination Levels. (Source:(Kota et al., 2014))
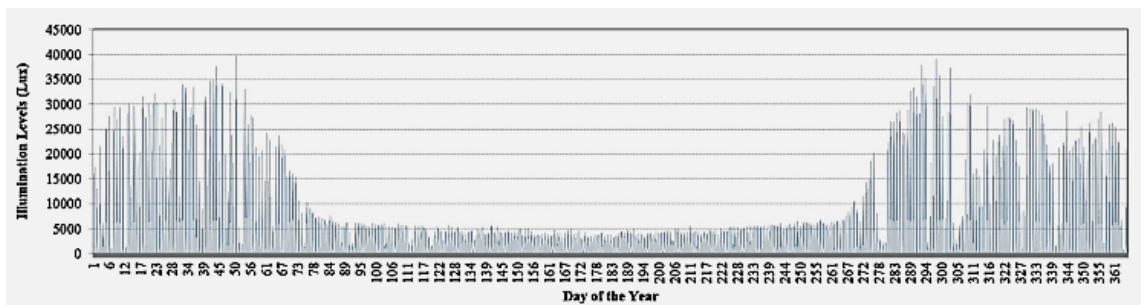
Figure 7.3: Annual DAYSIM Illumination Profile at a Sensor Point (Source:(Kota et al., 2014))

To begin with a visual comparison was performed to check the accuracy of the geometry translation. To accomplish this the RADIANCE model, that is generated by our REVIT2RADIANCE, was visualized using the RVIEW program. The view generated by the RVIEW program exactly matches the Revit model showing the accuracy of the geometry translation (Figure 7.4). Figure 7.5 shows the Revit material properties for a material "Sash". REVIT2RADIANCE uses the Revit RGB values and computes the Average Reflectance value using Equation 6-1. As described in Section 3.1, the reason for using the same Average Reflectance for all RADIANCE RGB components is to render a grayscale image in order to visualize only the illumination levels. (For rendering a color image, Equation 6-1will not be used by REVIT2RADIANCE). REVIT2RADIANCE also takes the custom parameter values "Specularity" and "Roughness" to write the RADIANCE material description. Table 7.3 shows the manually calculated values for the Average Reflectance for Revit material "Sash" and Figure 7.6 shows the prototype output of the RADIANCE material descriptions. Both the prototype-generated Average Reflectance (0.73 for RGB components) and the manually calculated Average Reflectance (0.73) match exactly. Also, the "Specularity" and "Roughness" values were passed from the Revit material to the RADIANCE material correctly. This is a sample comparison that validates the accuracy of our material translation.
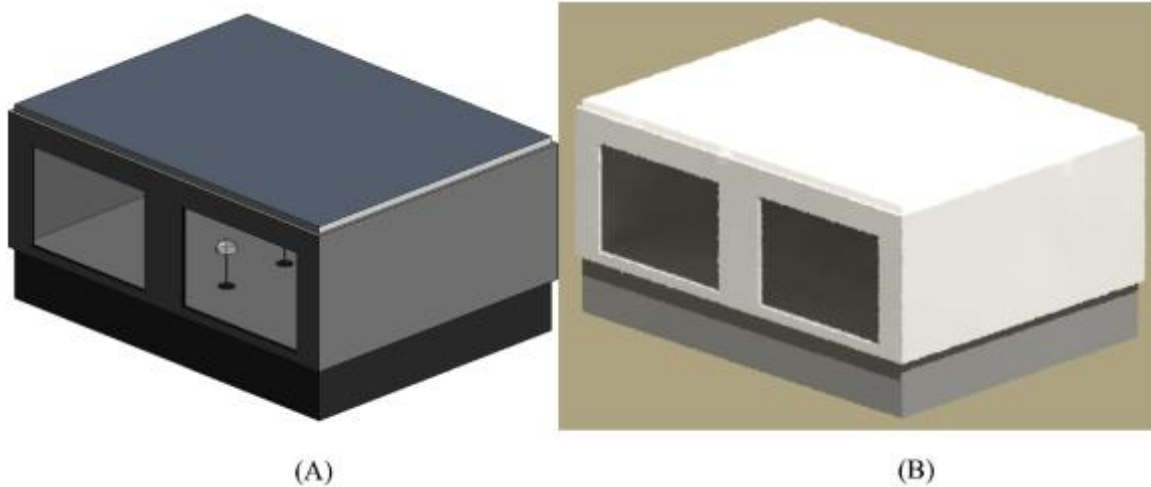
Figure 7.4: (A) The Revit Model and (B) RVIEW Visualization of the RADIANCE
Model Translated from the Revit Model (Source:(Kota et al., 2014))
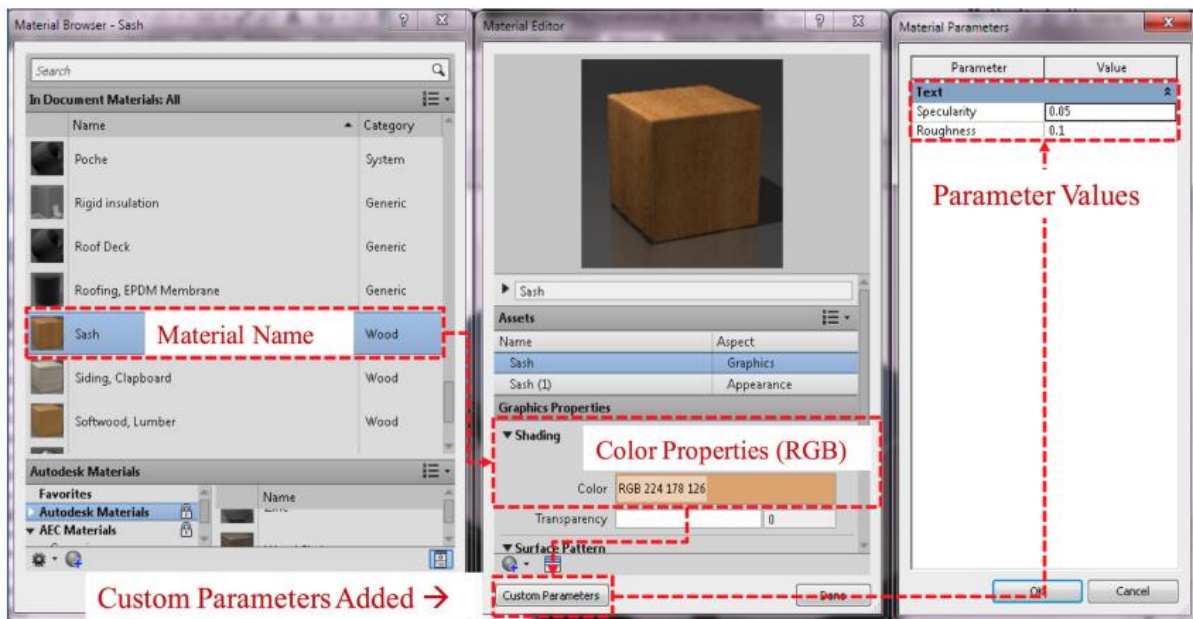
Figure 7.5: Revit Material Information for "Sash" with Custom Parameters "Specularity"
and "Roughness" (Source: Author)

Table 7.3: Manually Calculated Average Reflectance for the Material "Sash" (Source:(Kota et al., 2014))

Color channels	Red	Green	Blue	Average
Value	224	178	126	Reflectance
Normalized value (value/255)	0.878	0.698	0.494	
Color coefficients (from Eq. (1))	0.265	0.670	0.065	
Normalized value × coefficients	0.233	0.468	0.032	**0.73**

Radiance Material Output

void plastic Sash

0

0

5 0.73 0.73 0.73 0.05 0.1

Figure 7.6 REVIT2RADIANCE Prototype-Generated RADIANCE Material Description for Revit Material "Sash" (Source:(Kota et al., 2014))

7.1.2. Test Case 2 and Validation (Stanford University Solar Decathlon House)

The prototype was also tested on a complex case study to check the accuracy in translating the geometry for performing the daylighting simulation. The test case for this was the Stanford University Solar Decathlon 2013 house project[26], the Revit model of that was provided to us by the project team (personal communication). Figure 7.7A shows the floor plan and 3D views of the house. The main hall of the house has windows on the north wall, that are clearstory windows (Figure 7.7B) and the curtain panel

---

[26] http://solardecathlon.stanford.edu

windows on the south wall (Figure 7.7C). Table 7.4 gives the reflectance of different

building elements and visible transmittance of windows. Both renderings and annual

illumination profiles were produced correctly using REVIT2RADIANCE.
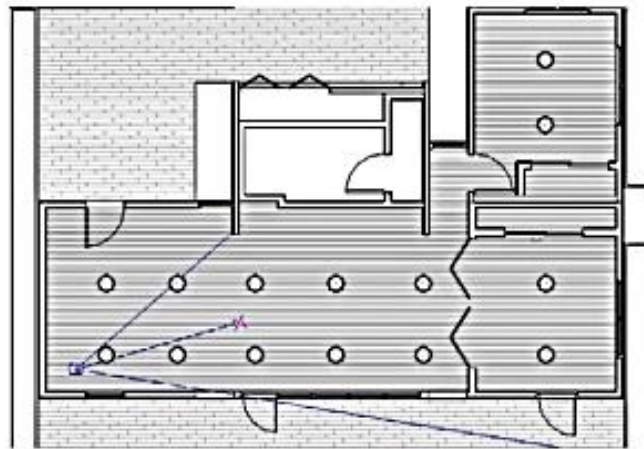
(A)
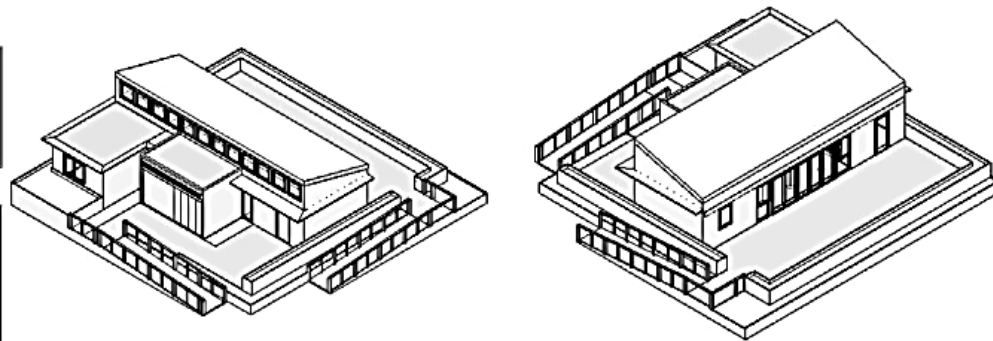
(B)   (C)

Figure 7.7: (A) Floor plan of the Stanford Solar-decathlon 2013 House Showing the
Camera Location and Direction and the Sensor Point Location; (B) North-west Isometric
3D View Showing the Clear Story Windows on the North Wall; and (C) South-West
Isometric 3D view Showing The Curtain Panel Windows on the South Wall. (Source of
images: Stanford University Solar Decathlon 2013 project team.
http://solardecathlon.stanford.edu).

Table 7.4: Surface Reflectance's of the Different Building Elements. (Source:(Kota et al., 2014))

Building Element	Reflectance/Transmittances
Walls	0.5
Floor	0.2
Roof	0.8
Clearstory window transmittance	0.8
Curtain Panel Window Transmittance	0.7
Southern side Window Transmittance	0.7

The accuracy of translating the model was also tested. Once the RADIANCE file is generated by REVIT2RADIANCE, the RADIANCE model is viewed in the RVIEW program and is visually compared with the view of the BIM model. Figure 7.8 (A and C) show the BIM model views and Figure 7.8 (B and D) show the RVIEW views of the RADIANCE input file generated by REVIT2RADIANCE. A visual inspection shows it can be concluded that the automated prototype is accurately translating the BIM model geometry and material information into the RADIANCE geometry and material data input file. Figure 7.9(A–C) show the RADIANCE simulation results of the Solar Decathlon house.
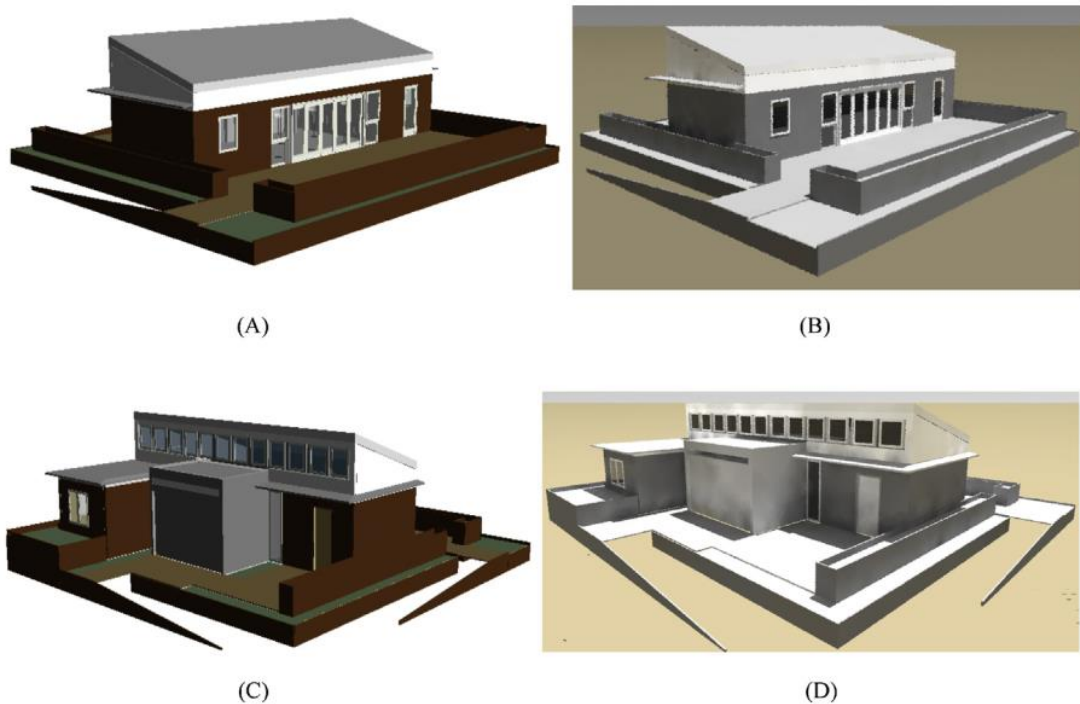
Figure 7.8: (A) The Southwest View of the Stanford 2013 Solar Decathlon House BIM Model; (B) the Southwest View of RVIEW Rendering of the RADIANCE Input File Generated by REVIT2RADIANCE; (C) the Northwest View of the BIM Model; and (D) the Northwest View of RVIEW Rendering of the RADIANCE Input File Generated by REVIT2RADIANCE. (Source:(Kota et al., 2014))
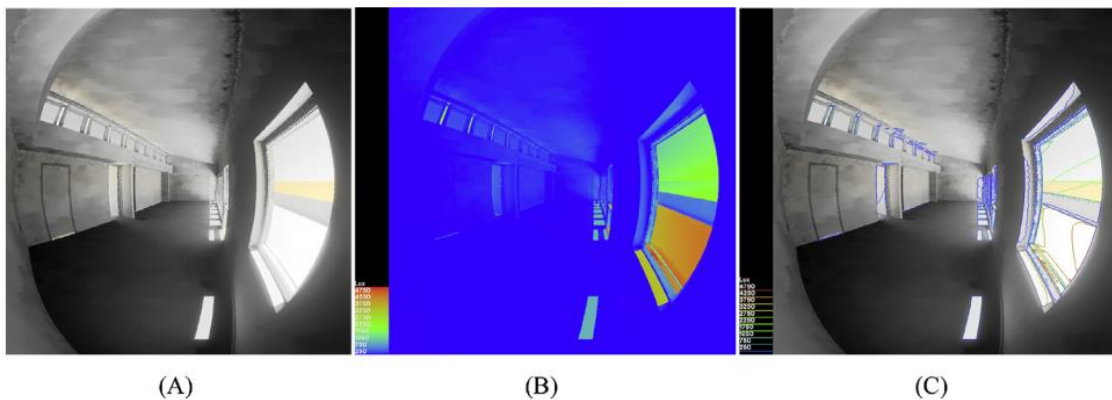
Figure 7.9: RADIANCE Simulation Results of the Solar Decathlon House: (A) Human Sensitivity Image; (B) False Color Image; and (C) Iso-Lux Contour Plot (Source:(Kota et al., 2014))

192

8. SUMMARY AND RESEARCH FINDINGS

8.1. High Efficiency and Accuracy

This research presents a method to directly integrate a BIM-authoring tool with daylighting simulation tools. The prototype directly creates RADIANCE and DAYSIM input files from the Revit models through automated steps with high efficiency and accurate translation of BIM geometry and material data. In addition, the prototype is intended to be an easy-to-use tool for architects and designers without requiring in-depth knowledge of how to operate the simulation tools.

8.2. Missing Information

The research has identified that a BIM does not have all the information that is necessary for creating the simulation input files for RADIANCE and DAYSIM; however, it provides options to incorporate the required information.

8.3. Variations in Geometry Representation

The research has also identified that the representations of the same building elements are not the same between Revit, RADIANCE and DAYSIM. For example, a glass pane, that is represented with a thickness in Revit, has to be represented as a surface without a thickness in RADIANCE and DAYSIM.

8.4. Validation of the Prototype and Parametric Simulation Capabilities

The prototype has been validated for the accurate translation of the geometry using two test cases. With the parametric change capability of BIM, it will be easier for the architects and designers to use the new tool to quickly to study different daylighting options since it provides a seamless link between Revit and RADIANCE/DAYSIM. The

integration of daylighting analysis into the BIM environment helps in making an informed design decision in the schematic stages of building design.

8.5. Limitation of the Study

The current method depends upon Revit and thus lacks the format neutrality of using IFC. Even though IFC data schema is being promoted and developed to facilitate interoperability among different BIM-based programs, it is thought to be complex to program and implement in software (Dong et al., 2007). Nonetheless, the IFC is considered to play an important role in the translation from a BIM to energy simulation (Bazjanac, 2008). The IFC approach has benefits compared with the approach adopted in this study as it can facilitate the data transfer between different IFC compatible tools. The major limitation of the present method is that this prototype works only with Revit. Therefore, additional effort would be needed for it to work with other BIM authoring tools such as Microstation V8 (Conforti, 2010) and ArchiCAD (Fischer & Golubkow, 2010). However, the concept and methodology developed in this study can be applied to any BIM-authoring tool that support API programming.

8.6. Future Work

8.6.1. Integration with BIM Based Thermal Simulation

An extension of the present research could be to study the effect of daylight on the electric lighting integrated into the BIM environment. Yan et al. (2013) demonstrated the integration of thermal performance analysis with Revit using a Modelica-based thermal simulation engine. The next step could be integrating the results of these two

194

performance simulations (thermal and daylighting) for multi-physics design optimization.

8.6.2. Adding Capability of Simulating Complex Fenestration Systems (CFS)

As of now, the prototype can only handle simple fenestration systems. Future improvement could be to include the simulation of Complex Fenestration Systems (CFS) such as windows with blinds, fritted glass, and laser-cut panels. Also, the incorporation of RADIANCE 3-Phase methodology and 5-Phase methodology in the current process to evaluate CFS.

8.6.3. Daylight Matrices

The functionality of generating different daylight matrices such as Daylight Autonomy (DA), Useful Daylight Illuminance (UDI), Daylight Saturation Percentage (DSP) and Annual Sunlight Exposure (ASE) that are available in tools such as DIVA, Ladybug and Honeybee and mapping the output on to the work plane for graphical representation would need to be added to the prototype.

8.6.4. Integrating Glare Analysis

Also, integrating the glare analysis tools such as EVALGLARE to study the glare for daylighting studies and reporting of different glare matrices would be a useful feature.

8.6.5. Dynamo Package of REVIT2RADIANCE for REVIT

Currently, visual scripting tools like Grasshopper for Rhino 3D and Dynamo for Revit are widely used for creating complex geometry and parametric modeling. A Dynamo package of REVIT2RADIANCE for Revit could be developed to take

advantage of the capabilities of visual scripting and also allowing customization of the tool by users.

8.6.6. Application of the Tool in Academic Environment

Finally, it would be a worthwhile exercise to further test this prototype in the architectural design studio with students and academicians to better understand the ease of using this new tool. Also, comparing the process of using the tool against existing methodologies, also used in the studio in carrying out daylight analysis of the design projects would be a useful exercise.

REFERENCES

Aish, R., & Woodbury, R. (2005). Multi-level interaction in parametric design. *International Symposium on Smart Graphics*, 151–162. Springer.

Altman, E. (2005). Computers and Lighting. *Lighting Design + Application*, *December*, 57–62.

An, J., & Mason, S. (2010). *Integrating Advanced Daylighing Analysis into Building Energy Analysis*. (August).

Andersen, M., Rubin, M., & Scartezzini, J.-L. (2003). Comparison Between Ray-tracing Simulations and Bi-directional Transmission Measurements on Prismatic Glazing. *Solar Energy*, *74*, 157–173.

Apian-Bennewitz, P., Goller, M., Herkel, S., Kovach-Hebling, A., & Wienold, J. (1998). Computer-oriented building design: Advances in daylighting and thermal simulation tools. *Renewable Energy*. https://doi.org/10.1016/S0960-1481(98)00089-5

Apian-Bennewitz, P., & Von Der Hardt, J. (1998). Enhancing and calibrating a goniophotometer. *Solar Energy Materials and Solar Cells*. https://doi.org/10.1016/S0927-0248(98)00082-8

Arecchi, A., Messadi, T., & Koshel, R. J. (2010). Integrating Sphere. In *Field Guide to Illumination* (pp. 67–67). https://doi.org/10.1117/3.764682.p67

Arvo, J. (1986). Backward ray tracing. *Developments in Ray Tracing*.

ASHRAE. (2014). ANSI/ASHRAE Standard 140-2001: Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs. *Ashrae*.

Asl, M. R., Bergin, M., AdamMenter, & Yan, W. (2014). BIM-based Parametric Building Energy Performance MultiObjective Optimization. *32nd ECAADe Conference*.

Autodesk. (2017). Modeling Global Illumination with Radiosity. Retrieved from https://knowledge.autodesk.com/support/3ds-max/learn-explore/caas/CloudHelp/cloudhelp/2018/ENU/3DSMax-Archive/files/GUID-C5A3C77B-794B-4444-9783-7F2EA11C16BD-htm.html

Autodesk. (2013). Autodesk Revit. *Http://Www.Autodesk.Com/Products/Autodesk-Revit-Family/Overview*.

Autodesk, F. B. X. (2011). *Autodesk fbx*.

Baker, N., & Steemers, K. (2014). *Daylight design of buildings: a handbook for architects and engineers*. Routledge.

Baker, S. M. (1990). Modeling complex daylighting with DOE 2.1C. *The DOE-2 User New*, *11*(1).

Baker, N. V, Fanchiotti, A., & Steemers, K. (2013). *Daylighting in architecture: a European reference book*. Routledge.

Bazjanac, V. (2002). *Building Information Modelling for the e-Lab at LBNL*.

Bazjanac, V. (2008). IFC BIM-based methodology for semi-automated building energy performance simulation. *CIB-W78 25th International Conference on Information Technology in Construction*.

Bryan, H. (1981). *QUICKLITE 1: A DAYLIGHTING PROGRAM FOR THE TI-59*

CALCULATOR.

Bryan, H. J., & Carlberg, D. B. (1985). Development of protractors for calculating the effects of daylight from clear skies. *Journal of the Illuminating Engineering Society*. https://doi.org/10.1080/00994480.1985.10748804

BT. (2008). *Building Technology Program*.

Carmody, J., Selkowitz, S., Lee, eleanor s., Arashteh, D., & Willmert, T. (2004). Window System for High-Performance Buildings. *WW Norton&Company*.

Carroll, W. L., & Hitchcock, R. J. (2005). *DELIGHT2 DAYLIGHTING ANALYSIS IN ENERGY PLUS: INTEGRATION AND PRELIMINARY USER RESULTS*.

CBI. (2008). *Commercial Building Initiative*.

Chopra, A. (2012). *Introduction to google sketchup*. John Wiley & Sons.

Clarke, J., Hensen, J., & Janák, M. (1998). Integrated Building Simulation: State-of-the-Art. *Proc. Indoor Climate of Buildings*.

Conforti, F. (2010). *Inside Microstation V8 XM*. Cengage Learning.

Contoyannis, D. (2010). Daylight and Whole-Building Energy Analysising Radiance in IES <Virtual Environment>. *Daylighting Forum 2010*, *May*.

Crawley, D. B., Lawrie, L. K., Winkelmann, F. C., Buhl, W. F., Huang, Y. J., Pedersen, C. O., … Glazer, J. (2001). EnergyPlus: creating a new-generation building energy simulation program. *Energy and Buildings*, *33*(4), 319–331.

Crone, S. (1992). Radiance users manual. *Glass*.

De Carli, M., De Giuli, V., & Zecchin, R. (2008). Review on visual comfort in office buildings and influence of daylight in productivity. *11th International Conference Indoor Air, Copenhagen*.

Dilaura, D. L., & Hauser, G. A. (1978). On Calculating the Effects of Daylighting in Interior Spaces. *Journal of the Illuminating Engineering Society*. https://doi.org/10.1080/00994480.1978.10748561

Dong, B., Lam, K. P., Huang, Y. C., & Dobbs, G. M. (2007). A comparative study of the IFC and gbXML informational infrastructures for data exchange in computational design support environments. *IBPSA 2007 - International Building Performance Simulation Association 2007*.

Dresler, A. (1954). The "Reflected Component" in Daylighting Design. *Lighting Research and Technology*. https://doi.org/10.1177/147715355401900203

Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2011). *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors*. John Wiley & Sons.

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Kadner, S., Minx, J., Brunner, S., … Zwickel, T. (2014). Technical Summary. In: Climate Change 2014: Mitigation of Climate Change. In *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. https://doi.org/10.1103/PhysRevD.70.106002

Ellis, P. G., Strand, R. K., & Baumgartner, K. T. (2004). *SIMULATION OF TUBULAR DAYLIGHTING DEVICES AND DAYLIGHTING SHELVES IN ENERGYPLUS*.

Energy Design Resources. (2014). *Skylighting Design Guidelines*. Retrieved from https://energydesignresources.com/med%0Aia/19173822/skylighting-

designguidelines_final_2014-02-19.pdf

Estes, M. J., Newsom, T., & Susan., P. E. S. (2004). Daylighting Prediction Software : Comparative Analysis and Application. *Fourteenth Symposium on Improving Building Systems in Hot and Humid Climates*.

Evangelos, C. D., & David, A. C. N. (2005). *Computer Simulation of Daylight: a comparison for architect's utilization* (pp. 13–16). pp. 13–16.

Fischer, F., & Golubkow, K. (2010). ArchiCAD 13. In *ArchiCAD 13*. https://doi.org/10.1007/978-3-8348-9675-9

Fletcher, S. (2007). CERA:Alternative Energy Sources Remain Hot Industry Topic. *Oil and Gas Journal*, *105*(8), 31.

Galasiu, A. D., & Atif, M. R. (2002). Applicability of daylighting computer modeling in real case studies: Comparison between measured and simulated daylight availability and lighting consumption. *Building and Environment*, *37*(4), 363–377. https://doi.org/10.1016/S0360-1323(01)00042-7

Geebelen, B. (2003). Daylighting Computation Methods: From Dot Chart to Digital Simulation. *Syllabus Studiedag Daglichttoetreding in Gebouwen, 6 February 2003*.

Glassner, A. S. (2002). *An Introduction to Ray Tracing*. San Francisco, CA: Morgan Kaufmann Publishers, Inc.

Grondzik, W. T., & Kwok, A. G. (2019). *Mechanical and electrical equipment for buildings*. John Wiley & Sons.

Herbert, H. K., & Irving, F. H. (1921). SKY-BRIGHTNESS AND DAYLIGHT-ILLUMINATION MEASUREMENT. *Monthly Weather Review*, *49*(9), 481–488.

Heschong, L. (2012). DAYLIGHT METRICS PIER Daylighting Plus Research Program. *Public Interest Energy Research (PIER) Program*, 387.

Hirsch, J. J. (2010). *eQUEST version 3.64 and DOE-2.2 version 47 Released*. Camarillo,CA: Lawrence Berkeley National Laboratory,James J. Hirsch and Associates.

Hitchcock, R. J., & Carroll, W. L. (2003). DElight: A Daylighting and Electric Lighting Simulation Engine. *Eighth International IBPSA Conference*.

Hopkinson, Petherbridge, & Longmore. (1954). An empirical formula for the computation of indirect component of daylight factor. *Transactions of the Illuminating Engineering Society*, *19*(7), 201–219.

Hopkinson, Petherbridge, & Longmore. (1966). *Daylighting*. London: Heinemann.

Hopkinson, R. G. (1972). Glare from daylighting in buildings. *Applied Ergonomics*, *3*(4), 206–215. https://doi.org/10.1016/0003-6870(72)90102-0

IESNA. (2002). IESNA LIGHTING DESIGN SOFTWARE SURVEY 2002. *Lighting Design + Application*, *July*, 35–42.

IESNA. (2012). Standard LM-83-12. Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). *Illuminating Engineering Society of North America, New York, USA*.

Igawa, N., Nakamura, H., & Matsuura, K. (1999). Sky Luminance Distributuion Model for Simulation of Daylit Environment. *Building Simulation 99: International IBPSA Conference*.

International Energy Agency. (2018). 2018 World Energy Outlook: Executive Summary.

Oecd/Iea, 11. Retrieved from www.iea.org/t&c/

Iversen, A., Roy, N., Hvass, M., Jørgensen, M., Christoffersen, J., Osterhous, W., & Johnsen, K. (2013). *Daylight calculations in practice: An investigation of the ability of nine daylight simulation programs to calculate the daylight factor in five typical rooms*.

James, A. L. (1992, April). *The Evolution of Performance Indicators for the Evaluation of Daylighting Systems*.

Jin, R., Zhong, B., Ma, L., Hashemi, A., & Ding, L. (2019). Integrating BIM with building performance analysis in project life-cycle. *Automation in Construction*. https://doi.org/10.1016/j.autcon.2019.102861

Johnsen, K., & Watkins, R. (2010). *Daylight in buildings*.

Jokela, M., Keinänen, A., Lahtela, H., Lassila, K., & Oy, I. O. G. (1997). Integrated building simulation tool RIUSKA. *Building Simulation*.

Kim, J. B., Jeong, W., Clayton, M. J., Haberl, J. S., & Yan, W. (2015). Developing a physical BIM library for building thermal energy simulation. *Automation in Construction*. https://doi.org/10.1016/j.autcon.2014.10.011

Kim, W., & Kim, J. T. (2010). A Position Index Formula for Evaluation of Glare Source in the Visual Field. *Indoor and Built Environment*, *20*(1), 47–53. https://doi.org/10.1177/1420326X10389267

Klems, J H. (1993). *A new method for predicting the solar heat gain of complex fenestration systems I. Overview and Derivation of the Matrix Layer Calculation*.

Klems, Joseph.H. (1994). A New Method for Predicting the Solar Heat Gain of Complex Fenestration Systems I. Overview and Dirivation of the Matrix Layer Calculation. *ASHRAE Transactions*, *100*(1).

Konis, K., & Selkowitz, S. (2017). *Effective daylighting with high-performance facades: emerging design practices*. Springer.

Konstantoglou, M., Jonsson, J. C., & Lee, E. (2009, June). *Simulating Complex Window Systems using BSDF Data*.

Kota, S., & Haberl, J. S. (2009). Historical Survey of Daylighting Calculations Methods and Their Use in Energy Performance Simulations. *Proceedings of the Ninth International Conference for Enhanced Building Operations*.

Kota, S., Haberl, J. S., Clayton, M. J., & Yan, W. (2014). Building Information Modeling (BIM)-based daylighting simulation and analysis. *Energy and Buildings*, *81*. https://doi.org/10.1016/j.enbuild.2014.06.043

Koti, R., & Addison, M. (2007, July). *An Assessment of Aiding DOE-2.1Es Simplified Daylighting Method with Daysim's Daylight Illuminances*.

Krarti, M. (2012). ENERGY AUDIT OF BUILDING SYSTEMS AN ENGINEERING APPROACH. In *Mechanical Engineering Series*. https://doi.org/10.1073/pnas.0703993104

Kumar, S. (2008). *Interoperability between building information models (BIM) and energy analysis programs*. University of Southern California.

Lagios, K., Niemasz, J., & Reinhart F, C. (2010). Animated Building Performance Simulation (Abps) – Linking Rhinoceros / Grasshopper With Radiance / Daysim. *Conference Proceedings of SimBuild 2010*.

Lechner, N. (2014). *Heating, cooling, lighting: Sustainable design methods for architects*. John wiley & sons.

Lee, G., Sacks, R., & Eastman, C. M. (2006). Specifying parametric building object behavior (BOB) for a building information modeling system. *Automation in Construction*. https://doi.org/10.1016/j.autcon.2005.09.009

Littlefair, P. J. (1992). Daylight coefficients for practical computation of internal illuminances. *Lighting Research & Technology*. https://doi.org/10.1177/096032719202400302

Mardaljevic, J. (1995). Validation of a lighting simulation program under real sky conditions. *Lighting Research & Technology*. https://doi.org/10.1177/14771535950270040701

Mardaljevic, John. (1995). Validation of a lighting simulation program under real sky conditions. *Lighting ResearchTechnology*, *27*(4), 181–188.

Mardaljevic, John. (2000a). *Daylight simulation: Validation, Sky models, and Daylight Coefficients*.

Mardaljevic, John. (2000b). Simulation of annual daylighting profiles for internal illuminance. *Lighting ResearchTechnology*, *32*(2), 111–118.

Marsh, A. (1997). *Performance Analysis and Conceptual Design (Phd Dissertation)*.

Marsh, A. (2003). The Interaction of Radiance and ECOTECT. *5th International Radiance Scientific Workshop*.

Martens, B., & Peter, H. (2004). *ArchiCAD*. Springer Science & Business Media.

McConahey, E., Haves, P., & Christ, T. (2002). *The integration of engineering and architecture: a perspective on natural ventilation for the new San Francisco federal building*.

McGrew, J. (2006). REVIT TO RADIANCE (VIA AN EXPENSIVE TRANSLATOR. Retrieved from https://www.becausewecan.design/blog/2006/05/17/revit-to-radiance-via-an-expensive-translator

McHenry, K., & Bajcsy, P. (2008). An overview of 3D data content, file formats and viewers. In *Technical Report Image Spatial Data Analysis Group National Center for Supercomputing Applications*.

McNeel, R. (2015). Rhinoceros. *NURBS Modleing for Windows: Http://Www. Rhino3d. Com/Jewelry. Htm*.

McNeil, A., Jonsson, C. J., Appelfeld, D., Ward, G., & Lee, E. S. (2013). A validation of a ray-tracing tool used to generate bi-directional scattering distribution functions for complex fenestration systems. *Solar Energy*, *98*(PC), 404–414. https://doi.org/10.1016/j.solener.2013.09.032

McNeil, A. (2013). The three-phase method for simulating complex fenestration with radiance. *Lawrence Berkley National Laboratory*.

McNeil, Andy. (2013). The five-phase method for simulating complex fenestration with radiance. *Lawrence Berkeley National Laboratory, Berkeley, CA, USA*.

McNeil, Andy. (2014). BSDFs, Matrices and Phases. *13th International Radiance Workshop*, *158*.

Milan, J. (1999). Coupling building energy and lighting simulation. *Proceedings of the 5th International IBPSA Conference*, 313–319.

Milan, J., & Macdonald, I. (1999). Current state-of-the-art of integrated thermal and lighting simulation and future issues. *Proceedings of Building Simulation*.

Millet, M. S., Adams, C., & Bedrick, J. R. (1980). *GRAPHIC DAYLIGHTING DESIGN METHOD: INCLUDING CLEAR SKY CONDITIONS.*

Mistrick, R. G. (2000). Desktop radiance overview. *The Pennsylvania State University, USA, Pacific Gas and Electric*.

Mistrick, R. G., & Choi, A. S. (1999). A comparison of the visual comfort probability and unified glare rating systems. *Journal of the Illuminating Engineering Society*, *28*(2), 94–101. https://doi.org/10.1080/00994480.1999.10748278

Moore, F. (1985). *Concepts and Practice of Architectural Daylighting*. New York: Van Nostrand Reinhold.

Mousiadis, T., & Mengana, S. (2016). Parametric BIM: Energy Performance Analysis Using Dynamo for Revit. *BIM-Dynamo*.

Nabil, A, & Mardaljevic, J. (2006). Useful daylight illuminance: A replacement for daylight factors. *Energy and Buildings*, *38*(4), 905–913.

Nabil, Azza, & Mardaljevic, J. (2006). Useful daylight illuminances: A replacement for daylight factors. *Energy and Buildings*. https://doi.org/10.1016/j.enbuild.2006.03.013

NIMBS Committe. (2007). National Building Information Modeling Standard. *Nbim*. https://doi.org/10.1017/CBO9781107415324.004

Oh, S., & Haberl, J. S. (2016a). Origins of analysis methods used to design high-performance commercial buildings: Whole-Building energy simulation. *Science and Technology for the Built Environment*. https://doi.org/10.1080/23744731.2015.1063958

Oh, S., & Haberl, J. S. (2016b). Origins of analysis methods used to design high-performance commercial buildings: Whole-Building energy simulation. *Science and Technology for the Built Environment*. https://doi.org/10.1080/23744731.2015.1063958

Omura, G. (1989). *Mastering AutoCAD*. Sybex San Francisco etc.

Perez, R., Seals, R., & J.Michalsky, J. (1993). All-weather model for sky luminance distribution-Preliminary configuration and validation. *Solar Energy*, *50*(3), 235–245.

Reinhart, C, & Breton, P. F. (2009). Experimental validation of 3ds Max® design 2009 and Daysim 3.0. *LEUKOS*, *6*(1).

Reinhart, C F, & Walkenhorst, O. (2001). Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. *Energy and Buildings*, *32*(7), 683–697.

Reinhart, Christoph F., Mardaljevic, J., & Rogers, Z. (2006). Dynamic daylight performance metrics for sustainable building design. *LEUKOS - Journal of Illuminating Engineering Society of North America*. https://doi.org/10.1582/LEUKOS.2006.03.01.001

Reinhart, Christoph F., & Walkenhorst, O. (2001). Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. *Energy and Buildings*. https://doi.org/10.1016/S0378-7788(01)00058-5

Reinhart, Christoph, & Fitz, A. (2004). KEY FINDINGS FROM A ONLINE SURVEY ON THE USE OF DAYLIGHT SIMULATION PROGRAMS. *International Symposium on Daylighting Buildings (IEA SHC TASK 31)*.

Reinhart, Christoph, & Herkel, S. (2001). The simulation of annual daylight illuminance distributions- a state-of-the-art comparison of six RADIANCE-based methods. *Energy and Buildings*, *32*(1), 167–187.

Roberts, A., & Marsh, A. (2001). ECOTECT: Environmental Prediction in Architectural Education. *19th ECAADE - Education for Computer Aided Architectural Design in Europe*.

Robin, M., Christian, Kohler Dragan, C., Zhu, L., & Simon, Vidanovic Stephen, Czarnecki Dariush, A. (2019). *WINDOW 7 User Manual*.

Roudsari, Sadeghipour, R. (2018). Ladybug library and plugin for DynamoBIM. Retrieved August 11, 2019, from https://github.com/ladybug-tools/ladybug-dynamo

Roudsari, Sadeghipour, R. (2019). How does Honeybee[ ] set up the input files for multi phase daylight simulation. Retrieved August 11, 2019, from https://github.com/ladybug-tools/honeybee/wiki/How-does-Honeybee%5B-%5D-set-up-the-input-files-for-multi-phase-daylight-simulation

Roudsari, M. S., & Pak, M. (2013). Ladybug: A parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design. *Proceedings of BS 2013: 13th Conference of the International Building Performance Simulation Association*.

Rubin, M., JONSSON, J., Kohler, C., Klems, J., Curcija, D., & Stojanovic, N. (2007). Bidirectional Optical Properties of Slat Shading: Comparison Between Raytracing and Radiosity Methods. *Submitted to Solar Energy*.

Rundell, R., & Stowe, K. (2005). Building Information Modeling and Integrated Project Delivery-Design-Build Synergy in Action. *Design—Build Dateline, June*.

Saxena, M., Saxena, M., Ward, G., Perry, T., Heschong, L., & Higa, R. (2010, August). *Fourth National Conference of IBPSA-USA*.

Selkowitz, S. E., Kim, J.-J., Navvab, M., & Winkelmann, F. C. (1982). The DOE-2 and Superlite Daylighting Programs. *Passive 82*. Knoxville, TN.

Suk, J. Y., Schiler, M., & Kensek, K. (2013). Development of new daylight glare analysis methodology using absolute glare factor and relative glare factor. *Energy and Buildings*. https://doi.org/10.1016/j.enbuild.2013.04.020

Sun, Y., Wu, Y., & Wilson, R. (2017). Analysis of the daylight performance of a glazing system with Parallel Slat Transparent Insulation Material (PS-TIM). *Energy and Buildings*. https://doi.org/10.1016/j.enbuild.2017.01.001

Szokolay, S. V. (2014). *Introduction to architectural science: the basis of sustainable design. 2014*. Routledge.

Torcellini, P., Pless, S., Deru, M., & Crawley, D. (2006, June). *Zero Energy Buildings: A Critical Look at the Definition*. National Renewable Energy Laboratory US Department of Energy.

Tregenza, P. R. (1987). Subdivision of the sky hemisphere for luminance measurements. *Lighting ResearchTechnology*, *19*(1), 13–14.

Tregenza, P. R. (1989). Modification of the split-flux formulae for mean daylight factor

and internal reflected component with large external obstructions. *Lighting ResearchTechnology*, *21*(3), 125–128.

Tregenza, P. R. (1993). The Monte Carlo method in lighting calculations. *Lighting ResearchTechnology*, *15*(4), 163–170.

Tregenza, P. R., & Waters, I. M. (1983a). Daylight coefficients. *Lighting ResearchTechnology*, *15*(2), 65–71.

Tregenza, P. R., & Waters, I. M. (1983b). Daylight coefficients. *Lighting Research and Technology*, *15*(2), 65–71.

Tregenza, P., & Wilson, M. (2011). Daylighting : architecture and lighting design. In *Routledge*.

Trotter, A P. (1911). *Illumination, Its Distribution and Measurements*. London: Macmillan.

Trotter, Alexander Pelham. (1911). *Illumination: its distribution and measurement*. Macmillan and Company, limited.

Truesdell, K., Andrew, C., & Vladimir, B. (2018). A DETAILED METHODOLOGY FOR CLOUD-BASED DAYLIGHT ANALYSIS. *Building Performance Analysis Conference and SimBuild Co-Organized by ASHRAE and IBPSA-USA*. Chichago, IL.

Tsangrassoulis, A., & Bourdakis, V. (2003). Comparison of radiosity and ray-tracing techniques with a practical design procedure for the prediction of daylight levels in atria. *Renewable Energy*. https://doi.org/10.1016/S0960-1481(03)00078-8

U.S. Energy Information Administration. (2019). Electricity in the United States - Energy Explained, Your Guide To Understanding Energy - Energy Information Administration.

Ubbelohde, S., & Humann., C. (1998). Comparative evaluation of four daylighting software programs. *ACEEE Summer Study on Energy Efficiency in Buildings Proceedings, American Council for an Energy-Efficient Economy*.

Walkling, A., & Schierz, C. (2011, July 10). *COMPARISON BETWEEN THE CIE AND LITG METHOD FOR MINIMIZING OBTRUSIVE GLARE CAUSED BY BRIGHT LUMINAIRES IN THE FIELD*. SUN CITY, SOUTH AFRICA: International Commission on Illumination.

Walsh, J. W. T. (1951). The early years of Illuminating engineering in Great Britain. *Transactions of the Illuminating Engineering Society*, *15*(3), 49–60.

Ward, G. and Shakespeare, R. (1998). Rendering with Radiance: The Art and Science of Lighting Visualization. In *Morgan Kaufman*.

Ward, G. (1992). *RADIANCE Visual Comfort Calculation* (Vol. 2009). Vol. 2009.

Ward, G. (1994). The RADIANCE Lighting Simulation and Rendering System. *Computer Graphics:Proceedings of '94 SIGGRAPH Conference*, 459–472.

Ward, G. (2009). *Fenestration and Annual simulation [PowerPoint slides]*.

Ward, G, & Rubinstein, F. (1988). A new technique for computer simulation of illuminated spaces. *Lawrence Berkeley Laboratory Report 23042*.

Ward, Greg, Shakespeare, R., Ashdowne, I., & Rushmeier, H. (1996). The materials and geometry format. *Available from: Radsite. Lbl. Gov/Mgf/Mgfdoc. Pdf [Accessed 1 July 2013]*.

Welle, B., Haymaker, J., & Rogers, Z. (2011). ThermalOpt: A methodology for automated BIM-based multidisciplinary thermal simulation for use in optimization environments. *Building Simulation*. https://doi.org/10.1007/s12273-011-0052-5

Wetter, M., Zuo, W., Nouidui, T. S., & Pang, X. (2014). Modelica buildings library. *Journal of Building Performance Simulation*, *7*(4), 253–270.

Whitted, T. (2005). An improved illumination model for shaded display. *ACM Siggraph 2005 Courses*, 4. ACM.

Wienold, J, & Christoffersen, J. (2006). Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. *Energy and Buildings*, *38*(7), 743–757.

Wienold, Jan. (2014). Daylight Glare Analysis and Metrics. *13th Radiance Workshop*. London.

Wienold, Jan, & Christoffersen, J. (2006). Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. *Energy and Buildings*. https://doi.org/10.1016/j.enbuild.2006.03.017

Winkelmann, F. C., Birdsall, B. E., Buhl, W. F., Ellington, K. L., & Erdem, A. E. (1993). *DOE-2 supplement, Version 2.1E*.

Winkelmann, F. C., & Selkowitz, S. (1985). Daylighting simulation in the DOE-2 building energy analysis program. *Energy and Buildings*, *8*(4), 271–286.

Yan, W., Clayton, M., Haberl, J., Jeong, W. S., Kim, J. B., Kota, S., … Dixit, M. (2013). Interfacing bim with building thermal and daylighting modeling. *Proceedings of BS 2013: 13th Conference of the International Building Performance Simulation Association*.

Yip, S.-F. (1972). *Daylighting in Architectural Design*. McGill.

APPENDIX A

PROJECT DIRECTORY FILES AND FOLDERS

ies	10-Jul-13 2:28 PM	File folder	
pts	02-Jul-18 11:31 AM	File folder	
rad	02-Jul-18 11:31 AM	File folder	
res	02-Jul-18 11:31 AM	File folder	
tmp	02-Jul-18 11:31 AM	File folder	
vf	02-Jul-18 11:31 AM	File folder	
wea	02-Jul-18 11:31 AM	File folder	
130304_Architectural.0002.rvt	10-Jul-13 7:46 PM	RVT File	17,252 KB
130304_Architectural.0003.rvt	10-Jul-13 9:57 PM	RVT File	17,256 KB
130304_Architectural.bat	10-Jul-13 2:31 PM	Windows Batch File	1 KB
130304_Architectural.hea	10-Jul-13 2:31 PM	HEA File	4 KB
130304_Architectural.rvt	31-Jan-14 9:57 AM	RVT File	17,256 KB
130304_Architectural_1.bat	10-Jul-13 2:31 PM	Windows Batch File	1 KB

RADIANCE AND DAYSIM INPUT FILES

B-1: Case600_Metric_FinvalVersion_sensor.pts (Sensor Point File for DAYSIM Simulation)

54.44 25.72 2.5 0 0 1 # 1101561
54.44 31.22 2.5 0 0 1 # 1101706
44.95 25.72 2.5 0 0 1 # 1101771
44.95 31.22 2.5 0 0 1 # 1101858
38.19 25.72 2.5 0 0 1 # 1101893
38.19 31.22 2.5 0 0 1 # 1101948
31.94 25.72 2.5 0 0 1 # 1101989
31.94 31.22 2.5 0 0 1 # 1102038
25.92 25.72 2.5 0 0 1 # 1102071
25.92 31.22 2.5 0 0 1 # 1102126
20.42 25.72 2.5 0 0 1 # 1102179
20.42 31.22 2.5 0 0 1 # 1102224
54.38 43.47 2.5 0 0 1 # 1102265
54.38

B-2: Case600_Metric_FinvalVersion_1.rad (Materials)

void glass AWGlazing
0
0
3 0.75 0.75 0.75

void plastic AWInteriorFinishWhite
0
0
5 0.83 0.83 0.83 0 0

void plastic AWExteriorWhite
0
0
5 0.85 0.85 0.85 0 0

void glass Glass11
0
0
3 0.39 0.39 0.39

void plastic Door---Panel
0
0
5 0.72 0.72 0.72 0.1 0.08

B-3: Case600_Metric_FinvalVersion_2.rad (Geometry)

Glass11 polygon 204405_0_0_0_0
0
0
9 -14.38 -8.1169 0.6662
-14.38 -8.1169 7.2064
-24.2016 -8.1169 0.6662

Glass11 polygon 204405_0_0_0_1
0
0
9 -24.2016 -8.1169 7.2064
-24.2016 -8.1169 0.6662
-14.38 -8.1169 7.2064

Sash polygon 204405_0_1_0_0
0
0
9 -14.3748 -8.169 7.2117
-14.38 -8.169 7.2064
-14.3748 -8.169 0.6615

Sash polygon 204405_0_1_0_1
0
0
9 -14.38 -8.169 7.2064
-14.3748 -8.169 7.2117
-24.2016 -8.169 7.2064

B-4: Case600_Metric_FinvalVersionsky.rad (Sky Description)

gensky 6 21 11:12CST +s -a 39.74 -o 104.98
Local solar time: 10.18
Solar altitude and azimuth: 61.8 -63.0
Ground ambient level: 15.5

void light solar
0

0
3 7.07e+006 7.07e+006 7.07e+006

solar source sun
0
0
4 0.421211 -0.215066 0.881095 0.5

void brightfunc skyfunc
2 skybr skybright.cal
0
7 1 1.62e+001 2.69e+001 9.70e-001 0.421211 -0.215066 0.881095
skyfunc glow sky_mat
0
0
4 1 1 1 0
sky_mat source sky
0
0
4 0 0 1 180
skyfunc glow ground_glow
0
0
4 1 .8 .5 0
ground_glow source ground
0
0
4 0 0 -1 180

B-5: Case600_Metric_FinvalVersion_view. vf (View Description)

rview -vta -vp -21.214 8.501 5.741 -vd 0.451 -0.893 0 -vu 0 0 1 -vh 35.353 -vv 35.353 -
vo 0 -va 0 -vs 0 -vl 0 -vv 180 -vh 180

RADIANCE AND DAYSIM HEADER FILE

```
# this is daysim header file
project_name Case600_Metric_FinvalVersion
project_directory C:\Users\SANDEEP\Documents\PBIMTEST\BESTTEST600\
bin_directory  C:/DAYSIM/bin/
tmp_directory C:\Users\SANDEEP\Documents\PBIMTEST\BESTTEST600\tmp\
material_directory      C:/DAYSIM/materials/
ies_directory  C:/DAYSIM/ies/
# ==========================================
place Denver Intl Ap_USA
latitude 39.83
longitude 104.65
time_zone 105
site_elevation 1650.0
ground_reflectance 0.2
wea_data_file C:\DAYSIM\wea\USA_CO_Denver.Intl.AP.725650_TMY3.wea
wea_data_file_units 1
first_weekday 1
time_step 60
wea_data_short_file wea/USA_CO_Denver.Intl.AP.725650_TMY3.wea
wea_data_short_file_units 1
lower_direct_threshold 2
lower_diffuse_threshold 2
output_units 2
# ===========================================
material_file rad/Case600_Metric_FinvalVersion_1.rad
geometry_file rad/Case600_Metric_FinvalVersion_2.rad
scene_rotation_angle 00.00
sensor_file
C:\Users\SANDEEP\Documents\PBIMTEST\BESTTEST600\pts\Case600_Metric_Finv
alVersion_sensor.pts
radiance_source_files
2,C:\Users\SANDEEP\Documents\PBIMTEST\BESTTEST600\rad\Case600_Metric_Fi
nvalVersion_2.rad,C:\Users\SANDEEP\Documents\PBIMTEST\BESTTEST600\rad\Ca
se600_Metric_FinvalVersion_1.rad
shading 1
static_system res/Case600_Metric_FinvalVersion.dc
res/Case600_Metric_FinvalVersion.ill
sensor_file_unit 0 0 0
sensor_file_info 0 0 0
ViewPoint 0
```

output_unit_index 1
display_unit_index 1
viewpoint_file no_DGP_view_file_provided
DC_file_format Daysim_original
==
NumberOfLuminaireSchedules 0
LuminaireScheduleList
CorrespondingBuildingModelFile
FloorMaterialList
LuminaireLayoutRadFileList
==
GAMonth 0
GADay 0
GAHour 0.0
GAInterval 1
GAIntervalScale 0.0
GAFontSize 12
GASkySelectIndex 2
GATaskStatus 0 0 0 0 0 0
GASignificantDigit 4
GASignificantDigitDimmingLevel 4
GAMinMaxIllForDA 500.0 1000.0
==
ab 5
ad 1000
as 20
ar 300
aa 0.1
lr 6
st 0.1500
sj 1.0000
lw 0.004000
dj 0.0000
ds 0.200
dr 2
dp 512
==
daylight_factor res/Case600_Metric_FinvalVersion.df
daylight_autonomy res/Case600_Metric_FinvalVersion.da
electric_lighting res/Case600_Metric_FinvalVersion.el.htm
direct_sunlight_file res/Case600_Metric_FinvalVersion.dir
thermal_simulation_active res/Case600_Metric_FinvalVersion_active.intgain.csv
thermal_simulation_passive res/Case600_Metric_FinvalVersion_passive.intgain.csv
DDS_sensor_file res/Case600_Metric_FinvalVersion.dds

DDS_file res/Case600_Metric_FinvalVersion.sen
percentage_of_visible_sky_file res/Case600_Metric_FinvalVersion.sky_view.dat
daylight_factor_RGB res/Case600_Metric_FinvalVersion.daylight_factor.DA
daylight_autonomy_active_RGB
res/Case600_Metric_FinvalVersion.daylight_autonomy.DA
continuous_daylight_autonomy_active_RGB
res/Case600_Metric_FinvalVersion.continuous_daylight_autonomy.DA
DA_max_active_RGB res/Case600_Metric_FinvalVersion.DA_max.DA
UDI_100_active_RGB res/Case600_Metric_FinvalVersion.UDI_100.DA
UDI_100_2000_active_RGB res/Case600_Metric_FinvalVersion.UDI_100_2000.DA
UDI_2000_active_RGB res/Case600_Metric_FinvalVersion.UDI_2000.DA
DSP_active_RGB
res/Case600_Metric_FinvalVersion.DaylightSaturationPercentage.DA
===
zone_description "zone"
zone_area 0.0
 ====================
= user description
 ====================
minimum_illuminance_level 500
daylight_savings_time 1
buildIndexFile true
buildTimeFile true
user_profile 2
active 100 1 1
passive 0 2 2 0
===========================
= electric lighting system
===========================
electric_lighting_system 1
 1 #manual 1.5 0.0
  installed_ligting_power_density 1.5
  standby_power 0.0
  delay_time 5
  ballast_loss_factor 20
 =======================
 = blind control system
 =======================
 blind_control 1
 0 #static_shading_device

APPENDIX D

BATCH FILES TO RUN RADIANCE AND DAYSIM

D-1: Case600_Metric_FinvalVersion.bat (RADIANCE)
path = C:\Radiance\bin
cd C:\Users\SANDEEP\Documents\PBIMTEST\BESTTEST600\
copy wea\Case600_Metric_FinvalVersion_sky.txt wea\sky.bat
call wea\sky.bat
copy wea\sky.txt+ wea\Case600_Metric_FinvalVersion_skymat.txt
wea\Case600_Metric_FinvalVersionsky.rad

oconv wea\Case600_Metric_FinvalVersionsky.rad
rad\Case600_Metric_FinvalVersion_1.rad rad\Case600_Metric_FinvalVersion_2.rad >
tmp\Case600_Metric_FinvalVersion.oct

rpict -vf vf\Case600_Metric_FinvalVersion_view.vf -x 1024 -y 1024 -ps 4 -pt .05 -pj .9 -
dp 512 -ab 2 -aa .15 -ar 128 -ad 512 -as 256 -lr 8 -lw .002
tmp\Case600_Metric_FinvalVersion.oct> res\Case600_Metric_FinvalVersion.pic
pcond -h
res\Case600_Metric_FinvalVersion.pic>res\Case600_Metric_FinvalVersion_HS.pic
falsecolor -ip res\Case600_Metric_FinvalVersion.pic -s 5000 -n 10 -l
Lux>res\Case600_Metric_FinvalVersion_FC.pic
falsecolor -i res\Case600_Metric_FinvalVersion.pic -p
res\Case600_Metric_FinvalVersion_HS.pic -cl -s 5000 -n 10 -l Lux >
res\Case600_Metric_FinvalVersion_CP.pic

D-2: Case600_Metric_FinvalVersion_1.bat (DAYSIM)
C:
cd C:\DAYSIM\bin\
start /high /wait gen_dc
C:\Users\SANDEEP\Documents\PBIMTEST\BESTTEST600\Case600_Metric_FinvalV
ersion.hea
cd C:\DAYSIM\bin\
ds_illum
C:\Users\SANDEEP\Documents\PBIMTEST\BESTTEST600\Case600_Metric_FinvalV
ersion.hea

APPENDIX E

FILES OF RADIANCE AND DAYSIM SIMUALTION RESULTS

Case600_Metric_FinvalVersion.dc	22-May-13 9:00 PM	DC File	10 KB
Case600_Metric_FinvalVersion.ill	22-May-13 9:00 PM	ILL File	203 KB
Case600_Metric_FinvalVersion.pic	21-Jan-14 11:02 AM	PIC File	1,550 KB
Case600_Metric_FinvalVersion_CP.pic	21-Jan-14 11:02 AM	PIC File	2,061 KB
Case600_Metric_FinvalVersion_FC.pic	21-Jan-14 11:02 AM	PIC File	337 KB
Case600_Metric_FinvalVersion_HS.pic	21-Jan-14 11:02 AM	PIC File	2,031 KB
Case600_Metric_FinvalVersion_V1.pic	24-Apr-13 9:42 PM	PIC File	141 KB

APPENDIX F

DAYSIM ILLUMINATION PROFILE

January 1st (1 to 24 Hours)

```
1 1 1.000  0 0 0
1 1 2.000  0 0 0
1 1 3.000  0 0 0
1 1 4.000  0 0 0
1 1 5.000  0 0 0
1 1 6.000  0 0 0
1 1 7.000  0 0 0
1 1 8.000  280 185 88
1 1 9.000  3197 2376 846
1 1 10.000  16031 15113 2998
1 1 11.000  6400 19020 3665
1 1 12.000  6661 6589 3938
1 1 13.000  6537 14897 3219
1 1 14.000  17328 15489 3110
1 1 15.000  8466 6479 1771
1 1 16.000  2834 1770 741
1 1 17.000  438 222 143
1 1 18.000  0 0 0
1 1 19.000  0 0 0
1 1 20.000  0 0 0
1 1 21.000  0 0 0
1 1 22.000  0 0 0
1 1 23.000  0 0 0
1 1 24.000  0 0 0
```

APPENDIX G

CAD GEOMETRY FILE FORMATES

G-1: Sample AutoCAD *.DXF file

```
0                       AcDbEntity              10                      -                       11
SECTION                 8                       -                       2.85359141379811        -
2                       0                       0.37850557551908        5                       0.57600557551908
ENTITIES                100                     58                      30                      65
0                       AcDbLine                20                      0.0                     21
LINE                    10                      -                       11                      0.64640691830188
5                       -                       1.85359223284811        -                       52
C0                      0.57600557551908        5                       1.30725557551908        31
100                     65                      30                      4                       0.0
AcDbEntity              20                      0.0                     21                      0
8                       -                       11                      -                       LINE
0                       2.29109223284811        0.24649442448091        2.85359141379811        5
100                     5                       42                      5                       AF
AcDbLine                30                      21                      31                      100
10                      0.0                     -                       0.0                     AcDbEntity
0.44399442448091        11                      1.85359223284811        0                       8
41                      -                       5                       LINE                    FRAME2
20                      0.59163559567446        31                      5                       100
0.64640691830188        92                      0.0                     B1                      AcDbLine
52                      21                      0                       100                     10
30                      -                       LINE                    AcDbEntity              -
0.0                     2.29109222522029        5                       8                       1.30725557551908
11                      2                       B3                      GLASS                   4
-                       31                      100                     100                     20
0.57600557551908        0.0                     AcDbEntity              AcDbLine
65                      0                       8                       10
21                      LINE                    FRAME2                  -
0.64640691830188        5                       100                     0.39100557551908
52                      BB                      AcDbLine                6
31                      100                     10                      20
0.0                     AcDbEntity              -                       -                       -
0                       8                       0.74475557551908        2.24979223284811        3.54159209281811
LINE                    0                       49                      4                       5
5                       100                     20                      30                      30
BD                      AcDbLine                -                       0.0                     0.0
100                     10                      3.54159209281811        11                      11
AcDbEntity              -                       5                       -                       -
8                       0.39100557551908        30                      0.39100557551908        0.99475557551908
0                       6                       0.0                     67                      48
100                     20                      11                      21                      21
AcDbLine                -                       0.89586942448091        0.64640691830188        -
10                      2.29109223284811        55                      52                      3.54159209281811
0.44399442448091        5                       21                      31                      5
41                      30                      -                       0.0                     31
20                      0.0                     3.54159209281811        0                       0.0
-                       11                      5                       LINE                    0
2.29109223284811        0.25899442448091        31                      5                       LINE
5                       44                      0.0                     B0                      5
30                      21                      0                       100                     AE
0.0                     -                       LINE                    AcDbEntity              100
11                      2.29109223284811        5                       8                       AcDbEntity
0.50524442448091        5                       B2                      GLASS                   8
51                      31                      100                     100                     FRAME1
21                      0.0                     AcDbEntity              AcDbLine                100
-                       0                       8                       10                      AcDbLine
2.29109223284811        LINE                    FRAME2                  -                       10
5                       5                       100                     0.57600557551908        -
31                      B8                      AcDbLine                65                      AcDbEntity
0.0                     100                     10                      20                      8
0                       AcDbEntity              0.50524442448091        -                       0
LINE                    8                       51                      2.29109223284811        0
5                       SPACER                  20                      5                       ENDSEC
BC                      100                                             30                      0
100                     AcDbLine                                        0.0                     EOF
```

216

G-2: Sample Wavefront *.OBJ file
Created with Kaydara FBX

g
Basic_Wall_exterior_wall__160
749_
v 0.000000 0.000000 0.000000
v 0.000000 20.000000 0.000000
v 0.000000 20.666666 0.000000
v 0.000000 20.666666
10.000000
v 0.000000 20.000000
10.000000
v 0.000000 0.000000 10.000000
v 0.000000 8.044922 6.910156
v 0.000000 11.955078 6.910156
v 0.000000 11.955078 3.000000
v 0.000000 8.044922 3.000000
v -0.895833 -0.895833 0.000000
v -0.895833 -0.895833
10.000000
v -0.895833 20.666666
10.000000
v -0.895833 20.666666 -
0.000000
v -0.895833 8.044922 6.910156
v -0.895833 8.044922 3.000000
v -0.895833 11.955078
3.000000
v -0.895833 11.955078
6.910156
vt 0.000000 0.000000
vt 8.044922 3.000000
vt 8.044922 6.910156
vt 20.000000 0.000000
vt 20.000000 10.000000
vt -0.000000 10.000000
vt 11.955078 6.910156
vt 20.666667 0.000000
vt 20.666667 10.000000
vt 11.955078 3.000000
vt 21.114583 0.000000
vt 12.402995 -3.000000
vt 12.402995 -6.910156
vt 8.492839 -3.000000
vt 21.114583 -10.000000
vt 8.492839 -6.910156

vt -0.447917 -0.000000
vt -0.447917 -10.000000
vt 0.000000 21.114583
vt 0.000000 20.447917
vt 0.895833 21.114583
vt 0.000000 0.447917
vt 0.895833 -0.447917
vt 0.000000 0.333333
vt -0.000000 -0.333333
vt 0.895833 -0.333333
vt 0.000000 20.333333
vt 0.895833 21.229167
vt 0.000000 10.000000
vt -0.000000 0.000000
vt 1.266900 0.000000
vt 1.266900 10.000000
vt 0.447917 -10.000000
vt 0.447917 0.000000
vt -0.447917 0.000000
vt -0.447917 -10.000000
vt 0.000000 3.910156
vt 0.000000 0.000000
vt 0.895833 3.910156
vt 0.895833 0.000000
vt -0.000000 3.910156
vt 0.895833 3.910156
vt 0.000000 3.910156
vt 0.895833 3.910156
vn 1.000000 -0.000000
0.000000
vn -1.000000 0.000000
0.000000
vn 0.000000 0.000000 -
1.000000
vn 0.000000 0.000000 1.000000
vn 0.707107 -0.707107
0.000000
vn 0.000000 1.000000 0.000000
vn -0.000000 -1.000000
0.000000
vn 0.000000 0.000000 0.000000
vn 1.000000 0.000000 0.000000
vn 0.000000 0.000000 0.000000
vn 0.577350 0.577350 0.577350

vn 0.514496 0.514496 0.685994
vn 0.491539 0.573462 0.655386
vn 0.000000 0.000000 1.000000
vn 0.683736 0.254969 0.683736
vn 0.707107 0.000000 0.707107
vn -0.000000 0.641601
0.767039
vn 0.707107 0.000000 0.707107
f 1/1/1 10/2/10 7/3/7
f 10/2/10 1/1/1 2/4/2
f 5/5/5 6/6/6 7/3/7
f 7/3/7 6/6/6 1/1/1
f 5/5/5 7/3/7 8/7/8
f 2/4/2 3/8/3 5/5/5
f 5/5/5 8/7/8 2/4/2
f 5/5/5 3/8/3 4/9/4
f 2/4/2 8/7/8 9/10/9
f 2/4/2 9/10/9 10/2/10
f 14/11/14 17/12/17 18/13/18
f 17/12/17 14/11/14 16/14/16
f 13/15/13 18/13/18 15/16/15
f 18/13/18 13/15/13 14/11/14
f 16/14/16 11/17/11 15/16/15
f 11/17/11 16/14/16 14/11/14
f 15/16/15 12/18/12 13/15/13
f 12/18/12 15/16/15 11/17/11
f 3/19/3 2/20/2 14/21/14
f 1/22/1 11/23/11 14/21/14
f 1/22/1 14/21/14 2/20/2
f 5/24/5 4/25/4 13/26/13
f 6/27/6 13/26/13 12/28/12
f 13/26/13 6/27/6 5/24/5
f 12/29/12 11/30/11 1/31/1
f 1/31/1 6/32/6 12/29/12
f 4/33/4 3/34/3 14/35/14
f 14/35/14 13/36/13 4/33/4
f 16/37/16 15/38/15 10/39/10
f 7/40/7 10/39/10 15/38/15
f 17/41/17 16/38/16 9/42/9
f 10/40/10 9/42/9 16/38/16
f 18/37/18 17/38/17 8/39/8
f 9/40/9 8/39/8 17/38/17
f 15/43/15 18/38/18 8/40/8
f 8/40/8 7/44/7 15/43/15

G-3: Sample Radiance Material Geometry File (*.MGF) file

roof material
m floor_mat =
c
cxy 0.362 0.283
rd 0.0402
c
rs 0.0284 0.05

m glass =
sides 2
ir 1.52 0
c
rs 0.0725 0
c
cxy .23 .38
ts 0.5815 0

SOUTH WALL
#FRONT-1-P = POLYGON (0,0,0) (100,0,0)
(100,0,10) (0,0,10) ..

v FRONT-1-P.1 =
p 0 0 0
v FRONT-1-P.2 =
p 100 0 0
v FRONT-1-P.3 =
p 100 0 10
v FRONT-1-P.4 =
p 0 0 10

SB 12 WALL
SB12-P = POLYGON (100,0,0) (87.5,12.5,0)
(87.5,12.5,10) (100,0,10) ..

v SB12-P.1 =
p 100 0 0
v SB12-P.2 =
p 87.5 12.5 0
v SB12-P.3 =
p 87.5 12.5 10
v SB12-P.4 =
p 100 0 10

SB14-P = POLYGON (12.5,12.5,0) (0,0,0)
(0,0,10) (12.5,12.5,10) ..

v SB14-P.1 =
p 12.5 12.5 0

v SB14-P.2 =
p 0 0 0
v SB14-P.3 =
p 0 0 10
v SB14-P.4 =
p 12.5 12.5 10

SB15-P = POLYGON (12.5,12.5,0)
(87.5,12.5,0) (87.5,12.5,10) (12.5,12.5,10) ..

v SB15-P.1 =
p 12.5 12.5 0
v SB15-P.2 =
p 87.5 12.5 0
v SB15-P.3 =
p 87.5 12.5 10
v SB15-P.4 =
p 12.5 12.5 10

TOP-1-P = POLYGON (0,0,10) (100,0,10)
(87.5,12.5,10) (12.5,12.5,10) ..

v TOP-1-P.1 =
p 0 0 10
v TOP-1-P.2 =
p 100 0 10
v TOP-1-P.3 =
p 87.5 12.5 10
v TOP-1-P.4 =
p 12.5 12.5 10

F1-1-P = POLYGON (0,0,0) (100,0,0)
(87.5,12.5,0) (12.5,12.5,0) ..

v F1-1-P.1 =
p 0 0 0
v F1-1-P.2 =
p 100 0 0
v F1-1-P.3 =
p 87.5 12.5 0
v F1-1-P.4 =
p 12.5 12.5 0

# WF-1   =WINDOW   WIDTH = 45
X = 10 ..
# SET-DEFAULT FOR WINDOW
HEIGHT=4.0 GLASS-TYPE=W-1 Y=3 ..

218

```
# 10 0 3 / 10 + 45, 0 3 / 10 + 45, 0 3+4/ 10 0 3+4
                                                          # windows
v WF-1-P.1 =
p 10 0 3                                                 o WF-1
v WF-1-P.2 =                                              m glass
p 55 0 3                                                  f WF-1-P.1 WF-1-P.2 WF-1-P.3 WF-1-P.4
v WF-1-P.3 =
p 55 0 7                                                 o DF-1
v WF-1-P.4 =                                              m glass
p 10 0 7                                                  f DF-1-P.1 DF-1-P.2 DF-1-P.3 DF-1-P.4


# DF-1 = WINDOW WIDTH = 8  HEIGHT = 8
X = 70  Y = 0  GLASS-TYPE=DOORS

v DF-1-P.1 =
p 70 0 0
v DF-1-P.2 =
p 78 0 0
v DF-1-P.3 =
p 78 0 8
v DF-1-P.4 =
p 70 0 8


# floor polygon
o F1-1
        m floor_mat
        f F1-1-P.1 F1-1-P.2 F1-1-P.3 F1-1-P.4

o TOP-1
 m floor_mat
  f TOP-1-P.1 TOP-1-P.2 TOP-1-P.3 TOP-1-P.4

o FRONT-1
  m floor_mat
        fh FRONT-1-P.1 FRONT-1-P.2
FRONT-1-P.3 FRONT-1-P.4 - WF-1-P.1 WF-1-
P.2 WF-1-P.3 WF-1-P.4 - DF-1-P.1 DF-1-P.2
DF-1-P.3 DF-1-P.4
o SB12
  m floor_mat
  f SB12-P.1 SB12-P.2 SB12-P.3 SB12-P.4
o SB14
        m floor_mat
        f SB14-P.1 SB14-P.2 SB14-P.3 SB14-
P.4
o SB15
  m floor_mat
        f SB15-P.1 SB15-P.2 SB15-P.3 SB15-
P.4
```